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U.S. NAVAL TEST PILOT SCHOOL FLIGHT TEST MANUAL

SYSTEMS TESTING

NAVAL AIR WARFARE CENTER
AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

U.S. NAVAL TEST PILOT SCHOOL
FLIGHT TEST MANUAL

USNTPS FTM NO. 109

SYSTEMS TESTING

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This Flight Test Manual is published under the authority of the Commanding Officer, U.S. Naval Test Pilot School, and is intended primarily as a text for the pilots, engineers, and flight officers attending the school. Additionally, it is intended to be a reference document for those engaged in flight testing. Corrections and update recommendations to this manual are welcomed and may be submitted to:

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INTRODUCTION

1.1 WHY SYSTEMS FLIGHT TESTING

Aircraft system performance generally can be defined as the weapon system tasks that the system must execute for successful mission accomplishment. Expected system performance parameters must be an integral part of the weapon system design process. Given the user's performance expectations, the designer makes decisions regarding system choices and design parameters. He must choose the types of systems installed on the aircraft, their operating modes, the resolutions required for each system, and the operator interface required to allow the aircrew to use the systems to best tactical utility. All of these help tailor the design to give the system the desired performance characteristics.

Actual aircraft system performance characteristics are not always the same as the design or the predicted system performance characteristics. Therefore, there is a need for systems flight testing to determine the actual performance. Systems flight testing is defined as the process of determining aircraft systems characteristics, or evaluating the aircraft's and weapon system's ability to accomplish its mission. Determining aircraft systems performance depends upon fundamental knowledge in several disciplines, including: radar, communications, electro-optics, and navigation. The test team must understand the basic measurements, instrumentation techniques, and equipment used to gather the data needed to determine the various elements of a system's performance. The team uses these disciplines to form the basis for the flight test methods and techniques for systems flight testing.

Using appropriate test methods and techniques, the flight test team begins to answer questions about the system's predicted or actual performance such as:

1. What is the maximum and minimum range of the radar?
2. What is the resolution of the radar and electro-optic sensors?
3. How accurate is the navigation system?
4. How easily can targets be designated and weapons solutions defined?
5. How accurate is the weapon delivery system?

The results of systems flight testing are used for several purposes:

1. Determine mission suitability of the aircraft.
2. Determine if the aircraft meets specific contractual systems performance guarantees, or systems performance requirements as specified in the user generated requirements.
3. Provide data to construct aircraft flight manuals for use by operational aircrews.
4. Determine techniques and procedures for use by operational aircrews to attain optimum system performance.
5. Obtain research information to advance systems knowledge or to develop new flight test techniques.

1.2 FLIGHT TEST MANUAL OBJECTIVE

The objective of the Systems Flight Test Manual (FTM) is to serve as a practical reference guide for planning, executing, and reporting systems flight testing. The FTM is intended for use as a primary instructional tool at the U.S. Naval Test Pilot School (USNTPS) and as a reference document for those conducting systems flight testing at the Naval Air Warfare Center Aircraft Division Center (NAVAIRWARCENACDIV) or similar organizations interested in systems flight testing. It is not a substitute for systems textbooks. Rather, the FTM summarizes applicable theory to facilitate an understanding of the concepts, techniques, and procedures involved in successful flight testing. The FTM is directed to test pilots, test flight officers, and flight test engineers (FTE); it deals with the more practical and prominent aspects of systems issues, sometimes sacrificing exactness or completeness in the interest of clarity and brevity.

The FTM does not replace the Naval Air Warfare Center Report Writing Handbook. The FTM contains examples of systems performance parameters discussed in narrative and graphic format. It contains discussions of the effect various systems parameters have on mission performance and suitability, and a discussion of specification compliance where applicable.

Since this FTM is a text for USNTPS, it contains information relative to operations at USNTPS and NAVAIRWARCENACDIV; however, it does not contain information relative to the scope of a particular USNTPS syllabus exercise or to the reporting requirements for a particular exercise. Details of each flight exercise vary from time to time as resources and personnel change and are briefed separately to each class.

1.3 FLIGHT TEST MANUAL ORGANIZATION

1.3.1 MANUAL ORGANIZATION

The FTM is organized to simplify access to desired information. Although there is some cross referencing, in general, each chapter stands as a distinct unit. Discussions of systems test techniques are presented together with pertinent background analytic presentations. Most of the discussion applies to weapons systems in general; with specific examples given where appropriate. The contents are organized in a classical grouping and follow the chronology of the systems syllabus at USNTPS.

Chapter 1, Introduction, is an overview of the FTM including the objectives of systems testing, flight test conditions and test technique, and use of confidence levels.

Chapter 2, Cockpit Evaluation, is a discussion of the techniques and issues involved in evaluating the crew/vehicle interface.

Chapter 3, Radar Theory, is a discussion of the theory of radar operation.

Chapter 4, Air-to-Ground Radar Testing, is a discussion of test techniques used to determine air-to-ground radar performance.

Chapter 5, Air-to-Air Radar Testing, is a discussion of test techniques used to determine air-to-air radar performance.

Chapter 6, Navigation System Testing, is a discussion of the theory behind different navigation systems, and the test techniques used to test these different systems. Included are INS, GPS, Doppler, and LORAN systems.

Chapter 7, Electro-optic Systems Testing, is a discussion of the theory behind FLIR operation, and the test techniques used to determine FLIR performance.

Chapter 8, Electronic Warfare Testing, is a discussion of test techniques used to evaluate defensive sensors.

Chapter 9, Ordnance Testing, is a reprint of a training manual originally compiled to teach ordnance flight testing at the Strike Aircraft Test Squadron.

Chapter 10, Night Vision Device Testing, is a discussion of test techniques used to evaluate night vision goggles.

Chapter 11, Radar Cross Section Testing (to be developed)

Chapter 12, Software Testing (to be developed)

1.3.2 CHAPTER ORGANIZATION

Each chapter, with the exception of the three radar chapters, has the same internal organization where possible. Following the chapter introduction, the second section gives the purpose of the test. The third section is a review of the applicable theory. The fourth discusses the test methods and techniques, data requirements, data reduction, data analysis, and safety precautions applicable to those methods. The 3 chapters on radar are organized differently. The first radar chapter covers theory for both air-to-ground and air-to-air radars. The next two chapters cover air-to-ground and air-to-air testing in the same manner as the sections on other sensors.

1.4 EFFECTIVE TEST PLANNING

To plan a test program effectively, sound understanding of the theoretical background for the tests being performed is necessary. This knowledge helps the test team establish the optimum scope of tests, choose appropriate test techniques and data reduction methods, and present the test results effectively. Because time and money are scarce resources, test data should be obtained with a minimum expenditure of both. Proper application of theory ensures the tests are performed at the proper conditions, with appropriate techniques, and using efficient data collection methods.

1.5 RESPONSIBILITIES OF TEST PILOT/TEST FLIGHT OFFICER AND FLIGHT TEST ENGINEER

Almost every flight test team is composed of one or more test pilots and test flight officers, and one or more project engineers. Team members bring together the necessary expertise in qualitative testing and quantitative evaluation. To perform the necessary tests and evaluations, the test pilot and test flight officer must know the applicable theory, test methods, data requirements, data analysis, instrumentation, and specifications. The flight test engineer must possess a thorough knowledge of the tasks required for mission performance in order to participate fully in the planning and execution of the test program.

1.5.1 TEST PILOT/TEST FLIGHT OFFICER

The test pilot/test flight officer is proficient in the required flight skills to obtain accurate data. They have well developed observation and perception skills to recognize problems and adverse characteristics. They have the ability to analyze test results, understand them, and explain the significance of the findings. To fulfill these expectations, they must possess a sound knowledge of:

1. The test aircraft and systems in general.
2. The total mission of the aircraft and the individual tasks required to accomplish the mission.
3. Theory and associated test techniques required for qualitative and quantitative testing.
4. Specifications relevant to the test program.
5. Technical report writing.

The test pilot/test flight officer understands the test aircraft in detail. They consider the effects of external configuration on aircraft performance. They should have flight experience operating many different types of weapons systems. By observing diverse characteristics exhibited by a variety of systems, the test pilot/test flight officer can make accurate and precise assessments of design concepts. Further, by operating many different systems, they develop adaptability. When flight test time is limited by monetary and time considerations, the ability to adapt is invaluable.

The test pilot/test flight officer clearly understands the aircraft mission. They know the specific operational requirements upon which the design was based, the detail specification, and other planning documents. Knowledge of the individual tasks required for total mission accomplishment is derived from recent operational experience. Additionally, they can gain knowledge of the individual tasks from talking with other systems operators, studying operational and tactical manuals, and visiting replacement pilot training squadrons.

An engineering test pilot/test flight officer executes a systems test task and evaluates the validity of the results to determine whether the test needs to be repeated. Often the test pilot/test flight officer is the best judge of an invalid test point and can save the test team wasted effort. Their knowledge of theory, test techniques, relevant specifications, and technical report writing may be gained through formal education or practical experience. An effective and efficient method is through formal study with practical application at an established test pilot school. This education provides a common ground for the test pilot/test flight officer and Flight Test Engineer (FTE) to converse in technical terms concerning system performance and its impact on mission suitability.

1.5.2 FLIGHT TEST ENGINEER

The FTE has general knowledge of the same items for which the test pilot/test flight officer is mainly responsible. Additionally, the FTE possesses sound knowledge of:

1. Instrumentation requirements.
2. Planning and coordination aspects of the flight test program.
3. Data acquisition, reduction, and presentation.
4. Technical report writing.

These skills are necessary for the FTE to form an efficient team with the test pilot/test flight officer for the planning, executing, analyzing, and reporting process.

Normally, the FTE is responsible for determining the test instrumentation. This involves determining the ranges, sensitivities, frequency response required, and developing an instrumentation specification or planning document. The FTE coordinates the instrumentation requirements with the instrumentation engineers who are responsible for the design, fabrication, installation, calibration, and maintenance of the flight test instrumentation.

The FTE is in the best position to coordinate all aspects of the program because he or she does not fly in the test aircraft often and is available in the project office. The coordination involves aiding in the preparation and revision of the test plan and coordinating the order of the flights. Normally, the FTE prepares all test flight cards and participates in all flight briefings and debriefings.

A great deal of the engineer's time is spent working with flight and ground test data. The FTE reviews preliminary data from ground tests and existing flight tests. From this data, critical areas may be determined prior to military flight testing. During the flight tests, the engineer monitors and aids in the acquisition of data through telemetry facilities and radio, or by flying in the test aircraft. Following completion of flight tests, the engineer coordinates data reduction, data analysis, and data presentation.

The FTE uses knowledge of technical report writing to participate in the preparation of the report. Usually, the FTE and the test pilot/test flight officer proofread the entire manuscript.

1.6 SYSTEMS SYLLABUS

1.6.1 OVERVIEW

The systems syllabus at USNTPS consists of academic instruction, flight briefings, familiarization flights, practice flights, exercise flights, flight reports, and evaluation flights. Each systems phase of instruction concludes with an individual evaluation flight. Toward the end of the syllabus, a group formal oral presentation is given in the form of an Operational Test Readiness Review (OTRR). The final exercise at USNTPS is a simulated Navy Developmental Test IIA (DT IIA). This exercise incorporates all the airborne systems instruction into the total evaluation of an airborne weapon system.

The systems syllabus includes exercises in air-to-ground radar, air-to-air radar, ESM, navigation systems, and FLIR. The syllabus is presented in a step-by-step, building block approach allowing concentration on specific objectives and fundamentals. This approach focuses on individual systems characteristics at the expense of evaluating the total weapon system. Progress through the syllabus is toward the end objective, the evaluation of the aircraft as a weapon system in the mission environment. The details of the current syllabus are contained in *U.S. Naval Test Pilot School Notice 1542*.

1.6.2 USNTPS APPROACH TO SYSTEMS TESTING

The USNTPS provides varied aircraft for systems testing, and, although the aircraft are not new ones, USNTPS assumes it has not been evaluated by the Navy. The syllabus assumes a DT IIA was not conducted and USNTPS is designated to conduct an OTRR for systems performance. The aircraft is assumed designated for present day use. Performance, stability and control, weapons delivery, and other testing is assumed to be assigned to other test squadrons of NAVAIRWARCENACDIV. The student is charged with the responsibility of testing and reporting on the systems performance characteristics of the syllabus aircraft.

Mission suitability is an important phrase at NAVAIRWARCENACDIV, and its importance is reflected in the theme of flight testing at USNTPS. The fact an aircraft meets the requirements of pertinent Military Specifications is of secondary importance if any systems performance characteristic degrades the airplane's operational capability. The mission of each aircraft is discussed and students conclude whether or not the systems performance characteristics they evaluate are suitable for the intended mission. This conclusion is supported by a logical discussion and analysis of qualitative and quantitative observations, drawing on recent fleet experience.

The evaluation of systems performance for comparison to specification requirements, contract guarantees, or other systems require accurate quantitative data. At USNTPS, every effort is made to test under ideal conditions with all instrumentation operational, however, problems may arise occasionally which cause errors in the data. If bad weather, instrumentation failure, or other factors result in large errors or excessive data scatter, the student critiques the data, and, if warranted, the flight is reflown. Precisely accurate data are not required before the data are presented in a student report. However, it is important to know if errors in the data exist and their effect on the results. The primary purpose of the systems syllabus at USNTPS is learning the basic supporting theory and proper flight test techniques.

1.6.3 FLIGHT BRIEFINGS

Printed and oral flight briefings are presented by the principal instructor for each exercise. The flight briefing gives specific details of the exercise and covers the objective, purpose, references, scope of test, method of test, test planning, and report requirements. The briefing also covers the applicable safety requirements for the exercise as well as administrative and support requirements.

1.6.4 FAMILIARIZATION FLIGHTS

Familiarization flights are preceded by thorough briefings including: theory, test techniques, analysis of test results in terms of mission accomplishment and specification requirements, and data presentation methods. In flight, the instructor demonstrates test techniques, use of special instrumentation, and data recording procedures. After observing each technique, the student has the opportunity to practice until attaining reasonable proficiency. Throughout the familiarization flight, the instructor discusses the significance of each test, implications of results, and variations in the test techniques appropriate for other type aircraft. Students are encouraged to ask questions during the flight as many points are explained or demonstrated easier in flight than on the ground. A thorough postflight discussion between instructor and students completes the familiarization flight. During the debrief, the data obtained in flight are analyzed.

1.6.5 PRACTICE FLIGHTS

Each student is afforded the opportunity to practice the test methods and techniques in flight after the familiarization flight and prior to the evaluation, or data flight. The purpose of the practice flight is to gain proficiency in the test techniques, data acquisition, and crew coordination necessary for safe and efficient flight testing.

1.6.6 EXERCISE FLIGHTS

Each student usually flies one flight as part of each exercise. The student plans the flight, has the plan approved, and flies the flight in accordance with the plan. The purpose of the flight is to gather qualitative and quantitative data as part of an overall systems evaluation. The primary in-flight objective is safe and efficient flight testing. Under no circumstances is flight safety compromised.

1.6.7 REPORTS

A fundamental purpose of USNTPS is to assist the test pilot/test flight officer/FTE team to develop their ability to report test results in clear, concise, unambiguous technical terms. After completing the exercise flight, the student reduces the data, and analyzes the data for mission suitability and specification compliance. The data are presented in the proper format and a report is prepared. The report process combines factual data gathered from ground and flight tests, and analysis of its effect on mission suitability. The report conclusions answers the questions implicit in the purpose of the test.

1.6.8 PROGRESS EVALUATION FLIGHT

The progress evaluation flight is an evaluation exercise and an instructional flight. It is a graded check flight on the phase of study just completed. The flight crew consists of one student and one instructor. The student develops a flight plan considering a real or simulated aircraft mission and appropriate specification requirements. The student conducts the flight briefing, including the mission, discussion of test techniques, and specification requirements.

As the student demonstrates knowledge of test techniques in flight, the student is expected to comment on the impact of the results on the real or simulated mission. The instructor may comment on validity of the results obtained, errors or omissions in test procedures, and demonstrate variations in test techniques not introduced previously.

During the debrief the student presents, analyzes, and discusses the test results. The discussion includes the influence of the results on aircraft mission suitability.

1.7 SYSTEMS FLIGHT TEST CONDITIONS AND PILOT TECHNIQUES

1.7.1 INITIAL CONDITIONS

Knowing the initial settings of the weapon system is important during systems test. It allows for repeatability of test results by giving each operator a known setup from which to deviate.

1.7.2 ENERGY MANAGEMENT

Proper energy management is critical to effective use of scarce flight test resources. Energy conservation when progressing from one test point or condition to another allows acquisition of a greater quantity of data.

The test pilot/test flight officer is mentally ahead of the aircraft and flight profile. They are aware of the next test point and effect a smooth energy conserving transition from point to point. A smooth transition between points might include trading airspeed for an airspeed/ altitude entry condition for a succeeding test point.

The test should be planned to make maximum use of the entire flight profile. Tests can often be combined to make best use of test time and assets.

1.7.3 DATA COLLECTION

Data collection in this Flight Test Manual is specified using manual methods, such as kneeboard cards and portable tape recorders. You may have the opportunity to use data extracted from the 1553 bus on the F-18. In the Test Squadrons you will have the opportunity to use more sophisticated data gathering techniques, including high resolution range tracking for precise positioning data, and instrumentation systems designed to more accurately record the performance of the aircraft and its sensors. Understanding the concepts presented here will help you determine the kinds of data recording options you will have available to you in the Test Squadrons, and the accuracy required for each type of test.

1.8 FLIGHT SAFETY

1.8.1 INCREMENTAL BUILDUP

The concept of incremental buildup is one of the most important aspects of flight testing. Buildup is the process of proceeding from the known to the unknown in an incremental, methodical pattern. Flight tests are structured in this manner. Testing begins with the best documented, least hazardous data points and proceeds toward the desired end points always conscious of the aircraft, aircrew, and evaluation limits. There should be no surprises in flight test. In the event a data point yields an unexpected result or a series of data points creates an unexpected trend, evaluation stops until the results are analyzed and explained.

CHAPTER 2

COCKPIT EVALUATION

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CHAPTER 2
COCKPIT EVALUATION

2.1 INTRODUCTION

The purpose of conducting a cockpit (cockpit is a general term for the particular operator's station (e.g., PPC, TACCO, ECMO, B/N, RIO, etc.)) evaluation at TPS is to acquaint the student with the evaluation of human engineering design requirements as related to aircraft testing. Because the cockpit is the focal point of the man-machine interface, it is the area which should receive maximum human engineering design emphasis. Unfortunately, many individual cockpit items receive little or no emphasis concerning human accommodation or compatibility. It is often not until all cockpit items are assembled into a mockup or actual cockpit during design and testing evaluations that human engineering design deficiencies become identifiable. Not until the working relationships of controls, displays, lighting, and cockpit environment are analyzed can an intelligent evaluation be conducted. Regardless of airplane or system performance and potential, the man in the cockpit must accomplish the transfer function of changing airplane potential into reality. Important variables which control this transfer function are (1) capabilities and limitations of the aviator and (2) the cockpit design, which is the link between action and reaction performed by the systems operator as a result of information received and processed.

The primary airplane mission must be emphasized during human engineering evaluation. Additionally, "worst case" events must be considered, such as degraded system operation emergencies.

The most important general principle to keep in mind when performing any human engineering evaluation is the concept of individual differences. We all tend to evaluate items such as controls and displays from a very subjective viewpoint, i.e., our own capabilities, limitations, and experience. The fact that system operators are all different must be thoroughly understood when evaluating cockpits. Test pilots and engineers, in particular, are perhaps not always entirely objective when it comes to admitting that particular human engineering design deficiencies are problems as far as they are concerned. The following differences are among the most important in cockpit evaluation.

2.2 ANTHROPOMETRY

Body sizes very considerably. Reference 1 is a compilation of 96 body dimensions based on measurements of 1,549 Naval Aviators. The data are presented in inches and centimeters as well as percentiles.

Detail airplane specifications generally require that cockpits accommodate 5th through 95th percentile sized aviators for older airplane cockpits and crew stations (prior to 1970) and that 3rd through 98th percentile be accommodated in newer cockpits (since 1970). It is generally assumed that if one's body measurements, such as height and weight, are 50th percentile (average) that all his dimensions will be 50th percentile; this is not true. Uniformity in body dimensions is very rare; e.g., it is doubtful that if a person's sitting eye height is 70th percentile that his functional reach will also be 70th percentile. It is important to know one's own percentile ranks of body dimensions.

Physiological Training Units (altitude chambers) are equipped with anthropometric measuring devices where you can be measured and have your measurements translated into percentile ranks. The most important dimensions relative to aircrew station design are:

a. Total sitting height.
b. Sitting eye height.
c. Sitting shoulder height.
d. Bideltoid diameter (shoulder width).
e. Functional reach (grasp between thumb and forefinger).
f. Fingertip reach ("pushbutton" reach with extended forefinger).
g. Buttocks-to-knee length (sitting).

Only by knowing your own various percentile ranks can you make relative judgments as to the overall anthropometric accommodation of a particular cockpit; e.g., if you know your functional reach is 35th percentile and that you cannot reach a particular control when fully restrained, you therefore know that anyone with a functional reach less than 35th percentile, when fully restrained, also cannot reach the control.

Equipments exist which can objectively measure anthropometric parameters such as reach distances, angles of vision, and ejection seat egress clearance (References 2 and 3).

Egress clearances in ejection seat cockpits are often jeopardized when modifications such as cameras, control boxes, or other equipments are added to canopy rails, glare shields, etc. Human engineering personnel are prepared to use particular equipments to attain quantitative data in cockpit anthropometry evaluations.

NOTE: It is critical that the Design Eve Position (DEP) be the source of measurements for anthropometric evaluations. The DEP is the point in space where the pilot's eyes should be positioned to see all displays and have adequate exterior vision. To further define the DEP, other preliminary definitions are in order and are presented as follows:

a. Seat Reference Point is a center line intersection of the seat back tangent line and seat surface.

b. Neutral Seat Reference Point (NSRP) is the location of the seat reference point when the seat is adjusted to the midpoint of vertical adjustments; e.g., with 5 in. of vertical seat travel available, the seat would be adjusted to 2.5 in. above the lower limit.

The DEP (figure 1) is then defined as the point in space located at the sitting eye height dimension of the 50th percentile average aviator (31.5 in.) measured vertically above the NSRP and 13 in. measured horizontally forward of the seat back tangent line. All anthropometric evaluations must originate at the DEP. Whatever the size of the individual evaluating items, such as control reach, display visibility, or cockpit space accommodation, the seat must be adjusted to place his eyes at the DEP. The necessity of adjusting the eyes to the DEP when making anthropometric evaluations is more critical now than ever with the increasing emphasis on heads-up displays and other optical devices which require strict adherence to line-of-sight criterion.

As with all human engineering evaluations, anthropometry must be checked against "worst case" conditions. An example of a "worst case" condition would be reaching for a critical control such as the emergency stores jettison when fully restrained (shoulder harness locked) and when under a high-g condition such as a catapult launch.

Additional items of anthropometric deficiency include insufficient sitting height, inability to reach rudder pedals or foot controls, inability to fit through emergency egress openings, etc.

2.2.1 PURPOSE

The purpose of this test is to evaluate the controls, displays, and display symbology for man/aircraft interface compatibility as defined by the assigned mission.

2.2.2 THEORY

As cockpits are designed, the anthropometric data of the aircrew are considered. The 50th percentile sitting height of 31.0 inches defines the cockpit Design Eye Position (DEP) (figure 1). The center of vertical travel of the ejection seat generally places a man with a 31.0 inch sitting height at the DEP. Compensation is required for sitting heights other than 31.0 inches. Controls which require manipulations while airborne should be reachable from the DEP (figure 2). Controls utilized during Air Combat Maneuvering (ACM) should be easily reached while performing high "g" maneuvers and while maintaining a body position ready for safe ejection. The control operative sense should conform to the standards presented in references 2 and 3. These standards generally reflect expected response. Displays and controls which require monitoring or adjustment airborne, should be placed inside a 30 degree cone centered on the Principal Line of Sight (PLOS) (figure 3). Visual lookout and bogey acquisition, as well as display monitoring, shall be considered in the placement of the PLOS. Displays should be large enough to provide adequate detail as required by mission tasking. Displays are historically smaller than desired because of area, weight, power, and cooling limitations.

2.2.3 PROPER LOCATION

Control placement should consider frequency and sequence of use. The design goal is a reduction in the required movement of the eyes, head, and hands to perform a given task. This is critical under high "g" loadings. The controls shouldn't require operator movements which are uncomfortable or produce fatigue. Controls should never be located such that the hand or arm manipulating the control is in the line of sight required to see the display effect or setting of the control.

2.2.4 NATURAL DIRECTION-OF-MOTION RELATIONSHIPS

Actuating controls such as toggle switches forward or up should turn systems on. Turning rotary controls clockwise should increase system output. Standard direction-of-motion relationships should be adhered to in cockpit control actuation.

2.2.5 SHAPE CODING

Controls which may require manipulation without direct visual monitoring should feel different to the touch if they are near controls of dissimilar systems.

2.2.6 INADVERTENT ACTUATION

Controls which can be activated incorrectly should be designed to prevent such activation either by electronic circuitry or mechanical guards; e.g., forward wing-sweep actuation during supersonic flight regimes which would potentially be damaging to airplane components should be electrically or mechanically prevented.

2.2.7 DISPLAYS

Displays should be clearly visible when viewed from the DEP in bright daylight as well as complete darkness. In clear daylight the sun positioned over the operator's shoulder produces a serious glare problem for most displays. At night the display should not be so bright that it distracts the operator, affects his night vision, or fills the cockpit with light. Bright cockpits produce glare on the canopy which is tactically undesirable at night. Display symbology alphanumerics must be clear, legible, and support mission requirements. The information displayed must be sufficient for the task assigned yet not overloading for the operator. This usually requires tailoring the display to a specific attack mode/mission or phase of flight.

Display video and symbology are produced by organizing small dots of light (or dark spots depending on display type) into recognizable patterns. The small dots are mechanically organized into a matrix of columns and rows (called raster lines). The larger the number of rows and columns, the smaller an individual matrix element becomes. The display spot size defines the limit of the smallest matrix element and available display resolution. Upon close inspection of the display glass, the row/column matrix can be seen (a magnifying glass helps). By counting the number of raster lines per inch and multiplying by the display size, the resolution in feet for a given display scale can be found. This display resolution can then be compared to radar resolution. To take full advantage of the radar design, the display resolution should be better than the radar resolution.

Night Vision Goggles (NVG's) amplify ambient light levels produced by the stars, the moon, and industrial sources. NVG light amplification provides the operator with visual cues at night which resemble daytime cues. This permits Visual Meteorological Condition (VMC) night low altitude flight as if clear daytime conditions prevailed. Cockpit lighting, because of its close proximity and relatively bright intensity, can degrade NVG use. Red or white lights appear as very bright sources to an NVG user. Blue or green lights are NVG compatible. Due to the increased outside scan requirement during an NVG low altitude flight, display symbology must be designed with maximum clarity in mind. Cockpit lighting must be thoroughly evaluated to modify light sources which distract the NVG user.

2.2.8 CONTROL DISPLAY INTEGRATION

The use of the controls and displays should be clear, requiring a minimum amount of operator concentration. This leaves the operator free to make tactical decisions. The controls should operate harmoniously with the other cockpit controls to allow simultaneous operation of other airplane systems. This control integration should be evaluated during mission relatable workloads while simultaneously operating all the other aircraft systems.

Care should be exercised in determining proper safeguards to prevent inadvertent actuation of controls, switches, etc., which might be actuated by flight clothing or items of personal equipment, such as survival vests, flotation devices, anti-exposure garments, etc.

2.2.9 ACTUATION FEEDBACK

Controls-should have proper tactical cues relative to actuation. One should "feel" the lock of a toggle switch or push buttons without necessarily hearing it. Controls should have the proper resistance and range of displacement as specified by Reference 4.

2.3 LABELING

Items of equipment which must be identified, manipulated, or located should be adequately labeled to permit efficient human performance. Blueprints which illustrate control panels often portray a straight-on-view. However, when the control panel is installed in a cockpit, it is often offset from direct line of sight. The three dimensional line-of-sight offset often results in labels (number, ON/OFF legends, or other nomenclature) being obscured by the very controls to which they are related.

It is important to evaluate labeling legibility in low ambient light (dark) conditions as well as in daylight. If an item must be labeled for normal daylight use, it should be legible at night.

2.4 ENVIRONMENT

Heating, ventilation, and air conditioning shall be evaluated and compared with the criterion specified in Reference 4 or in the applicable specification listed in the detail specification of the airplane being evaluated. Hand-held instruments are available to measure temperature as well as relative humidity. Specifications generally require an Environmental Control System (ECS) to maintain between 60 and 80°F ambient temperature in a crew station and 10° maximum differential between hand and foot level.

Interior ambient air should also be sampled throughout the flight regime or mission profile of any aircraft. Carbon monoxide or other toxic fumes can be potential hazards, particularly during operations such as taxiing downwind, gun or rocket firing, and during refueling operations when directly behind a tanker.

Noise is the most serious and persistent problem among those associated with aircraft environment. The maximum allowable noise limits relative to aircraft type are described in Reference 5. It should be recognized that high noise levels of less intensity than those specified as physically damaging to hearing can produce human fatigue and degrade an aviator's effectiveness.

As a project officer, you should evaluate ambient exterior noise to which maintenance or deck personnel are exposed as a result of being in the immediate vicinity of the aircraft during ground operations. Maintenance personnel often neglect the required ear protection because hearing loss is a slow insidious process.

Various levels of instrumentation are available in evaluating the acoustical environment, ranging from small pocket sized decibel meters to sophisticated tape recording devices that record noise samples which can be analyzed in detail for various frequency bands.

NOTE: When conducting an interior noise survey, exercise any additional equipments which may increase the acoustic level, such as air conditioning or defogging systems, heater blowers, ambient air vents, and the extended configuration of in-flight refueling probes.

2.5 LIGHTING

A concerted effort in the evaluation of cockpit lighting usually identifies numerous lighting deficiencies. Often there is little emphasis on lighting evaluation. Typically, during night flights general lighting observations are made by crewmen who are busy flying or conducting other airborne tasks, thereby overlooking numerous lighting deficiencies.

2.6 METHOD OF TEST

2.6.1 METHOD

The aircrew should perform the ground tests in full flight gear (gloves are important for feedback cues) while seated at the DEP. Airborne tests may be performed with the body positioned as required for mission accomplishment (i.e., aircrew comfort, ejection envelope, maximum interior/exterior cockpit visibility). Comments on display control utility when not seated at the DEP are pertinent. A bright clear day will enhance evaluation of display brightness capacity. Night tests focus concern on display/canopy interaction, cockpit ambient light levels, and Night Vision Goggle (NVG) compatibility. All possible modes and display combinations should be evaluated. The dynamic effects of "g" loading, roll, and pitch rates should also be evaluated.

2.7 TEST CONDITIONS

DAYLIGHT

- GROUND TESTS
  - Cockpit Overview
  - First Impressions May Indicate Areas of Operator Compensation

- AIRBORNE
  - Evaluate Dynamic Response of System
  - Mission Utility

NIGHT

- GROUND
  - Evaluate Cockpit Lighting Schemes
  - Canopy Glare
  - NVG Compatibility

- AIRBORNE
  - Mission Utility
  - NVG Compatibility

2.7.1 SAFETY CONSIDERATIONS

The crewmember not directly involved in the evaluation shall assume primary cockpit lookout responsibilities.

2.8 DATA ANALYSIS

2.8.1 DATA COLLECTION

A tape measure, protractor, and data cards will help record data during ground tests. A voice recorder should be utilized airborne to record mission utility.

Controls - Make qualitative comments on following areas.

- Placement - are mission relatable controls centrally located?

- Functional Grouping - are functionally related controls grouped?

- Tactically Significant Control - Are these strategically placed for easy access?

- Frequency of Use - Is consideration given to placement of commonly used controls?

- Sequence of Use - Does arrangement of controls reflect patterns of use?

- Distance Between Controls - Is it sufficient to prevent accidental use? Is it too far to prevent rapid adjustments?

- Within Reach - Is it accessible to operator with defined anthropometric data?

- Operative Sense - Is forward, clockwise, to the right, or up = ON?

- Tactile Feedback - Control shape/size/movement/forces required.

- Control Movement - Range/breakout force/damping/friction/sensitivity.

- Fatigue - Does repeated control use produce fatigue/stress?

- Labeling - Are controls clearly and simply labeled?

- Manual Operation - Does it provide adequate control?

- HOTAS Operation - Does it reduce operator workload?

- Error Analysis - Does unintentional actuation of adjacent control produce undesirable effects?

- Operative Utility - Does control provide adequate control of system throughout flight regime?

- Aircrew Compensation Required - The first indication of a design oversight.

Displays - Make qualitative comments on the following areas.

- Brightness - Is a sufficient illumination range provided?

- Contrast - Are light/dark variations accurately presented?

- Resolution - Does provided raster lines/inch provide adequate detail to present desired information?

- Spot Size - How does smallest element contribute to resolution?

- Screen Size - Can information be provided in adequate detail?

- Refresh Time - Does display flicker or smear? Is information timely and stable in dynamic scenarios (roll rates, pitch rates, G's)?

- Sunlight - Does sunlight glare wash out display? Is operator required to compensate for changing sun angles?

- Night - What is impact of display on cockpit ambient light levels; is canopy glare produced?

- Automatic Brightness/Contrast - Does circuitry adequately compensate for changing light levels?

- Target Video - Shape/size/brightness/contrast/movement characteristics.

- Automatic Gain - Does circuitry adequately compensate for situation dynamics?

- Manual Gain - Is sufficient range provided?

- Color - Is information clearly displayed without operator fatigue?

- Polarity - Does FLIR White/Black hot perform as advertised?

- Placement - Does placement complement inside/outside 30° cone of view from DEP?

- Viewing Distance - Does placement require aircrew eyestrain to read information?

- DEP sensitivity - Is the display usable if not seated at the DEP?

- Information Load - Is too much information provided?

- NVG Compatible - Does lighting interfere with NVG's? Does information support NVG flying?

- Utility - Is it functionally useful for aircrew?

- Mission Compatibility - Does symbology support mission requirements?

- NVG's - Lighting Compatibility/Functional utility with NVG's.

- Familiarity, clarity and usefulness in a tactically offensive environment - Does the display provide the information where you want it, how you want it, when you want it, while aggressively pursuing a target?

- Aircrew Compensation Required - The first indication of a design oversight.

Display Symbology - Make qualitative comments on following areas.

- Size - Is it large (small) enough to be effective?

- Brightness - Is the range of illumination sufficient?

- Clarity - Does it clearly present desired information?

- Resolution - Is it clear and legible?

- Placement - Is it easily viewed? Does it interfere with other information?

- Antenna Pointing Symbol - Does it provide adequate detail of antenna location?

- Weapon Envelope Cues - Does it provide sufficient missile/gun envelope information?

- Steering Symbology - Is it clear, understandable, correct sense?

- Airspeed/altitude/velocity cues - Is target aerodynamics information presented clearly?

- Dynamic Response - Does display symbology degrade under g loadings, roll rates, etc.

A particular procedure which has been effective in static lighting evaluation is described below.

1. Get into the airplane attired in the complete compliment of proper flight clothing and equipment (take a tape recorder with you).

2. Have the canopy covered with an opaque cover preventing any ambient light from entering. This allows you to conduct the evaluation day or night.

3. Have electrical power supplied to the aircraft to enable interior light actuation.

4. Adjust your seat to place your eyes in the design eye position (or where you normally fly).

5. Allow your eyes to become adjusted to the dark (10 to 15 min).

6. Begin by locating the auxiliary light (if you can find it in the dark) and see if it is suitable for minimum illumination if all other lights were lost.

7. After the auxiliary light evaluation, systematically exercise all light controls in the cockpit. Vary the intensity, look for instrument lights on a particular rheostat which extinguish before others when adjusting from bright to OFF. Look for brightness imbalance such that, at a given light adjustment, some instruments may be too bright or too dim when most other instruments on that particular lighting control are at a reasonable intensity. Identify any glare or reflection which might possibly be shielded.

8. Verbally record on your tape recorder any deficiencies noted; this allows evaluation uninterrupted by turning on floodlights or flashlights to write down deficiencies which in turn would require readjustment of the eyes to low ambient light.

9. Adjust your seat to various positions to determine if lighting is sufficient throughout a typical range of particular eye locations. This may be one of the few times you evaluate lighting strictly for its own sake. Take as much time as is required to evaluate all lighting variations, legibility of labels, visibility of controls, etc.

Data Reduction

$$\text{Display Resolution} = \frac{\text{Scale (nm)} \times 6076 \text{ ft/nm}}{\text{Size (inches)} \times \text{resolution (raster lines/inch)}}$$

$$\text{Radar Range Resolution} = \frac{c \times Pw}{2}$$

where

c = 161,875 nm/sec speed of Electromagnetic wave propagation

w = Pulse width (radar specific)

NOTE: Display resolution should be better than range resolution.

Results

1. Present crewmember anthropometric data.
2. Present flight equipment worn.
3. Define the ejection seat position (from bottom of seat travel in inches) required to achieve DEP.
4. Define Test Conditions (i.e., weather, ambient light levels, ACM, etc.).

5. Controls Evaluation
6. Displays Evaluation
7. Symbology Evaluation

2.9 STATISTICAL ANALYSIS

N/A

2.9.1 ERROR ANALYSIS

N/A

CHAPTER 3

RADAR THEORY

CHAPTER 3

CONTENTS

CHAPTER 3
RADAR THEORY

3.1 INTRODUCTION

Modern multimode tactical radars have evolved considerably in the last few decades. Air-to-ground radars have evolved from simple real beam pulse radars to sophisticated, computer controlled systems employing complex digital signal processors. They generally operate at a fairly low PRF, although it may vary depending on the range scale selected. Pulse widths vary, but are generally short for increased range resolution. Small target detection may require advanced techniques such as pulse compression, monopulse, Doppler Beam Sharpening (DBS), or Synthetic Aperture Radar (SAR) techniques. Inverse Synthetic Aperture Radar (ISAR) techniques may be used to image targets, such as ships, that have rotational motion. Moving Target Indicators (MTI) may be used to detect moving ground targets. The radars are usually highly integrated with the other sensors on the aircraft and with the weapon delivery systems. The radar may be used to provide initial pointing information to other sensors such as Forward Looking InfraRed (FLIR). The radar may provide precise positioning data to allow updating a navigation system. It may provide target position information to the weapon system computer so it can develop the targeting solution. It may be possible to freeze the radar display to allow target area study without radiating. For visual bombing, the radar may provide air-to-ground ranging (AGR) to allow the computation of a very accurate aircraft-to-target range.

Air-to-ground radars are used for varied missions, including ground mapping, ground attack, ground moving target tracking, anti-shipping and Anti-Submarine Warfare (ASW), navigation, and weather avoidance. To improve covertness, Low Probability of Intercept (LPI) techniques are being developed, based on limiting power or radiation time, sweeping the transmit frequency, and increasing the signal-to-noise ratio to detect weaker signals from more distant targets.

The operational requirements for a tactical air-to-air radar are different from those for an air-to-ground radar.[1] In some respects, the requirements are more stringent. The target is likely fast-moving and highly maneuverable, and is not constrained to move on the surface of the earth. The maximum range of interest is likely to be much greater, thereby requiring greater transmitted power and the signal-to-noise ratio improvement provided by coherent signal processing and precise and unambiguous velocity gating.[2] Special requirements are imposed by air-combat maneuvers and tactics, and the need for long-range target recognition. For use with a semi-active radar-guided missile, an air-to-air radar must operate at a carrier frequency and waveform consistent with the design of the missile. On the other hand, except for the air-to-air look-down or low altitude situation, the background clutter is likely to be much smaller. Furthermore, because of the weapons utilized, the long-range tracking accuracy requirements for air-to-air weapon delivery are likely to be less stringent than those for an air-to-ground radar. (High

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[1] Airborne Systems course textbook: Principles of Radar System Test and Evaluation; Revised February, 1994, Section 3.3

[2] Ibid. Section 3.3.2

resolution detection and tracking are generally required only for close-in gunnery and for raid assessment.)

There are two basic philosophies currently applied to the design of air-to-air radars.[3] In order to achieve long-range performance, the older design employs a high peak power, a large pulse width, and a high PRF in order to obtain a high average power and to put more pulses on a given target during search. At the same time, the high PRF avoids ambiguous velocities and blind velocities.[4] Unfortunately, the high PRF also creates a severe ambiguous range and blind range problem. The newer design, employed in some modes of the APG-65, employs a medium PRF, (to reduce the blind range/range ambiguity problem), and avoids velocity ambiguities and blind velocities by utilizing PRF agility. The APG-65 also employs automatic parameter selection that utilizes high, medium, and even low pulse repetition frequencies in appropriate scenarios.[5] The advantage of this approach is that the PRF agility also avoids range ambiguities and blind ranges. Long-range performance is achieved by the use of extensive signal processing and velocity discrimination to increase the signal-to-noise ratio. These two basic approaches result in different parameters and operational characteristics in the respective radars. As a result of the extensive modulation and signal processing employed in the APG-65, the operational characteristics of that radar are obscured, making it difficult to detect and measure such characteristics as blind ranges, blind velocities, and the maximum range for tracking. However, even though it may be difficult to measure, or even to detect, these operational characteristics, it is important to test for them in order to verify their presence or absence and to examine their effect on mission suitability.

3.2 PURPOSE OF TEST

The purpose of airborne radar testing is five-fold- (1) to determine specification compliance, (2) to determine mission suitability, (3) to identify operational constraints and limitations, (4) to evaluate the man/machine interface, and (5) to gather information to be used in further testing and correction of the deficiencies and limitations identified in test.

3.3 THEORY

3.3.1 PARAMETERS AND OPERATIONAL FEATURES OF AIRBORNE RADARS

As a result of the mission requirements and design approach mentioned above, the parameters and operational characteristics of a modern, multimode, frequency-agile radar such as the APG-65 are generally consistent with those presented below. (See Section 3.13 of the Radar T&E text for definitions and a general description of these parameters and features.)

3.3.1.1 OPERATIONAL MODES

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[3] Ibid. Section 3.3

[4] Ibid. Section 2.16.10

[5] Ibid. Section 2.13

Typical air-to-ground modes (those of the APG-65) are: Real Beam Ground Map (RBGM), Real Beam Navigation Ground Map (RBNGM), Expanded modes (using DBS and medium resolution SAR processing, called EXP 1, EXP 2, and EXP 3), Ground Moving Target (GMT), Sea Surface Search (SEA), Ground Moving Target Track (GMTT), Air to Ground Ranging (AGR), Precision Velocity Update (PVU), and Terrain Avoidance (TA).

Typical air-to-air modes (again, those of the APG-65) are: Range While Search (RWS), Velocity Search (VS), Track-While-Scan (TWS), Single-Target-Track (STT), Air-Combat Maneuvering (ACM), and Raid Assessment (RA).

3.3.1.2 CARRIER FREQUENCY

Primarily air-to-ground radars such as those used in the A-6E and F-111 operate in the J band (12 to 18 GHz). This allows a narrow beamwidth with a moderately sized antenna. Tactical air-to-air and modern multimode radars generally operate in the X-band (9 to 10 GHz) for compatibility with air-to-air missiles such as the Sparrow, Phoenix, and AMRAAM. Narrow-band frequency modulation, at high PRF, is sometimes used, as discussed in the section on modulation, to allow ranging on the FM waveform.

3.3.1.3 CARRIER POLARIZATION

Air-to-ground radars generally utilize horizontal polarization to enhance ground returns. They may use circular polarization to improve all-weather operation. Air-to-air radars generally utilize vertical polarization to reduce ground clutter returns in a look-down or low altitude situation.

3.3.1.4 BANDWIDTH

Air-to-ground radars need high range resolution, hence narrow pulses, requiring a high bandwidth (about 2 MHz). Despite the relatively large pulse width generally utilized (for greater average power) and the absence of a requirement for high-resolution ranging, the bandwidth of a modern air-to-air radar is generally narrow (about 1 MHz) in order to allow the use of narrow-band filtering to reject noise, thereby increasing maximum range and improving anti-jam performance.

3.3.1.5 CARRIER POWER

Older radars such as those in the A-6 and F-14 used relatively high transmitted power (on the order of 100 kW). Modern multimode radars use much less power (5 to 10 kW), even though relatively large detection and track ranges are required, and rely on signal processing to achieve large signal-to-noise ratios.

3.3.1.6 MODULATION

In order to maximize signal-to-noise ratio and provide for pulse-to-pulse ranging, most airborne radars are pulsed. (Some air-to-air missiles require a CW support mode.) Many air-to-air radars employ FM ranging at high PRF. The high PRF provides a high average power and unambiguous velocity determination while the pulse-to-pulse frequency modulation allows unambiguous range determination. The pulse repetition frequency is often modulated (varied with time) to avoid range and velocity ambiguities, as discussed in the section on general background.

3.3.1.7 PULSE WIDTH

Air-to-ground radars generally employ narrow pulse widths (as narrow as .1 μsec) for high range resolution. In the absence of a requirement for high-resolution ranging, an air-to-air radar generally employs a relatively large pulse width (about 2 μsec) to provide the large average transmitted power required for long-range detection. In order to provide more precise range information for tracking, it employs a somewhat smaller pulse width (about 0.4 μsec) in the track mode. In order to trade range resolution for greater range at long ranges, pulse width is often varied as a function of range. Pulse compression is generally used to restore the range resolution lost by the use of larger pulse widths.[6]

3.3.1.8 PULSE REPETITION FREQUENCY

Air-to-ground radars generally use a very low pulse repetition frequency (PRF), from several hundred hertz to a few KHz. PRF is often varied with range selected to avoid second-time-around-echoes. Some air-to-air radars employ a high PRF (around 300 KHz) in order to avoid velocity ambiguity and blind velocities. Other radars employ a medium PRF (around 20 KHz) and avoid both range and velocity ambiguities by PRF agility. In special situations, some air-to-air radars employ a low PRF (around 1 KHz) to avoid range ambiguity.[7] PRF is also sometimes varied with pulse width to maintain a constant duty cycle.

3.3.1.9 ANTENNA BEAMWIDTH

The beamwidth of an airborne antenna is normally dictated by the carrier frequency and the diameter of the largest antenna that can feasibly be installed in the aircraft. Antennas in tactical aircraft are typically about two feet in diameter, and, at X-band, produce beam widths of about 3.5 deg.

3.3.1.10 ANTENNA RADIATION PATTERN

The antenna radiation pattern is determined by the geometry and size of the physical elements in dish antenna and by the carrier frequency; or by the geometry, size, and phase relationships in a phased array. (See Section 3.13 of the Communication System T&E text.)

3.3.1.11 ANTENNA SCAN PATTERN

Air-to-ground radars generally scan in a single bar pattern, with the tilt constant depending on the range of interest. Air-to-air radars generally employ raster-scanned (bar-scanned) antennas. Many radars use an interleaved-bar pattern, with signal parameters that vary bar-to-bar, to avoid blind ranges, blind speeds, and scintillation effects.[8]

3.3.1.12 ANTENNA SCAN RATES

A radar utilizes echoes from a reflective target for detection. The amount of energy received is a function of beamwidth and time-on-target (TOT). Time-on-target is the

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[6] Ibid. Section 2.10
[7] Ibid. Section 2.3.4
[8] Ibid. Section 2.13

antenna beamwidth divided by the antenna scan rate. The slower the scan, the longer the antenna beam is on the target, the more energy hits the target, and the larger the number of returned echoes that can be integrated and processed. This results in increased target detection performance, but a decreased display update rate due to the slower scan rate. A wide beam width may also lead to a decrease in real beam mapping quality due to the decrease in azimuth resolution. The antenna scan rate determines the time on target for any given beamwidth and, in conjunction with the scan angle, the refresh rate of the radar display. The scan angle can be decreased to increase the frequency of updates with the same scan rate if sufficient situational awareness can be obtained from the smaller area mapped. A faster scan rate provides more frequent updates of target position or navigation information but may sacrifice target detection due to the decreased hits and reduced integration time available with which to build a consistent radar display. If the scan rate is too slow, the operator may not be presented with the most up-to-date information as a result of rapid aircraft movement. (For example, a radar with a 120 deg scan with a scan rate of 60 deg/sec covers 1,600 ft between updates when traveling at 480 kt.) Measured scan rates may not match the specification due to antenna turnaround time, the time it takes the antenna to stop and change direction at each gimbal stop. Some manufacturers interpret the scan rate specification as applying to the rate at which the antenna actually scans in between the stops, not the scan rate when you time more than one scan.

3.3.1.13 DOPPLER BEAM SHARPENED AND SYNTHETIC APERTURE RADAR BUILD TIMES

DBS radars and SAR have an update interval called the build time, the time between successive refreshes of the display. DBS build times can vary depending on how the mode is mechanized. A DBS radar may have a constant build time with varying resolution, the resolution increasing with angle off the nose (called squint angle) and antenna depression angle, or it may be mechanized to provide a constant resolution but varying build time as the squint angle and antenna depression angle move further away from the velocity vector. Build times can be mission related similarly to update rates.

3.3.1.14 ANTENNA SCAN ANGLE LIMITS

The scan angle determines the width of the sector to be searched, and the amount of aircraft heading change that is possible without losing contact with any given point on the ground or area of the sky. Coupled with the scan rate, it also determines the update frequency of the display. High scan rates and small scan angles generate the quickest update frequencies. When utilizing a narrow scan angle to increase the update frequency there is a tradeoff against the area covered, which may lead to loss of the "big picture" and some situational awareness. Typically, as you move closer to your target with an air-to-ground radar you need less of a big picture view, since the areas with which you are concerned are identified, and you are more concerned about developing targeting information based on a small area than you are concerned about mapping a large area. In the air-to-air mission, once you have a contact and are prosecuting it, the search mission is over and your concerns are maintaining contact on your target until it is destroyed.

3.3.1.15 ANTENNA SCAN/DISPLAY STABILIZATION

In most radar modes, the antenna scan and the display are stabilized with respect to the ground rather than to the aircraft. (Actually, the frame of reference is stabilized with respect to inertial space, in a plane parallel to the ground.) A stabilized frame of reference is not only useful to facilitate interpretation of the display, but is essential to the weapon-delivery task. If the weapon delivery computer had to perform its target tracking and weapon delivery computations in the wildly gyrating aircraft coordinate frame, target “lock” probably could not be maintained during violent air combat maneuvering. The effects of vibration and “g”-loading also must be overcome.

Two basic methods of stabilization are commonly used. The older method is to mechanically rotate the antenna to maintain a constant orientation with respect to the ground. The newer method is to stabilize only the antenna scan and the display (not the antenna itself) by software coordinate transformations (rotations) of the data. The end result is the same from the viewpoint of the test planner. That is, both methods can exhibit limitations on both the angle of rotation and the rate of rotation. The purpose of an antenna stabilization test is to determine those limits.

The ability of a radar to display a usable ground map or maintain target tracking during aircraft maneuvers relies primarily on antenna performance. When ground mapping, the antenna must continue to scan in a stable orientation parallel to the horizon. While trying to do this, antennas are limited by their range of motion, rates, and ability to overcome load factor, or "g". Antennas have limits on their range of motion. Gimbal stops, either mechanical or controlled by the servo motors or software, limit the range of antenna motion possible. Elevation angle limits, or antenna tilt, are controlled by pitch gimbal stops, and define the amount of steady state pitch angle an aircraft can attain, or the amount of antenna look-down angle possible, and still maintain a stable radar picture of the ground, or a scan parallel to the horizon. The lower limit of antenna tilt may directly impact the minimum range of an air-to-ground radar. The upper limit has a greater impact on scan volume in an air-to-air radar, but may impact air-to-ground modes while doing maneuvers such as roll-ins. Lateral angle limits are similarly controlled by gimbal stops or software stops, and result in limits on the horizontal scan angles possible. These limits are typically tested during the scan angle tests, and are not usually considered during stabilization tests. The servo motors must be able to position and scan the antenna while coping with aircraft motion and the effects of antenna weight and inertia. The servos have maximum rates of motion, and are limited in the amount of “weight” they can handle. These limits affect the amount of aircraft maneuvering that can be done before the antenna cannot maintain a correct scan orientation to the horizon. Hopefully the antenna drive and control mechanisms have been scaled to take into account the maneuvers necessary to perform the air-to-ground mission. At a constant angle of bank, or during a rolling maneuver, the antenna is no longer scanning just in azimuth with respect to the aircraft. The radar must mix elevation commands with azimuth commands to maintain an antenna scan parallel to the horizon. Roll stabilization, in constant-angle-of-bank flight, while rolling, is a measure of how well the radar is able to maintain that scan when the aircraft is banked, or during rolling maneuvers. Note that antennas may not be symmetric in vertical and horizontal dimensions. Typically, if they are not symmetric they will be wider than they are tall to yield better azimuth resolution. This may result in different mapping qualities as the antenna changes in relative orientation with respect to the ground during rolling maneuvers, even though it should still scan parallel to the horizon. The antenna's ability to maintain the correct scan orientation is also dependent on the forces the servos are able to generate to overcome the increased weight of the antenna due to load factor, or "g", during pitch maneuvers. The servos must be able to match the aircraft pitch rates.

3.3.1.16 DISPLAY TYPES

Air-to-ground radars generally employ PPI Scan (Plan Position Indicator, a polar plot of radial range and azimuth), sector PPI (a sector of a PPI display), depressed center PPI (a sector of a PPI with the center at the bottom of the display), or sector patch (a section of a PPI sector between 2 ranges) displays. Air-to-air radars generally employ B-Scan (range vs. azimuth), C-Scan (elevation vs. azimuth), PPI-Scan (polar plot of radial range and azimuth), or B-Prime-Scan (velocity vs. azimuth) displays. In air-to-air modes, the APG-65 employs a B-Scan as the primary display for all modes except the velocity search mode, for which it employs a B-Prime-Scan. It also employs a C-Scan on a second display. In air-to-ground modes the APG-65 employs a depressed PPI in MAP mode, and a sector patch in EXPAND modes

3.3.1.17 MOVING TARGET INDICATORS

Many modern radars employ some sort of moving-target-indicator signal processing. (All Doppler-filtering radars are moving-target indicators, although that term usually implies the use of a delay canceller.)[9] The intended effect of the moving-target indicator signal processing is to eliminate non-moving targets, primarily ground clutter. A sometimes unwanted effect is to create blind speeds--that is, target velocities at which moving targets are invisible.

3.3.1.18 TRACK ACQUISITION MODES

In general (except for track-while-scan) an airborne radar cannot launch a weapon while operating in a search mode. That is, the radar must be tracking a target. The process of establishing a track on a given target is called track acquisition. In the APG-65 radar, air-to-ground tracking is accomplished by designating a point on the ground as your target. A moving-target mode is also available to track moving ground targets. There are four basic air-to-air acquisition “modes” or processes: manual acquisition, fast acquisition, long range auto acquisition, and ACM acquisition. In manual acquisition and fast acquisition, the target to be tracked is designated by the operator. In auto acquisition, the target to be tracked is designated by the computer as the “priority” target, depending upon the mode from which track acquisition was commanded (closest target from RWS, most rapidly closing target from VS). In ACM acquisition, a prescribed search “volume”, depending upon the ACM mode selected, is scanned and the first target encountered in that volume is “locked-up”. ACM acquisition sub-modes are: boresight (BST), gun (GUNACQ or HUDACQ), wide (WACQ), and vertical (VACQ). These ACM acquisition modes differ in their search volumes and acquisition criteria and are optimized for various ACM situations.

3.3.1.19 PULSE COMPRESSION

The energy in a radar pulse is proportional to the length of the pulse. The maximum range of the radar, therefore, improves with increasing pulse length. The range resolution of the radar, however, deteriorates with increasing pulse length. Most modern radars employ a technique, known as pulse compression[9], to obtain the maximum range of a long transmitted pulse while retaining the range resolution of a short received pulse. In order to be able to compress the received pulse, the transmitted pulse is “time-colored” by intra-pulse frequency or phase modulation. There are both analog and digital techniques for compressing such time-colored pulses. Compression ratios of about 50 to 1 are possible. When pulse compression is employed, range resolution tests must be based upon the compressed pulse width, rather than the transmitted pulse width. The minimum range and blind-range zone widths are unaffected by pulse compression.

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[9] Ibid. Section 2.16

3.3.1.20 DOPPLER BEAM SHARPENING AND SYNTHETIC APERTURE RADAR

In the absence of special signal processing, the angular resolution of a radar is limited by the beam width of its antenna. There are special signal processing techniques, known as DBS and SAR, which greatly improve the angular resolution of a radar by creating the effect of a very narrow antenna beam. The APG-65 radar utilizes either DBS or SAR processing in its high-resolution ground-mapping modes. Doppler Beam Sharpening utilizes the difference in the Doppler shifts of the ground returns, which depend on angular offset from the ground velocity vector of the radar aircraft, to distinguish between two points on the ground.[10] An improvement in angular resolution by a factor of about 100 is possible. Due to the relative insensitivity of the Doppler shifts of ground returns in the direction of the ground velocity vector, DBS does not work well in that direction. Many radars either blank the display in the region “off the nose” or substitute a real-beam ground map in that area. Synthetic aperture processing creates the effect of a very long antenna, (that is, very narrow beam width), by combining the returns received at successive antenna locations as the radar aircraft moves.[11] Angular resolution tests in DBS and SAR modes should be based upon the beam-sharpened angular resolution, rather than the real-beam resolution. Such tests also should evaluate the effects of the “hole off the nose” and the effects of the characteristically long display “build” times exhibited by both DBS and SAR radars.

3.3.1.21 INVERSE SYNTHETIC APERTURE RADAR (ISAR)

If an extended radar target is rotating, the radar returns from various points on the target have Doppler shifts that are proportional to the distances of the points from the axis of rotation. These Doppler shifts can be utilized, with the proper mathematical modeling, to improve the angular resolution of the radar in directions transverse to the axis of rotation. The technique is known as inverse synthetic aperture radar (ISAR). The process is “inverse” to synthetic aperture radar in that it is the Doppler shift due to motion of the target that is utilized, rather than the Doppler shift due to the radar aircraft. The information is displayed as Doppler vs. range.

3.3.2 PERFORMANCE CHARACTERISTICS OF AIRBORNE RADARS

3.3.2.1 GENERAL COMMENTS

As a result of the extensive signal processing employed in a modern, multimode radar such as the APG-65, (range and velocity gating, carrier frequency agility, PRF agility, pulse compression, digital frequency filtering, track extrapolation, and hit/miss detection logic), some of the performance characteristics of such a radar are difficult or impossible to determine in flight.[12] For example, without extensive internal radar signal instrumentation and range instrumentation, it is sometimes impossible to determine

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[10] Principles of Radar System Test and Evaluation, Section 2.18.1

[11] Airborne Systems course textbook: Communication System Test and Evaluation, Section 2.6.13

[12] Ibid. Sections 2.12 and 2.13

whether two targets were broken out (resolved as two targets) on the basis of range, velocity, or bearing. For that reason, precise determination of some radar performance characteristics is best performed on the ground, employing artificial target radar stimulation.

In the following paragraphs, formulas are given for calculating, for test planning purposes, the major performance characteristics of an airborne radar.[13]

For convenience in converting units, the following conversion factors are presented.

1 nmi = 6,076 ft
1 kt = 1.69 ft/sec
1 ft = 1.64 x 10^{-4} nmi
1 ft/sec = 0.59 nmi/hr
c = 3.00 x 10^{8} m/sec
c = 9.84 x 10^{8} ft/sec
c = 1.62 x 10^{5} nmi/sec
c = 5.83 x 10^{8} nmi/hr

3.3.2.2 RANGE DETERMINATION

The range to a given target is determined by "time-coloring" the transmitted signal and measuring the elapsed time between the transmission of the signal and the reception of the corresponding return.[14] Thus, the range to a given target is given by the equation:

$$R = c\,(\Delta t) / 2 \quad (\text{ft})$$

where: $c = 9.84 \times 10^{8}$ ft/sec and (Δt) = Elapsed Time (sec)

(The range can be obtained in nautical miles by utilizing $c = 1.62 \times 10^{5}$ nmi/sec.)

3.3.2.3 RANGE, ANGLE, AND VELOCITY GATING

Most modern radars determine range by "gating" the receiver on for a brief time interval. The elapsed time between the time of the transmitted pulse and the time of the "gate" is varied (swept) until the return from the target is "captured" in the gate. The time at which the target return is "captured" indicates the range to the target. The same time-sweeping process is applied to the determination of the bearing (angle) of the target and a similar process (sweeping frequency) is applied to the determination of the velocity of the target.[15]

3.3.2.4 RANGING ACCURACY

The accuracy with which a radar can determine the range to a target is determined by the accuracy with which the radar's intervalometer can measure elapsed times and by anomalous delays in the hardware. Because such information is not usually available to the tester, an estimate of the ranging accuracy of a given radar, for test planning

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[13] Ibid. Sections 2.3 to 2.15 for definitions and a general discussion of these characteristics.

[14] Ibid. Section 2.3.1

[15] Ibid. Sections 2.14 and 2.17.8,9, and 10

purposes, is best obtained from the manufacturer. When an operator is involved in the process, the ability of the operator to “read” the display may be a significant factor.

3.3.2.5 RANGE RESOLUTION

Range resolution is the minimum separation in range between two objects that can be resolved as two objects on that basis.[16] For a simple pulse-ranging radar, range resolution is a function of pulse width.[17] For such a radar, the range resolution is given by the equation:

$$\Delta R = c\ \tau_p / 2 \text{ (ft)}$$

where τ_p is the pulse width in seconds and $c = 9.84 \times 10^8$ ft/sec.

For an FM-ranging radar, the range resolution depends upon the ability of the signal-processing circuitry to discriminate between two frequencies.[18] The calculation of the range resolution for such a radar therefore requires information not usually available to the tester. When an estimate of the range resolution is required for test planning purposes, it is best obtained directly from the manufacturer of the radar.

In addition to the signal processing limitations of the radar, the radar display has a limited ability to individually display two closely-spaced targets, and thus has a significant effect on observed resolution. The display may be the limiting factor in determining the ability of an operator to resolve two targets. The display resolution depends not only upon the characteristics of the display screen, but also upon the scale being displayed. The radar display has a finite number of vertical pixels, and the ratio of the number of vertical pixels per nautical mile of radar display is dependent on the range scale selected. This ratio is an ultimate limit on observed range resolution of the radar. The effective resolution must be determined for all relevant modes of operation and display settings. Range and azimuth resolution should also be matched to show targets in correct proportion.

Expanded display modes such as ARE 30 (Automatic Range Expansion) and ARE 60 in the A-6 increase the display resolution (at some expense to position and shape fidelity), yielding an increase in range and azimuth resolution of the radar in these modes. Internal signal processing quantities are sometimes recorded in radar test to see if the radar breaks out targets the operator is not able to recognize because of display resolution problems.

3.3.2.6 MINIMUM RANGE

The minimum range is that range below which a target cannot be detected due to eclipsing. The minimum range is caused by the transmitting interval blanking the receiver and is present in all pulsed radars.[19] The minimum range is given by the equation:

$$R_{min} = c\ \tau_p / 2 \text{ (ft)}$$

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[16] Ibid. Section 2.3.3

[17] Ibid. Section 2.3.3

[18] Ibid. Section 2.11.3

[19] Ibid. Section 2.3.2

where τ_p is the pulse width in seconds and $c = 9.84 \times 10^8$ ft/sec .

Minimum range is important because it determines the operator's ability to track a target all the way to weapon release, or to be able to track a target until you are able to visually confirm the target, especially when operating under conditions of restricted visibility.

There are factors other than eclipsing that affect minimum range. The smallest display range scale available must be small enough to allow you to see the target all the way to minimum range. The antenna tilt mechanism must allow the antenna to point at the target all the way to minimum range, also. Receiver gain and video gain must be adjustable to a small enough value to reduce blooming, which would obscure the target in the background clutter.

3.3.2.7 BLIND RANGES

Blind ranges are those ranges at which a target cannot be detected due to eclipsing. Blind ranges are caused by the transmit intervals blanking the receiver and are present in all pulsed radars for which special signal-processing, such as PRF agility, has not been provided.[20] (Minimum Range is sometimes called the zero-order blind range.) The ranges at which blind ranges occur are given by the equation:

$$R_B = n\, c / 2\, f_r \text{ (ft)} \quad \text{for } n = 1, 2, 3, \ldots .$$

where f_r is pulse repetition frequency in pulses per second and $c = 9.84 \times 10^8$ ft/sec.

Blind ranges should not be a problem in an air-to-ground radar if the PRFs were suitably chosen for each range scale. Nevertheless, the theoretical blind ranges should be calculated to see if they are within the display range of the radar.

3.3.2.8 BLIND RANGE ZONE WIDTH

The width of the blind range zones is a function of the pulse width and is given by the equation:

$$\Delta R_B = c\, \tau_p / 2 \text{ (ft)}$$

where τ_p is the pulse width in seconds and $C = 9.84 \times 10^8$.

In some radar modes, such as those in the APG-65 in medium PRF, the blind range zones and the blind velocity zones are interdependent. That is, the blind zones are dependent on both range and velocity. The coupling is caused by three factors: (1) the dependence of both the blind ranges and blind velocities on PRF, (2) the use of multiple PRF's (8 in the APG-65) in an attempt to avoid both blind/ambiguous ranges and blind/ambiguous velocities, and (3) the use of hit/miss detection logic (3-out-of-8 in the APG-65) to reduce false alarms. The result is that, when such signal processing is employed, the blind zones of the radar can best be represented on a “map” of blind

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[20] Ibid. Section 2.3.4 and 2.3.8

"zones" as a function of range on one axis and velocity on the other axis. In order to "plot" such a map, a very large amount of data are required over a large range of values of range and velocity.

3.3.2.9 RANGE AMBIGUITY

Range ambiguity is an anomalous indication of range caused by second-time-around radar returns (STAE). That is, the radar signal processor treats a return from a previous transmitted pulse as if it were from the latest transmitted pulse, thus measuring a shortened time interval and indicating a reduced range. An ambiguous range is related to a blind range. That is, if the range to a target is great enough that the return pulse coincides with the transmitting interval, it is a blind range. If the range to a target is even greater, so that the return pulse arrives after the next transmitting interval, the indicated range will be ambiguous.[21] In a pulse-to-pulse ranging radar, the maximum unambiguous range depends upon pulse repetition frequency, and occurs in all ranging modes unless special signal processing is employed to avoid it.[22] The maximum unambiguous range of such a radar is given by the equation:

$$R_{MU} = c / 2 f_r \text{ (ft)}$$

where f_r is pulse repetition frequency in pulses per second and $c = 9.84 \times 10^8$ ft/sec.

An alternative expression for R_{MU} is:

$$R_{MU} = 81 / f_r \text{ (nmi)}$$

where f_r is pulse repetition frequency in kilohertz.

Ambiguous ranges occur at:

$$R_A = n R_{MU} \quad \text{for } n=1,2,3,\ldots .$$

In an fm-ranging radar, the maximum ambiguous range depends upon the length of the frequency modulation interval, T_{fm} . For such a radar, the maximum unambiguous range is given by the equation:

$$R_{MU} = c\, T_{fm} / 2 \quad \text{(ft)}$$

where T_{fm} is the Frequency Modulation Repetition Interval in seconds and $c=9.84 \times 10^8$ ft/sec.

3.3.2.10 MAXIMUM RANGE FOR DETECTION

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[21] Ibid. Section 2.3.4

[22] Ibid. Section 2.3.4

The maximum range for detection is that range beyond which the radar cannot detect a given target due to insufficient signal-to-noise ratio.[23] The maximum range of detection for a modern, multimode air-to-air radar depends upon many factors including the target radar cross section, the radar's parameters, the signal-to-noise ratio required for detection, and the blip-to-scan ratio deemed sufficient for detection.[24] The maximum range of detection for a radar employing coherent pulse integration, non-coherent pulse detection, range gating, and velocity gating is given by the equation:

$$R_{MD}=[P_a G_a^2 \lambda^2 \sigma G_{ci}G_{nci}G_{rg} G_{vg} e^{-\alpha Rmd} / (4\pi)^3 f_r \tau_p L_s N_s (S/N)_{Min\ Det}]^{1/4}(ft)$$

where25:

P_a = Average Transmitted Power (watts)
G_a = Antenna Gain (nd)
λ = Carrier Wavelength (ft)
σ = Target Radar Cross Section (ft^2)
G_{ci} = Coherent Pulse Integration Gain (nd)
G_{nci} = Non-Coherent Pulse Integration Gain (nd)
G_{rg} = Range Gate Noise Reduction Gain (nd)
G_{vg} = Velocity Gate Noise Reduction Gain (nd)
α = Atmospheric Attenuation Constant (1/ft)
f_r = Pulse Repetition Frequency (Hz)
τ_p = Pulse Width (sec)
L_s = Total System Loss Factor (nd)
N_s = System Noise (watts)
$(S/N)_{Min\ Det}$ = Minimum signal-to-Noise Ratio Required for Detection

Many of the parameters in the range equation are poorly defined or difficult to obtain. Furthermore, detailed information about the radar's signal processing is required to arrive at a meaningful estimate of maximum range. Also, if the factor involving atmospheric attenuation is included, as shown, the expression is a transcendental equation in R_{MD} and thus cannot be solved for R_{MD} without an iterative procedure. Inclusion of the term for atmospheric attenuation also requires a measurement (or estimate) of the atmospheric attenuation coefficient. In practice, atmospheric attenuation is often neglected in estimating maximum range for detection. For purposes of test planning, an estimate of the maximum range of detection for a given target is best obtained from the manufacturer of the radar.

In ground mapping and targeting modes, there are different types of maximum detection ranges to consider:

- The maximum range for detection is the maximum distance any radar returns are detected .

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23 Ibid. Section 2.4
24 Ibid. Section 2.4 and 2.15
25 Ibid. Section 2.15

- The maximum range for navigation is the range at which returns show terrain features, major cultural buildups, and land/water contrast with enough detail to navigate.
- The maximum range for identification is the range at which an area surrounding a target can be identified, which would allow you to decrease your scale or change modes in order to develop targeting information on a specific target. Tasks you should be able to do in this phase are identifying an area within a city, such as a railyard, military installation, or bridge.
- The maximum range for targeting is the range at which a particular target such as a building, a runway, a specific point on a bridge, or a tactical sized target such as a tank or other vehicle, can be identified sufficiently to be designated for attack.

Note that range affects the grazing angle of the radar beam, thereby also affecting the quality of a ground map.

Airplane altitude must be considered when testing maximum ranges since your radar horizon depends on your line-of-sight, which depends on altitude. The radar horizon as a function of altitude is:

$$\text{Radar horizon (nmi)} = 1.23 \sqrt{\text{(altitude in ft AGL)}}$$

Ensure that measurements are taken at an altitude where the radar horizon is greater than the maximum expected range to the target.

A radar may be display limited or power limited at its “maximum” range. If it is display limited, you will have returns all the way out to maximum range on the display. In this case you have enough power to detect targets beyond your display range, but are limited in display range to see them. If you are power limited, you will not have returns all the way to the maximum range of the display, since you do not have the power to effectively illuminate targets at that range. Being display limited may have an impact on how covert you may be able to stay, since you are radiating more power than you can use, which allows enemy EW receivers to receive your signal at a greater range than they would if your power output were matched to your ability to display range.

3.3.2.11 BEARING/ELEVATION DETERMINATION

The relative bearing to a target is determined by one of two methods.[26] In a “spotlight” radar, a narrow beam is placed upon the target and the direction to the target is taken as the direction in which the beam is pointed for maximum return. In an interferometric radar, the returns from the target are received at two or more locations (“antennas”). The difference in the phase (or amplitude) of the returns received at the two locations is a measure of the angular offset of the target from the boresight of the antenna.[27] True interferometry involves measurement of the phase difference and provides an order of magnitude improvement in accuracy and resolution over that of a “spotlight” radar.

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26 Ibid. Section 2.3.5

27 Ibid. Section 2.13.2

3.3.2.12 BEARING/ELEVATION DETERMINATION ACCURACY

The accuracy with which a non-interferometric radar can determine the bearing of a target is determined by several factors, including the antenna boresight error, the antenna radiation pattern, the radar signal processor, and the radar display when visual observation is involved. The bearing accuracy of an interferometric radar is determined by the antenna boresight error and the ability of the radar signal processor to measure the difference in phase of two signals.[28] For test planning purposes, an estimate of the bearing accuracy for a given radar is best obtained from the manufacturer.

3.3.2.13 ANGULAR RESOLUTION

Angular, or azimuth, resolution is the minimum separation in bearing (angle) between two objects that can be resolved as two objects on that basis.[29] The angular resolution of a non-interferometric (non-monopulse) radar without Doppler beam sharpening or synthetic aperture signal processing is assumed to be numerically equal to the beamwidth of the antenna (which is determined by the effective diameter of the antenna and the carrier wavelength). The angular resolution is given by the equation:

$\theta_R = (BW)_{Ant}$ (deg)

where $(BW)_{Ant}$ is the beamwidth of the antenna in degrees.

For an X-band, circluar antenna with uniform illumination, an estimate of the antenna beamwidth can be made by the equation:

$\theta_R = 70/d$ (inches) degrees
where d is the antenna diameter in inches.

The angular resolution of a monopulse radar, or one employing Doppler beam sharpening or synthetic aperture signal processing, is determined by the ability of the signal-processing circuitry to distinguish between two signal phases or frequencies and requires information not normally available to the tester.[30] For purposes of test planning, an estimate of the angular resolution of such a radar is best obtained from the manufacturer of the radar.

For Doppler beam sharpened radars, and depending on whether the radar is mechanized to give constant resolution or constant build time, you may have better resolution with a larger angle off the nose. In any event, there will be a “notch” off the nose for both DBS and SAR.

In addition to the signal processing limitations of the radar, the radar display has a limited ability to individually display two closely-spaced targets, and so has a significant effect on observed resolution. The display may be the limiting factor in determining the ability of an operator to resolve two targets. The display resolution depends not only upon the characteristics of the display screen, but also upon the scale being displayed.

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[28] Ibid. Sections 2.3.5 and 2.13.2

[29] Ibid. Section 2.3.6

[30] Ibid. Section 2.18

The radar display has a finite number of horizontal pixels, and the ratio of the number of horizontal pixels per degree of scan angle of radar display is dependent on the range to the target. This ratio is an ultimate limit on observed azimuth resolution. The effective resolution must be determined for all relevant modes of operation and display settings. Range and azimuth resolution should also be matched to show targets in correct proportion.

Expanded display modes such as ARE 30 (Automatic Range Expansion) and ARE 60 in the A-6 increase the display resolution (at some expense to position and shape fidelity), yielding an increase in range and azimuth resolution of the radar in these modes. Internal signal processing quantities are sometimes recorded in radar test to see if the radar breaks out targets the operator is not able to recognize because of display resolution problems.

3.3.2.14 ANGLE AMBIGUITY

Angle ambiguity is an anomalous indication of target bearing due to detection of that target in the side lobes of the antenna.[31] In order to avoid ambiguous bearing indications, some radars employ a sidelobe-rejection scheme such as the use of a guard channel.[32] All directive antennas, including phased arrays and interferometric antennas, have sidelobes.[33] The angle ambiguity (antenna sidelobe structure) is determined by antenna design and is best obtained from the manufacturer of the radar.

3.3.2.15 VELOCITY DETERMINATION

The velocity of a target with respect to the radar aircraft is calculated from measurements of the range, range-rate, and line-of-sight slew rate of the target.[34] The velocity of the target with respect to the air mass can then be computed by vectorally adding the relative velocity to the velocity of the radar aircraft.

Although radial velocity (range rate) can be computed directly by calculating the time-rate-of-change of range, Doppler radars compute range rate by measuring the Doppler shift of the target return signal.[35] The latter method avoids the time differentiation process and thus yields a less noisy measure of range rate. The relative, radial component of the velocity of the target with respect to the radar aircraft is given by the equation:

$$V_{RR} = \lambda f_d / 2 \quad \text{(ft/sec)}$$

where:

λ = Carrier wavelength (ft)
f_d = Target Return Doppler Shift (Hz)

For an X-band radar, the doppler shift is approximately 35 Hz per knot.

3.3.2.16 VELOCITY DETERMINATION ACCURACY

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[31] Ibid. Section 2.3.7
[32] Ibid. Section 2.3.7
[33] Ibid. Section 2.13.2
[34] Integrated Weapon System T&E, Section 2.4
[35] Principles of Radar System Test and Evaluation, Section 2.13.3

The accuracy with which a given radar can determine the velocity of a target depends upon the method employed for velocity measurement. The accuracy of velocity measurement for a radar that measures Doppler shift depends upon the accuracy of the radar's frequency discrimination circuitry.[36] The accuracy of velocity measurement for a radar that measures time-rate-of-change of range depends upon the accuracy of the radar's intervalometer, as for ranging accuracy. In any case, an estimate of the target velocity measurement accuracy of a given radar is best obtained from the manufacturer.

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[36] Ibid. Section 2.13.3

3.3.2.17 VELOCITY RESOLUTION

Velocity resolution is the minimum separation in velocity between two targets that can be resolved as two targets on that basis. The velocity resolution of a pulsed Doppler radar employing Doppler filtering bins is determined by the width of the frequency bins.[37] The velocity resolution of such a radar is given by the equation:

$$\Delta V = \lambda\ (\Delta f)_{DF} / 2\ \text{(ft/sec)}$$

where λ is the carrier wavelength in ft, and $(\Delta f)_{DF}$ is the width of the Doppler bandpass filter in Hz. As an example, to resolve velocities of 5 kt would require a Doppler filter of 101.6 Hz.

The velocity resolution of a radar employing phase-locked-loop frequency discrimination depends upon the filters employed in the phase-locked-loop.[38] The velocity resolution of a radar employing digital signal processing depends upon the sample size of the fast-fourier-transform process. For purposes of test planning, it is best to obtain an estimate of the velocity resolution of a given radar from the manufacturer.

The resolution of the radar display may be the limiting factor in determining the ability of the operator to resolve two targets. A radar display has a limited ability to individually display two closely-spaced targets. The display resolution depends not only upon the characteristics of the display screen, but also upon the scale being displayed. Thus, the effective resolution must be determined for all relevant modes of operation and all relevant display conditions.

3.3.2.18 MINIMUM VELOCITY

The minimum velocity is that relative radial velocity of the target with respect to the radar below which the target cannot be detected due to clutter interference or clutter filtering.[39] The minimum velocity at which a target can be detected is determined by the frequency range obscured by the clutter return and/or the frequencies filtered out by the clutter filters. If it is assumed that no targets can be seen within the entire clutter pedestal, the minimum detectable velocity of the target with respect to the radar is numerically equal to the radar aircraft groundspeed. That is, the minimum velocity is given by the equation:

$$V_{min} = V_G\ \text{(ft/sec)}$$

where V_G is the radar vehicle ground speed in ft/sec.

If it is assumed that targets cannot be seen only within the main lobe clutter, the minimum detectable target velocity with respect to the radar is determined by the center frequency and width of the mainlobe clutter filter. The center frequency, in turn, depends upon the radar antenna angle off the nose (off the ground velocity vector). For purposes

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[37] Ibid. Section 2.13.3
[38] Ibid. Section 2.17.9
[39] Ibid. Section 2.13.4

of test planning, it is best to obtain an estimate of the minimum velocity of such a radar from the manufacturer of the radar. In the absence of specific information, a conservative approach is to assume a worst-case value of minimum velocity equal to that for the preceding case.

3.3.2.19 MAXIMUM VELOCITY

The maximum relative radial target velocity that can be detected by a Doppler signal processing radar is a function of the radar's signal processing circuitry or of its display. In either case, a value of the maximum velocity is best obtained from the manufacturer of the radar.

3.3.2.20 VELOCITY AMBIGUITY

Velocity ambiguities are anomalous target velocity indications due to sampled-data effects caused by pulsing. Velocity ambiguities in pulse Doppler radars are caused by frequency folding and aliasing due to pulsing and are determined by the pulse repetition frequency. Velocity ambiguities occur when the true relative radial component of the velocity of the target exceeds V_{MU} , where[40]:

$$V_{MU} = (+/-)\ n\ (\lambda\ f_r / 4)\ (\text{ft/sec})$$

The ambiguous velocity indications will be given by:

$$V_{IND} = V_R\ (+/-)\ n\ (\lambda\ f_r / 2)\ (\text{ft/sec})$$

where:

V_{IND} = Indicated Target Relative Radial Velocity (ft/sec)
V_R = True Target Relative Radial Velocity (ft/sec)
λ = Carrier Wavelength (ft)
f_r = Pulse Repetition Frequency (Pulses/sec)

3.3.2.21 BLIND VELOCITIES

Blind velocities are those relative radial velocities of the target with respect to the radar for which the target cannot be detected due to coincidence, in the frequency domain, of the target and clutter signals and/or due to clutter filtering or speed gating. The blind velocities of a pulse Doppler radar are caused by frequency folding and aliasing of the clutter returns and of the clutter return notch filtering.[41] The blind velocities are given by the equation:

$$V_B = n\ (\lambda\ f_r / 2)\ (\text{ft/sec})$$

where λ is the carrier wavelength in feet and f_r is the pulse repetition frequency in pulses per second.

3.3.2.22 BLIND VELOCITY ZONE WIDTH

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[40] Ibid. Section 2.13.5

[41] Ibid. Section 2.13.6

If the mainlobe clutter return filter filters out only those returns that fall within the main lobe clutter, as for the medium PRF modes of the APG-65, the width of the main lobe clutter filter notch is given by the equation:

$$\Delta V_{mlcf} = V_G\, \theta_B\, \mathrm{Sin}(\delta) \quad \text{(ft/sec)}$$

where: V_G = Radar Aircraft Ground Velocity (ft/sec)

θ_B = Radar Antenna Beamwidth (Radians)

δ = Depression Angle of Target (Deg) (assuming zero side-look angle)

If the clutter filter filters out all returns that fall within the entire clutter pedestal, as for the high PRF modes of the APG-65, the width of the clutter filter notch is given by the equation:

$$\Delta V_{cf} = 2\, V_G$$

In the air-to-air modes of some radars, such as the APG-65, the blind velocity zones are deliberately extended to avoid moving targets on the ground. These extended blind regions are called speed gates and apply to systems that filter out only the main-lobe clutter as well as those that filter out the entire clutter pedestal. Information on the extent of speed gates must be obtained from the manufacturer of the radar.

In some radar modes, such as those in the APG-65 in medium PRF, the blind range zones and the blind velocity zones are interdependent. That is, the blind zones are dependent on both range and velocity. The coupling is caused by three factors: (1) the dependence of both the blind ranges and blind velocities on PRF, (2) the use of multiple PRF’s (8 in the APG-65) in an attempt to avoid both blind/ambiguous ranges and blind/ambiguous velocities, and (3) the use of hit/miss detection logic (3-out-of-8 in the APG-65) to reduce false alarms. The result is that when such signal processing is employed, the blind zones of the radar can best be represented on a “map” of blind “zones” as a function of range on one axis and velocity on the other axis. In order to “plot” such a “map”, a very large amount of data are required over a large range of values of range and velocity.

3.3.2.23 GROUND MAPPING QUALITY

For an air-to-ground radar, a perfect display would appear as a photograph of the surface upon which the radar is focusing. The features displayed could be directly related to a navigation chart with geographic and cultural features a duplicate of the actual features. Features would be displayed with the correct orientation, with correct relative sizes, in correct proportion, and with sufficient resolution at the appropriate ranges to enable targeting. The quality of the ground map is directly related to the radar's ability to resolve, and ultimately display, closely spaced ground features. The required resolution cell size (the size of the smallest distance the radar can resolve in range and bearing) depends on the mapping requirements, these being anywhere from large cities to automobile size targets. The smaller the target, the finer the resolution required. The relationship between the resolution cell size and how it is translated to the display is extremely important. The pixel resolution of the display may vary considerable from the radar resolution cell size.

Range resolution can be improved by narrowing the pulse width. The penalty paid is the loss of radiated radar energy compared to using a longer pulse. You can gain back the amount of radiated energy by using a larger PRF, but only at the expense of maximum range capability. Pulse compression techniques can be used to gain the power output advantage of a long pulse width while preserving or enhancing range resolution, albeit at some loss in minimum range. The resolution problem is more difficult in azimuth. Azimuth resolution depends on beamwidth. To get better azimuth resolution requires either a higher frequency, which results in greater atmospheric attenuation losses and a loss of range, a larger antenna, which may not fit in the space available, or the use of DBS or SAR techniques. DBS techniques will yield increased resolution at the expense of increased processing times and the inability to point the aircraft at the area of interest. SAR creates a desired antenna length using optical or digital methods, also at the expense of increased processing time and the inability to point at the target. This may not preclude mission accomplishment if the navigation system is good enough to support accurate position keeping from the point at which you designate the target until the release point, or until you can bring another sensor into use for final designation and release cueing.

3.3.2.24 PREFLIGHT AND BUILT-IN-TEST

Built-In-Test (BIT) is a common characteristic of modern weapon systems. It is typically a software function that checks equipment at power-up or when commanded, and may continuously monitor equipment status to detect faults. Fault insertion techniques are used to determine how well the BIT is able to locate equipment failures by inserting cards with known failures into otherwise operating avionics boxes, and then running the BIT to see if it can identify the fault.

3.3.2.25 SYSTEM INTEGRATION

The integration of a radar system into an aircraft weapon system is a major factor in the potential operational and mission success of a radar system. System integration is a measure of the integration of the radar with the airplane's other systems, particularly in the areas of navigation and mission computer interaction. The radar system should interact with the navigation system in general navigation, target acquisition and designation, and patrol area maintenance. The mission computer may be tied to the radar to provide and control antenna tilt and target designations. Human factors considerations are very important in the integration of a weapon system since good human factors design allows the operator to efficiently manage the systems under his control. The integration of the radar system to the aircraft computer allows a synergistic effect on the systems, a major factor in mission completion.

3.4 TEST METHODS AND TECHNIQUES

3.4.1 GENERAL CONSIDERATIONS

The quantitative testing of a radar entails making measurements of the performance characteristics of the radar under carefully instrumented conditions. Measurements must be made in all relevant modes, for all appropriate system operating and display settings, and for various carefully controlled scenarios involving the radar aircraft, the target aircraft, and the operating environment. The tests must be designed to examine the performance of the radar as it performs three basic functions: search, track acquisition, and track. The order in which the tests are performed is generally dictated by considerations of flight test safety, efficiency, and economy. A number of tests can be performed while operating in a given mode, or a number of modes can be examined while set up for a given test. In the following 2 chapters, the information is grouped according to the tests performed. It must be understood that, for a given test, the radar operating modes and the test scenario are varied to cover all cases of interest.[42]

A major factor in test planning is the inherently stochastic nature of the testing process. Both the system under test and the test instrumentation are subject to random errors and disturbances. For that reason, redundant data must be taken to allow for statistical data processing. At a minimum, simple averaging of redundant test results should be employed to obtain a "best estimate" of the test results.

Another major factor in test planning is the need to perform a post-test error budget closure analysis.[43] An error budget closure analysis uses estimates of the error contributions of both the system under test and the test instrumentation to derive an estimate of the total random error (dispersions) to be expected in the quantitative test results. Calculation of the estimated dispersions requires that all major sources of error be identified and that estimates be obtained for their error contributions. Calculation of the actual dispersions in the test results requires that redundant measurements be taken. The estimate is then compared to the actual dispersions in the test results. A failure of the actual dispersions to agree with the estimated dispersions indicates either that the test planner failed to account for all major error sources or that the test measurements were inaccurate, thus necessitating a rerun of the tests.

In air-to-air testing, it should be noted that tests that may involve aircraft approaching one another on reciprocal headings often can be performed with the aircraft in trail. Such an arrangement, when feasible, will allow more time for "gradual" adjustments of aircraft position or velocity. The extra time is especially useful, for example, in the test for range resolution where, while increasing the separation in range between the two target aircraft, care must be taken to minimize their difference in velocity.

3.4.2 SAFETY CONSIDERATIONS

A preflight safety checklist should be established and executed exactly.

An approved flight test plan should be established and followed without exception. Any change to the test plan must be reviewed and approved in the same rigorous manner as that employed for the original test plan.

Preflight examination and analysis should ensure that flight test instrumentation does not adversely affect safety of flight. For example, electronic data acquisition and recording equipment must not adversely affect flight-critical aircraft systems; cockpit-mounted equipment such as over-the-shoulder cameras must not adversely affect emergency cockpit egress; and instrumentation-induced aircrew workload must not interfere with safe operation of the aircraft.

All established minimum and/or maximum flight restrictions should be continuously monitored and maintained, including those on altitude, airspeed, g-loading, flightpath separation, night operations, weather conditions, and aircraft weight and balance.

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[42] Ibid. Section 4.2.3

[43] Integrated Weapon System Test and Evaluation, Section 5.6

No aircraft combat maneuvering will be performed. Only preapproved, explicitly defined maneuvering is authorized. Establish, brief, and rigidly observe rules of engagement, including those concerning flightpath separation, loss-of-visual contact, and break-off procedures.

In order to maintain safe flight path separation, aircraft on reciprocal heading or otherwise intersecting paths should maintain vertical separation until visual contact has been established.

All of these tests involve a significant mid-air potential. Maintain a heads-out lookout doctrine to the maximum extent possible. Do not get so involved in system operation or data taking that you neglect your responsibilities, as part of the aircrew, to maintain safe flight.

Test plans sometimes utilize ground-controlled vectoring and separation assistance. While such assistance should be utilized where applicable, it must be remembered that the responsibility for safe flight lies with the aircrew. Do not become complacent or allow a ground controller to put your aircraft in a hazardous situation.

CHAPTER 4

AIR-TO-GROUND RADAR TESTING

CHAPTER 4

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CHAPTER 4
AIR-TO-GROUND RADAR TESTING

4.0 OVERVIEW

This chapter is designed to help familiarize the reader with some of the general radar test techniques that can be used in testing many of the air-to-ground modes of modern airborne radars. This chapter is by no means exhaustive, but is designed to give direction for testing common mechanical scanned mapping radars that employ real-beam and Doppler Beam Processing techniques. The section is broken down into three primary groupings: Interface testing, mechanical issues, and radar performance.

4.1 TEST METHODS AND TECHNIQUES (INTERFACE)

4.1.1 PREFLIGHT AND BUILT-IN TESTS

4.1.1.1 PURPOSE

The purpose of these tests is to assess the suitability of radar preflight procedures and the Built-In Test (BIT) to quickly and easily bring the system on line, alert the operator to any faults while initializing the radar, and keep the operator appraised of the radar status while it is in use.

4.1.1.2 METHOD

Perform a normal system turn-on using the checklist or the applicable system manual. Note the time of turn-on and the time the system is ready for use. Record the time required completing the checklist procedures. Record qualitative comments on ease of checklist use, including observations on checklist complexity, order of switch actuation, control placement and sense, and other cockpit evaluation considerations. Observe alerts provided during startup for usefulness of information about the progress and status of the startup. Run the BIT, noting the time it takes to complete, and the status reporting method, including the usefulness of status indications. Record BIT indications, and correlate those indications to actual radar performance once you are airborne. Record comments on the accessibility of BIT indications and their clarity and accuracy.

Develop baseline settings for whatever system you are operating so you have a repeatable starting point from which to vary the system controls. This makes your testing repeatable, and will allow different operators to start from the same place when evaluating a system.

4.1.1.3 DATA REQUIRED

- Time required for power up
- Time required completing the checklist procedures
- Time the system is ready for use
- Taxi time
- Qualitative comments on ease of checklist use
- Alerts provided, usefulness of information
- BIT completion time

- BIT indications, clarity, accuracy
- Baseline settings

4.1.1.4 DATA REDUCTION

No data reduction required.

4.1.1.5 DATA ANALYSIS

The complexity and time to perform the preflight checklist for any piece of equipment or sensor should be related to the operator's overall preflight workload, including alert launch constraints. Good cockpit design should prevail, with frequently used and similar-function controls grouped together and easily within reach. Consider how operator intensive the startup procedures are. Typical crew duties during startup entail more than just equipment preflight. The crew must do tasks such as monitor taxi progress, operate and talk on the radio, etc., so the turn-on should not preclude performance of these duties. The BIT complexities, clarity, time to run, and usefulness should also be related to operator workload and alert launch impact. Any incorrect BIT results should be related to mission impact. A false bad indication may be just an annoyance, but a false good indication could have major mission impact.

Fault insertion techniques are beyond the scope of TPS exercises, but should be used for complete evaluations conducted for any system.

4.1.1.6 ERROR ANALYSIS

Times are considered to be accurate to ±1 sec.

4.1.1.7 SAFETY CONSIDERATIONS

Checklists should be followed explicitly; deviations should be made only with proper maintenance approval. Fault insertion techniques should also be analyzed for adverse permanent impact to the system under test.

4.1.2 CONTROLS AND DISPLAYS

See the Cockpit Evaluation chapter.

4.2 TEST METHODS AND TECHNIQUES (MECHANICAL)

4.2.1 ANTENNA SCAN RATES

4.2.1.1 PURPOSE

The purpose of this test is to measure radar antenna scan rates.

4.2.1.2 METHOD

Antenna scan rate tests are performed on the ground for all azimuth scan angles and a small sample verified in flight. If discrepancies between ground and flight tests are observed, all azimuth scan tests should be repeated in flight. No ground interlocks should be bypassed.

The test procedure involves measuring the time required to scan from one side of the display to the other and then back to the origin. For larger azimuth scan angles, ten scans are sufficient to obtain an accurate average. For smaller scan angles, twenty scans should be utilized to reduce the effect of operator response times on the measurements.

4.2.1.3 DATA REQUIRED

- Radar mode
- Azimuth scan angle selected (the number of degrees from one side of the scan to the other)
- Number of scans timed (one scan is defined as a sweep from one side to the other and back to the starting point)
- Time to complete the desired number of scans
- Qualitative comments on scan utility for target detection, tracking, and situational awareness

4.2.1.4 DATA REDUCTION

Compute the actual scan rate utilizing the following equation:

scan rate (deg/sec) = [(scan angle selected)*X*2/ time (sec) for X scans]

where X is the number of scans timed. Ensure you enter the appropriate number for scan angle selected, since some systems define their scan angles in a ± format (i.e., a selection of 60 may mean ±60 deg, or a 120 deg sector), and others may define 60 as a 60 deg sector. To get this equation to be correct, you should enter the scan angle as the number of degrees from one side of the scan to the other. If your scan rates come out half or twice the value expected, take a close look at how you are counting the scans and accounting for the number of degrees covered.

4.2.1.5 DATA ANALYSIS

Compare values to contractor data and/or specifications. Mission Relation: Is the display updated frequently enough, taking into account your speed, to provide adequate information?

4.2.1.6 ERROR ANALYSIS

Evaluator response when starting and stopping the timer introduces the largest amount of error. By increasing the number of scan cycles, the percentage error introduced is minimized over the longer time interval. Timing accuracy will be ±1.0 sec.

4.2.1.7 SAFETY CONSIDERATIONS

During ground evaluations, care should be taken to prevent inadvertent system radiation.

4.2.2 NON-MANEUVERING SCAN STABILITY (GIMBAL LIMITS)

The purpose of these tests is to evaluate the capability to provide a stabilized antenna scan throughout the scan volume limits of a mechanically scanned antenna as defined by the mechanical gimbal stops in all axes.

4.2.2.1 ANTENNA SCAN ANGLE (GIMBAL) LIMITS

4.2.2.1.1 PURPOSE

The purpose of this test is to measure the antenna scan angles (horizontal limits) available in the various radar modes.

4.2.2.1.2 METHOD

Antenna scan angle limits are tested by positioning a radar significant target ahead of the aircraft and turning until the target falls off the edge of the display. The target should be more than 20 nmi ahead of the test aircraft to limit the effects of aircraft movement off the original course line. If the edges of the scan sector are truncated by the display, as in figure 1, ensure that the target video is at a range inside of the truncated area by increasing the radar scale.

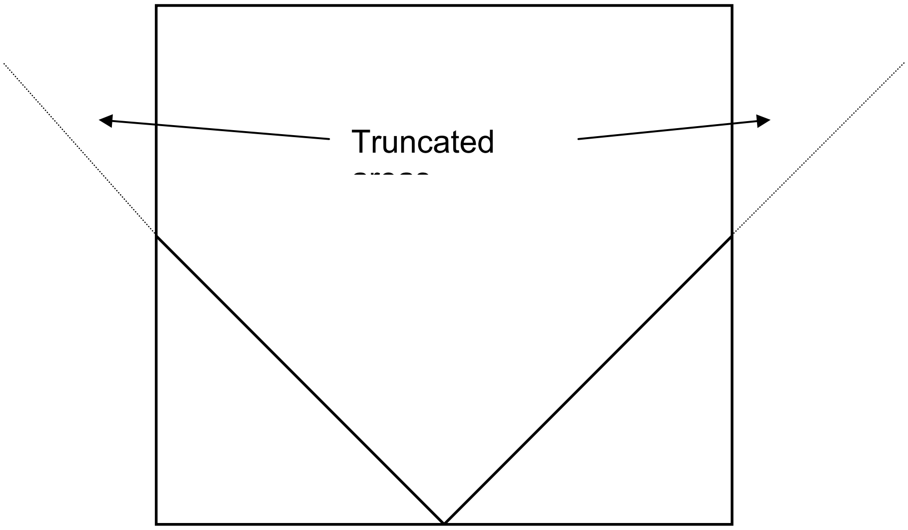


Figure 1

Truncated Radar Display Areas

Maneuver the test aircraft to place the target on the centerline of the radar display and record your heading. Turn the aircraft until the target video moves off the display. Large turn rates may be used during the initial portion of the turn, but the turn should be eased as the target nears the edge of the display to avoid overshooting the target in the time it takes the scan to return to the side of the display. Record the heading as the target is lost off the side of the display, then turn the aircraft to put the target on the centerline, note the heading, and repeat the test with a turn to the other side. Repeat the test for each scan angle. The test may be done by putting the target on the side of the display first, and bringing it to the center. This method may allow a harder turn rate at the beginning of the turn and better data accuracy.

4.2.2.1.3 DATA REQUIRED

- Radar mode
- Aircraft heading when target is centered on the display, and at both the left and right limits

- Qualitative comments on utility of wide angles for searching large areas, and use of narrow angles for tracking

4.2.2.1.4 DATA REDUCTION

Determine the radar scan limits by subtracting the start and the end headings. Compare the actual limits with those of the scan angle selected.

4.2.2.1.5 DATA ANALYSIS

Compare the data to contractor data and/or specifications. Compare the measured data for symmetry about the centerline.

4.2.2.1.6 ERROR ANALYSIS

Errors are introduced by the fact that the test aircraft cannot turn and still remain on the line from the initial position to the target. The turn introduces a lateral offset that causes the actual angle to be different from the aircraft heading, which is measured. If the range between the aircraft and the target is large, and the turn is made quickly, the lateral offset is minimized. Care should be taken to prevent the turn from creating any degradation as a result of stabilization or load factor. The effects of target range to the aircraft will be considered minimal if the target range is approximately 20 nmi or greater when the test commences. The aircraft heading will be resolved to within 3 deg, yielding scan angle calculations of the same accuracy.

4.2.2.1.7 SAFETY CONSIDERATIONS

No unique safety concerns are posed by this test.

4.2.2.2 PITCH GIMBAL LIMIT TESTS

4.2.2.2.1 METHOD

Testing should be done at an altitude compatible with the maneuvers to be performed. Pitch maneuvers should be tailored to aircraft performance and mission requirements. Airplanes can gain or lose speed very rapidly while doing pitch maneuvers. Pitch up maneuvers should be performed first. Pick an area on the nose to map that affords a good mix of terrain and cultural features. The aircraft should begin a slow pitch up until radar performance is degraded, display degradation is noticed, or your test limit is reached. Record radar tilt, aircraft pitch angle, and degradations noticed. Reduce the pitch angle and start a slow pitch down maneuver until radar performance is degraded, display degradation is noticed, or your test limit is reached. Record radar tilt, aircraft pitch angle, and degradations noticed. These tests can be combined with load factor and rate testing paragraph 4.1.9.

4.2.2.2.2 DATA REQUIRED

- Radar Tilt
- Aircraft Pitch Angle
- Degradation Noted

4.2.2.2.3 DATA REDUCTION

Calculate the pitch gimbals limit as the combination of aircraft pitch angle and radar tilt.

4.2.2.2.4 DATA ANALYSIS

Compare the calculated result to contractor data or other specifications. Mission impact: Does the radar provide sufficient radar coverage during all climb and dive profiles.

4.2.2.2.5 ERROR ANALYSIS

Errors in aircraft pitch can be as high as ±5 deg as viewed from a HUD or other attitude reference source.

4.2.2.2.6 SAFETY CONSIDERATIONS

Ensure adequate initial airspeed is used when entering the pitch up maneuver. Set test plan limits accordingly to avoid excessively high pitch up or down conditions.

4.2.2.3 ROLL GIMBAL LIMIT TESTS

4.2.2.3.1 PURPOSE

Purpose of this test is to evaluate the radar's scan stability when performing roll maneuvers. This test is applicable to radar systems that maintain an earth stabilized antenna scan within set gimbal limits during aircraft roll maneuvers.

4.2.2.3.2 METHOD

Testing should be done at an altitude compatible with the maneuvers to be performed. Pick an area on the nose to map that affords a good mix of terrain and cultural features. Use moderate to low roll rates through out the test. Start with a small bank angle and increase until degradations are noted or your test limit is reached. Roll the aircraft and stabilize at the bank angle of interest. Notice any degradation in radar performance. Record bank angle and any degradation noticed. Increase the bank angle and make more observations. Return to straight and level flight.

4.2.2.3.3 DATA REQUIRED

- Bank angle
- Degradation Noted
- Qualitative comments

4.2.2.3.4 DATA REDUCTION

None required.

4.2.2.3.5 DATA ANALYSIS

Compare the calculated result to contractor data or other specifications. Mission impact: Does the radar provide an adequate picture within a mission representative-maneuvering envelope.

4.2.2.3.6 ERROR ANALYSIS

Errors in aircraft bank can be as high as ±3 deg as viewed from a HUD or other attitude reference source.

4.2.2.3.7 SAFETY CONSIDERATIONS

Set test plan limits accordingly to match the particular platform’s limits to avoid excessively high bank angles.

4.2.3 ANTENNA STABILIZATION (RATE AND LOAD FACTOR EFFECTS)

4.2.3.1 PURPOSE

The purpose of this test is to evaluate the radar antenna's capability to maintain a stable orientation with respect to the ground during aggressive aircraft maneuvering, and to assess the impact on the mission.

4.2.3.2 METHOD

4.2.3.2.1 GENERAL

All stabilization tests should be performed above 5,000 ft AGL. Buildup is important. Select test limits based on the limits of the aircraft, and considering what kinds of mission maneuvers may be required. Maximum maneuvering limits, rates, and load factors should be verified from the NATOPS and Aircraft Discrepancy Book (ADB), and briefed prior to the flight. A pre-maneuvering checklist should be completed prior to conducting stabilization tests. It should contain, as a minimum:

- loose gear stowed
- harnesses locked

Maneuvers are done in one axis at a time to start. When looking at pitch rates, you will get load factor data, too, since it cannot be separated from pitch rate. Load factor will, however, vary with speed at a given pitch rate, so using lower airspeeds will allow the tester to see the effects of pitch rate with less load factor applied. Since yaw rates have limited mission relation, yaw rate tests are not performed.

4.2.3.2.2 ROLL RATE TESTS

The tests are performed by rolling the aircraft at increasing roll rates while noting any display degradation. A buildup approach should be used, starting with slow roll rates and increasing the roll rate until you notice any degradation, or until you reach your test limit. A good technique is to roll from one wing down to the other wing down, noting the time it takes to complete the roll. Due to roll mode time constant effects, the roll rate will not reach a steady state instantaneously, so you should time between points inside the starting and ending points of your roll. A build up approach using increasing stick displacements should be used. If the aircraft limits allow, you should roll through a full 360 deg. Record bank angle changes, time to complete the changes, and any degradations noted.

4.2.3.2.3 PITCH RATE AND LOAD FACTOR TESTS

Pitch rate and load factor tests can be performed during pitch gimbals limit testing. Plan a build-up approach, considering the limits of the aircraft and the mission requirements. With your nose high after the pitch up for the gimbals limit test, you can roll inverted and pull down, recording the load factor, number of degrees pitched, time to complete the pitch maneuver, and any display degradations. With your nose low after the pitch down for the gimbals limit test, you can pull up, recording the load factor, number of degrees pitched, time to complete the pitch maneuver, and any display degradations. These maneuvers should be part of a build-up plan, so it should take several runs to collect all your data.

Although load factor cannot be separated from pitch rates, a relationship exists so that as speeds increase, a smaller pitch rate is needed to develop the same load factor.

If no degradations or detection losses are found, perform rolling push overs and pull ups and note any system degradation. Pitch, roll, and yaw stabilization should be performed in all air-to-ground modes.

4.2.3.3 DATA REQUIRED

For all tests:

- Aircraft altitude, airspeed
- Qualitative comments on radar performance and display degradation during the maneuvers
- Comments on the limits imposed on tactics and mission due to any degradation during mission relatable maneuvers

For roll rate tests:

- Amount of bank angle change
- Time to complete the bank angle change

For pitch rate and load factor tests:

- Amount of pitch change
- Time to complete the pitch maneuver
- "g" loading

4.2.3.4 DATA REDUCTION

To get rates, the angular displacement of the maneuvers is divided by the time to complete in order to compute the average rate of motion.

4.2.3.5 DATA ANALYSIS

If no degradation is visible during the maneuvers, the antenna subsystem is satisfactory. Any degradation is analyzed for mission impact and severity. The quantitative data is compared to system design parameters for specification compliance.

4.2.3.6 ERROR ANALYSIS

Roll and pitch angles will be considered accurate to within ±3 deg accounting for instrument and interpretation errors. Load factors will be considered accurate to within ±0.3g accounting for instrument and interpretation errors. Timing, using a hand held stopwatch would be considered accurate to within ±1.0 sec, accounting for human reaction time.

4.2.3.7 SAFETY CONSIDERATIONS

Consider aircraft limits, performance, and mission requirements when you design your tests. Don't exceed the limits of the aircraft. Ensure you don't depart the aircraft when you conduct the tests. You must carefully monitor the state of the aircraft during testing to avoid exceeding aircraft limits.

4.3 TEST METHODS AND TECHNIQUES (PERFORMANCE)

4.3.1 NON-MANUEVERING MAPPING

4.3.1.1 PURPOSE

The purpose of this test is to evaluate the overall mapping quality of the radar to include: general mapping quality, maximum useable mapping range, display uniformity, and scan stability.

4.3.1.2 METHOD

Testing should be conducted at varying altitudes, since the radar picture will vary with the grazing angle. Testing should be performed from extended ranges to minimum range of the radar as applicable. Use varying airspeeds, scan angles, and look angles to see if they have any affect on the picture. Varying backscatter environments should be used including desert, forest, water, urban areas, and land-sea interface. Areas with large cities, small towns, highways, and rivers with bridges provide good navigational returns as well as mission relatable targets. Qualitative comments on the radar display should be recorded, using all modes.

4.3.1.3 DATA REQUIRED

- Initial set-up to include mode, azimuth, and range scale. Perishable data would include: image loss at range, scintillation effects (sparkling), large target blooming, loss of picture or lines (spoking) in the picture during moderate maneuvers (<30 deg AOB) and how quickly the picture is regained once maneuvering is complete. Qualitative comments about how well the radar represents the area mapped.

4.3.1.4 DATA REDUCTION

No data reduction required, the data are qualitative.

4.3.1.5 DATA ANALYSIS

Qualitative analysis should be used to discuss mission utility and tactical employment. Comment on the overall impact of the various scan angles for large area search and any tactical limitations.

4.3.1.6 ERROR ANALYSIS

No error analysis, the data are qualitative.

4.3.1.7 SAFETY CONSIDERATIONS

Maintain diligent lookout when testing since some testing may require VFR flight outside of restricted ranges and Military Operating Areas.

4.3.2 MAXIMUM DETECTION RANGES

4.3.2.1 PURPOSE

The purpose of this test is to determine the maximum detection ranges for navigation, target area identification, and targeting.

4.3.2.2 METHOD

To evaluate detection ranges, select an area that provides varied types of terrain, cultural returns, and mission relatable targets. Areas with large cities, small towns, highways, and rivers with bridges provide good navigational returns as well as mission relatable targets. Determine your criteria for defining each of the detection ranges discussed. Pick a mission relatable altitude for each of the tasks. For example, navigation is typically done from a high or medium altitude, target area identification and targeting from a medium altitude. Depending on your mission, these altitudes may change. Know what performance to expect from the radar, and make predictions about what you will see on the display for returns from different target areas.

Record the maximum ranges for each type of detection, along with qualitative comments on the usability of the picture for doing each of the tasks.

4.3.2.3 DATA REQUIRED

- Radar mode
- Aircraft altitude
- Type of terrain
- Radar range when your defined detection occurs
- Qualitative comments to back up your quantitative data
- Describe the operational environment for which mission utility is described, i.e., clutter background, etc.

4.3.2.4 DATA REDUCTION

No data reduction required, the ranges are the data.

4.3.2.5 DATA ANALYSIS

Each maximum detection range is usually defined as that range where a certain mission relatable task can be performed. Discuss the relationship of your measured detection range to mission relatable tasks such as ingress or target identification. Ensure you relate radar ranges to weapons ranges as part of your analysis. Comparisons with threats and tactics are also applicable. For the maximum range for any return, tell whether you are display or power limited.

4.3.2.6 ERROR ANALYSIS

Lacking precise tracking data, ranges are typically measured using the aircraft's own sensors. This can be radar range directly, or by comparing ownship INS position and the position of the target mapped. You will have to estimate radar error, taking into consideration cursor width and the number of significant digits in the range readout. INS error is your closeout error. Target size and reflective capabilities should also be discussed.

4.3.2.7 SAFETY CONSIDERATIONS

No unique safety concerns are posed by this testing.

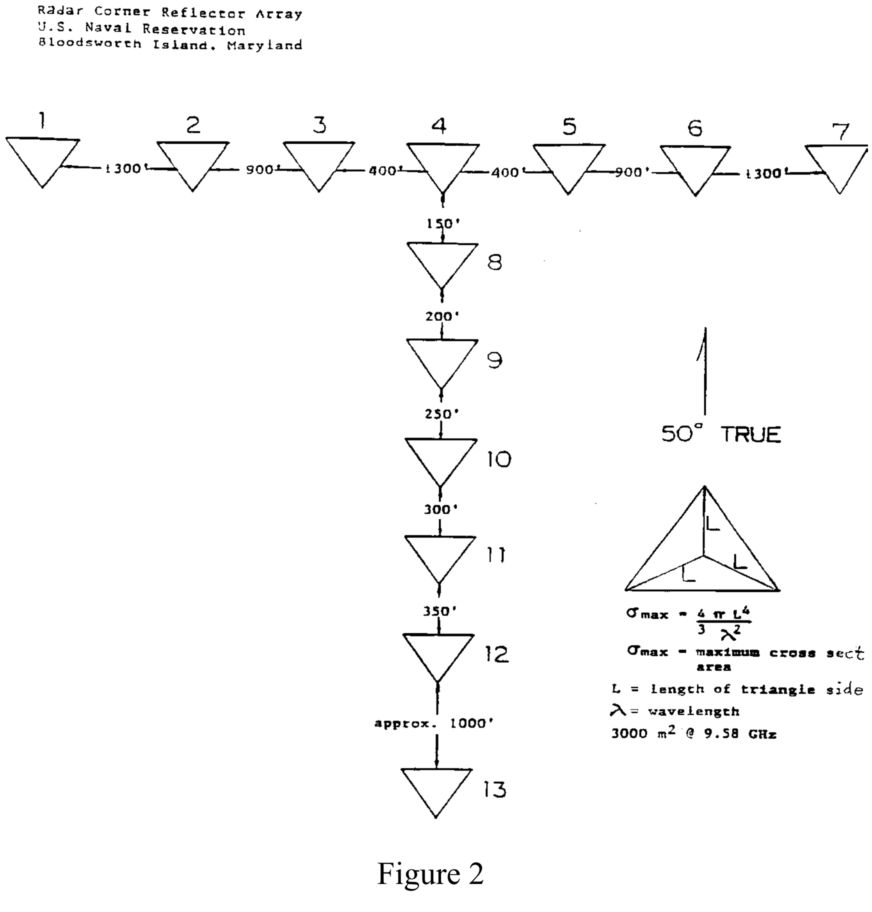
4.3.3 RANGE AND AZIMUTH RESOLUTION

4.3.3.1 PURPOSE

The purpose of these tests is to evaluate the capability of the radar to resolve targets closely spaced in range and azimuth, and to qualitatively evaluate the effect of radar resolution on typical mapping and attack missions.

4.3.3.2 METHOD

Quantitative range and azimuth resolution testing requires a large amount of flight time. Qualitative testing should be performed initially to identify any problem areas requiring involved quantitative evaluation. For quantitative testing, closely spaced hangers, parked aircraft, rivers, or designated range/bearing arrays such as the Bloodsworth Island target, shown in figure 2, can be used. When using non-designated test arrays, care should be used to avoid a grazing angle that causes the front target to mask the back target. Test runs should be made starting from a range beyond the range scale of interest, with the targets aligned with, or perpendicular to, the run-in heading. The aircraft must stay reasonably aligned during the run. Test altitudes, airspeeds, and maneuvers should be mid-range and stepped up to mission relatable values, which allows a safe buildup. It is recommended the initial run be at a constant speed and altitude.



Radar Corner Reflector Array
U.S. Naval Reservation
Bloodsworth Island, Maryland

$\sigma_{max} = \frac{4 \pi L^4}{3 \lambda^2}$

σ_{max} = maximum cross sect area

L = length of triangle side

λ = wavelength

3000 m^2 @ 9.58 GHz

Figure 2

Bloodsworth Target Array

Descending runs are allowable, and may provide the best data if the array reflectors are set at a specific elevation angle. As the airplane proceeds inbound the range and altitude should be recorded when the targets break out. Testing of a DBS radar requires a zigzag run-in pattern to keep the targets out of the doppler notch. Care must be taken during these runs to not get too far off the array axis, as the RCS of the array will decrease and may affect your data if you get too far off axis. The other problem is that as you get too far off axis, you are not looking at the targets in a pure range/azimuth orientation, which may result in breaking out the azimuth targets in range, or the range targets in azimuth, and will affect the accuracy of your data.

Range resolution runs can be made in conjunction with azimuth runs on a designated array, but the workload required to gather all the required data accurately increases.

4.3.3.3 DATA REQUIRED

- Separation distance between the targets (a known value)
- Radar mode.
- Radar range selected.
- Radar parameter deviations from baseline settings.
- Test aircraft airspeed, altitude, and heading.
- Distance from the test aircraft to the targets at breakout in range and azimuth

4.3.3.4 DATA REDUCTION

For range resolution, no data reduction is required; range resolution is the distance between the targets that can be broken out. Note that you can only say the resolution is better than the smallest interval of the targets discriminated. The azimuth resolution for each data point will be computed utilizing the following equation:

Azimuth Resolution (deg) = ARCTAN (LS/RB) (LS/RB=radians)
where:
LS is lateral separation = distance in feet between the two targets
RB is range at breakout = range in feet from test aircraft to targets at target breakout

The results of the range resolution test can be presented in tabular or written format with the resultant resolution correlated to the radar mode, range scale, and target to test aircraft geometry.

The results of the azimuth resolution test can be presented in tabular or written format with the resultant resolution correlated to the radar mode, range scale, and target to test aircraft geometry. Azimuth resolution is expressed as a number of degrees, as opposed to a number of feet as in range resolution. This means azimuth resolution in feet varies with range, as the resolution in degrees is constant.

4.3.3.5 DATA ANALYSIS

Consider the impact of the resolution on the mission. Resolution must be adequate to support the requirements for detection, identification, and tracking of the targets that make up the mission.

4.3.3.6 ERROR ANALYSIS

Theoretically the range resolution should not vary with the number of data points, but increasing the number of data points should lessen the effects of range inaccuracies and operator technique. The accuracy of the methods used to determine the distance between the two targets and their range from the test aircraft will be the accuracy of the test results.

4.3.3.7 SAFETY CONSIDERATIONS

Descending runs should conclude with the test aircraft at minimum altitude when over the target. Testing should use a buildup approach to arrive at mission relatable altitudes, airspeeds, and maneuvers.

4.3.4 DYNAMIC RANGE

4.3.4.1 PURPOSE

The purpose of this test is to determine the capability of the radar to detect a small RCS target within close proximity of several large RCS targets.

4.3.4.2 METHOD

Using a radar reflector array such as Bloodsworth Island seen in figure 2, a radar reflector should be replaced with one that is two orders (20dB) of magnitude smaller than the surrounding reflectors but at sufficient distance to have adequate range and azimuth separation. Confirm that the difference in RCS of the two reflectors is within the radar's dynamic range envelope. The radar will map the modified array and any reduction in apparent resolution performance noted.

4.3.4.3 DATA REQUIRED

Preflight: Radar reflector RCS, array spatial separation
Inflight: Qualitative comments noting any resolution degradation.

4.3.4.4 DATA REDUCTION

Qualitative data only.

4.3.4.5 DATA ANALYSIS

Consider the impact of the resolution on the mission. Resolution must be adequate to support the requirements for detection, identification, and tracking of the targets that make up the mission. Although two targets can be adequately spaced geometrically, dynamic range effects have a significant impact on overall target resolution.

4.3.4.6 ERROR ANALYSIS

Ensure that the difference in RCS of the two reflectors is within the radar's dynamic range envelope. Variations in RCS of actual corner reflectors may occur do to damage or orientation. This may cause targets to be lost that theoretically fall within the dynamic range.

4.3.4.7 SAFETY CONSIDERATIONS

No unique safety concerns are posed by this test.

4.3.5 RANGE AND BEARING ACCURACY

4.3.5.1 PURPOSE

The purpose of this test is to determine how accurately the radar can determine the range and bearing to a radar target.

4.3.5.2 METHOD

Utilizing a surveyed radar target and a surveyed visual reference point (approximately 15-20 nmi from the target) the test aircraft should fly a course and altitude that will keep the radar target in the scan at overflight of the visual target. Altitude and airspeed should be low to minimize mark-on-top error. Upon marking on top the visual target, the indicated range to the radar target should be recorded. Multiple runs, placing the radar target at different aspects from the aircraft, should be performed. Testing should also utilize the different radar modes, ranges, and scan volumes.

4.3.5.3 DATA REQUIRED

- Surveyed radar target coordinates
- Surveyed visual target coordinates
- Target types
- Altitude
- Range and bearing- from radar display

4.3.5.4 DATA REDUCTION

Calculate the actual range and bearing from the difference in surveyed radar and visual coordinates. The displayed range can be compared to the known range between the surveyed targets. The displayed bearing can be compared to the known bearing between the surveyed targets.

4.3.5.5 DATA ANALYSIS

The radar derived range should be compared to the surveyed range. The radar derived bearing should be compared to the surveyed bearing. Consider the aspect from aircraft nose to target if the error varies. Compare these numbers to the range and bearing readouts available to the operator. The range and bearing accuracy’s can be used to determine their effect upon radar designation.

4.3.5.6 ERROR ANALYSIS

Surveyed coordinates of both the visual geographic reference point and radar target will be used to minimize the errors in truth data calculations using the flat earth model. The truth data accuracy using this model will be considered accurate to within ±133 ft in range, and within ±0.01 deg in bearing. In addition, mark-on-top error is generally considered to be half the absolute altitude at mark-on-top. Bearing and range accuracy’s will also be dependent on aircraft displayed information, if not instrumented.

4.3.5.7 SAFETY CONSIDERATIONS

Low altitude runs increase the possibility of a bird strike.

4.3.6 DOPPLER BEAM SHARPENED MODES

Doppler beam sharpened modes have many unique testing issues. Due to their typical use of a Fast Fourier Transform to process a digitized signal for determining its frequency components the size of the FFT (number of bits) and the speed at which it is integrated will affect many performance parameters. The primary performance factors to be looked at are Notch Width (region around the aircraft's ground track that cannot be processed due to insufficient change in doppler frequency as a function of azimuth angle from ground track) and Build Time (the amount of processing time required to integrate and present the data to the operator).

4.3.6.1 NOTCH WIDTH

4.3.6.1.1 PURPOSE

The purpose of this test is to determine the angular width of the DBS notch.

4.3.6.1.2 METHOD

The notch size can be determined using a technique similar to the one used to determine azimuth scan angles. Turn the aircraft until a target is at one edge of the notch. Note the heading. Turn the aircraft until the target is on the other side of the notch. Note the heading again. The notch width is the difference in the two headings.

The notch should be measured in all DBS modes. You should also perform mission relatable simulated attacks and ingress's to see the effects the doppler notch has on mission operations. DBS mode and size changes should be made as would occur in an actual mission.

4.3.6.1.3 DATA REQUIRED

- Radar mode
- Aircraft ground speed
- Beginning and ending headings (headings at edge of notch)
- Qualitative comments

4.3.6.1.4 DATA REDUCTION

The notch width is the difference in the two headings.

4.3.6.1.5 DATA ANALYSIS

Consider the width of the notch in relation to how closely you can point the nose of the aircraft at the area of interest. If the DBS modes are used for target designation, consideration must be given to how difficult it is to transition from the offset heading to an attack heading.

4.3.6.1.6 ERROR ANALYSIS

Headings are considered accurate to ± 3 deg.

4.3.6.1.7 SAFETY CONSIDERATIONS

No unique hazards are posed by this testing.

4.3.6.2 DBS PATCH MAP BUILD TIME

4.3.6.2.1 PURPOSE

The purpose of this test is to determine the time required presenting a DBS patch map to the operator.

4.3.6.2.2 METHOD

The build time can be measured during other tests using DBS modes. The technique is to record the time from initial selection of the mode to completion of the first image. Once the initial image is presented, begin timing a series of patch map builds to determine the average time between builds. Record time, aircraft ground speed, angle off of ground track (AOT) of the image center, and mode settings. Some systems have a feature that will allow the initial patch map to be presented more rapidly than subsequent images, ensure this mode setting is noted.

The build time should be measured in all DBS modes. You should also perform mission representative attacks and target ingress to see the effects the patch map build time has on mission operations.

4.3.6.2.3 DATA REQUIRED

- Operating modes
- Ground Speed
- Angle off of Ground Track (AOT)
- Build time
- Qualitative comments

4.3.6.2.4 DATA REDUCTION

Simply divide the time by the number of patch map builds to calculate the average build time.

4.3.6.2.5 DATA ANALYSIS

Compare values determined with contractor data and/or specifications. Determine if the build time has an impact on time to find and designate a radar target during mission representative attack profiles.

4.3.6.2.6 ERROR ANALYSIS

Time is considered accurate to within ± 1 sec.

4.3.6.2.7 SAFETY CONSIDERATIONS

No unique hazards are posed by this testing.

4.3.7 SYSTEM INTEGRATION

4.3.7.1 PURPOSE

The purpose of this test is to qualitatively evaluate the system integration of the radar system as installed in the test aircraft.

4.3.7.2 METHOD

Utilize the comments/remarks section of individual tests to add qualitative comments about integration problems or contributing factors. A scenario to test integration by duplicating a typical mission profile also should be used. The radar should be capable of providing navigation information to identify a coast-in point. The navigation systems integration should allow the radar to designate points on the ground that can be passed to other platforms, and, given a specified lat/long, the navigation system should be able to place a radar cursor on that point.

The radar should allow the navigator to follow a designated track to a target area, find the target, and designate it for an attack. You should be able to enter final attack modes and simulate weapon release. Repeat the scenario for high and low altitude attacks utilizing mission relatable jinks, evasive tactics, and weapon loft maneuvers. Using other aircraft systems (e.g., FLIR, LST, HUD, Moving Map) attempt to transfer data to/from the radar. Record comments concerning the individual and overall integration.

4.3.7.3 DATA REQUIRED

Qualitative comments should be collected during all phases of air-to-ground testing as well as during dedicated system integration tests.

4.3.7.4 DATA REDUCTION

No data reduction required, data is qualitative.

4.3.7.5 DATA ANALYSIS

Using the qualitative comments, discuss the effects of the integration on mission performance, and the capability to use the radar and test airplane as a whole. Results will be qualitative and address the capability of the radar system to interact with the aircraft systems to accomplish the mission.

4.3.7.6 ERROR ANALYSIS

No error analysis, data is qualitative.

4.3.7.7 SAFETY CONSIDERATIONS

Mission scenario testing involves a high workload, since you're not only trying to do mission relatable tasks, but evaluate how the weapon system is performing while you take data. Ensure you have a proper build-up to high workload test profiles. Don't become so engrossed in testing that you forget to maintain minimum safe altitudes, assist the pilot with lookout, and other safety of flight tasks.

CHAPTER 5

AIR-TO-AIR RADAR TESTING

CHAPTER 5

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CHAPTER 5
AIR-TO-AIR RADAR TESTING

5.1 TEST METHODS AND TECHNIQUES

5.1.1 RANGING ACCURACY

5.1.1.1 PURPOSE OF TEST

The ranging accuracy of a radar is the maximum error within which the radar can measure the range to a target. The purpose of this test is to determine that maximum error.

5.1.1.2 METHOD

In test, the ranging accuracy of a radar is determined by comparison of the radar-indicated range with truth data, as the range between the target and the radar is varied.[44]

The radar aircraft/target aircraft geometry and scenario employed for this test may depend on other measurements to be made during the same run. Typically, the radar and target aircraft approach one another on reciprocal headings, with suitable flightpath separation. Once a solid range track has been obtained, the radar-to-target range is varied through the full range of values of interest. Range accuracy measurements should be made for all relevant radar/target scenarios and radar modes, including look-up, look-down, ACM (maneuvering) situations, and various ranges and range-rates, both opening and closing. Repeated runs should be made for each set of conditions to provide for statistical data processing.

5.1.1.3 DATA REQUIRED

The radar-indicated range is obtained from the radar display, using an over-the-shoulder camera, or by recording the internal video signals, or, for tracking modes, by recording the internal track file signals. The truth data are obtained with suitable on-board or range instrumentation. All measurements should be validated by comparison of the display data, the internal radar signals, and the time, space, position indication (TSPI) data.

5.1.1.4 DATA REDUCTION/ANALYSIS

The radar range determination errors are obtained by subtracting the range truth data from the radar-indicated ranges. These errors are then averaged for each nominal range and the averages are plotted versus nominal range. The maximum excursions of the plots of range error represent the ranging accuracy.

5.1.1.5 SOURCES OF MEASUREMENT ERROR

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[44] Airborne Systems course textbook: Principles of Radar System Test and Evaluation; Revised February, 1994, Section 4.2.3-2

For this test, the major sources of error are those associated with acquiring and recording the truth data. The magnitudes of those errors depend upon the source of the truth data and are best obtained from published specifications. For data taken from the radar display, a significant source of error is that associated with “reading” the display.

5.1.1.6 SAFETY CONSIDERATIONS

In order to ensure safe flightpath separation, aircraft on reciprocal headings should maintain adequate separation in altitude until visual contact has been established.

5.1.2 RANGE RESOLUTION

5.1.2.1 PURPOSE OF TEST

The range resolution of a radar is the minimum difference in range between two targets that can be resolved as two targets on that basis.[45] The purpose of this test is to determine that minimum difference in range.

5.1.2.2 METHOD

In test, the range resolution of a radar is determined by gradually increasing the difference in range of two initially-unresolved targets while monitoring the radar display and internal signals for an indication of two separate targets. Target resolution in range occurs when two targets are resolved as two targets solely on the basis of their difference in range. Care must be taken to ensure that resolution does not occur based upon a difference in target velocity or bearing. The two target aircraft must have nearly the same bearing, velocity, and radar cross section. Often, the tester can be certain that a resolution was based solely upon range only by recording, and examining, internal radar signals.

For this test, the radar aircraft and the two target aircraft generally approach one another on reciprocal headings, but with appropriate separation of flightpaths, until solid radar contact has been obtained. (An alternative approach is for the radar aircraft to close on the two target aircraft on the same heading. This approach can provide more time for the gradual change in target aircraft separation required for this test.) The two target aircraft are in a lead-trail formation. At the beginning of the run, the range distance between the two target aircraft is held at a value well below the anticipated range resolution of the radar and is then gradually increased until resolution in range occurs. The differential velocity of the two target aircraft must be kept to a minimum during separation to avoid target breakout on the basis of velocity. In order to minimize the delay in detecting target breakout, a minimum-azimuth, single-bar scan with minimum aging should be selected, when available. The headings of the target aircraft relative to the radar aircraft must be held constant within 5 deg to ensure that the assumed radar cross section is valid.

Runs should be made in all appropriate radar modes and with all display and other settings of interest. (The display range scale, for example, can affect range resolution.)

5.1.2.3 DATA REQUIRED

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[45] Ibid. Section 4.2.3-4

The radar indications of multiple targets are obtained by observation and recording of the radar display and internal signals (e.g., display video and track files). The radar display can be recorded using an over-the-shoulder camera. Internal radar signals can be recorded from the data bus or other instrumented test points. Radar aircraft and target aircraft time-space-position truth data are obtained and recorded using appropriate range and on-board instrumentation. Repeated runs are made as required to obtain redundant data for statistical data processing.

5.1.2.4 DATA REDUCTION/ANALYSIS

In non-scanning modes, the display and/or internal radar signals are continuously monitored for indications of multiple targets. In scanning modes, the radar display and internal radar signals are examined scan-by-scan for indications of multiple targets. The range resolution of the radar is obtained by time correlation of the range resolution event with the separation in range at the time of resolution.

5.1.2.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are the delays in identifying target resolution and errors in TSPI truth data.

5.1.2.6 SAFETY CONSIDERATIONS

In order to ensure safe flightpath separation, aircraft on reciprocal headings or otherwise intersecting flightpaths should maintain adequate vertical separation until visual contact has been established.

5.1.3 MINIMUM RANGE

5.1.3.1 PURPOSE OF TEST

The minimum range of a radar is the range below which an otherwise valid target cannot be detected, or tracked, due to eclipsing of the target return by the radar transmitting interval.[46] The purpose of this test is to determine that minimum range.

5.1.3.2 METHOD

In test, the minimum range is determined by decreasing the separation in range of the radar aircraft and the target aircraft until the target is lost by the radar as indicated by the radar display or internal signals.

For this test, the radar aircraft is in trail of the target aircraft with an initial range separation greater than the minimum range, as indicated by a valid target indication on the radar display. The range separation is then reduced until the radar target indication is lost, or until minimum safe separation is reached. Repeated runs are made to allow statistical data analysis.

5.1.3.3 DATA REQUIRED

The display can be recorded by an over-the-shoulder camera. The internal display video and/or other internal signals can be recorded from the data bus or other

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[46] Ibid. Section 4.2.3-7

instrumented test points. Time-space-position truth data are obtained using suitable on-board instrumentation.

5.1.3.4 DATA REDUCTION/ANALYSIS

The target range at the time of loss of target indication is obtained by time correlation of the loss-of-target event with the target range at that time. The data should be examined to ensure that the observed loss-of-target was due to eclipsing at minimum range and not to some other effect such as another blind range, target scintillation, or a blind velocity. Once other possibilities have been eliminated, the target range at loss-of-target can be identified as the minimum range of the radar.

5.1.3.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are delays in recognizing loss-of-target and errors in TSPI truth data.

5.1.3.6 SAFETY CONSIDERATIONS

This test involves aircraft in close proximity. Aircraft separation should be closely monitored during closure and the test terminated if minimum safe separation is violated.

5.1.4 BLIND RANGE ZONES

5.1.4.1 PURPOSE OF TEST

Blind ranges are those ranges at which a target cannot be detected due to eclipsing of the target return by the radar transmitting interval. There are multiple blind ranges at intervals determined by the PRF. The width of the blind range zones depends upon the radar pulse width.[47] The purpose of this test is to determine the location and extent of any blind range zones.

5.1.4.2 METHOD

In test, blind ranges are determined by varying the radar aircraft-to-target aircraft range while observing for target aircraft radar indication dropouts.

For this test, care must be taken to ensure that a dropout caused by a blind velocity or other factor is not mistaken for one caused by a blind range. To minimize that possibility, the test planner should design the test to minimize interfering signals and to avoid anticipated blind velocities. Thus, the test should be conducted at a relatively high altitude, in a look-up situation, and at a controlled, appropriate relative range rate between the radar and target aircraft. (Recommended altitudes are 14,000 ft for the radar aircraft and 19,000 ft for the target aircraft.) In order to minimize the delay in detecting loss-of-target, a minimum-azimuth, single-bar scan with minimum aging should be selected, when available.

The radar aircraft/target aircraft geometry and scenario for this test may depend on other tests to be made during the same run. Typically, the radar and target aircraft approach one another on reciprocal headings, with suitable flightpath separation, until solid radar contact has been made. (Alternatively, the radar aircraft can close on the

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[47] Ibid. Section 4.2.3-14

target aircraft from a position in trail, thus providing more time for the gradual change in range required for this test.) The radar aircraft and target aircraft then continue to close in range while the radar is monitored for target drop-outs. As the target returns approach, in time, the radar transmission intervals, eclipsing occurs and the target return signal decreases until dropout occurs. The ranges during loss-of-target are those within a blind range zone. Repeated runs are required to test for blind ranges in all relevant modes and to provide redundant data for statistical data reduction.

5.1.4.3 DATA REQUIRED

The radar display can be recorded by an over-the-shoulder camera. Radar display video and other internal signals are obtained from the data bus or other instrumented test points. TSPI truth data are obtained and recorded using suitable range or on-board instrumentation.

5.1.4.4 DATA REDUCTION/ANALYSIS

The data reduction process consists of identifying periods during which the target was lost due to blind ranges and correlating those periods with the ranges of the target during those times. Often, uncertainty as to the cause of a target dropout can be resolved only by examination of internal radar signals. Valid dropouts are those which correlate on the display, in the internal radar signals, and in the TSPI data. In the final analysis, apparent blind ranges should be correlated with the anticipated blind ranges.

For scanning modes, the data acquisition and reduction process consists of the following steps.

(1) Record “hits” and “misses” for each scan during the test.

(2) By correlation with TSPI data, associate each “hit” or “miss” with a range.

(3) Divide the data points into intervals of range.

(4) Calculate the blip-to-scan ratio for each range interval.

(5) Designate range intervals in which the blip-to-scan ratio falls below a specified value as being within a blind range zone. Both the locations of the blind range zones and their widths are of interest.

For non-scanning modes, the data acquisition and reduction process consists of the following steps.

(1) Examine the loss-of-target indicator (memory cue),or internal signal, for loss-of-target indication.

(2) By correlation with TSPI data, associate loss-of-target indications with ranges.

(3) Designate as blind range zones those range intervals for which loss-of-target was indicated.

Valid “hits” are those which correlate on the display, in the internal radar signals, and in the TSPI data. In the final analysis, apparent blind ranges should be correlated with the anticipated blind ranges calculated from the pulse repetition frequency. Often, uncertainty as to the cause of a target dropout can be resolved only by examination of internal radar signals.

In some radar modes, such as those in the APG-65 in medium PRF, the blind range zones and the blind velocity zones are interdependent. That is, the blind zones are interdependent on range and velocity. This coupling is caused by three factors: (1) the dependence of both the blind ranges and blind velocities on PRF, (2) the use of multiple PRF’s (8 in the APG-65) in an attempt to avoid both blind/ambiguous ranges and blind/ambiguous velocities, and (3) the use of hit/miss detection logic (3-out-of-8 in the APG-65) to reduce false alarms. The result is that, when such signal processing is employed, the blind zones of the radar can best be represented on a “map” of blind “zones” as a function of range on one axis and velocity on the other axis. In order to “plot” such a “map”, a very large amount of data are required over a large range of values of range and velocity.

5.1.4.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with delays in recognizing loss-of-target and with errors in the TSPI truth data.

5.1.4.6 SAFETY CONSIDERATIONS

This test involves aircraft in close proximity. Aircraft separation should be closely monitored during closure and the test terminated if safe aircraft separation is violated.

5.1.5 AMBIGUOUS RANGES

5.1.5.1 PURPOSE OF TEST

Ambiguous ranges are those ranges at which the radar indicated range is in error due to second-time-around echoes. As indicated in the discussion in the section on performance characteristics, range ambiguities are related to blind ranges. That is, as the range to the target increases, a blind range may be immediately followed by a range ambiguity unless special provision such as PRF stagger is provided. The purpose of this test is to determine the existence and location of any range ambiguities due to STAE exhibited by the radar.

5.1.5.2 METHOD

In test, range ambiguities are detected by varying the radar aircraft-to-target aircraft range while observing the radar display and internal signals for anomalous range indications.

Care must be taken to ensure that an apparently anomalous range indication is not, in fact, the return from a real, though unintended, target. To minimize that possibility, the test planner should design the test to minimize interfering signals such as ground clutter and extraneous airborne traffic. The test should be conducted at a relatively high altitude and in a co-altitude or look-up situation. In the final analysis, apparent range ambiguities should be correlated with the anticipated range ambiguities and with the TSPI data. Redundant runs should be made to allow for statistical data reduction and to verify the results.

The radar aircraft/target aircraft geometry and scenario for this test may depend on other tests to be performed during the same run. Typically, the radar and target aircraft approach one another on reciprocal headings, with suitable flightpath separation, until solid radar contact has been made. The radar and target aircraft then continue to close in range until the range is well within the anticipated maximum unambiguous range with the radar aircraft assuming a position in trail with the target aircraft. The two aircraft then establish an opening velocity so as to gradually increase the target range while the radar is monitored for anomalous indications of range. As the target range exceeds the calculated value of maximum unambiguous range, the radar display and internal signals are closely monitored. Tests should be conducted for all relevant radar modes and situations.

5.1.5.3 DATA REQUIRED

The display can be recorded by an over-the-shoulder camera and internal video and radar processor signals can be recorded from the data bus or other instrumented test points. Time-space-position truth data are measured and recorded by suitable range or on-board instrumentation.

5.1.5.4 DATA REDUCTION/ANALYSIS

The data reduction process consists of an examination of the recorded radar display and internal signals to identify any anomalous range indications. The ranges at which these anomalous indications occurred are then obtained by time correlation of the anomalous range indication events with the target ranges at those times.

5.1.5.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with delays in recognizing range anomalies and with errors in the TSPI truth data.

5.1.5.6 SAFETY CONSIDERATIONS

This test involves aircraft in close proximity. Aircraft separation should be closely monitored during closure and the test terminated if safe aircraft separation is violated.

5.1.6 MAXIMUM RANGE FOR DETECTION

5.1.6.1 PURPOSE OF TEST

The maximum range for detection is the maximum range at which the signal-to-noise ratio is sufficient for the radar (or the operator for manual detection) to distinguish a target, of specified radar cross section, from the ambient noise, under specified conditions. The purpose of this test is to determine the maximum range for detection of the radar, under specified conditions.

5.1.6.2 METHOD

In test, the maximum range for detection of a radar is determined by decreasing the range to a target aircraft, initially beyond detection range, until target detection occurs as indicated by the radar display or by internal radar signals.

For this test, the radar aircraft and the target aircraft approach one another, on reciprocal headings but with appropriate vertical and/or lateral separation, from an initial range well beyond the anticipated maximum range for detection.[48] The run-in is continued until the radar display indicates that detection has occurred or until crossover. Target aircraft relative heading must be held constant within five degrees to ensure that assumed radar cross section is valid. In order to minimize the delay in detecting the target, a minimum-azimuth, single-bar scan with minimum aging should be selected when available. Repeated runs are made for each set of test conditions to provide for statistical data processing.

5.1.6.3 DATA REQUIRED

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[48] Ibid. Section 4.2.3-6

The radar display can be recorded using an over-the-shoulder video camera and the internal radar system signals are recorded from the data bus or other instrumented test points. Radar aircraft and target aircraft time-space-position truth data are obtained and recorded using appropriate range and on-board instrumentation.

5.1.6.4 DATA REDUCTION/ANALYSIS

One method of determining when an individual detection has taken place is to adopt, as the point of detection, that point in range/time at which a valid target first appears on the display. A better method is to record the video for every scan and to take, as the point of detection, that point in range/time at which the blip-to-scan ratio first remains above 0.5.[49] For a target detection to be considered valid, the radar display indications must be consistent with the internal system data and with the time-space-position truth data.

The cumulative detection range is taken as that range by which a prescribed percentage of the test targets had been detected. Typically, an "R90" detection range is determined as that range by which the cumulative probability of detection was 0.9 for all runs made with a given set of test conditions.

5.1.6.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with delays in recognizing target detection and with errors in the TSPI truth data.

5.1.6.6 SAFETY CONSIDERATIONS

This test may involve aircraft in close proximity. Crossover may occur due to failure, for various reasons, to detect the target aircraft on the radar. In order to ensure safe aircraft separation, aircraft on reciprocal headings, or otherwise intersecting flightpaths, should maintain adequate vertical separation until visual contact has been established.

5.1.7 BEARING DETERMINATION ACCURACY

5.1.7.1 PURPOSE OF TEST

The bearing determination accuracy of a radar is the maximum error within which the radar can determine the bearing to a target. The purpose of this test is to determine that maximum error.

5.1.7.2 METHOD

In test, the bearing determination accuracy of a radar is determined by comparison of the radar-indicated target bearing with truth data, as the relative bearing of the target is varied.[50]

The radar aircraft/target aircraft geometry and scenario employed for this test may depend upon other tests to be performed on the same run. Typically, the radar and target aircraft fly a prearranged flightpath, at constant altitude, until solid radar contact has been made. At that point, one or both aircraft fly an orbital path to provide the desired range of relative bearings. Measurements should be made with the radar aircraft in both maneuvering and nonmaneuvering flight and well within the maximum range of the radar. The radar modes and parameters are varied as required.

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[49] Ibid. Section 3.2

[50] Ibid. Section 4.2.3-2

5.1.7.3 DATA REQUIRED

The radar-indicated bearing is obtained from the radar display using an over-the-shoulder camera or by recording the radar internal signals. The truth data are obtained by combining radar aircraft and target aircraft position data with radar aircraft attitude data. The position data are obtained with suitable on-board or range instrumentation. The radar aircraft attitude truth data are obtained with on-board instrumentation such as an inertial measurement unit. All measurements should be validated by comparison of the display, internal radar signals, and TSPI data. Multiple measurements should be taken to provide for statistical reduction of the data.

5.1.7.4 DATA REDUCTION/ANALYSIS

The radar bearing determination errors are obtained by subtracting the target bearing truth data from the radar-indicated bearings. These errors are then averaged for each nominal target bearing and the averages are plotted versus nominal target bearing. The maximum excursions of the plots of bearing error represent the bearing determination accuracy.

5.1.7.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with the target bearing truth data. The errors in those data depend upon the errors in aircraft position data, the errors in aircraft attitude data, and the radar aircraft/target aircraft geometry at the time of the measurement.

5.1.7.6 SAFETY CONSIDERATIONS

This test may involve maneuvering aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if minimum safe separation is violated.

5.1.8 ANGULAR RESOLUTION

5.1.8.1 PURPOSE OF TEST

Angular Resolution is the minimum angular separation between two targets that can be resolved as two targets on the basis of bearing.[51] The purpose of this test is to determine that minimum angular separation in both azimuth and elevation.

5.1.8.2 METHOD

In test, the angular resolution of a radar is determined by gradually increasing the angular separation between two initially unresolved targets until the radar recognizes the two targets as two separate targets.

Target resolution in bearing occurs when two targets are resolved as two targets solely on the basis of a difference in azimuth and/or elevation. In test, care must be taken to ensure that resolution does not occur based upon a difference in target range or velocity. The two target aircraft must have nearly the same range, velocity, and radar

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[51] Ibid. Section 2.3.6

cross section. Often, the tester can be certain that a resolution was based solely upon bearing only by recording, and examining, internal radar signals.

Typically, the radar aircraft and the two target aircraft approach one another on reciprocal headings, but with appropriate separation of flightpaths. (The radar aircraft and target aircraft should never be at the same altitude until visual contact has been made.) The two target aircraft are abeam, with the same velocity and with a constant, controlled lateral separation such that the two target aircraft will initially be detected by the radar as a single target. After (unresolved) solid radar contact has been made, the radar aircraft and the target aircraft continue to approach one another. The differential ranges and velocities of the two target aircraft must be kept to a minimum in order to avoid breakout on the basis of range or velocity. As the target aircraft approach the radar aircraft, the apparent angular separation between the two target aircraft increases. At some point, the radar will succeed in breaking out the two targets in bearing. At that point, the radar-to-target range and the target-to-target lateral separation determine the angular separation at the point of resolution. In order to minimize the delay in detecting target breakout, a minimum-azimuth, single-bar scan with minimum aging should be selected when available. The lateral separation between the two target aircraft should be set at a value such that the anticipated breakout occurs at a range not in a blind range zone and not within the minimum range. Repeated runs should be made to provide redundant data for statistical data reduction.

5.1.8.3 DATA REQUIRED

The position data and/or range separation of the radar and target aircraft are obtained and recorded using appropriate range or on-board instrumentation. Since the radar display may be a factor in the overall angular resolution of the radar, an over-the shoulder camera should be used to record the display imagery. Radar internal signals are recorded from the data bus or other instrumented test points.

5.1.8.4 DATA REDUCTION/ANALYSIS

In non-scanning modes, the display and/or internal radar signals are continuously monitored for indications of two separate targets. In scanning modes, the radar display and internal radar signals are examined scan-by-scan for indications of the targets. The bearing resolution of the radar is obtained by time correlation of the bearing resolution event with the range to the targets, (and, hence, their angular separation), at the time of resolution.[52]

Care must be taken to distinguish resolution on the basis of bearing from resolution on the basis of range or velocity. Often, the question can be resolved only by examining internal radar signals.

5.1.8.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are the delays in identifying target resolution and errors in TSPI truth data.

5.1.8.6 SAFETY CONSIDERATIONS

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[52] Ibid. Section 4.2.3-4

This test involves aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if safe aircraft separation is violated. In order to ensure safe flightpath separation, aircraft on reciprocal headings or otherwise intersecting flightpaths should maintain adequate vertical separation until visual contact has been established.

5.1.9 ANGLE AMBIGUITY

5.1.9.1 PURPOSE OF TEST

Angle ambiguities are erroneous indications of target bearing due to reception of target returns in the sidelobes of a radar antenna or, for phase monopulse systems, at target angles-off-boresight exceeding the maximum unambiguous phase measurement capabilities of the radar signal processor.[53] The purpose of this test is to detect such angle ambiguities and determine the relative bearings at which they occur.

5.1.9.2 METHOD

In test, angle ambiguities are determined by varying the angular offset between the target line-of-sight and the radar antenna boresight while observing the radar display and/or internal signals for anomalous indications of target bearing.

In order to test for the presence or absence of angle ambiguities, the tester must position a well-defined target at angles-off-boresight of potential ambiguity and look for an erroneous (ambiguous) indication of that target at the anticipated ambiguous offset angle. The desired target aircraft angular offset can be obtained by positioning the target aircraft at a desired relative bearing utilizing external (range) instrumentation or by positioning the radar antenna at the appropriate angular offset as indicated by the radar display itself.

The radar aircraft/target aircraft geometry and scenario employed for this test may depend upon other tests to be performed on the same run. Typically, the radar and target aircraft are at the same altitude with the radar aircraft in trail. The target is acquired on the radar display and the radar antenna is then swept through the anticipated ambiguous range in bearing.

5.1.9.3 DATA REQUIRED

The true and offset (ambiguous) target indications can be recorded using an over-the-shoulder camera or by recording the internal radar video and/or other signals from the data bus or other instrumented test points.

5.1.9.4 DATA REDUCTION/ANALYSIS

The radar display and/or internal radar signals are examined for anomalous (ambiguous) indications of target bearing. Care must be taken that an apparently anomalous target indication is not, in fact, a valid return due to an actual, though unintended, target. An ambiguous bearing indication will be revealed as a false target indication appearing at the same range as the true target indication but at the bearing coincident with the mainlobe of the antenna. All measurements should be validated by

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[53] Ibid. Section 2.13.2

comparison of the display, the internal radar signals, and the calculated potentially ambiguous bearings.

5.1.9.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are failures to identify anomalous target indications and, for data taken from the radar display, errors in estimating angular offsets.

5.1.9.6 SAFETY CONSIDERATIONS

This test involves aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if safe aircraft separation is violated.

5.1.10 VELOCITY DETERMINATION ACCURACY

5.1.10.1 PURPOSE OF TEST

Velocity determination accuracy is that maximum error within which a given radar can determine the velocity of a target. The purpose of this test is to determine that maximum error.

5.1.10.2 METHOD

In test, velocity determination accuracy is determined by comparison of the radar-indicated target velocity with truth data, as the relative velocity of the target is varied in both magnitude and direction.[54]

The radar aircraft/target aircraft geometry and scenario employed for this test may depend upon other tests to be performed during the same run. Typically, the radar and target aircraft approach each other at constant altitude, on reciprocal headings, until solid radar contact has been made. The target aircraft is then maneuvered to vary the relative velocity over the desired range in both magnitude and direction. Data should be taken to obtain readings for both opening and closing velocities, including readings in the vicinity of zero relative radial velocity. Measurements also should be taken for situations involving low-altitude, look-down geometry and for a highly-maneuvering target. The test should be performed for all relevant radar modes and settings. Multiple measurements should be taken to provide for statistical data reduction.

5.1.10.3 DATA REQUIRED

Radar-indicated velocity is obtained from the radar display using an over-the-shoulder camera or by recording the radar internal video and other signals. Target velocity relative to the radar aircraft and target velocity relative to the air mass are both of interest, depending upon the radar mode. The truth data consist of both position and velocity of both the radar aircraft and the target aircraft. The internal radar signal data can be recorded from the data bus or from other instrumented test points. The TSPI truth data are obtained and recorded using suitable on-board or range instrumentation.

5.1.10.4 DATA REDUCTION/ANALYSIS

The velocity-determination errors are obtained by subtracting the velocity truth data from the radar-indicated velocities. These errors are then averaged for each nominal velocity and the averages are plotted versus nominal velocity. The maximum excursions

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[54] Ibid. Section 4.2.3-14

of the plots represent the velocity-determination accuracy. All measurements should be validated by comparison of the display, internal radar signals, and TSPI data.

5.1.10.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with acquiring and recording the truth data. The magnitudes of these errors depend upon the source of truth data and are best obtained from published specifications. For data taken from the radar display, a significant source of error is that associated with reading the display.

5.1.10.6 SAFETY CONSIDERATIONS

This test may involve maneuvering aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if minimum safe separation is violated.

5.1.11 VELOCITY RESOLUTION

5.1.11.1 PURPOSE OF TEST

Velocity resolution is the minimum difference in relative, radial velocity of two targets that can be resolved as two targets on that basis. The purpose of this test is to determine that minimum difference in velocity.

5.1.11.2 METHOD

In test, the velocity resolution of a radar is determined by gradually increasing the difference in relative, radial velocity of two initially-unresolved target aircraft until the radar recognizes them as two targets on the basis of that difference in velocity.

Target resolution in velocity occurs when two targets are resolved as two targets solely on the basis of a difference in velocity. Care must be taken to ensure that resolution does not occur based upon a difference in range or bearing. The two target aircraft must have nearly the same range, bearing, and radar cross section. Often, the tester can be certain that a resolution was based solely upon velocity only by recording, and examining, internal radar signals.

For this test, the radar aircraft and the two target aircraft approach one another on reciprocal headings, with appropriate separation of flightpaths, until solid radar contact is made. The two target aircraft are abeam with a lateral separation small enough to prevent target resolution on the basis of bearing. Once (unresolved) radar contact has been made, and at a prearranged signal, one target aircraft accelerates and/or the other decelerates to establish an increasing velocity differential. When the velocity differential is sufficient for the radar to break out the two target aircraft, that velocity differential is the velocity resolution of the radar. In order to minimize the delay in detecting target breakout, a minimum-azimuth, single-bar scan with minimum aging should be selected when available. Care must be taken to prevent the target differential in range or bearing from becoming large enough to trigger resolution of the targets in range or bearing.

Repeated runs should be made to allow statistical data reduction. Radar and target aircraft ranges and velocities should be set to avoid anticipated blind ranges and blind velocities. Performance should be examined for all relevant radar modes and for all radar aircraft/target aircraft scenarios, including both opening and closing velocities.

Redundant runs should be made to allow for statistical data reduction and to verify the results.

5.1.11.3 DATA REQUIRED

The radar display can be recorded using an over-the-shoulder camera. The internal radar video and other signals can be recorded from the data bus or other instrumented test points. The TSPI truth data can be obtained and recorded using appropriate on-board or range instrumentation.

5.1.11.4 DATA REDUCTION/ANALYSIS

In non-scanning modes, the radar display and/or internal signals are continuously monitored for indications of two separate targets. In scanning modes, the radar display and/or internal signals are examined scan-by-scan for indications of two separate targets. The velocity resolution of the radar is obtained by time-correlation of the velocity resolution event with the target velocity difference at the time of resolution.

Care must be taken to distinguish resolution on the basis of bearing from resolution on the basis of range or velocity. Often, the question can be resolved only by examining internal radar signals. All determinations of velocity resolution must be validated by comparison of the display, internal radar signals, and TSPI truth data.

5.1.11.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with delays in identifying target resolution and errors in the target relative velocity truth data.

5.1.11.6 SAFETY CONSIDERATIONS

This test may involve maneuvering aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if minimum safe separation is violated.

5.1.12 MINIMUM VELOCITY

5.1.12.1 PURPOSE OF TEST

The minimum velocity is that relative, radial target velocity below which the target cannot be detected, or tracked, because of interference due to clutter or because of the clutter filtering itself.[55] The purpose of this test is to determine that minimum velocity. (Note that the minimum velocity of a radar is one of the blind velocities and that this test can be combined with the test for the other blind velocities.)

5.1.1.2.2 METHOD

In test, the minimum velocity of a radar is determined by gradually reducing the target aircraft closing or opening velocity until target dropout occurs due to minimum velocity.

The radar aircraft/target aircraft geometry and scenario for this test may depend upon other tests to be performed during the same test run. Typically, the radar aircraft and target aircraft approach one another on reciprocal headings, with suitable flightpath separation, until solid radar contact is made. The target aircraft then executes a

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[55] Ibid. Section 4.2.3-18

continuous orbital maneuver to produce a sinusoidally-varying relative radial velocity with respect to the radar aircraft. As the relative radial velocity approaches the ground velocity of the radar aircraft, the frequency of the target return will approach the minimum frequency for detection or track. The velocity of the target aircraft at the time of dropout is then noted. In scanning modes, dropout is best determined by observing the radar display and internal signals scan-by-scan.

Tests for minimum velocity should be conducted in all relevant modes and for all relevant radar aircraft/target aircraft geometries and scenarios, including low-altitude, look-down situations and for both opening and closing velocities. Repeated runs should be made to provide for statistical data reduction and to verify the results. Care must be taken to ensure that target dropout was not caused by a blind range or other phenomenon.

5.1.12.3 DATA REQUIRED

Target dropout is detected by observation of the radar display and/or internal signals. The radar display can be recorded using an over-the-shoulder camera. Radar display video and other internal signals are obtained from the data bus or from other instrumented test points. TSPI truth data are obtained and recorded using suitable range or on-board instrumentation.

5.1.12.4 DATA REDUCTION/ANALYSIS

The target velocity at the time of loss of target indication is obtained by time correlation of the loss-of-target event with the target velocity at that time. The data should be examined to ensure that the observed loss-of-target was due to minimum velocity and not to some other effect such as target scintillation or blind range. Once other possibilities have been eliminated, the target velocity at loss-of-target can be identified as the minimum velocity of the radar.

5.1.12.5 SAFETY CONSIDERATIONS

This test may involve maneuvering aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if minimum safe separation is violated.

5.1.13 BLIND VELOCITY ZONES

5.1.13.1 PURPOSE OF TEST

Blind velocities are those target velocities for which the target cannot be detected due to coincidence of the target return, in the frequency domain, with the clutter returns, or due to the clutter filtering itself. The purpose of this test is to determine the location and extent of any blind velocity zones.

5.1.1.3.2 METHOD

There are multiple blind velocities, at intervals determined by the PRF, including the Minimum Velocity[56]. The width of the blind velocity zones depends upon the width of

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[56] Ibid. Section 3.4.14

the clutter filtering and speed gating.[57] In test, blind velocities are detected by varying the relative, radial component of the target velocity while observing the radar display and internal signals for target dropouts.

The radar aircraft/target aircraft geometry and scenario for this test may depend upon other tests to be performed during the same run. Typically, the radar aircraft and target aircraft approach one another on reciprocal headings, with suitable flightpath separation, until solid radar contact is made. (Alternatively, the radar aircraft can close on the target aircraft on the same heading.) The target aircraft then executes a continuous orbital maneuver to produce a sinusoidally-varying velocity component in the direction of the radar aircraft. As the relative radial component of the target velocity approaches a value coincident with one of the aliased clutter filter "notches", the target return signal will decrease until target dropout occurs. The velocities of the target aircraft during times of dropout are those within a blind velocity zone.

For this test, care must be taken to ensure that dropouts due to blind ranges or other factors are not mistaken for dropouts due to blind velocities. To minimize that possibility, the test planner should design the test to avoid anticipated blind ranges. Multiple runs should be made to provide data for statistical data reduction and to confirm the data.

Tests for blind velocity zones should be conducted in all relevant radar modes and settings and for all relevant radar aircraft/target aircraft geometries and scenarios, including low-altitude, look-down situations and for both opening and closing velocities.

5.1.13.3 DATA REQUIRED

The radar display can be recorded by an over-the-shoulder camera. Radar display video and other internal signals are obtained from the data bus or other instrumented test points. TSPI data are obtained and recorded using suitable range or on-board instrumentation.

5.1.13.4 DATA REDUCTION/ANALYSIS

The data reduction process consists of identifying periods during which the radar target indication was lost due to blind velocities and correlating those periods with the velocities of the target during those times. Often, uncertainty as to the cause of a target dropout can be resolved only by examination of internal radar signals. Valid dropouts are those which correlate on the display, in the internal radar signals, and in the TSPI data. In the final analysis, apparent blind velocities should be correlated with the anticipated blind velocities.

For scanning modes, the data reduction process consists of the following steps.

(1) "Hits" and "misses" are recorded for each scan during the test.

(2) By correlation with TSPI data, each "hit" or "miss" is associated with a target velocity.

(3) The data points are divided into intervals of velocity.

(4) The blip-to-scan ratio is calculated for each interval.

(5) Intervals in which the blip-to-scan ratio falls below a specified value are designated as being within a blind velocity zone. Both the locations (in velocity) and the widths of the blind zones are of interest.

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[57] Ibid. Section 2.16.10

For non-scanning modes, the data reduction process consists of the following steps.

(1) Examine the loss-of-target indicator (memory cue),or internal signal, for loss-of-target indication.

(2) By correlation with TSPI data, associate loss-of-target indications with velocities.

(3) Designate as blind velocity zones those velocity intervals for which loss-of-target was indicated.

In some radar modes, such as those in the APG-65 in medium PRF, the blind range zones and the blind velocity zones are interdependent. That is, the blind zones are interdependent on range and velocity. This coupling is caused by three factors: (1) the dependence of both the blind ranges and blind velocities on PRF, (2) the use of multiple PRF's (8 in the APG-65) in an attempt to avoid both blind/ambiguous ranges and blind/ambiguous velocities, and (3) the use of hit/miss detection logic (3-out-of-8 in the APG-65) to reduce false alarms. The result is that, when such signal processing is employed, the blind zones of the radar can best be represented on a "map" of blind "zones" as a function of range on one axis and velocity on the other axis. In order to "plot" such a "map", a very large amount of data are required over a large range of values of range and velocity.

5.1.13.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with delays in recognizing loss-of-target and with errors in TSPI truth data.

5.1.13.6 SAFETY CONSIDERATIONS

This test may involve maneuvering aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if minimum safe separation is violated.

5.1.14 AMBIGUOUS VELOCITIES

5.1.14.1 PURPOSE OF TEST

Ambiguous velocities are those target velocities for which the radar-indicated velocity is ambiguous due to frequency aliasing caused by pulsing.[58] The purpose of this test is to detect velocity anomalies due to frequency aliasing and to determine the velocities at which they occur.

5.1.1.4.2 METHOD

In test, velocity ambiguities are detected by varying the radar aircraft-to-target aircraft relative, radial velocity while observing the radar display and internal signals for erroneous or multiple target velocity indications.

For this test, care must be taken to ensure that an apparent anomalous velocity indication is not, in fact, the return from a real, though unintended, target. To minimize that possibility, the test planner should design the test to minimize interfering signals such as those from ground vehicles and extraneous airborne traffic. The test should be

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[58] Ibid. Section 2.13.5

conducted at a relatively high altitude and in a co-altitude or look-up situation. Redundant runs should be made to allow for statistical data reduction and to verify the results. Tests should be conducted for all relevant radar modes and settings and for all relevant radar aircraft/target aircraft situations.

The radar aircraft/target aircraft geometry and scenario for this test may depend upon other tests to be performed during the same run. Typically, the radar and target aircraft approach one another on reciprocal headings, with suitable flightpath separation, until solid radar contact is made. The target aircraft then executes a continuous orbital maneuver to produce a sinusoidally-varying velocity component in the direction of the radar aircraft. When the relative, radial component of the target aircraft velocity exceeds the calculated maximum unambiguous velocity, the radar may produce an anomalous velocity indication. Both opening and closing velocities should be examined. Multiple ambiguous (anomalous) velocities may exist, both opening and closing. That is, a closing velocity may be indicated as an opening velocity and vice-versa.

It should be noted that the use, by the radar, of multiple PRF's and hit/miss detection logic creates the possibility of multiple velocity ambiguities and makes difficult the detection of existing ambiguities. (The use of those signal-processing techniques is, of course, intended to resolve velocity ambiguities.)

5.1.14.3 DATA REQUIRED

The radar display can be recorded by an over-the-shoulder camera and the display video and other internal signals can be recorded from the data bus or other instrumented test points. The TSPI data are measured by suitable range or on-board instrumentation.

5.1.14.4 DATA REDUCTION/ANALYSIS

The data reduction process consists of examining the target velocities indicated by the radar for anomalous values caused by velocity ambiguities. Any anomalies detected are then correlated with the target velocities at those times. It should be noted that the use, by the radar, of multiple PRF's and hit/miss detection logic creates the possibility of multiple velocity ambiguities and makes difficult the detection of existing ambiguities. (The use of those signal-processing techniques is, of course, intended to resolve velocity ambiguities.) In the final analysis, apparent velocity ambiguities should be correlated with the anticipated ambiguous velocities and with the TSPI data. Valid ambiguous velocity indications occur at intervals of the PRF.

5.1.14.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with TSPI time correlation errors and with failure to properly identify ambiguous velocity indications.

5.1.14.6 SAFETY CONSIDERATIONS

This test may involve maneuvering aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if minimum safe separation is violated.

5.1.15 ANTENNA SCAN/DISPLAY STABILIZATION

5.1.15.1 PURPOSE OF TEST

The radar antenna scan pattern and display orientation are often stabilized with respect to the ground rather than to the aircraft. In general, there are limits on both the maximum angle of rotation and the maximum angular rate of rotation. The purpose of this test is to measure those limits.

5.1.15.2 METHOD

The basic method of test is to alter the attitude and attitude rate of the radar aircraft while tracking a target, thereby determining both the maximum allowable target angle off-the-nose and the maximum allowable line-of-sight slew rate before one or the other limit causes target break-lock.

For this test, the radar aircraft is in trail of the target aircraft, on the same heading, and 1,000 ft below the target aircraft. The radar aircraft closes on the target aircraft until solid radar contact is established. At that point, the radar aircraft executes a series of yawing, pitching, and rolling maneuvers, at gradually-increasing angular rates. Each maneuver is continued until break-lock occurs or until the limitations of the aircraft have been reached. For radars capable of tracking at very high slew rates, suitable rates may require having the radar and target aircraft approach one another on reciprocal headings and with suitable altitude and/or lateral separation. As the aircraft approach crossover, both the line-of-sight slew rate and the target angle-off-the-nose increase sharply if the lateral separation is appropriately small.

In order to minimize the delay in detecting break-lock, the highest available radar scan rate should be selected in scanning modes.

5.1.15.3 DATA REQUIRED

Radar aircraft attitude, attitude rates, and g-loading can be recorded from the data bus or from other instrumented test points. Internal radar signals also can be taken from those sources. If internal signals are unavailable, data from the radar, vertical gyro, g-meter, and other instruments can be recorded from their displays, using an over-the-shoulder camera. Angular rates also can be obtained by timing angular displacements.

5.1.15.4 DATA REDUCTION/ANALYSIS

The data reduction process consists in correlating break-lock events with the angle or angular rate limits that caused them. Care must be taken to ensure that break-lock was not caused by some other factor such as a blind-range, blind velocity, or target scintillation. Care also must be taken to distinguish between a break-lock due to an angle limit and a break-lock due to an angular rate limit.

5.1.15.5 SOURCES OF MEASUREMENT ERROR

For this test, the major sources of error are those associated with delays in recognizing break lock and with errors in the angle and angle rate truth data.

5.1.15.6 SAFETY CONSIDERATIONS

This test may involve maneuvering aircraft in close proximity. Aircraft separation should be closely monitored and the test terminated if minimum safe separation is violated.

CHAPTER 6

NAVIGATION SYSTEM TESTING

CHAPTER 6

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CHAPTER 6
NAVIGATION SYSTEM TESTING

6.1 INTRODUCTION

"Of all the inventions and improvements the wit and industry of man has discovered and brought to perfection, none seems to be so universally urgent, profitable, and necessary as the art of navigation."

John Locke
(English Philosopher, 1632-1704)

"Be it known that all ships officers shall be responsible to hold regular religious services, forbid gambling, not allow swearing or communication of ribaldry, filthy tales, or ungodly talk and keep detailed navigation logs based on sighting of the north star and southern cross."

General Rules of Sea Service
(Circa 1700)

Navigating is the process of determining the position, velocity, and orientation of a vehicle, with respect to a specified reference position, and in a specified coordinate system. (The process of determining the direction in which to proceed to arrive at a specified position is termed guidance. The process of executing the guidance commands is termed flight control.) The reference position and coordinate system may be fixed in inertial space, fixed with respect to the earth, or fixed with respect to a moving (translating and/or rotating) reference, such as another vehicle. Long range airborne navigation (position) information is typically presented in terms of latitude, longitude, and altitude (in spherical coordinates). Short range navigation information often is presented in Cartesian coordinates, as linear distance from a local, specified reference. The usual attitude reference directions are north, east, and the local vertical. It should be noted that a navigation system often does not sense motion or compute position in the same reference system in which the information is presented to the user.

Modern aircraft require continuously available, accurate, "real-time" navigational information. These requirements are a result of the nature of modern aircraft (e.g., speed and range) and of the missions they perform (e.g., rendezvous and weapon delivery). The need for "real-time" information, combined with the need for an automated navigational process, imposes restrictions upon the manner in which the various methods of navigation are employed in modern aircraft. Systems which possess long-term accuracy but which entail an appreciable delay between the sensing of input data and the presentation of output data (such as those employing the Transit satellite and those employing intermittent celestial fixes), require an independent means of extrapolating between measurements. Such extrapolation is best accomplished by a system with good short-term accuracy and continuous output; such as an inertial navigation system. The test characteristics of both systems can be exploited by using the system with intermittent, long-term-accuracy data to periodically update the system with continuous, short-term-accurate data. Such "integrated" navigation systems are commonly employed in aircraft. The integration of the performance characteristics of two or more systems in this manner requires correspondingly integrated test procedures for evaluation of the composite system.

6.1.1 POSITION FIXING VERSUS DEAD RECKONING

Two basically different methods of navigation exist: position fixing and dead reckoning. The TPS systems syllabus allows evaluation of both of these methods. Position fixing entails a direct, independent determination of position at each point in time. Each determination is independent of those positions which were determined at previous times. Dead reckoning (derived from DEDUCED RECKONING), entails the deduction of position at a specified point in time from a known position at a previous time and the measurement of speed and direction between the two time points. That is:

$$P(t_1) = P(t_0) + \int_{\tau_0}^{\tau_1} V(\tau)\delta\tau$$

where:

P = Position Vector
V = Velocity Vector

Because of the time integration and dependence on the previously computed position evidenced by the above equation, dead reckoning navigation systems are susceptible to the accumulation of errors. Therefore, they exhibit relatively poor long-term accuracy. Position fixing systems, however, do not accumulate errors in this manner since each fix is independent of previous fixes and, therefore, exhibit relatively good long-term accuracy. However, the error characteristics of the two types of systems tend to be reversed with respect to short-term errors. That is, dead reckoning systems tend to exhibit good short-term accuracy and position fixing systems tend to exhibit relatively poor short-term accuracy. These complementary error characteristics are the principal reason for the widespread use of composite systems. (Currently operational radio navigation systems are position-fixing systems, while inertial navigation and Doppler navigation use dead reckoning techniques.) These differences in short and long-term accuracy strongly influence the test methods appropriate to the two types of navigational systems.

6.1.2 BASIC METHODS OF POSITION FIXING

Position fixing navigation systems generally determine position as the intersection of two or more lines (or curves) of position as shown in figure 6.1. Four basic geometric configurations are commonly encountered:

Polar coordinates, illustrated in figure 6.1a, involves the determination of range and bearing of the vehicle from a single, known reference point. The TACAN system is an example of such a system.

Triangulation, illustrated in figure 6.1b, involves determining position as the intersection of the two lines of bearing from two known reference points. A position fix determined by radio direction finding is an example of triangulation.

Trilateration, illustrated in figure 6.1c, involves determining vehicle position as the common intersection of the three circles of range from three known reference points. A position fix determined by measuring ranges from three Distance Measuring Equipment

(DME) stations is an example of trilateration. Global Positioning System (GPS) is essentially a trilateration system operating in three dimensions rather than in two dimensions.

A hyperbolic system, illustrated in figure 6.1d, involves determining vehicle position by measuring the difference in the ranges from the vehicle to two (or three) pairs of known reference points. The actual ranges to the reference points is not measured, but the differential range to the reference points is measured which yields a hyperbolic line of position. (The fix provided by only two pairs of reference points can be ambiguous, but the geometry generally is such that the ambiguity is easily resolved without the use of a third pair of reference points.) Loran and Omega are examples of hyperbolic systems.

The nature of a navigation system, whether it uses position fixing or dead reckoning, and the geometric configuration of the lines of position determine the system error model. The error model, in turn, determines the performance testing required for a given system.

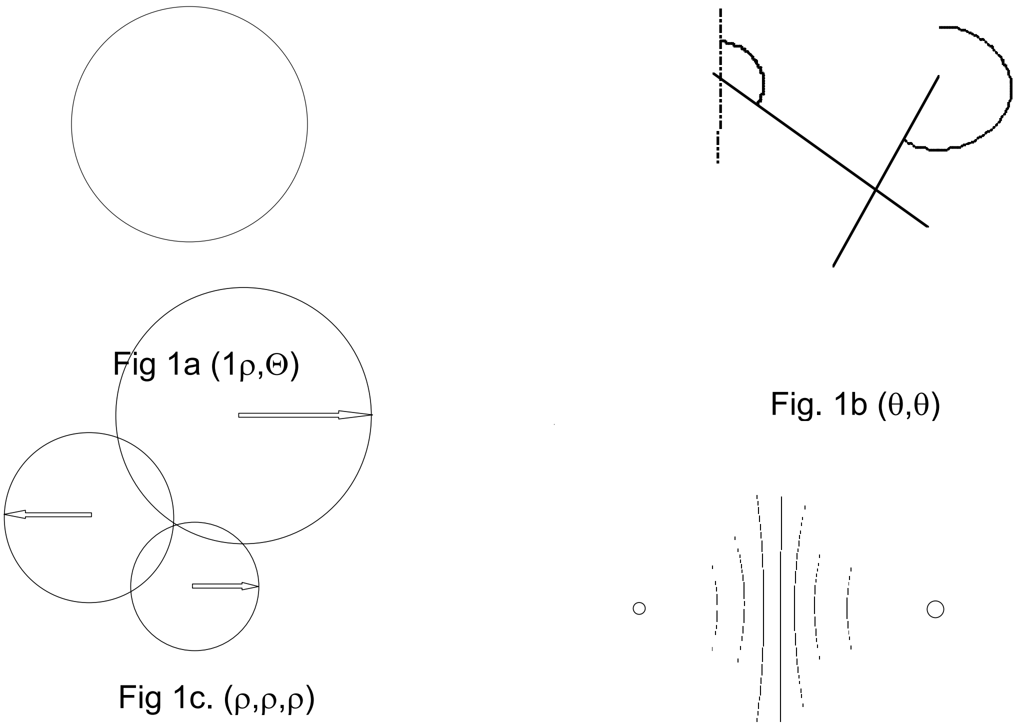
Fig 1a (1ρ,Θ)

Fig. 1b (θ,θ)

Fig 1c. (ρ,ρ,ρ)

Fig 1d (Δρ,Δρ)

Figure 6.1
Basic Methods of Position Fixing

6.2 INERTIAL NAVIGATION SYSTEM EVALUATION

6.2.1 BACKGROUND

The development of highly accurate, self-contained inertial navigation systems (INS) has been one of the major engineering accomplishments of the past 50 years. It has taken the combined efforts of hundreds of engineers of all types, as well as physicists, mathematicians, metallurgists, skilled craftsmen, and managers to bring inertial navigation to its present advanced state; however, the principles upon which it is based are actually quite simple.

In the simplest terms, an INS is a system which uses Newton's laws of motion and a set of initial conditions to continuously determine the velocity, position, and attitude of the vehicle in which it is contained. The INS differs from other types of navigation systems in that it is completely self-contained, requiring no external references such as radio links, radar contact with the surface of the earth, or measurement of the vehicle's velocity through the air or water. An INS gives the military an accurate, nonemitting, unjammable navigation system requiring no ground-based or airborne support.

6.2.2 THEORY

Airborne inertial navigation systems (INS) are dead reckoning systems that measure the accelerations of the aircraft relative to "inertial space" or relative to the "fixed" stars. Because of this frame of reference, the accelerations must then be corrected to represent accelerations relative to the Earth coordinate system being output by the navigation system. Because the earth is a rotating spheroid, there are centrifugal accelerations which are a function of latitude that can be measured by the accelerometers that do not contribute to the motion of the vehicle across the surface of the Earth, so these centrifugal accelerations must be computed and subtracted from the total measured acceleration. Likewise, when the platform has either a North/South or a Vertical velocity, there are coriolis accelerations which are a function of latitude, North/South velocity, and Vertical velocity which are measured by the accelerometers which do not contribute to the motion of the vehicle across the surface of the Earth. These coriolis accelerations must be computed and subtracted from the total measured acceleration.

All INS systems have the following fundamental components:

- Accelerometers
- Stable Platform
- Gyroscopes
- Computer

These four interact, with the accelerometers measuring the vehicle (aircraft) accelerations in three orthogonal axes, the stable platform providing a reference plane, and the gyroscopes maintaining the reference level condition of the stable platform. The computer calculates current velocity and position from the measured accelerations, provides correction signals due to the transport rates over the Earth's surface to bias the gyroscopes to properly stabilize the stable platform, and provides the centrifugal and coriolis corrections to the accelerometer outputs.

There are two basic platform stabilization techniques. These are the north-pointing and wander azimuth systems. The north-pointing system maintains a reference axis on the stable platform aligned with true north at all times while the wander azimuth system allows the reference axis to assume an arbitrary, continuously changing angle relative to true north. The north-pointing system must apply correction torques to the gyros as it translates across the earth's surface to maintain the proper alignment of the reference axis, while the wander azimuth system must continuously compute the wander azimuth angle to resolve the measured accelerations into north/south and east/west components. The U.S. Navy LTN-72 is a wander azimuth system.

The stable platform can also be designed to maintain its orientation with respect to the earth and inertial space in one of the following ways:

Analytic- the gyroscopes and accelerometers are oriented to a fixed reference point in inertial space.

Semi-Analytic- the gyroscopes and accelerometers are oriented to local vertical at the present latitude and longitude (perpendicular to the earth's gravitational force).

Geometric- the gyroscopes are oriented in inertial space and the accelerometers are oriented to local vertical.

Strap-Down- the gyroscopes do not maintain any set orientation and the accelerometers follow orientation of the vehicle.

Modern local vertical tracking INS systems are designed with Schuler tuning to eliminate errors in the orientation of the stable platform due to acceleration and motion across the surface of the earth. The correct orientation of a semi-analytic system is to maintain the vertical axis of the stable platform with the local vertical at that latitude and longitude. If this orientation is not maintained, the horizontal accelerometers will sense an acceleration due to the force resisting the gravitational pull of the earth and incorrectly compute a horizontal velocity and horizontal displacement of the platform. This incorrect horizontal displacement would result in an error in true position which would be bounded by the local vertical tracking mechanism and would oscillate with a period of 84.4 min, equivalent to the period of an earth radius pendulum. This oscillation has become known as the Schuler cycle.

For a more detailed description of inertial navigation systems, references 1, 2, and 5 should be consulted. INS testing should include testing throughout an airplane's airspeed, attitude, altitude, and mission segments (high altitude, strike, inflight refueling, carrier operations, etc.) to ensure compatibility.

6.2.3 PREFLIGHT AND ALIGNMENT

6.2.3.1 BACKGROUND

The preflight and alignment procedures for an INS must enable the operator to ensure system preparation and start-up in a timely, accurate, and concise manner.

6.2.3.2 PURPOSE

To evaluate the preflight and alignment procedures of a specific inertial navigation system.

6.2.3.3 THEORY

Preflight and alignment are two major steps in the INS's ability to perform its functions. Without proper initial validation the operators could be falsely led to believe that the system is functioning correctly. The major items checked during preflight and alignment are the warm-up and leveling times, alignment time and accuracy, self-calibration, build-in-test, controls and displays, response to transients (external to internal power sources, generator checks, mode changes, etc), and other system interfaces. Initial testing can be done in a laboratory, but ground tests in the actual platform must also be performed. All types of alignments (e.g., normal, fast, inflight) should be examined, and ground testing (drift runs) should be done after the alignments to evaluate the accuracy of the system after performing each type of alignment. Flight testing must be done to validate the test results obtained during laboratory testing and ground testing. Since the accuracy of an alignment may depend on the amount of earth rate present during the alignment process, the alignment testing should be done at various latitudes, including equatorial and high polar latitudes, and in both the Northern and Southern hemispheres.

6.2.3.4 METHOD

All available publications by the manufacturer and U.S. Navy should be consulted to obtain specific information on the INS system under test. The tester should time the preflight and alignment procedures (P & A) for total time required and for the time required for each individual portion. System response to inputs and indications as to status should be examined. The location and accessibility of controls and displays should be reviewed. Many of the cockpit evaluation questions should be re-examined with respect to the INS system. Built-in-Test operation should be reviewed as to time of occurrence, type of readouts provided, and fault display utility. For example, are faults displayed as they are detected or only after the test is complete? Additionally, does the test stop at a fault or can it be stepped through (a major time consideration)? What provisions are made for un-installed, optional, or improper modes of peripheral equipment? If no faults are observed, how can testing be performed to examine the BIT results with a fault condition present (pre-faulted module insertion)? The required platform conditions, such as motion, need to be reviewed (e.g., the LTN-72 in the P-3C must be stable through acceptance of the navigation mode). There are many qualitative and quantitative points to be examined in the P & A portion of testing.

6.2.3.5 DATA REQUIRED

Qualitative:
- thoroughness
- logical sequencing
- clarity
- equipment location
- display condition during different lighting conditions
- qualitative views

Quantitative:
- System serial number
- Alignment location (specifically latitude)
- Alignment heading
- Ambient Temperature
- Wind velocity and direction
- Time required to complete preflight

- Time required to complete alignment
- Fault indications
- Magnetic variation
- Warm-up time allowed
- Motion/movement of aircraft during alignment
- Large metal object(s) in vicinity of the aircraft
- Power (type and source) requirements

For carrier testing:

- Level, frame number, spot on ship
- Ship's heading, speed, and magnitude of motion
- Sea state
- SINS status

Items that should be varied during the test phase across the entire range of conditions expected to encountered during operational use:

- System serial number
- Alignment location (specifically latitude)
- Alignment heading
- Ambient Temperature
- Ship's heading and speed
- Sea state
- SINS status

6.2.3.6 DATA ANALYSIS

The average time to complete the preflight checklist, the average alignment time, and the amount of time the operator must dedicate specifically to the navigation system should be mission related to other aircraft preflight items and checklists. The accuracy and clarity of fault indications and the effects of failures on system operation and accuracy are details that should also be considered.

6.2.3.7 SAFETY

Fault insertion procedures will be not be undertaken without proper authorization. The preflight checklist will be halted at faults and inaccuracies until proper technical investigation indicates that it is safe to proceed.

6.2.3.8 ERROR ANALYSIS

Confidence levels for timed tests will be from the specification. Sampling size has a direct impact on the confidence level.

6.2.4 STATIC POSITION ACCURACY

6.2.4.1 BACKGROUND

In support of its mission, an INS equipped aircraft is frequently required to stand-by in a ready posture. This ready posture requires the airplane to have all systems on or warmed up to become airborne quickly. Often times an INS must remain in an operating mode and must retain an accurate static position.

From a technical viewpoint, once a "navigate" mode has been selected, the INS must in fact navigate to maintain a static position with respect to the earth. Therefore, the accuracy of an INS during a static drift test reveals pertinent information about the accuracy of the alignment and the ability of the system to compensate for earth rotation, centrifugal accelerations, vibration, and the effects of wind and crew motion on the platform.

6.2.4.2 PURPOSE

The purpose of this test is to evaluate the static position accuracy of the INS.

6.2.4.3 METHOD

The operator should perform a normal preflight and alignment of the INS. Upon completion and entry in a normal navigation mode, the aircraft position should be recorded at 5 min intervals. The test should run a minimum of three hours through at least two complete Schuler cycles. Aircraft location and weather conditions should be noted.

6.2.4.4 DATA REQUIRED

The data for the preflight and alignment should be recorded as discussed in the section of this manual for those procedures.

NOTE

It is important to record the time that the alignment mode is exited and the navigate mode is selected.

Then the following data should be recorded at 5 min intervals:

- Time (or elapsed time from accept)
- Actual latitude and longitude (truth data)
- INS indicated latitude, longitude, and ground speed
- INS advisory/warning indications
- Any changes in original conditions

6.2.4.5 DATA REDUCTION

Position errors in latitude and longitude should be computed and converted to errors in units of nautical miles. A simple method of doing this is to assume that one arc minute of latitude is 1 nmi. Even though this method ignores the true shape of the earth and assumes that it is a sphere, the results are reasonably accurate. Thus, the north/south and east/west errors can be computed as follows:

$$\Delta LAT = (LAT_{INS} - LAT_{TRUTH}) * 60\,\mathrm{nmi/deg}$$

$$\Delta LONG = (LONG_{INS} - LONG_{TRUTH}) * COS(LAT) * 60\,\mathrm{nmi/deg}$$

Radial error computation can similarly be simplified by assuming a flat earth over the fairly short distances involved in the error computations. This method will not work at high polar latitudes, but should be accurate at lower latitudes. Thus, the radial error can be computed as follows:

$$ERR_{RADIAL} = \sqrt{\Delta LAT^2 + \Delta LONG^2}$$

If more accuracy is required or desired, data reduction methods using geodesy are available. The computed errors should then be plotted as a function of time to determine INS drift rates. Statistical operations should be utilized as required to provide mean INS error with the required confidence level.

6.2.5 NON-MANEUVERING DYNAMIC POSITION ACCURACY

6.2.5.1 BACKGROUND

The ability of an INS to maintain accurate positioning is essential, especially when the aircraft must transit to meet specified Air Defense Investigation Zone (ADIZ) points and battle group entry and exit positions.

As well as the computations required of an inertial system during a static drift test, additional forces act upon the system while it is in motion, and these forces require additional computations by the INS. These additional forces include coriolis accelerations which are a function of the north/south and vertical velocity of the airframe, and changes in the centrifugal accelerations which are a function of the east/west velocity, latitude, and altitude of the airframe. The system must therefore accurately recognize changes in aircraft heading and attitude to constantly dead reckon the current aircraft position. The inaccurate resolution of accelerations into north/south and east/west components will lead to position errors which will lead to further inaccuracies in the resolution of the measured accelerations which will lead to further position errors. Therefore, position errors tend to compound and accumulate as a function of time. The ability of the INS to minimize this cumulative error is demonstrated by its accuracy in computing current aircraft position during a non-maneuvering flight test. In examining non-maneuvering position accuracy, the rates and forces imparted on the airframe in all three axes should be kept to a minimum.

6.2.5.2 PURPOSE

To evaluate non-maneuvering dynamic position accuracy of the INS.

6.2.5.3 METHOD

The flight should be flown from point-to-point over surveyed waypoints at the minimum altitude consistent with standard operating procedures currently in effect. Low bank angles and rates should be used with constant 1 g flight to establish baseline performance of the INS while in flight. Flight duration should be consistent with the projected mission length for the airplane and weapon system under test. Surveyed check points should be approximately 5 min apart but no longer than 10 min apart. The flightpath should be planned to gain maximum separation from the point of origin at flight midpoint or terminus to exercise to the maximum extent possible the INS earth model. A north/south track should be included to exercise the ability of the system to compute and compensate for coriolis and centrifugal accelerations, and an east/west track should be included to exercise the ability of the system to compute and compensate for transport rate and to apply corrections to earth rates and centrifugal calculations. Because the meridians converge at the poles, a flight test at high latitudes would also be appropriate. If possible, transit of the equator and the 0 and 180 deg meridians should be performed to evaluate system and software tolerance of hemisphere shifts. Updates of the INS position should not be performed during the flight test.

6.2.5.4 DATA REQUIRED

Data recorded at each checkpoint will include:

- Time
- System position (Test data)
- Surveyed position (Truth data)
- Altitude
- Heading, airspeed, winds
- Method of observation
- Comments on observation accuracy

6.2.5.5 DATA REDUCTION

Position errors in latitude and longitude should be computed in the same way as described in the Static Position Accuracy section of this manual. The computed errors should be plotted as a function of time to determine INS drift rates under nonmaneuvering flight conditions. The appropriate statistical operations should be utilized as required to provide mean INS error with the required confidence level.

6.2.5.6 DATA ACCURACY/ERROR ANALYSIS

Test data are assumed accurate, however several sources of error can be present during the data taking process. Sources of error include the procedure used to fix the aircraft position, time delays in recording data, display accuracy, and surveyed data accuracy. These sources combine to create an error in the accuracy of each data point.

The usual data taking procedure is to fly over a surveyed waypoint (e.g., radio tower, a building) at test altitude and when that point appears to pass under the aircraft, the pilot calls "mark", the INS position display is frozen at that point, and the data recorded. The inaccuracy in flying over a surveyed point is assumed to be one-half the flight altitude above the waypoint (i.e., at 1,000 ft above the waypoint, the error is estimated at ±500 ft). The delay in freezing the INS display and recording data can be as long as 0.5 sec, which equates to ±200 ft at 240 kt groundspeed. The accuracy to which INS data is presented to the aircrew is generally 0.1 min of latitude and longitude, the least significant digit in the data readout is generally tenths of minutes. At a latitude of 40 deg, longitude measurements rounded to 0.1 min equate to an accuracy of ±230 ft and latitude measurements rounded to 0.1 min equate to an accuracy of ±300 ft. The accuracy of the survey which was used to define the position of the waypoint will vary from a few feet to perhaps hundreds of feet depending on the waypoint and the purpose for which it was surveyed. If this error is available, it should be obtained when the survey data is obtained.

Combining errors from all these sources is usually done by assuming that the errors are random in nature and the mean error can be computed by taking the square root of the sum of the squares of all of the error sources. This method will give an average error that can be expected, but the error inputs can also be summed to yield a worst case maximum error that can be expected. For this example, the square root of the sum of the squares method would yield an error of approximately 600 ft whereas the summation of errors would yield approximately ±1,000 ft in the north/south direction and approximately ±930 ft in the east/west direction.

Very coarse "truth" data can be obtained by measuring the radial and DME to a TACAN station with a known latitude and longitude. This truth data is derived from equations which assume a flat earth model and account for the aircraft altitude, range and true bearing from the TACAN station. This "truth" data can be computed as follows:

Compute lateral range to the TACAN:

$$R_L = \sqrt{R_S^2 - ((ALT_{A/C} - ALT_{TACAN})^2 / 6076)}$$

where:

R_L = Lateral Range to the TACAN
R_S = Slant Range to the TACAN (DME)
$ALT_{A/C}$ = Aircraft Altitude in feet
ALT_{TACAN} = TACAN Altitude in feet

Next compute Latitude using the following equation:

$$\Delta \text{LAT(nmi)} = R_L * \cos(\phi)$$

where ϕ is the smallest angle measured from the North/South axis, and convert ΔLAT from nmi to degrees with the following conversion equations:

The number of nmi per degree of latitude is:

M = [111,132.09 - 566.05*COS(2*LAT) + 1.20*COS(4*LAT) -0.002*COS(6*LAT)]/1852

$$\Delta \text{LAT(deg)} = \Delta \text{LAT(nmi)} / M$$

To obtain the actual latitude of the airplane, take the latitude of the TACAN station and ADD ΔLAT if North of the station or SUBTRACT ΔLAT if South of the station.

Next, compute longitude using the following equations:

$$\Delta \text{LONG(nmi)} = R_L * \sin(\phi)$$

and convert ΔLONG from nmi to degrees with the following conversion equations: The number of nmi per degree of longitude is:

P = [111,415.13*COS(LAT) - 94.55*COS(3*LAT) + 0.012*COS(5*LAT)]/1852

$$\Delta \text{LONG(deg)} = \Delta \text{LONG(nmi)} / P$$

To obtain the actual longitude of the airplane, take the longitude of the TACAN station and ADD ΔLONG if West of the station or SUBTRACT ΔLONG if East of the station.

The errors involved in obtaining "truth" data in this manner are dependent upon the accuracy of the range and bearing reading to the TACAN station, which can be in error by as much as 2,000 ft and 2 deg depending on the range between the aircraft and the TACAN. The error in the "truth" data could then exceed the navigation error in the system under test.

6.2.5.7 CONFIDENCE LEVEL

Statistical analysis shows that increasing the confidence of the data to represent the true population's mean (fleet average for the INS system) does not mean simply improving the error bandwidth. In statistical terms the more degrees of freedom associated with the data the more confident we are that it portrays the true population's mean. INS is a DR system with each INS data point dependent on the time elapsed since the system entered it's navigation mode. To increase the degrees of freedom (2 times sample population), we must increase the number of data points (test flights). From the plot in figure 6.2, 18 test flights (36 deg of freedom) would be required before a 90% confidence that the data was within 20% of the true population's mean.

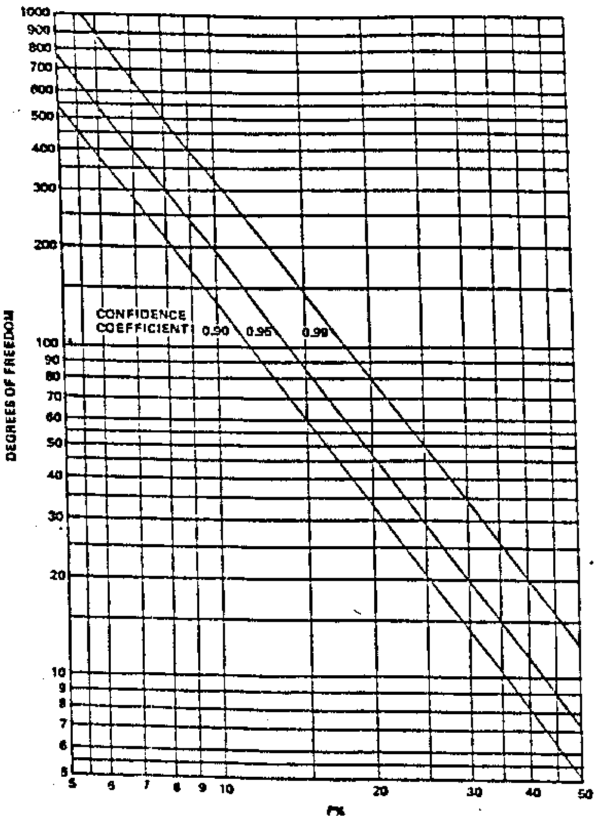

Figure 6.2
Degrees of Freedom Needed to Estimate Sn Within P% of its True Value with the Prescribed Confidence[59]

6.2.6 MANEUVERING DYNAMIC POSITION ACCURACY

6.2.6.1 BACKGROUND

The INS must be able to successfully navigate within the maneuvering limits of its host airplane. Rapid changes in airplane attitude, direction, and airspeed will have a

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[59] NAVORD Report 3369, Statistics Manual, 1960, Edwin L. Crow, Francis A. Davis, and Margaret W. Maxfield

definite impact on the INS in terms of measured accelerations. The ability of the system to accurately measure and resolve these accelerations into north/south, east/west, and vertical components, to compensate for transport motion across the surface of the earth, and to maintain the stable platform perpendicular to the local vertical will be strongly influenced by the severity of the maneuvers imposed on the INS by the host airplane, especially in the case of a tactical jet. The INS must be able to compensate for the effects of strenuous maneuvers and still maintain an accurate dead reckoning position to facilitate mission success.

6.2.6.2 PURPOSE

The purpose of this test is to evaluate INS dynamic maneuvering position accuracy.

6.2.6.3 METHOD

A normal preflight and alignment should be performed on the INS under test. The airplane should then be flown at low level collecting navigation data over surveyed points as performed in nonmaneuvering dynamic flight testing to establish baseline performance for this particular alignment. The duration of the nonmaneuvering portion of this flight should approximate the airplane's normal mission transit time. At the conclusion of the nonmaneuvering portion of the flight, and once established on a suitable range or in a suitable military operating area, the airplane should be maneuvered through various simulated mission tasks. These tasks might include photo rigging maneuvers, MAD hunting circles and cloverleafs, weapon delivery runs using various profiles, and offensive or defensive air combat maneuvering. During the maneuvering period, position data should be taken after each major maneuver by marking on top surveyed points. After a mission relatable maneuvering period, the airplane should be flown on a low level nonmaneuvering route over surveyed check points with navigation data being collected by marking on top of surveyed checkpoints. The return portion of the flight should be of a long enough duration to allow any errors created by the maneuvers to be manifested as position errors in the INS. After landing, static position data should continue to be taken for 2 hr at 5 min intervals. At the completion of this test, the airplane true heading should be recorded and the INS re-aligned and true heading again recorded for comparison.

6.2.6.4 DATA REQUIRED

The same data should be recorded as specified in the Preflight and Alignment and Non-maneuvering Position Accuracy sections of this manual. In addition to that data, the following items should be recorded:

- Transit time (prior to maneuvering)
- Maneuvering time
- Maneuver type
- Transit time (after maneuvering)

6.2.6.5 DATA REDUCTION

Latitude error, longitude error, and radial error should be plotted as a function of time with a notation as to the time that the maneuvers took place. The error rates can then be categorized as prior to maneuvering, during maneuvering, and post maneuvering. In addition, the INS drift rates for the entire flight can be evaluated for mission suitability. The appropriate statistical operations should be utilized as required to provide mean INS error under maneuvering conditions with the required confidence level.

6.2.6.6 DATA ACCURACY/ERROR ANALYSIS

The accuracy of the data should be the same as for nonmaneuvering dynamic position accuracy if it is collected in the same manner.

6.2.7 SYSTEM INTEGRATION

6.2.7.1 BACKGROUND

The ability of one system to operate with other systems to create an efficient, serviceable, and functional weapon system is the ultimate goal of system design.

6.2.7.2 PURPOSE

To evaluate the system integration (interoperability) of the INS within the platform (airplane) in which it is installed.

6.2.7.3 METHOD

System integration is a qualitative investigation of the INS. Data should be gathered throughout all tests, both ground and flight. Evaluation points should include, but are not limited to:

- Display of information
- Formatting
- Updating
- Interoperability with the platform's
- radar
- steering
- FLIR
- other navigation systems
- other weapon systems
- Operator interface
- Task loading
- System utility

6.2.7.4 DATA REQUIRED

- qualitative comments throughout testing
- format examples
- time required to interact between systems

6.2.7.5 DATA REDUCTION

Qualitative review of the INS ability to enhance (or degrade) the airplane in accomplishment of its mission.

6.2.8 INS TESTING

Complete INS testing will require other dedicated test events/points. A full system may provide ground speed, track, waypoint/steering, and other features. These functions would require more examination in functionality, accuracy, and operator interface. Data would also be collected for specification compliance during developmental testing.

6.3 DOPPLER NAVIGATION SYSTEM EVALUATION

6.3.1 BACKGROUND

For use aboard platforms where the use of an inertial navigation system would prove to be difficult, such as aboard small ships with no means to convey the ships inertial navigation system information to the aircraft, or where no ships inertial navigation system exists, a Doppler radar navigation system can be used to provide continuous velocity and position measurements in very nearly any weather conditions at any position on the Earth. A Doppler navigation system provides for autonomous operation since it is not dependent upon external communications such as radio navigation signal sources, and it does not require a lengthy pre-flight alignment which allows its use aboard vehicles which must react quickly to a variety of wartime and peacetime emergency situations.

6.3.2 THEORY

Airborne Doppler navigation systems are dead reckoning systems, but unlike inertial navigation systems which measure accelerations, a Doppler navigator measures vehicle ground velocity directly by measuring the Doppler frequency shift in radar returns from the surface of the Earth. It accomplishes this measurement by illuminating a portion of the surface beneath the aircraft with a directional radar beam as shown in figure 6.7.

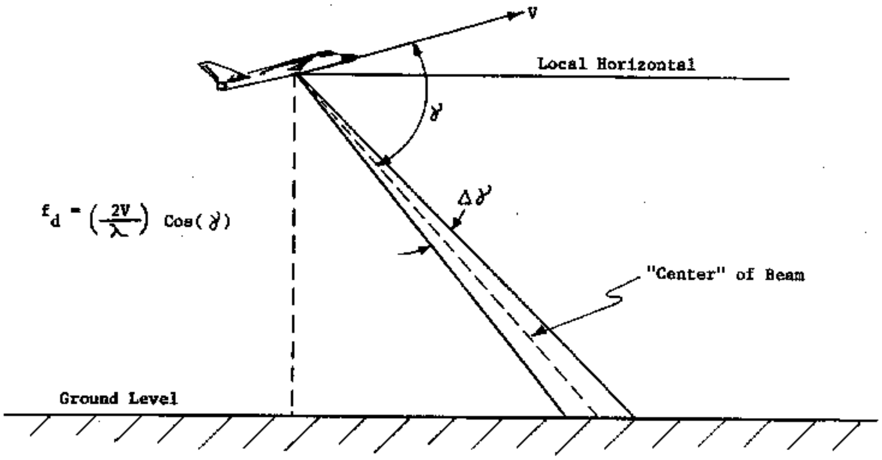


Figure 6.7
Doppler Navigation Beam Geometry

By knowing the depression angle, γ, and the wavelength, λ, of the transmitted frequency, the velocity of the aircraft is computed by measuring the Doppler shift, f_d, of the returned radar signal.

However, a single radar beam would yield only a single velocity measurement, and a Doppler navigator typically tries to measure not only the velocity along the track of the moving platform, but also the velocity across the track of the platform, and the vertical velocity of the platform. The three velocity computations then require three measurements which are typically taken simultaneously by three radar beams which are positioned around the aircraft in what is commonly referred to as a "Janus" or lambda configuration as shown in figure 6.8.

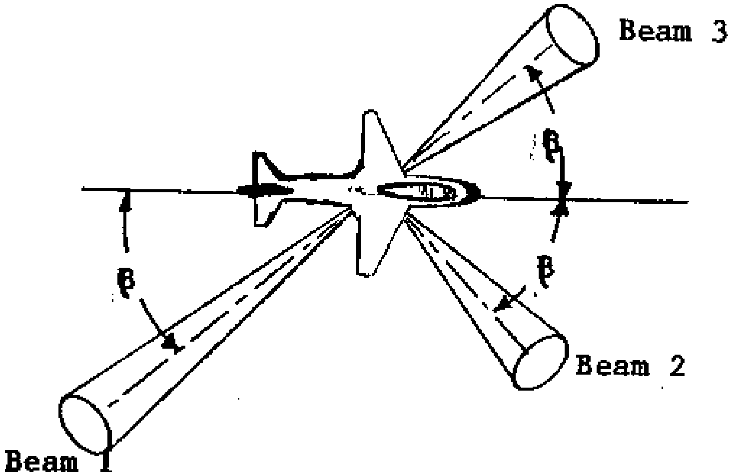


Figure 6.8
Doppler Navigator Beam Configuration

The Doppler measurement in each beam is therefore not only a function of the depression angle, γ, which can not be shown in the plan view of figure 6.8 but is still present, but also a function of the offset angle from the aircraft centerline, β. These three Doppler measurements are then resolved into along-track, cross-track, and vertical velocities. A fourth beam is sometimes included for redundancy.

The ultimate goal of the Doppler navigator is to dead reckon itself with respect to the Earth; therefore, the system must also resolve the three velocity components into North, East, and Vertical velocities. In order to do this, the system requires external inputs that define the direction of North and the direction of the local vertical. The three velocity components can then be continuously integrated to determine the displacement or offset of the vehicle from the starting position, and, hence, the computed present position.

6.3.3 PREFLIGHT/INITIALIZATION

6.3.3.1 BACKGROUND

The preflight and initialization procedures for a Doppler Navigation system must enable the operator to ensure system preparation and start-up in a timely, accurate, and concise manner.

6.3.3.2 PURPOSE

To evaluate the preflight and initialization procedures of the Doppler Navigation system.

6.3.3.3 THEORY

The preflight and initialization procedures for a system are major areas that allow examination of the operating status of a system. In a navigation system an accurate initialization minimizes the error budget with which a system must enter operation. The number of steps, complexity, time required, and mission utility directly impact the operator's ability to adequately preflight this specific system, as well as the weapon system as a whole.

6.3.3.4 METHOD

The appropriate publications should be followed to examine their interoperability with the specific Doppler navigation system under test. The tester should time the preflight and initialization procedures both as a whole and for individual portions. System response to inputs and indications as to status should be examined. The location and accessibility of controls should be reviewed. Many of the cockpit evaluation questions should be re-examined with respect to the Doppler navigation system. Built-in-Test operation should be reviewed as to when it occurs, what type of readouts, and whether faults are displayed as they are detected or after the test is complete. Additionally, does the test stop at a fault and must it be stepped through (a major preflight time consideration)? What provisions are made for un-installed, optional, or improper modes of peripheral equipment? If no faults are observed how can testing be performed to examine the system under a fault condition (pre-faulted module insertion)? The required platform conditions, such as motion, need to be reviewed. There are many qualitative and quantitative points to be examined in the preflight and initialization portion of testing. These should include:

- thoroughness
- logical sequencing
- clarity

6.3.3.5 DATA REQUIRED

- Time to preflight
- Equipment location
- Display condition under various lighting conditions
- Fault indications
- Power (type and source) requirements
- Qualitative views
- System serial number(s)

6.3.3.6 DATA ANALYSIS

Average time to complete the checklist and the initialization. Operator dedicated time and mission relation to other preflight times. Mission relation of preflight and initialization procedures, fault indications, fault effects on system operation/accuracy.

6.3.3.7 SAFETY

- No fault insertion without proper authorization
- The checklist will be halted at faults until proper technical investigation indicates that it is safe to proceed.

6.3.3.8 ERROR ANALYSIS

Confidence levels for timed tests will be from the specification. Sampling size has a direct impact on the confidence level.

6.3.4 POSITION ACCURACY

6.3.4.1 BACKGROUND

The ability of a Doppler navigation system to maintain accurate positioning is essential, especially when the aircraft must transit to meet specific ADIZ entry points and battle group entry/exit coordinates. The Doppler navigation system must provide accurate position data for turnovers between units and for over-the-horizon targeting. The system must be accurate enough to allow cross checks with other navigation systems.

6.3.4.2 PURPOSE

The purpose of this test is to evaluate the position accuracy of the Doppler navigation system.

6.3.4.3 METHOD

The flight should be flown from point-to-point over surveyed targets at altitudes between 500 and 1,000 ft AGL. Low bank angles and rates will be used with constant 1 g flight to measure inflight Doppler navigation performance baseline. Flight duration will be consistent with the projected mission length for the airplane/weapon system. Surveyed check points will be approximately 5 min apart, but no longer than 10 min. Data at each check point will include surveyed and system latitude/longitude, time, barometric altitude, Doppler navigation system advisories or warnings, and remarks. Tracks should be planned to gain maximum separation from the point of origin at flight midpoint or terminus to exercise the Doppler navigator over long ranges. Flights should be planned to allow investigation of overland and overwater performance, maximum or minimum functional altitudes or "holes" in the altitude coverage, performance at a variety of airspeeds and at a variety of headings, and performance during mission relatable maneuvers. Doppler navigation system position updates should not be performed unless a hazard to navigation exists.

6.3.4.4 DATA REQUIRED

- Time (Zulu)
- Position - surveyed and Doppler navigation system
- Heading
- Altitude
- Airspeed
- Method of Observation
- System status (warnings/cautions)
- Mode of operation

6.3.4.5 DATA REDUCTION

Position errors should be computed and converted to errors in units of nautical miles using the techniques discussed in the section on inertial navigation data reduction. The primary errors of concern are the along-track and the cross-track components of the position errors at the waypoint and the total radial error. The along-track component results from an error in the computation of the true velocity over the ground, and the cross-track component results from an error in the independent determination of North. The computed errors should be plotted as a function of distance traveled to determine Doppler navigation system error rates under nonmaneuvering flight conditions. Distance traveled is an appropriate independent variable since the errors tend to accumulate as a function of distance traveled rather than as a function of time. For example, if an error exists in the determination of true heading, then the cross-track position error of the Doppler navigator will grow linearly with displacement from the original starting position and will not depend upon how long it took to achieve that displacement. The appropriate statistical operations should be utilized as required to provide a mean error with the required confidence level.

6.3.4.6 DATA ACCURACY/ERROR ANALYSIS

Test data is assumed accurate, however several error sources can combine to create a worst case error. Sources of error include the procedure used to fix the aircraft position, time delays in recording data, display accuracy, and surveyed data accuracy. The discussion on how these inaccuracies combine and an example of their magnitudes has previously been presented in the Data Accuracy/Error Analysis portion of the Inertial Navigation System Evaluation of this document. The same example is relevant to the recording of Doppler navigation data.

6.3.4.7 CONFIDENCE LEVEL

The discussion of data confidence levels that were discussed in the Inertial Navigation System Evaluation section of this document also applies here.

6.3.5 DOPPLER NAVIGATION ERROR SOURCE COMPENSATION TESTING

6.3.5.1 BACKGROUND

All navigation systems are subject to error, with the Doppler navigation system being no exception. The Doppler navigator is susceptible to errors introduced by the surface over which it is navigating and how well that surface reflects the radar energy, by the airspeed, altitude, and heading of the vehicle, and by the maneuvers the vehicle is subjected to during the process of navigating.

6.3.5.2 PURPOSE

The purpose of these evaluations will be to examine the Doppler navigation systems error sources and to provide an overview of the common error sources that should be investigated during the testing process.

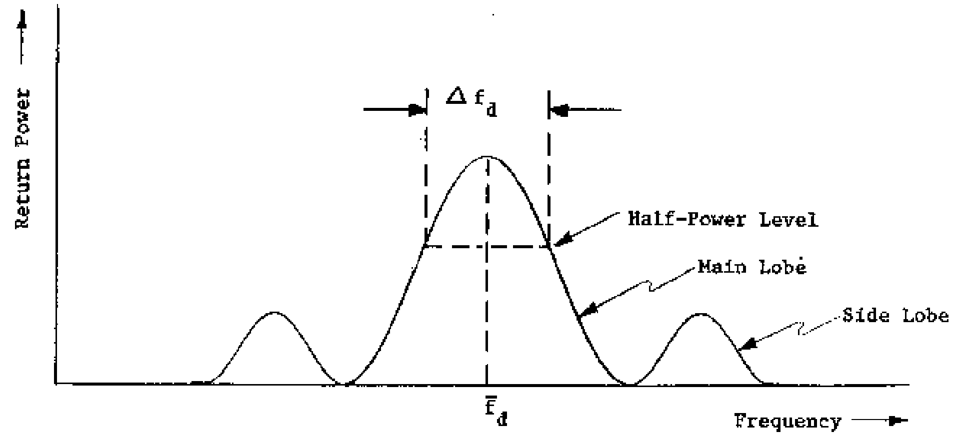
6.3.6 DOPPLER NAVIGATION SYSTEM ERROR SOURCES

6.3.6.1 EXTERNAL INPUT OF NORTH

The external device that provides the direction of North to the Doppler navigator is usually a flux valve or a magnetic compass. If this device is not properly aligned with the correct direction of North, the Doppler navigation system will deviate from the intended course of travel with an angular displacement that will create an ever increasing navigation error as the vehicle travels an increasing distance. The error due to a misalignment of the external direction reference will manifest itself as a cross-track error. The magnitude and direction of this error may vary with the direction of travel, therefore, the test plan should include flightpaths which exercise all of the points of the compass.

6.3.6.2 DOPPLER VELOCITY MEASUREMENT

The Doppler navigation system attempts to measure the Doppler shift of the surface over which the vehicle is traveling with a pencil beam radar as was shown in figure 6.7. Note, however, that the Doppler shift is dependent upon the depression angle of the radar beam. Because the beam is not infinitely narrow, the spread in depression angles between the leading edge of the radar beam and the trailing edge of the radar beam will cause a spread, or a "smearing" of the Doppler shift being received and being processed by the radar receiver. The spread in the Doppler shift being received will depend on the width of the radar beam being transmitted. The return power as a function of frequency will then appear something like the example shown in figure 6.9.



$$\Delta f_d = \left(\frac{2V}{\lambda}\right) \sin(\gamma)\, \Delta\gamma$$

Figure 6.9
Spectrum of Doppler Returns

A typical Doppler navigator beam width is approximately 4 deg resulting in a Doppler spread of about 20% at a depression angle of 70 deg. The Doppler processor must correctly determine the center of this spread of Doppler frequencies or it will not accurately compute the velocity of the vehicle. An inaccurate computation of vehicle velocity will result in the computed position being ahead of or lagging the true vehicle position and will thus exhibit itself as an along-track error as the flight progresses. The magnitude of a Doppler measurement error may vary as the velocity of the vehicle changes, hence the magnitude of the center of the Doppler spread changes, therefore, the test plan should include flights at a variety of vehicle velocities that cover the mission relatable ground speeds that are expected.

6.3.6.3 OVERWATER OPERATION

Operating a Doppler navigation system in an overwater environment creates several difficulties for the system processor. One of these difficulties arises from the fact that the water tends to reflect the radar energy away from the receiver rather than to backscatter it toward the receiver. This tendency generally results in a lower signal level at the receiver, and may result in the receiver not having enough energy to process. This loss of signal will often cause a Doppler navigator to go into a memory mode of operation until the energy level is restored. While in memory, the system is generally using previously obtained velocity data and dead reckoning the vehicle based on this old data. A flight test that forces the Doppler navigator to memory would seem to be indicated to determine how well the system "navigates" while in memory.

Another effect of overwater operation arises from the fact that the backscatter coefficient of the surface of the water can be a strong function of the angle of incidence of the radar beam. Specifically, the portion of the beam with the steepest depression angle, the "trailing" edge in figure 6.7, is reflected more strongly back toward the radar than is the portion of the beam with the shallower depression angle, the "leading" edge. This effect is more pronounced as the sea state decreases, that is, as the surface of the water gets smoother. As a result of this phenomenon and the fact that Doppler shift from the radar beam is also a function of the depression angle of the beam as shown in figure 6.9, a shift in system calibration can result. The energy returned to the Doppler navigator in an overwater situation as compared to an overland situation may appear as shown in figure 6.10.

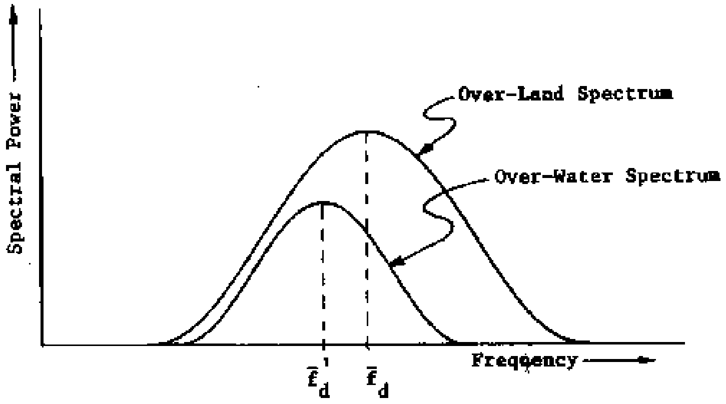


Figure 6.10
Effect of Overwater Operation on Doppler Spectrum

As can be seen in the figure, in an overwater situation, not only must the Doppler navigator contend with less energy being returned to the receiver, but also the energy is skewed to the left resulting in the "centerline" frequency being lower than what the mean Doppler frequency would be if the system were operating overland. This shift in system calibration can easily result in an incorrectly computed velocity, and thus result in poor navigation accuracy. Many systems provide the operator with an overland/overwater switch to compensate for the effect that overwater operation has on the Doppler spectrum that is returned to the receiver. In order to fully test a Doppler navigator, flights should be conducted both overland and overwater. A "failure" mode or compromise mode of operation could be examined by deliberately placing the overland/overwater switch in the incorrect position to simulate the effects on the navigation accuracy if a flight were to be conducted in both environments and the switch was set in one position and left there for the duration of the flight.

In addition to the reduction in signal power and the shift in system calibration, another significant effect of operating a Doppler navigator overwater results from the motion of the water itself. If the water mass is moving relative to the surface of the Earth, the computed velocity based on Doppler shift will be relative to the water, but the computed position will be relative to the Earth. It is very important, therefore, when testing over water to note events which would affect the motion of the water relative to the surface such as tidal flow and prevailing currents. It should be noted that wave motion does not necessarily result in a velocity computation error even though the waves appear to be moving across the surface since in pure wave motion, the individual particles of water do not have sustained forward motion, but tend to move vertically, merely oscillating up and down. If , however, there are strong winds that are blowing water droplets across the surface, the Doppler navigator may measure the motion of the droplets and could also measure the actual surface motion of the water being created by the strong winds. The surface conditions should therefore be documented for each overwater flight.

6.3.6.4 ALTITUDE EFFECTS

There are two ways to modulate the energy being transmitted by the Doppler navigation system. The energy can either be pulsed or it can be continuous wave (CW). Both of these techniques have advantages and disadvantages that require examination during a flight test program.

A pulsed system has the advantage of avoiding transmitter-to-receiver leakage and a coherent pulsed system will result in a higher signal-to-noise ratio, which will allow this type of system to operate at higher altitudes than would be possible with a CW system. A serious disadvantage of a pulsed system is that the returns are subject to "eclipsing" as is any pulsed radar system which will result in "blind ranges" or "altitude holes" in the system coverage. When the radar return is eclipsed, the Doppler navigator will not be receiving a signal with which to navigate. If the return is only partially eclipsed, a shift in system calibration can result since the leading edge and the trailing edge of the beam have different Doppler characteristics as discussed in the section on overwater operation. These effects can be minimized by varying the pulse repetition frequency as a function of time, but the first blind range, the one near zero time delay, or minimum altitude, will always be present. A flight test on a pulsed Doppler navigation system should therefore include operating the system over the altitude range that the host vehicle is expected to operate during its mission. This altitude excursion should specifically include a look at the minimum altitude requirements of the platform to insure that the minimum altitude hole has not been entered.

A continuous wave Doppler navigation system avoids the problem of altitude holes and should therefore work well down to zero altitude. The major problem with CW systems is that of transmitter-to-receiver leakage. Most CW systems solve this problem by frequency modulating the transmitted signal so that after the time delay incurred by the signal during its flight time to the surface and back, the received signal is at a different frequency than is the signal currently being transmitted. A problem may still arise at very low altitudes where the delay time of the signal is very short and the transmitter is still very near the received signal frequency. A flight test of a CW Doppler navigation system should therefore include a close look at the minimum operating altitude.

6.3.6.5 MANEUVERING EFFECTS

In order for a Doppler navigation system to function properly, it is a fairly obvious prerequisite that the Doppler radar beams illuminate the ground below the aircraft. It is possible that by vigorously maneuvering the aircraft, the beams can be rotated so that they are no longer pointed at the surface, and consequently, the system can no longer measure the Doppler shift needed to compute the velocity of the host platform. The test plan should therefore include a maneuvering flight phase that will exercise the Doppler navigation system to the prescribed limits of the platform in which it is installed. The test plan should include maneuvers in pitch and roll to examine the limits of the system, and it should include maneuvers in yaw to examine the effects of excursions in that axis.

6.4 LORAN NAVIGATION SYSTEM EVALUATION

6.4.1 BACKGROUND

Soon after the development of LORAN-A or "Standard LORAN" during World War II, the need for a more accurate long range navigation system was recognized, and the development of an improved radio navigation system was initiated. Extensive tests were conducted between 1952 and 1956, and the first operational LORAN-C stations were established along the East coast of the United States in 1957. Since then coverage has expanded to include the continental United States, Hawaii, the Gulf of Alaska, the North Atlantic, the Mediterranean, and parts of the Far East. The U. S. Coast Guard currently operates 49 Loran-C stations worldwide, including those in Italy, Japan, Spain, and Turkey, and several other countries operate the Loran stations within their own borders including China, the former Soviet Union, South Korea, Germany, Egypt, France, Denmark, Norway, Iceland, Canada, and Saudi Arabia. The future of LORAN-C is in doubt, but it will probably remain operational until the year 2000 when support of the LORAN-C transmitters will be terminated in favor of more modern navigation systems such as NAVSTAR Global Positioning System.

6.4.2 THEORY

LORAN-C is a pulsed, long range, hyperbolic navigation system that uses carefully synchronized signals transmitted from precisely surveyed land based stations. The user equipment measures the time difference in arrival of two radio signals which can be translated into a *difference in distance* between the two stations which then determines a line of position relative to the two transmitting stations that takes the form of a hyperbola. To obtain a position fix, at least one additional line of position is required from another pair of stations or from another independent source such as a visual fix or a celestial observation. LORAN stations are organized into "chains" of three or more stations each transmitting pulses on a single frequency centered on 100 kHz. Each chain is organized such that one station is designated as the master station, labeled M, and the other stations are designated as secondary stations, labeled V, W, X, Y, or Z. An example of a chain of

LORAN stations and a hyperbolic lattice formed by the pattern of intersecting lines of position between the master station, M, and the secondary stations, X and Y, is depicted in figure 6.11.

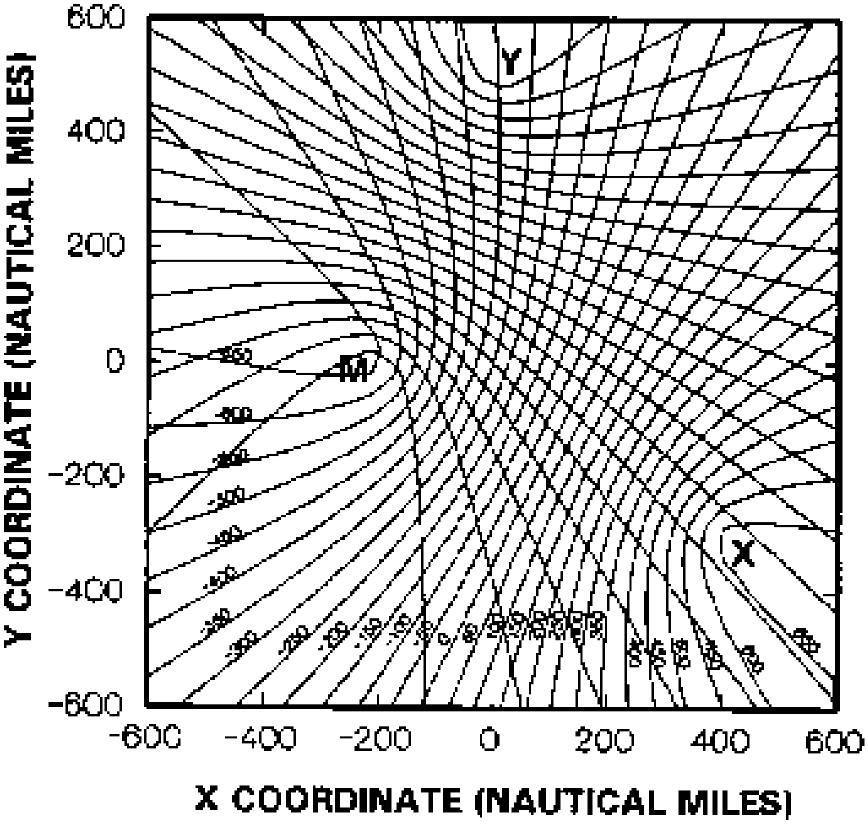


Figure 6.11
LORAN "Chain" and Lattice of Intersecting Lines of Position[60]

The master station transmits a group of nine pulses 250 μsec wide spaced one millisecond apart. The secondary stations transmit a similar group of eight pulses at a precisely controlled time interval after the transmission of the master station pulses. The *emission delay*, or total time delay between master and secondary pulse train emissions, consists of a *baseline travel time,* or the computed time it would take energy to travel from the master station to the secondary station, and a secondary *coding delay,* a unique, fixed time interval for each secondary in the chain that varies from 11,000 μsec to 81,000 μsec. Normally, the secondary stations transmit in alphabetical order. The pulse trains transmitted by the master and secondary stations are repeated at 10 to 25 times per second depending upon the specific chain. The use of multiple pulses allows the signal-to-noise ratio in the receiver to be increased significantly without increasing the peak power of the transmitting stations. The power of a LORAN-C station is normally between 165 kW and 1.8 MW and the signal is capable of being received to distances of

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[60] LORAN-C Users Handbook, COMDTPUB P16562.5, U.S. Coast Guard, U.S. Department of Transportation, 18 Nov 1992

1,200 nmi by ground waves and to distances of 3,000 nmi with sky waves. The time delay between the master and secondary stations transmission pattern results in the user always receiving the master station pulses first with the associated time delay between master station signal reception and secondary station signal reception being a minimum at or near the secondary station and at a maximum at and beyond the master station. The timing of the transmissions from secondary stations is not "slaved" to the master station as it was in the LORAN-A system, but it is precisely controlled by the use of multiple cesium time and frequency standards located at each station. One or more System Area Monitoring (SAM) stations with precise receiving equipment are established within the coverage area of a LORAN-C chain to monitor the measured time differential between the master and each secondary. When the measured time differential is out of tolerance, the SAM directs a change in the timing of the secondary station to remove the error.

The use of the groups of pulses and the precise timing between the transmissions allows the use of the same carrier frequency for all transmitting stations. The user equipment identifies the particular groups or chains of stations by the group repetition interval (GRI) of the transmitted pulses or, essentially, how many times per second the pulse train is repeated by the chain of stations. Each station transmits one pulse group in each group repetition interval. Further identification of each individual station is provided by changing the phase of the carrier in a systematic manner with respect to the pulse envelope to make it either in phase or 180 deg out of phase with a stable 100 kHz reference oscillator. The group of eight pulses from each secondary station thus has a different phase code.

A major improvement in the accuracy of LORAN-C over LORAN-A results from using a technique in the receiver known as "cycle matching" in which the LORAN-C receiver uses a specific cycle of the carrier within the pulse to determine the time deferential. Since the carrier is transmitted at 100 kHz, matching a particular cycle results in time measurement differentials that would not be possible using the envelope of the pulse amplitude. The system is designed to use the signal that arrives at the receiver first and this signal arrives via ground wave propagation. The positive zero crossing of the third cycle of the carrier within the pulse is used, even though the magnitude is less than maximum, since it occurs about 30 μsec from the leading edge of the pulse, and the arrival of the sky wave, which could potentially contaminate the reading, can be as short as 35 μsec. The ability to use the ground wave without contamination from the sky wave allows very precise time differential measurement which results in precise position accuracy. A depiction the pulse groups transmitted during one GRI and of cycle matching is shown in figure 6.12.

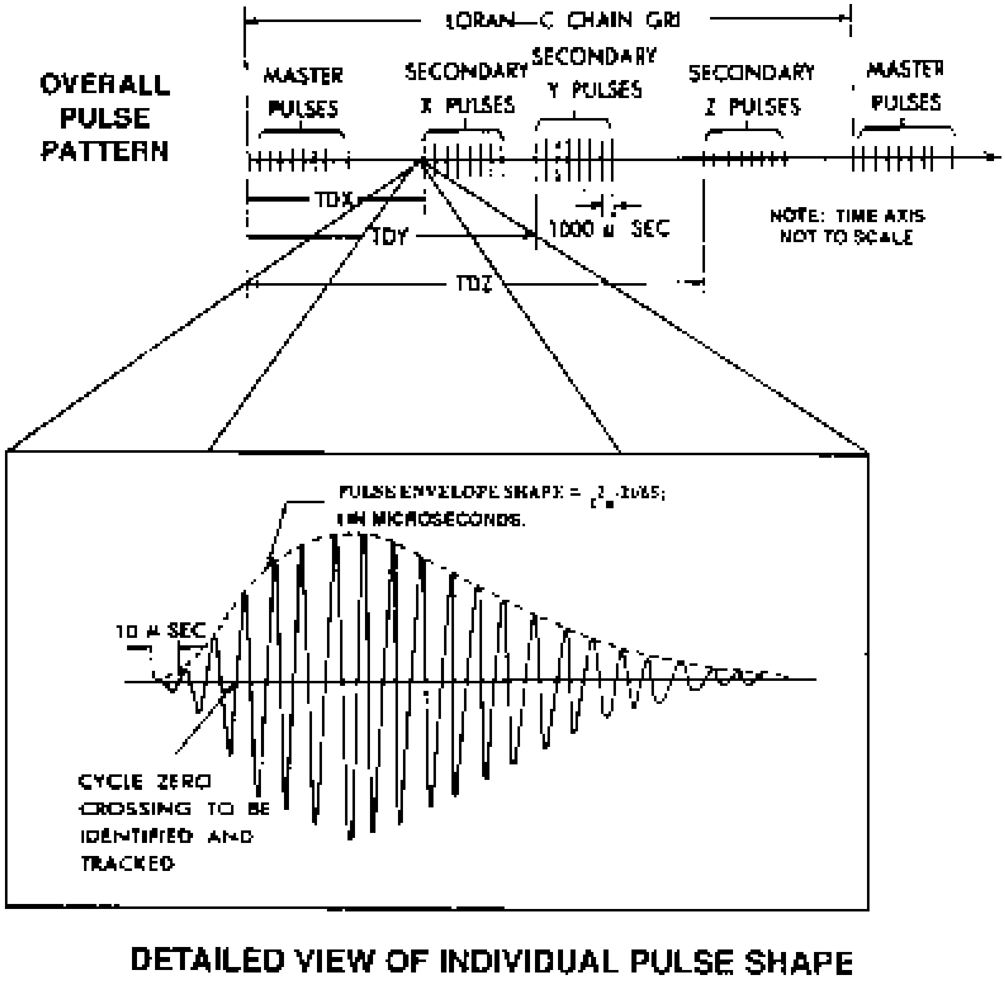

Figure 6.12
LORAN-C Pulse Waveform[61]

6.4.3 LORAN-C ACCURACY

The accuracy with which a LORAN-C receiver can navigate really depends upon what task the navigator has given the system. There are actually three major types of accuracy which can be discussed relevant to a LORAN. There is absolute accuracy, repeatable accuracy, and relative accuracy.

Absolute (or geodetic) accuracy refers to the ability of the receiver to position itself with respect to a surveyed point on the surface of the earth. For example, if one were attempting to land a helicopter at a predetermined point for troop insertion and was given the latitude and longitude of that point from a chart or a map, the navigator would be concerned with the absolute accuracy of the system.

Repeatable Accuracy is the ability of the system to return to a position whose coordinates have previously been measured with the same navigation system. To

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[61] Ibid.

continue with the above example, if the helicopter pilot had previously dropped troops off at a specific location and had noted the latitude and longitude (or the time differentials) of that location as shown on the LORAN readout(as opposed to the latitude and longitude shown on the map), the pilot could use those coordinates as a waypoint and ask the LORAN receiver to provide navigation information to return to that waypoint. The pilot would then be more concerned with the repeatable accuracy of the system than with the absolute accuracy. To many users, repeatable accuracy may be more important than the absolute accuracy because it allows the user to take advantage of the outstanding repeatable accuracy inherent in the LORAN-C navigation system. The drawback, of course, is that the user would have had to have already been at the desired position to get the LORAN coordinates, or the coordinates would have to have been obtained and published for use by the navigator. The Coast Guard does, in fact, publish LORAN derived coordinates for many locations of interest to mariners such as light structures, day markers, channel centerlines, etc.

Relative Accuracy is the accuracy with which one LORAN receiver can measure position relative to another receiver at the same time. An application where relative accuracy may be of primary importance is search and rescue when the vessel needing to be rescued has called out its location in LORAN derived latitude and longitude.

Of the three types of accuracy discussed, most users are concerned with either absolute or repeatable accuracy. When testing for these, keep in mind that the absolute accuracy includes both the random errors inherent in the system and the biases or systematic errors, while the repeatable accuracy includes only the random errors. The distinction between absolute and repeatable accuracy becomes quite important then when discussing the expectations that one has in obtaining an accurate position fix with the system. The specification of the LORAN-C system states that the absolute accuracy should be no greater than 0.25 nmi within the defined coverage area of the chain. In fact, the absolute accuracy varies from approximately 0.1 to 0.25 nmi depending on the users location relative to the transmitters. While there is no specification for the repeatable accuracy of LORAN-C, the *1990 Federal Radio Navigation Plan* refers to a range of accuracies from 60 ft to about 300 ft that can be expected depending on the users location in the coverage area.

6.4.4 PREFLIGHT/INITIALIZATION

6.4.4.1 BACKGROUND

The preflight and initialization procedures for an LORAN-C navigation system must enable the operator to ensure system preparation and start-up in a timely, accurate, and concise manner.

6.4.4.2 PURPOSE

To evaluate the preflight and initialization procedures of the LORAN-C navigation system under test.

6.4.4.3 THEORY

The preflight and initialization procedures for a system are major areas that allow examination of the operating status of a system. In a navigation system, an accurate initialization minimizes the error budget with which a system must enter operation. The number of steps, complexity, time required, and mission utility directly impact on the operator's ability to adequately preflight this specific system, as well as the weapon system as a whole.

6.4.4.4 METHOD

Manufacturer and/or U.S. Navy publications should be followed to examine their interoperability with the LORAN-C system under test. The tester should time the preflight and initialization procedures (P & I) both as a whole and for individual portions. System response to inputs and indications as to status should be examined. The location and accessibility of controls should be reviewed. Many of the cockpit evaluation questions should be re-examined with respect to the LORAN-C system. Built-in-Test operation should be reviewed as to when it occurs, what type of readouts, and whether faults are displayed as they are detected or after the test is complete. Additionally, does the test stop at a fault and must it be stepped through (a major preflight time consideration)? What provisions are made for un-installed, optional, or improper modes of peripheral equipment? If no faults are observed how can testing be performed to examine the system under a fault condition (prefaulted module insertion)? There are many qualitative and quantitative points to be examined in the P & I portion of testing. These should include:

- thoroughness
- logical sequencing
- clarity

6.4.4.5 DATA REQUIRED

- Time to preflight
- Equipment location
- Display condition under various lighting conditions
- Fault indications
- Power (type and source) requirements
- Qualitative views
- System serial number(s)

6.4.4.6 DATA ANALYSIS

Average time to complete the checklist and the initialization. Operator dedicated time and mission relation to other preflight times. Mission relation of P & I, fault indications, fault effects on system operation/accuracy.

6.4.4.7 SAFETY

- No fault insertion without proper authorization
- The checklist will be halted at faults until proper technical investigation indicates that it is safe to proceed.

6.4.4.8 ERROR ANALYSIS

Confidence levels for timed tests will be from the specification. Sampling size has a direct impact on the confidence level.

6.4.5 POSITION ACCURACY

6.4.5.1 BACKGROUND

The ability of a LORAN-C system to maintain accurate positioning is essential, especially when the aircraft must transit to meet specific ADIZ entry points and battle group entry/exit coordinates. The LORAN-C must provide accurate position data for turnovers between units and for over-the-horizon targeting. The system must be accurate enough to allow cross checks with other navigation systems.

6.4.5.2 PURPOSE

The purpose of this test is to evaluate the position accuracy of the LORAN-C system.

6.4.5.3 METHOD

The flight should be flown from point-to-point over surveyed targets at altitudes between 500 and 1,000 ft AGL. Low bank angles and rates will be used with constant 1 g flight to measure inflight LORAN-C performance baseline. Flight duration will be consistent with the projected mission length for the airplane/weapon system. Surveyed check points will be approximately 5 min apart, but no longer than 10 min. Data at each check point will include surveyed and system latitude/longitude, time, barometric altitude, LORAN-C system under test advisory or warnings, and remarks. Tracks should be planned to gain maximum separation from the point of origin at flight midpoint or terminus to exercise the LORAN-C over long ranges. If possible, flights should be planned to allow investigation of geometric dilution of precision, sky wave contamination, three dimensional slant range error, and atmospheric noise. LORAN-C system position updates should not be performed unless a hazard to navigation exists. If the LORAN-C test flight is not combined with INS testing, aircraft maneuvers in excess of 1 g, within airframe limits, is allowed. Night testing will be difficult due to the use of visual references but at least twilight testing should be attempted to determine if any navigation accuracy differences exist that are dependent upon the time of day.

6.4.5.4 DATA REQUIRED

- Time (Zulu)
- Position - surveyed and LORAN-C
- Altitude
- Heading/Airspeed
- Method of Observation
- LORAN-C stations selected
- LORAN-C station signal quality
- System status (warnings/cautions)
- Mode of operation

6.4.5.5 DATA REDUCTION

Position errors in latitude and longitude should be computed and converted to errors in units of nautical miles using the techniques discussed in the section on inertial navigation data reduction. Position error data should be further reduced to provide a circular error probable (CEP) figure. CEP is defined as the 50th percentile value of the circular (radial) position error population. This method is desirable because of its robustness under various test conditions and because an efficient estimate of its value (in the statistical sense) can be attained with a modest quantity of test data. Two methods of data reduction to produce a CEP exist. The RMS method provides CEP about the target (surveyed point) and must be coupled with the mean point of impact (MPI) for distribution display. The Nowak or Sigma method provides a CEP about the MPI.

6.4.5.6 DATA ACCURACY/ERROR ANALYSIS

Test data is assumed accurate, however several error sources can combine to create a worst case error. Sources of error include the procedure used to fix the aircraft position, time delays in recording data, display accuracy, and surveyed data accuracy. The discussion on how these inaccuracies combine and an example of their magnitudes has previously been presented in the Data Accuracy/Error Analysis portion of the Inertial Navigation System Evaluation of this document. The same example is relevant to the recording of LORAN-C data.

6.4.5.7 CONFIDENCE LEVEL

The discussion of data confidence levels that were discussed in the Inertial Navigation System Evaluation section of this document also applies here.

6.4.6 LORAN-C POSITION ERROR SOURCES

6.4.6.1 BACKGROUND

All navigation systems are subject to error, with LORAN-C being no exception. The LORAN-C is susceptible to errors introduced by the geometry of the receiver within the chain of stations, by assuming or modeling the velocity of propagation of the electromagnetic signal over land mass and over sea water, by the physical characteristics of the earth, and by signal processing errors in the LORAN-C receiver due to atmospheric noise.

6.4.6.2 PURPOSE

The purpose of these evaluations will be to examine the LORAN-C navigation systems error sources and to provide an overview of the common error sources that should be investigated during the testing process.

6.4.7 LORAN-C ERROR COMPENSATION

6.4.7.1 GEOMETRIC DILUTION OF PRECISION

A significant source of error in a LORAN system is the loss of precision resulting from the lines of position crossing at oblique angles at the fringes of the area of coverage. Because of the uncertainty in the measurement process, hence, the uncertainty in, or "width" of, the line of position, the greatest precision in any position fixing system is obtained when the lines of position cross at right angles. Examples of the position uncertainty that might result for a measurement uncertainty of 0.1 μsec when the lines of position cross at right angles and when they cross at a more oblique angle are given in figure 6.13. The width of the lines in each case represents the uncertainty in the measurement process and is equal in both cases, but the position uncertainty represented by the shaded area is much larger when the lines of position cross at 30 deg than when they cross at 90 deg.

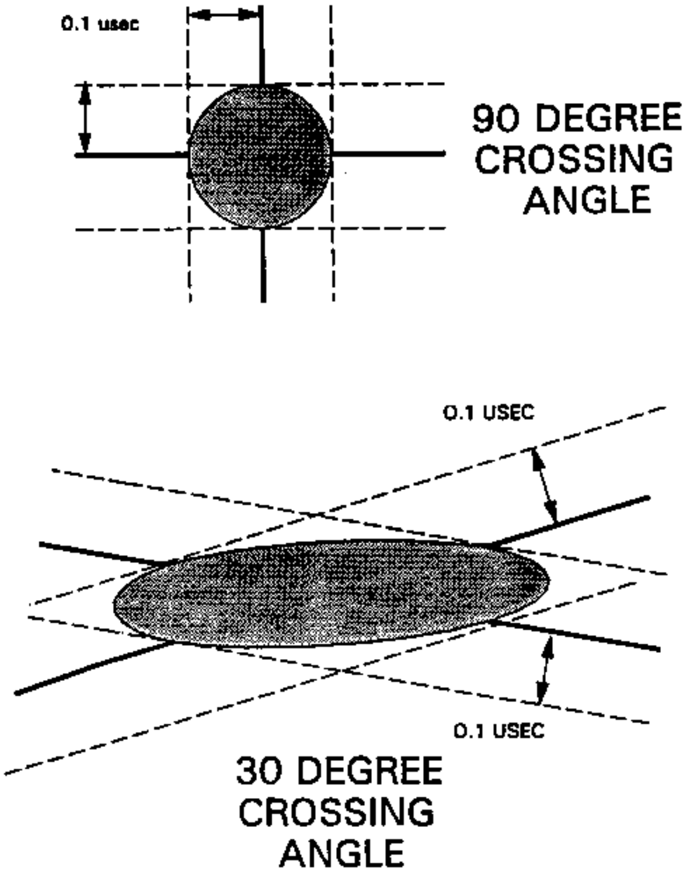

Figure 6.13
Geometric Dilution of Precision[62]

The lines of position tend to be more orthogonal when the receiver is in the middle of the chain of stations and they tend to be more oblique when the receiver is located outside the area enclosed by the ground stations, as depicted in figure 6.11. As a specific example, look Southeast of the Xray station and note that the line of position labeled "650" for the Master-Xray pair is nearly parallel to the adjacent line of position from the Master-Yankee pair. These two lines of position have very shallow crossing angles and would result in a very inaccurate position fix. Therefore, if at all possible, the position accuracy of the LORAN-C receiver should be tested with mission relatable considerations given to the geometric dilution of precision that occurs when the receiver has an unfavorable geometry relative to the transmitting stations.

6.4.7.2 GRADIENT

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[62] Ibid.

Another error source that occurs because of geometry in a hyperbolic system is the fact the lines of position are spaced farther apart near the baseline extension of a pair of stations than they are at other positions on the same chart. Figure 6.14 illustrates this point.

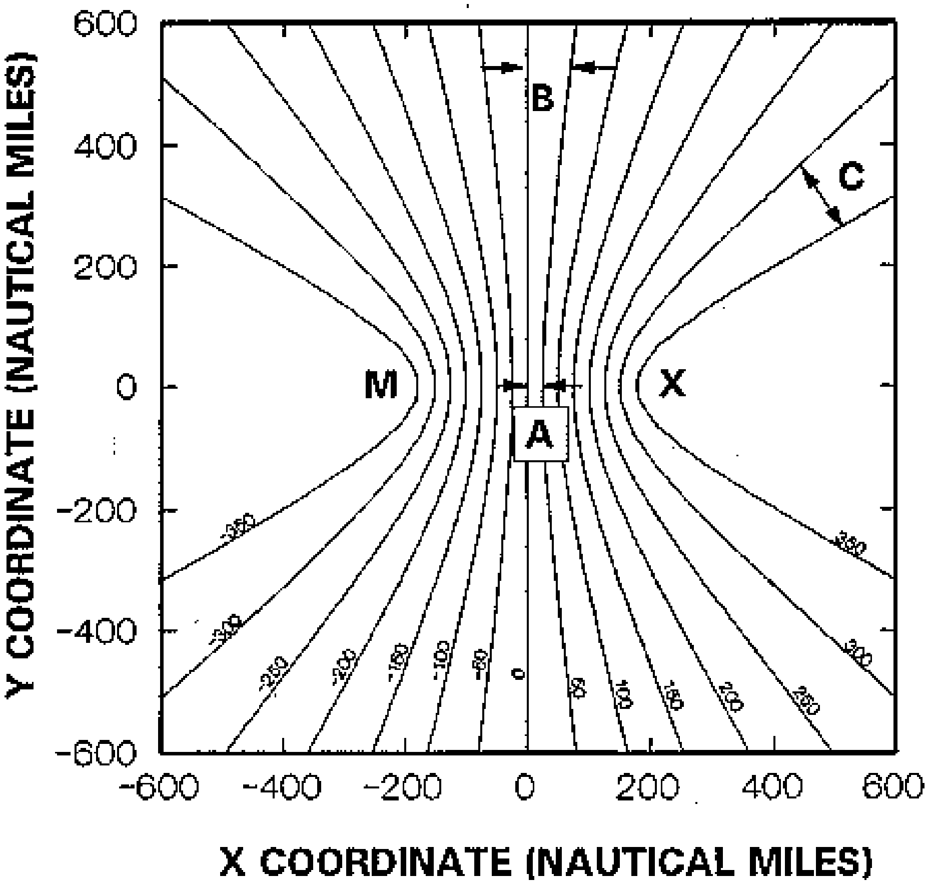

Figure 6.14
Varying Gradients within the LORAN Chain[63]

Note that the time differentials are the same at points A, B, and C, but Point A on the baseline covers the smallest physical distance over the surface of the Earth. Point B is in between, and Point C near the baseline covers the largest distance, or has the largest gradient. Therefore, at Point C, a small change in the LORAN-C reading will result in a larger shift in the location of the corresponding line of position associated with the measured time differential than will occur at Point A. The gradient can be expressed numerically in terms of ft/microsecond or meters/µsec. The gradient is smallest along the baseline and has a constant value of 491.62 ft/µsec (149.85 meters/µsec). Near the baseline extension, the gradient becomes much larger, and it can be shown that if the gradient exceeds 2,000 ft/µsec, the specified absolute accuracy requirements of the LORAN-C system will not be satisfied. Due to the large gradients near the baseline extension, a small measurement error will correspond to a large position error. Therefore,

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[63] Ibid.

a pair of stations should never be used near the baseline extension, and some user sets are programmed to automatically deselect a pair of stations near the baseline extension and choose another pair of stations with more favorable geometric characteristics. There is also the possibility of introducing large position errors by not knowing on which side of the baseline extension the receiver is located since the time differential is symmetrical around the baseline extension.

When testing a LORAN receiver, the automatic deselection of stations with unfavorable geometry due to geometric dilution of precision and due to large position gradients near the baseline extensions should be investigated.

6.4.7.3 FIX AMBIGUITY

Another problem associated with operating near the baseline extension of a pair of stations is the possibility that the lines of position may not yield a unique position fix. Again, looking at figure 6.11, near the master station, M, the line of position labeled "-650" for the Master-Xray pair crosses the second line of position from the Master-Yankee pair in two places - once almost directly west of the Master station and once slightly northeast of the Master station. These two positions on the chart, therefore, have exactly the same time differentials from the two station pairs. In the absence of additional information, a receiver processing these time differentials would not be able to determine which of these positions is correct. This problem is termed fix ambiguity and occurs only in the vicinity of the baseline extension of any master-secondary pair. Some receivers may warn the user with an "ambiguity alarm," and some receivers may automatically track three secondaries to resolve the ambiguity. As previously stated, some receivers will automatically deselect a master-secondary pair near the baseline extension so that an ambiguous fix is not a problem, but a user may be forced to use an less than optimum station pair due to signal-to-noise considerations or other constraints that may be difficult to foresee. The possibility of being in a position where an ambiguous fix is a possibility should be explored in the test planning process.

6.4.7.4 ADDITIONAL SECONDARY FACTORS

In order to accurately compute a range difference based on a time difference measurement, the velocity of propagation of the electromagnetic energy must be known. Since the velocity of propagation is slower in the atmosphere than in free space, this correction is a fundamental modification made to the LORAN calculations. This correction is referred to as the *primary phase factor.* A second correction factor, referred to as the *secondary phase factor,* is applied because the velocity of propagation is further reduced when the wave travels over, and in, seawater as opposed to the atmosphere. When both of these factors are applied, the time differentials are computed as if the energy had traveled entirely over seawater in getting from the transmitter to the receiver. However, this is not always the case, and if it were assumed to be true, the absolute accuracy of the LORAN system would be adversely affected. In the real world, the LORAN signals travel over a variety of paths which include over land with various conductivities and perhaps over seawater. The correction which compensates for the additional factors affecting the velocity of propagation is called the *additional secondary factor* (ASF). Since many things affect the value of ASF, it is the least predictable of the correction factors. The magnitude of the ASF is a function of the conductivity of the earth over which the signal is passing, which in itself is affected by the water content of the soil and the temperature, and the distance which was traveled over land instead of over the seawater. The accuracy to which a receiver can position itself with either time differentials or a direct conversion to latitude and longitude depends a great deal on the value of ASF applied in the propagation model.

The accuracy of the ASF values in a particular receiver may be difficult to measure or test because the corrections are many times applied automatically before the set displays the latitude and longitude or the time differentials to the user. It is also possible for two LORAN receivers to compute the exact same time differentials and to display different latitudes and longitudes because the coordinate conversion program is not standardized, and each manufacturer can use a different software conversion to obtain latitude and longitude from the associated time differentials. In many cases, LORAN receivers designed for use in aircraft do not display time differentials, but display latitude and longitude exclusively. Therefore, the actual testing of ASF may have to be included in the overall accuracy figures of the receiver.

6.5 GLOBAL POSITIONING SYSTEM

6.5.1 BACKGROUND

The idea of satellite navigation really began when Karl F. Gauss (1777-1855) wrote a paper entitled “The Theory of Motion of the Heavenly Bodies” in which he developed a method of using least squares estimators to estimate the orbit of the asteroid Ceres. However, the launch of Sputnik I on October 4, 1957, was the prime mover of the modern concept. While viewing the Earth’s first artificial satellite, physicists at the Applied Physics Laboratory were intrigued by the substantial Doppler shifts that they could measure from the radio frequency signals that were being broadcast by Sputnik. From the measurements made from a single ground station, they were able to predict the parameters of the orbital equations of motion and, hence, the characteristics of the entire orbit of the satellite. By reverse engineering this measurement process, they reasoned that if the orbital parameters of the satellite were precisely known, they could make similar Doppler measurements and determine the position of the receiver.

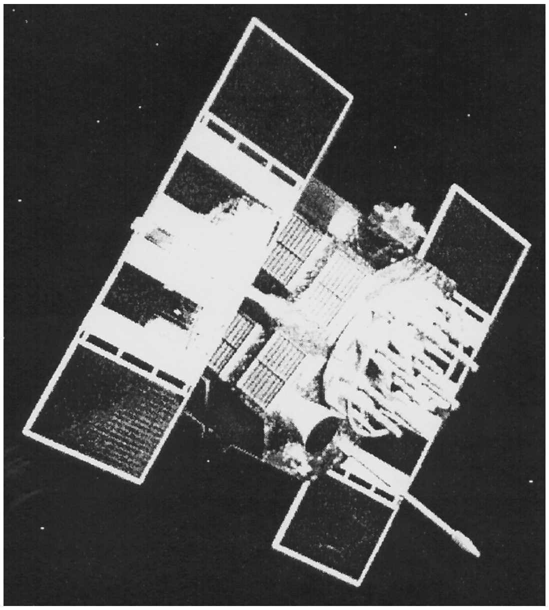
The initial effort for a satellite navigation system in the United States was funded in 1958 to address: the development of the required spacecraft; the modeling of the earth’s gravitational field to the extent necessary to permit accurate determination of the satellite orbits; and the development of the user equipment to obtain the positioning results. The result of this effort was the Transit system which was declared operational in January 1964, and which was then declassified and released for civilian use in July 1967. The Transit system consists of six satellites in circular, polar orbits roughly 580 nmi above the surface with an orbital period of about 107 minutes. The satellites transmit information on two carrier frequencies -- one at 400 MHz and the other at 150 MHz -- to mitigate the effects of the atmosphere on the positioning accuracy of the receiver. Ground stations located in California, Maine, Minnesota, and Hawaii monitor the satellites and record Doppler measurements on each pass of every operational satellite. These data are sent to the Naval Astronautics Group located at Point Mugu, California, which computes new orbital parameters and sends them to each satellite twice a day.

The Transit system works on the principle of Doppler positioning in that the receiver measures the Doppler shift of the signals transmitted by the satellite and then computes a line of position based on the rate at which the range to the satellite is changing and the computed point of closest approach. The advantage of the Transit system is that it provides worldwide availability that is virtually unaffected by local weather. The major disadvantage of the Transit system is that because of the requirement to map the Doppler profile and determine the point of closest approach, it does not provide a continuous fix of position. The time between position fixes varies from about one-half hour to about one and one-half hours depending on the latitude of the receiver. Another disadvantage is that since the basic measurement is Doppler shift, the velocity of the host vehicle interferes with the ultimate positioning accuracy. Therefore, the Transit system has traditionally been restricted to use by slow moving vehicles such as ships at sea, and when thus constrained, has been able to achieve positioning accuracies about 200 meters CEP. The constraints on the use of the Transit system led to the requirement for a new generation of satellite navigation system, and the Navstar global positioning system was developed to provide position accuracies on the order of 15 meters in three dimensions, to provide velocity information on the order of 0.1 meter/second (0.2 kts), to have a high jamming resistance, and to provide positioning information to highly dynamic vehicles such as tactical aircraft.

The global positioning system (GPS) was developed in three phases. Phase 1 was the concept validation phase which took place between 1973 and 1979 during which the “inverted” range was developed at Yuma. The “satellites” were ground stations that transmitted similar code and positioning information that the proposed satellite constellation was destined to use. Phase 2 was the full scale engineering development and system test phase which took place between 1979 and 1985 and used the Block I satellites to provide on orbit transmissions to test the positioning accuracy of the system. Phase 3 is the production and deployment phase that began in 1985 and is still currently in progress during which the Block II and Block IIA satellites are being used as an operational constellation. The initial operational capability (IOC) phase was entered on 9 December 1993, and the U. S. Air Force declared that the Global Positioning System satellite constellation met all the requirements for full operational capability (FOC) on 17 July 1995. FOC marked the successful completion of Department of Defense testing of the 24 Block II satellites in orbit and confirmation of the operational capabilities of the system.

6.5.2 THEORY

The GPS is funded and controlled by the U. S. Department of Defense. While many thousands of civil users enjoy the benefits of its positioning accuracy, the system was designed for and is operated by the U. S. military. It should also be noted that this is not the Global **Navigation** System. The ability to navigate from one place to another is a function of the software program in the particular receiver that an individual, an aircraft, or a sea-going vessel is using and is **not** a function of the GPS satellites or the information being transmitted by the satellites. However, knowing the current **position** of the receiver to a high level of accuracy should enable one to solve the navigation problem very precisely. That bit of soap box rhetoric out of the way, the following brief discussion will focus on the basic elements of the GPS and how these elements combine



to provide the user with precise positioning information. The GPS consists of the same three elements that comprised the Transit system. These elements are the space segment, the control segment, and the user equipment. We will briefly discuss the three segments.

6.5.2.1 SPACE SEGMENT

The space segment consists of 25 satellites as of 15 May 1996. The final constellation is designed to consist of 24 satellites -- there are to be 21 operational satellites plus three active spares in orbit. The vehicles are in placed in six orbital planes inclined 55 degrees to the equator with nominally four satellites per orbit. The orbital planes are spaced at 60 degree intervals around the equator. Orbital height is 10,898 nmi above the surface of the planet which gives the satellites an orbital period of approximately 12 hours. For an observer on the surface of the earth, any particular satellite is above the horizon and useable for navigation for about five hours of its 12 hour orbital period. Depending on the time and location, the number of satellites useable for positioning will vary from a minimum of five to a maximum of about nine.

Figure 1. Block II GPS Satellite

The Block II satellites, shown in Figure 1, are built by Rockwell International, weigh approximately 1860 lb when inserted into orbit, have 78 sq ft of solar panel surface area that generates 720 Watts, and carry four atomic clocks on board. These frequency standards (two cesium atomic clocks and two rubidium atomic clocks) operate as a quadruple redundant system -- when one clock fails, another is switched on to take its place. Three nickel-cadmium batteries store excess electrical power to handle peak power demands and to provide power to the onboard systems during the time the satellite is eclipsed in earth shadow. The internal temperature of the satellite is maintained at about 70 degrees Fahrenheit by seven thermostatically controlled louvers on opposite sides of the satellite, electrical resistance heaters, and thermal insulation. The projected service life of the satellite is 7 1/2 years with a budget for the consumables, primarily hydrazene propellants, of 10 years.

General Electric has been awarded a contract to build 20 replacement satellites that are designated Block IIR. The Block IIR satellites have the capability for 180 day autonomous operation without updates from the ground segment by incorporation of a technique known as cross-link ranging. This technique involves ranging and communication between the Block IIR satellites to estimate and update the parameters of the navigation message.

6.5.2.2 CONTROL SEGMENT

The control segment consists of five unmanned ground tracking stations located at precisely surveyed locations in Hawaii, Kwajalein, Diego Garcia, Ascension Island, and the master control station at Colorado Springs. The monitor stations track all satellites in view, collect ranging and timing data from each satellite, and compare the "positioning" information from the satellites to the actual position of the monitor station. These differences are transmitted to the master control station that processes the complete set of observation data to determine the actual position of each satellite and to compute the errors in the onboard atomic clocks. The new ephemeris and clock data are then uplinked to the satellite periodically which can then use fresh data to reduce the errors in the position fix of the receivers. The ground stations with the capability to uplink information to the satellites are located at Ascension Island, Diego Garcia, and Kwajalein. Figure 2 illustrates the relative locations and communication capabilities of the ground stations.

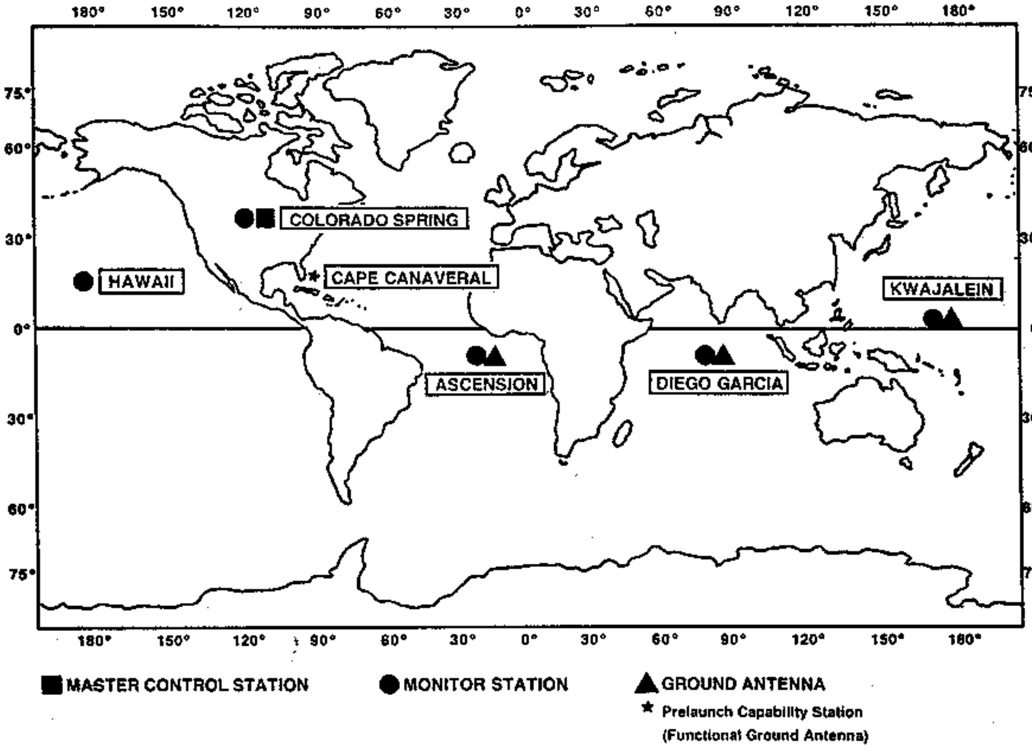


Figure 2. Ground Station Locations

6.5.2.3 USER SEGMENT

The user set architecture may be one of several different types including a single channel sequential receiver, a two channel sequential receiver, or a multiple channel continuous receiver.

A single channel receiver processes the information from a single satellite at a time and obtains the required number of measurements -- typically four -- by sequencing from one satellite to the next satellite. It may accomplish this process with a slow-sequencing routine in which it dwells on a single satellite for one-half to two seconds and then goes on to the next satellite, or it may use a fast-sequencing routine in which it dwells on each satellite for one-two hundredth of a second or less. A slow-sequencing receiver must propagate the sequential measurements to a reference time and then compute the position solution. Any movement of the host vehicle during the measurement process can degrade the final position solution, therefore this type of receiver is normally constrained to stationary or low dynamic vehicle applications. A fast-sequencing receiver essentially collects data from all the satellites being tracked all the time, therefore, the host vehicle can be more dynamic without adversely affecting the solution.

A two channel sequential receiver collects data from two satellites simultaneously and then sequences to the next two satellites much like a single channel receiver does. Since the data collection rate is twice as fast as in a single channel receiver due to the additional hardware channel, the influence of the dynamics of the host vehicle is reduced and this type of receiver is suitable for medium dynamic vehicles such as helicopters.

A continuous receiver requires four (or more) or more hardware channels and tracks several satellites continuously. A fifth channel may be used to read the navigation message of the next satellite selected for inclusion into the solution or it may be used to over specify the existing solution for redundancy. Many receivers employ at least six channels to track all of the satellites in view to minimize problems if a satellite is shielded or blocked by objects such as terrain, trees, or part of the vehicle during a maneuver. A multiple channel continuous receiver has the best anti-jamming performance, does not degrade in a high dynamic environment, and has the lowest time-to-first-fix.

Time-to-first-fix is the time required for a receiver to obtain its first successful position fix after power is applied to the system. With a position uncertainty of 100 km (54 nmi) and a velocity uncertainty of 150 meters/sec (292 kts), a typical multiple channel receiver should obtain a first fix in less than 2 minutes. If the position uncertainties are decreased to less than 10 km (5.4 nmi) and the velocity uncertainty is negligible -- as for a stationary receiver -- the time-to-first-fix should be reduced to less than 1 minute. When a receiver is turned off, it will store the last set of position coordinates and the last set of almanac constants in nonvolatile memory and use these values as initial conditions when the receiver is turned back on. If the almanac is erased or the receiver is moved during the time it is turned off, the time-to-first-fix will increase. Without a stored almanac, the receiver could take as long as 30 to 45 minutes to obtain a position fix.

6.5.2.4 GPS SATELLITE SIGNALS

The GPS satellites transmit positioning information on two basic carrier frequencies -- 1575.42 MHz is referred to as the L1 frequency and 1227.60 MHz is referred to as the L2 frequency. The signals are broadcast in a spread spectrum format. That is, the actual bit rate being broadcast is much higher than the rate at which the data is being broadcast. There are two different spread spectrum functions that provide two levels of positioning service.

The precise positioning service (PPS) is specified to provide 16 meter spherical error probable (SEP) accuracy 50% of the time and 100 nanosecond (one sigma) time transfer accuracy to authorized users. This equates to approximately 30 meter accuracy 95% of the time.

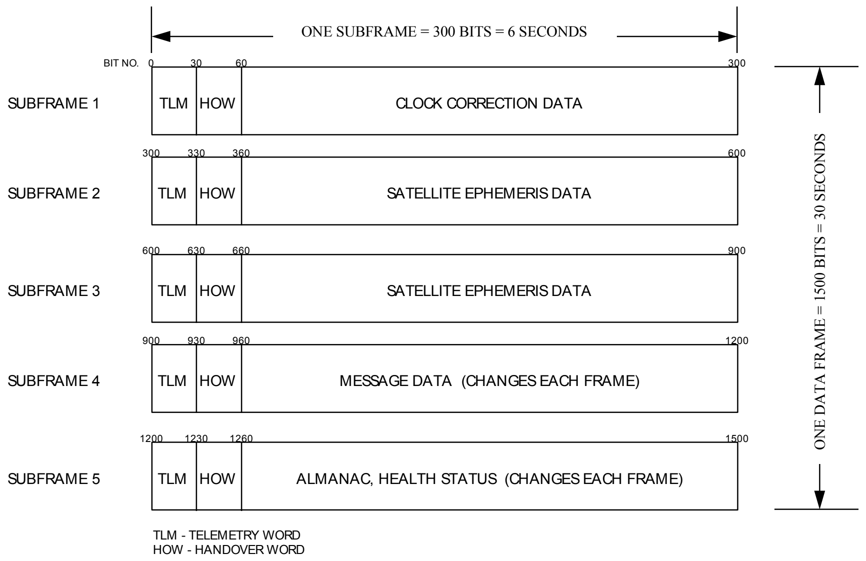
The standard positioning service (SPS) is specified to provide 100 meter horizontal positioning accuracy 95% of the time and 337 nanosecond (95%) time transfer accuracy. The SPS accuracy is deliberately degraded by the application of selective availability (SA) which is the primary SPS error source. The SA position error is created by an extremely low frequency bias with an error distribution that resembles a Gaussian distribution with a long-term mean of zero. The SPS velocity degradation due to SA is classified.

The P code is a linear maximal code that is approximately $2.35 * 10^{14}$ bits long (actually 235,469,592,765,000 bits) which is transmitted at a rate of 10.23 MHz. (More precisely, since this is a spread spectrum code, the bits of code are referred to as "chips" by the spread spectrum people and the code is said to be sent at a chipping rate of 10.23 MHz.) A code of this length being transmitted at that rate takes 266 days 9 hours 45 minutes and approximately 55.499 seconds to complete one entire code sequence. The code is divided into 38 1-week segments and each satellite is assigned a unique 1-week segment of the code. These code sequences are referred to as the pseudo-random number (PRN) sequences. The first 1-week segment of the code is PRN 1, the second 1-week segment is PRN 2, and so forth. A space vehicle is sometimes referred to by which week of the code sequence it is transmitting. For example, Space Vehicle Number 39 may be referred to as "PRN 9" since it has been assigned and is transmitting the ninth 1-week segment of the P code. The satellites restart the code sequence at Saturday/Sunday midnight and normally transmit the P code on both L1 and L2. The P code is protected against unauthorized use and against spoofing by encryption. The encrypted P code is called the Y code and can only be accessed by authorized users that have the appropriate receivers and have the encryption sequence being used by the satellite at that time.

The C/A code is 1023 bits long and is transmitted at a chipping rate of 1.023 MHz and, thus, it takes only one millisecond to complete the entire code. Each satellite is assigned a unique C/A code that is chosen from a set of codes known as "Gold codes." The Gold codes are a compromise between the time it will take a receiver to synchronize to the code, the number of 1's and 0's contained in the code sequence, and the cross-correlation with other Gold codes. These restrictions mean that there are only 30 sequences that can be used by the satellites. The C/A code is normally transmitted on L1 only. These codes are not classified and are made available free of charge to all civilian users. The C/A code is used by P code receivers to reduce the time it requires the receiver to acquire and lock on to the longer P code.

6.5.2.5 THE NAVIGATION MESSAGE

The navigation message is superimposed on both the P code and the C/A code and is transmitted at a rate of 50 data bits per second. The data is formatted into 30-bit words that are grouped into subframes of 10 words that are 300 bits in length and 6 seconds in duration. A frame consists of 5 subframes which is 1500 bits long and 30 seconds in duration. The entire data stream consists of a superframe which is 25 frames long and is 12.5 minutes in duration. Figure 3 depicts the layout of one frame of transmitted GPS data.



Navigation Data Format

TWL 5/29/96

Figure 3

GPS Data Stream

Words 1 and 2 of each subframe are used for timing synchronization and acquisition of the P code. The telemetry word contains a fixed 8-bit synchronization pattern and a message which contains status and diagnostic messages. The handover word contains the “Z-count” which is the number of 1.5 second increments of the P code, or X1 epochs of the P code, since the restart of the P code at the Saturday/Sunday midnight transition. The remainder of subframe 1, words 3 through 10, provide four constants and coefficients necessary for the user set to correct the space vehicle clock to “GPS time,” space vehicle health, and user range accuracy information. Words 3 through 10 of subframes 2 and 3 contain the information necessary to compute the satellites approximate position as a function of time. This information is transmitted as 16 coefficients of a modified Keplerian model of the satellite orbit that accounts for perturbations to the ideal orbit that include nonspherical earth gravitational harmonics, lunar and solar gravitational attractions, solar radiation pressure (which is present except when the satellite is in earth shadow), indirect radiation pressure from the light reflected from the earth’s surface (albedo effect), and atmospheric drag. The parameters for this model are changed frequently to give an accurate fit of the satellite orbit. In normal operations, a set of coefficients is used for 4 hours.

Subframes 1, 2, and 3 have the same format in each frame, but subframes 4 and 5 have contain 25 different sets of data which are cycled through one frame at a time. In other words, it takes 25 frames or 12.5 minutes to observe all of the data in subframes 4 and 5, but it takes only one frame or 30 seconds to observe the data in subframes 1, 2, and 3. Subframe 4 contains almanac, clock correction, and health status data for satellites

25 through 32 (if there happens to be that many satellites in the constellation), ionospheric modeling coefficients, and UTC - GPS clock correction data. Subframe 5 contains almanac, clock correction, and health status data for satellites 1 through 24 which is cycled through at a rate of one satellite per frame (30 seconds).

The almanac and clock correction data transmitted in subframes 4 and 5 are much less accurate than the detailed ephemeris data transmitted in subframes 2 and 3. This data consists of eight coefficients (vice 16 coefficients) for the Keplerian model of the orbit and two coefficients (vice four coefficients) for the clock correction algorithm. Although it is a truncated, reduced precision set of data, it is used to aid the receiver in satellite selection and gives approximate Doppler and delay information to aid in the acquisition and tracking of the satellite signal. This data set is valid for a much longer period of time than is the more precise data transmitted in subframes 2 and 3, and may be used for up to 1 week without catastrophic degradation of accuracy. When there is no satellite spaceborne to fill an almanac data slot, the same satellite almanac data may be repeated in more than one page, or a dummy set of alternating ones and zeros may be transmitted to aid in synchronization.

The subframes, frames and superframes are all synchronous with the X1 epochs of the P code. Recall that the portion of the P code used by each satellite begins or resets at Saturday/Sunday midnight. A superframe also begins at the beginning of the week as do subframes. Each subframe is numbered consecutively from the beginning of the week to aid in the C/A code to P code transition or handover. Since each data bit is transmitted at a specific time from the beginning of each numbered subframe (one-fiftieth of a second), the time of transmission of each data bit can be calculated. Also, since the P code clock is used as the method of synchronization, the time of transmission of any one chip of the 10.23 MHz P code can be computed. The C/A code was designed to also be synchronized with the P code so that the time of transmission of any one of the 1.023 MHz C/A code chips could be calculated, but this synchronization is “jittered” by selective availability so that the time of transmission of the C/A code chips, and hence the data bits decoded by a C/A code receiver can only be approximated, thus reducing the accuracy of the position fix.

Each 30-bit word contains six parity bits that allow the receiver to check for errors in the received data stream. Even though the digital data stream is normally received with a very low error probability of having a bit error, it is important to have a parity check algorithm to detect and reject any data words with errors in them. The GPS parity check code is an extended Hamming code with a distance of four. This means that it would take certain patterns of four errors to cause an undetectable error. If the probability of any particular bit being in error is moderately low, then with the GPS parity check code, the probability of an undetected error causing the receiver to use incorrect positioning data is negligible.

6.5.2.6 HOW DOES IT WORK?

The basic calculations of the GPS are performed in an Earth-Centered, Earth-Fixed XYZ (ECEF XYZ) coordinate system. This coordinate system is defined as having its origin at the center of the Earth, the x-axis intersect the Equator at the Prime Meridian, the z-axis intersect the North Pole at the earth’s spin axis, and the y-axis intersect the equator at the appropriate longitude to complete a right-hand coordinate system. Thus, every position can be defined by the (x, y, z) coordinates in the reference system. The satellites are constantly transmitting the navigation data stream that contains satellite position information at precisely known times, and the receiver with its own internal clock can measure the time of arrival of the satellite signal. The range to the satellite can then be computed:

$$R = c*(t_{rec} - t_{xmt})$$

where: R is the range to the satellite
c is the assumed velocity of propagation
t_{rec} is the time of signal reception
t_{xmt} is the time of signal transmit

In ECEF XYZ coordinates, this becomes:

$$R_1 = [(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2]^{1/2} = c*(t_{rec1} - t_{xmt1})$$

where: R_1 is the range to satellite number 1
x_1, y_1, z_1 are the coordinates of satellite number 1
x_u, y_u, z_u are the coordinates of the receiver

However, since we need to find x, y, and z, we have three unknowns, so we need three equations. We do this by ranging on two more satellites. So:

$$R_2 = [(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2]^{1/2} = c*(t_{rec2} - t_{xmt2})$$

$$R_3 = [(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2]^{1/2} = c*(t_{rec3} - t_{xmt3})$$

This set of equations would give us three intersecting spheres, which should define our position. It is assumed that the satellite clocks are synchronized with each other and are keeping correct time since each vehicle has four atomic clocks on board. However, the receiver generally does not have as accurate a clock due to weight and expense constraints. The receiver clock could conceivably (and probably does) have a time offset from satellite time, or a Δ t, so the previous equations should be modified to:

$$R_1 = [(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2]^{1/2} = c*(t_{rec1} - t_{xmt1} + \Delta t)$$

$$R_2 = [(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2]^{1/2} = c*(t_{rec2} - t_{xmt2} + \Delta t)$$

$$R_3 = [(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2]^{1/2} = c*(t_{rec3} - t_{xmt3} + \Delta t)$$

We can simply treat the receiver clock offset as another unknown, so in order to solve for four unknowns (x, y, z, and Δ t), we need a fourth equation. So by ranging to a fourth satellite, we get:

$$R_4 = [(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2]^{1/2} = c*(t_{rec4} - t_{xmt4} + \Delta t)$$

The receiver can now solve for its position in three dimensions and for the time offset in its internal clock.

The process of computing the position of the receiver in ECEF XYZ is predisposed to many errors. For example, the position of the satellite is given as a function of time by the ephemerides in the navigation message and must be converted to an XYZ position by the receiver. The ionosphere affects both the path and the velocity of the energy between the satellite and the receiver, and since the basic measurement is pseudorange, these effects must either be measured of modeled to yield the correct answer. The receiver must be correctly tracking the satellite signal -- a measurement inaccuracy will result if there are any tracking inaccuracies due to the Doppler shift of the signals being received from the satellite, which affects the transmitted carrier frequency as well as the P code and C/A code chipping frequencies. The rotation of the earth must be taken into account during the time the signal leaves the satellite and the time it reaches the receiver. And any dynamics of the host vehicle have the capacity to corrupt the final measurement. The result is that there will be a measurement error that will be receiver dependent which is usually called the user equivalent range error (UERE). How well any particular receiver handles the computational load and uncertainties is dependent on the software program in that particular receiver. The caution here is that if accurate positioning results are obtained with one GPS receiver, those results should not be extrapolated to other receivers with different computational software loads on board.

In addition to the measurement error in the receiver, another factor affects the positioning accuracy of the system. This factor is the dilution of precision (DOP) which is a measurement of the capability of the satellite constellation to yield an accurate solution. This factor is essentially a measure of how the lines of position, or spheres of position in the case of GPS, intersect to yield a specific position solution and is used as a multiplier of the user range error to determine total system accuracy. In other words, the position error in the receiver can be described as:

$$PA = DOP * UERE$$

where: PA is the positioning accuracy

The magnitude of DOP will change as a function of time since the satellites are constantly in motion in their orbits, and it will change as a function of position since the satellite configuration will be different at every point on the surface of the earth. One of the goals of the receiver software should be to select the satellites that will minimize the value of DOP at all times. However, there are many varieties of DOP depending on what particular coordinates are most important to the user. There are values for:

PDOP which is the accuracy of position in three dimensions
HDOP which is the accuracy is the horizontal (two dimensions)
VDOP which is the accuracy in the vertical dimension
TDOP which is the accuracy in determining time
GDOP which is usually the total geometrical accuracy in 3D position and time

As the satellite geometry continually changes and satellites rise above the horizon and others fall below the horizon, the receiver should continually reassess the strength of the constellation and the value of the DOP for the satellites that it is using and determine whether a different set of satellites should be used or if the current set is still the best choice for computing the position of the receiver in ECEF XYZ. This assessment is normally done every few minutes.

Rather than display the position in ECEF XYZ coordinates to the user, the receiver performs another internal computation to convert the computed position to latitude and longitude. In order to do this, it must have an internal model of how the earth “fits” into the ECEF XYZ coordinate system. There are many earth models or datum planes in use in all parts of the world. Over a period of time, specific areas have been surveyed and fitted as accurately as possible to oblate spheroids which represent the shape of the earth.

The resultant maps can be quite accurate over the area for which they were constructed, but the fit at distant locations may not be particularly snug. For this reason, a global approach had to be taken for the global positioning system, and a datum plane had to be chosen that that models the entire earth with reasonable precision. This approach results in the accuracy of the contour being less that ideal in any particular region , but the accuracy is acceptable anywhere on the surface of the earth. The World Geodetic System of 1984 (WGS-84) is an example of a global datum plane that exhibits excellent worldwide characteristics, and, therefore, has been chosen as the standard coordinate system for the Global Positioning System, and most GPS receivers will default to WGS-84 when displaying latitude and longitude Many receivers have the constants and coefficients in memory to convert the ECEF XYZ position coordinates to other map datum planes, and these maps are generally selectable by the user. Care should be taken to ensure that if the coordinates of a point need to be precisely located that the coordinate system of the chart used to determine the latitude and longitude of that point is the same coordinate system being "read out" by the GPS receiver. Errors of hundreds of meters may be induced by measuring in one coordinate system and navigating in another coordinate system. Many of the charts currently being published by the National Oceanic and Atmospheric Administration division of the U. S. Department of Commerce for military aviation use the North American Datum of 1983 (NAD-83) as a horizontal mapping reference. The NAD-83 coordinates should not differ from WGS-84 by more than 5 meters in the horizontal, but more severe errors may occur in the vertical.

6.5.3 DIFFERENTIAL GPS (DGPS)

The U. S. Coast Guard is mandated by federal law to implement, maintain, and operate electronic aids to navigation that meet the needs of the U. S. Armed Forces, maritime commerce, and air commerce. The Coast Guard's history of operating and maintaining electronic navigation aids covers seven decades of service providing operational radiobeacons, Loran-A, Loran-C, and Omega services. As a natural outgrowth of this service, when the Department of Defense requested that the Department of Transportation assume the lead in developing a civil GPS system, the Coast Guard was assigned as the lead agency in February, 1989. The Coast Guard was searching for a system that would provide the capability to meet the accuracy requirements of the Federal Radionavigation Plan for Harbor/Harbor Approach (HHA) navigation of 8 to 20 meters (2 drms) with a signal availability exceeding 99.7%. The Coast Guard concluded that the GPS military user's precise positioning service accuracy was 21 meters (2 drms) which was short of the HHA requirement. Building on the technology gained by applying differential techniques to enhance the accuracy of Loran-C and Omega, the decision was made to apply these techniques to the C/A code GPS signal which showed great promise to meet the strict accuracy requirements required for harbor navigation and would be available to civil users who do not have access to the protected military code.

Very basically, the differential process requires installing GPS receiving equipment at a precisely surveyed location. The equipment receives the signals from all of the satellites in view, computes a position solution from these signals, and compares that solution to its precisely known location. As a result of this comparison, correction data can be computed which can then be provided to local users through an independent data link. The correction data is then applied by the user's receiving equipment to reduce the system position error and improve the absolute accuracy.

In 1987, the Coast Guard Research and Development Center demonstrated that differential corrections broadcast to local users improved GPS C/A code positioning to a predictable accuracy of 10 meters (2 drms) inside the coverage area of the correction broadcast. In 1989, the Coast Guard modified the existing marine radiobeacon located at Montauk Point, New York, to broadcast differential corrections. These field tests demonstrated that the differential corrections could be modulated on the existing radiobeacon carrier with no adverse effect on the automatic direction finding receivers of traditional marine radiobeacon users. The format of the transmissions was a standard differential GPS format that had been developed by the Radio Technical Commission for Maritime Services Special Committee 104 (RTCM SC-104). Important to both the Coast Guard and to the public, this format is economical to implement both at existing radiobeacons and within user receiving equipment. Montauk Point began the first continuous broadcast of DGPS corrections on August 15, 1990. Three more prototype DGPS broadcast sites were installed at existing radiobeacons, and, with the Montauk Point site, provided nearly continuous coverage of the Northeast coast of the United States by June, 1992.

After successfully demonstrating that DGPS had the capability to meet the accuracy requirements for HHA navigation, the Coast Guard turned its attention to the second area of concern - the recognized shortfall of GPS with regards to system integrity. The monitor and control segment design of the GPS can allow a satellite to transmit erroneous positioning information for six hours before it is corrected or before users are notified of the error. This would fail the requirement for 99.7% signal availability and could lead to catastrophic loss due to a shipping navigation error while traversing harbor areas. To put this stringent requirement in perspective, the Coast Guard position is that the risk and penalties associated with a large hazardous product tanker transiting New York harbor and a modern passenger airliner approaching Kennedy Airport are of similar magnitude.

The signal availability problem was solved by colocating an integrity monitor with the DGPS station. The Integrity Monitor consists of a radiobeacon receiver and a precisely located GPS receiver capable of applying differential corrections to the position solution. The corrected GPS position can be compared to the precisely known position to determine if the correction broadcast is in tolerance. If the Protection Limit is exceeded, the local users are notified within a maximum allowable time to alarm of 10 seconds.

DGPS user equipment then must consist of two interfaced receivers: a radiobeacon receiver capable of demodulating the correction signal and a GPS receiver capable of applying differential corrections to the position solution.

After extensive computer simulation of signal strength and coverage scenarios, the Coast Guard determined that 50 radiobeacon sites would provide sufficient DGPS coverage for the United States. One remaining problem to be overcome was that the radiobeacon had evolved over its 70 year life span from a primary radionavigation aid to its present status as a tertiary aid. Therefore fiscal support had to reoriented to place the radiobeacon back in a place of prominence in the budgeting process. Also of the 50 proposed sites for DGPS transmitters, one-third were not existing marine radiobeacons and had to be installed as new installations. The budgetary constraints resolved, the Coast Guard entered the Initial Operational Capability phase on 30 January 1996.

GPS correction data is based on the NAD-83 coordinate system and is broadcast for all satellites at an elevation angle higher than 7.5 degrees above the horizon relative to the differential station. Satellites at lower elevation angles are subject to the problems of adverse atmospheric delays and multipath interference. Because of restrictions in the RTCM SC-104 message format and the requirement to keep the transmitted data as current as possible, correction data for a maximum of nine satellites can be broadcast. If more than nine satellites are above the 7.5 degree limit, the differential station will broadcast correction data for the nine satellites with the highest elevation angles. With a full constellation of 24 satellites, more than nine satellites meet the elevation criteria less than one percent of the time; however, if the constellation consists of more than 24 satellites, this percentage will increase. Differential GPS coverage of the continental United States (CONUS), Alaska, and Hawaii as of November 1996 is shown in figure 4.

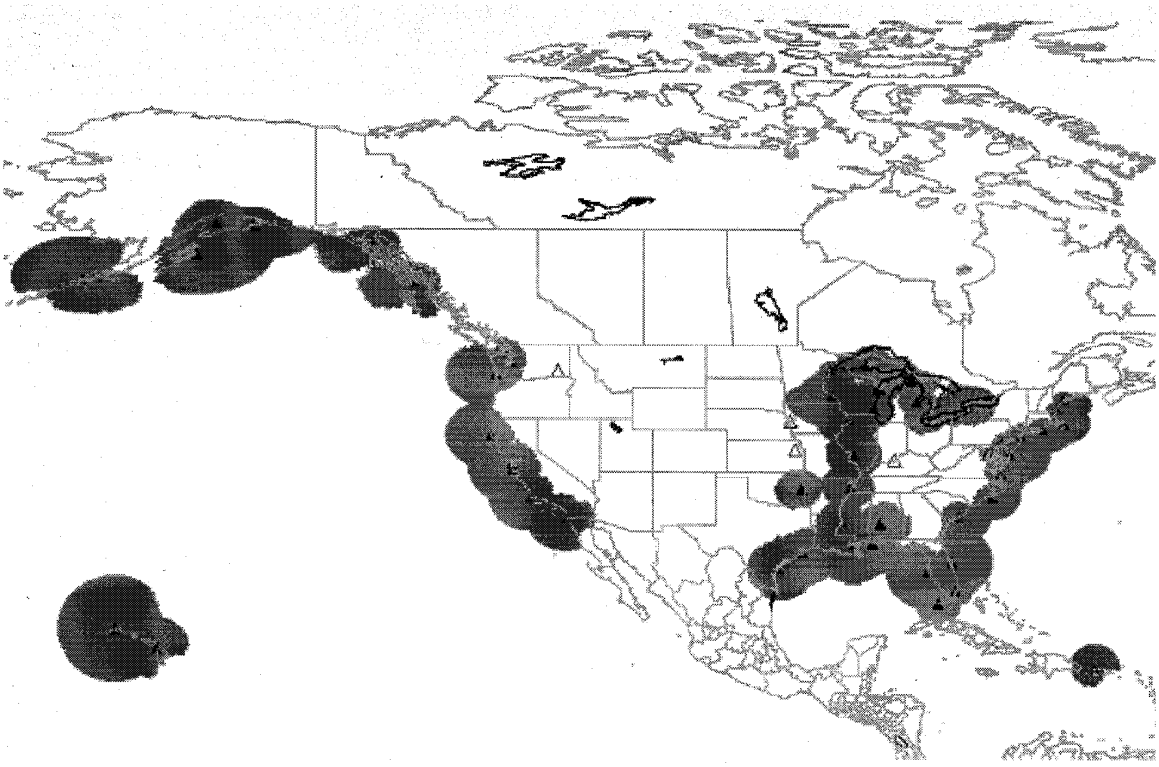


Figure 4

CONUS, Alaska, Hawaii DGPS Coverage

6.5.4 PREFLIGHT/INITIALIZATION

6.5.4.1 BACKGROUND

The preflight and initialization procedures for a GPS receiver and navigation system must enable the operator to ensure system preparation and start-up in a timely, accurate, and concise manner.

6.5.4.2 PURPOSE

To evaluate the preflight and initialization procedures of the GPS receiver and navigation system under test.

6.5.4.3 THEORY

The preflight and initialization procedures for a system are major areas that allow examination of the operating status of a system. In a navigation system, an accurate initialization minimizes the error budget with which a system must enter operation. The number of steps, complexity, time required, and mission utility directly impact on the operator's ability to adequately preflight this specific system, as well as the weapon system as a whole.

6.5.4.4 METHOD

Manufacturer and/or U.S. Navy publications should be followed to examine their interoperability with the GPS system under test. The tester should time the preflight and initialization procedures (P & I) both as a whole and for individual portions. System response to inputs and indications as to status should be examined. The location and accessibility of controls should be reviewed. Many of the cockpit evaluation questions should be re-examined with respect to the GPS system. Built-in-Test operation should be reviewed as to when it occurs, what type of readouts, and whether faults are displayed as they are detected or after the test is complete. Additionally, does the test stop at a fault and must it be stepped through (a major preflight time consideration)? What provisions are made for un-installed, optional, or improper modes of peripheral equipment? If no faults are observed how can testing be performed to examine the system under a fault condition (pre-faulted module insertion)? There are many qualitative and quantitative points to be examined in the P & I portion of testing. These should include:

- thoroughness
- logical sequencing
- clarity
- time-to-first-fix under different ambient temperatures

6.5.4.5 DATA REQUIRED

- Time to preflight
- Equipment location
- Display condition under various lighting conditions
- Fault indications
- Power (type and source) requirements
- Qualitative views
- System serial number(s)
- Ambient Temperature
- Time-to-First-Fix
- Geometric Dilution Of Precision (GDOP) (if available)

6.5.4.6 DATA ANALYSIS

Average time to complete the checklist and the initialization. Operator dedicated time and mission relation to other preflight times. Mission relation of P & I, fault indications, fault effects on system operation/accuracy.

6.5.4.7 SAFETY

- No fault insertion without proper authorization
- The checklist will be halted at faults until proper technical investigation indicates that it is safe to proceed.

6.5.4.8 ERROR ANALYSIS

Confidence levels for timed tests will be from the specification. Sampling size has a direct impact on the confidence level.

6.5.5 POSITION ACCURACY

6.5.5.1 BACKGROUND

The ability of a GPS system to provide accurate positioning is essential, especially when the aircraft must transit to meet specific ADIZ entry points and battle group entry/exit coordinates. The GPS must provide accurate position data for turnovers between units and for over-the-horizon targeting. The system must be accurate enough to allow cross checks with other navigation systems.

6.5.5.2 PURPOSE

The purpose of this test is to evaluate the position accuracy of the GPS system.

6.5.5.3 METHOD

The usual method of flying from point-to-point over surveyed landmarks at altitudes between 500 and 1000 feet AGL will not be precise enough to determine the position accuracy of a GPS receiver. The system will need to be flown on a range with a laser tracking station or other highly accurate tracking device providing time, space, position information (TSPI) for post-flight processing. Data points will include TSPI and system latitude/longitude/altitude, time, GPS system under test advisories or warnings, GDOP (if available) and remarks. If possible, flights should be planned at various times to allow investigation of geometric dilution of precision with various satellite geometry configurations, multipath error, and atmospheric noise. If the GPS test flight is not combined with INS testing, aircraft maneuvers in excess of 1 g, within airframe limits, is allowed.

6.5.5.4 DATA REQUIRED

- Time (Zulu)
- Position - TSPI and GPS
- Heading/Airspeed
- Number of GPS satellites being observed
- GPS signal quality (GDOP - if available)
- System status (warnings/cautions)

6.5.5.5 DATA REDUCTION

Position errors in latitude and longitude should be computed and converted to errors in units of meters using the techniques discussed in the section on inertial navigation data reduction. Position error data should be further reduced to provide a circular error probable (CEP) figure and a spherical error probable (SEP). CEP is defined as the 50th percentile value of the horizontal (radial) position error population and SEP is defined as the 50th percentile value of the three dimensional position error population. In addition to CEP and SEP, for comparison to other GPS test results, a commonly used parameter is to compute the RMS value of the individual errors and double this distance. This value is called the 2drms value and is purported to contain 95% of the data points. These methods are desirable because of their robustness under various test conditions and because an efficient estimate of its value (in the statistical sense) can be attained with a modest quantity of test data.

6.5.5.6 DATA ACCURACY/ERROR ANALYSIS

Test data is assumed accurate, however several error sources can combine to create a worst case error. Sources of error include the difference in position on the aircraft between the laser reflector and the GPS receiving antenna, time offsets in recording data, display accuracy, on-board data recording accuracy, and TSPI data accuracy.

6.5.5.7 CONFIDENCE LEVEL

The discussion of data confidence levels that were discussed in the Inertial Navigation System Evaluation section of this document also applies here.

6.5.6 GPS POSITION ERROR SOURCES

6.5.6.1 BACKGROUND

All navigation systems are subject to error, with GPS being no exception. The GPS is susceptible to errors introduced by satellite clock errors, by satellite ephemeris errors, by the geometry of the receiver within the constellation of satellites (GDOP), by assuming or modeling the path and the velocity of propagation of the electromagnetic signal through the ionosphere and troposphere (C/A code), by multipath effects, by the physical characteristics of the earth, by signal processing errors in the GPS receiver due to noise in the code tracking and carrier tracking loops, and by the effects of selective availability.

6.5.6.2 PURPOSE

The purpose of these evaluations will be to examine the GPS navigation systems error sources and to provide an overview of the common error sources that should be investigated during the testing process.

6.5.7 GPS ERROR SOURCES

6.5.7.1 CLOCK BIAS ERRORS

The accuracy of the GPS as a positioning tool – or for that matter, any navigation system -- is inherently connected to the ability to measure time very precisely. GPS satellites time tag their individually coded messages when they are broadcast, and the receiver measures the precise time of that messages reception. Using the computed time it took for the message to travel from the satellite to the receiver and the assumed velocity of propagation, the receiver computes a range to the satellite, yielding a "sphere of position." Using three intersecting spheres of position will result in an ambiguous, but solvable position fix. Any error in the receiver clock can be computed and corrected by the reception of a fourth satellite signal essentially treating the receiver clock bias as an unknown, and then solving four equations for the four unknowns. This process still assumes that the satellite clocks are all perfect and do not drift from standard GPS time. GPS satellites carry two rubidium and two cesium frequency standards to attempt to insure that the time tagging of messages is accurate. Even though the space environment is relatively kind to atomic clocks, they are not perfect and will drift over a period of time. There is no attempt to “reset” the clocks, but the drift is monitored and is accounted for in the navigation message in the form of a reference time and three coefficients to a second order polynomial:

$$dt = a_0 + a_1 * (t - t_0) + a_2 * (t - t_0)$$

where t is the current time, t_0 is the reference time, a_0 is the time offset, a_1 is the rate of clock drift, and a_2 is the rate of change of the clock drift.

This correction will account for the predictable and steady state errors in the satellite clock, but it will not account for the transient variations caused primarily by temperature changes and to a lesser degree by the effects of the earth’s magnetic field on the clock. It will also not account for the fact that the satellite may be transmitting “stale” clock correction data. Since the speed of light is approximately one foot every one-billionth of a second, a satellite clock error of one-billionth of a second will result in a positioning error of about one foot. The predicted value of receiver ranging error due to the satellite clock error is approximately 3.0 meters.

6.5.7.2 EPHEMERIS ERRORS

To compute its position, a GPS receiver must know the satellites position in space. The information for the satellite position is passed to the receiver as part of the navigation message the form of 16 coefficients to a standard set of orbital mechanics equations formulated by Keppler. These coefficients and equations are functions of time, therefore, to know the satellite position in space at the moment the decoded message was transmitted, the receiver must solve this complex set of equations. Any errors in the coefficients being transmitted due to a “stale” set of ephemerides or in the position computations - for instance, round off error - will result in an incorrect knowledge of the satellite position. In order to keep the signal short enough to be transmitted and received in a reasonable amount of time, the coefficients are limited to approximately five meter accuracy. Any error in the computed position of a satellite will be transferred directly to a position error on the ground. That is, if a 1 meter error exists in the computation of the satellite position in space, the result will be a 1 meter error in position on the ground. The overall average predicted value of receiver ranging error due to uncertainties in the satellite position is approximately 2.6 meters

6.5.7.3 GEOMETRIC DILUTION OF PRECISION

A significant source of error in a GPS system is the loss of precision resulting from the spheres of position crossing at oblique angles due to a less than ideal arrangement of the satellites being used by the receiver for the position fix. Because of the uncertainties in the measurement process, hence, the uncertainty in, or “width” of the sphere (or line) of position, the greatest precision in any position fixing system is obtained when the lines of position cross at right angles. Examples of the position uncertainty that might result when the lines of position cross at right angles and when they cross at a more oblique angle are given in figure 4.13 in the section on LORAN . The width of the lines in each case represents the uncertainty in the measurement process and is equal in both cases, but the position uncertainty represented by the shaded area is much larger when the lines of position cross at 30 degrees than when they cross at 90 degrees. This uncertainty effect due to the geometry of the receiver with respect to the transmitters is known as geometric dilution of precision (GDOP). The GDOP factor is multiplied by the receiver uncertainty in position to yield a total position error. For example, if a receiver had a nominal position error of 8.7 meters and was operating in an area with a GDOP of 2.3, the total expected error in position would be 8.7 * 2.3 or 20.0 meters. The global time average for GDOP with a 24 satellite constellation is about 2.3 according to Logsdon. If the GDOP exceeds 6.0, there is said to be a satellite outage in which the system is no longer useable.

There are five types of DOP in popular use. The most inclusive is GDOP which relates to the error multiplier in the three orthogonal position axes plus time. Position Dilution of Precision (PDOP) relates only to the uncertainty in the three position coordinates. PDOP may be of interest to airborne users who need to navigate in three dimensions, but are not inordinately concerned with time. Horizontal Dilution of Precision (HDOP) relates only to the two orthogonal position errors in the horizontal plane. HDOP may be of interest to mariners or to land based vehicles who are not concerned with computing altitude. Vertical Dilution of Precision (VDOP) relates to the error in the vertical or altitude component. VDOP may be of interest to an airplane pilot who is attempting to execute a precision approach to an airfield. Time Dilution of Precision (TDOP) is concerned with the errors concerned with accurate time transfer. TDOP may be of interest to a group of scientists attempting to synchronize two or more very accurate timing devices such as atomic clocks. The satellites which result in the minimum value of the DOP of primary interest to a particular user may not be the same as the satellites which yield a minimum value of a different DOP to another user who may be co-located with the first receiver. The selection of the satellites being used by a receiver should be updated about once per minute to ensure that the currently selected set of satellites provide the minimum dilution of precision for the specific application being performed by the receiver.

6.5.7.4 IONOSPHERIC PROPAGATION ERRORS

The ionosphere is generally considered to be that portion of the atmosphere that has had some of the resident molecules ionized by the ultraviolet radiation from the sun releasing free electrons. The ionosphere extends from approximately 30 nmi to maybe 250 nmi or more above the surface of the earth. GPS signals, like any other electromagnetic wave propagating through the ionosphere, have the speed and direction of the wave altered by the ionosphere in proportion to the number of free electrons resident at the time. The ion content is a function of the time of day, local latitude, sunspot activity, solar cycles, season, and other factors and can fluctuate considerably. The effect on the ranging accuracy of a GPS receiver may be as little as 5 meters or so to up to a maximum worst case error of more than 150 meters. Since the effects of the ionosphere are frequency dependent, the P-code users can accurately estimate the effects by receiving two frequencies (the L1 and L2) that are broadcast from each satellite. The dual frequency correction removes all but about 1 meter of error for a well calibrated receiver. C/A code receivers, on the other hand, have only the L1 frequency with which to work, and must therefore rely on an internal diurnal model to correct for the ionospheric delays. Parameters for these models can be obtained from information contained in the GPS message, but the correction is still an approximation rather than a measurement. Residual errors from these ionospheric models are estimated to be on the order of 5 to 10 meters on the average. During excursions in the free electron content of the ionosphere or while using satellites at low elevation angels near the horizon for which the signal has more of its path in the ionosphere, the values may be much higher. However, these models are becoming more accurate as they gain maturity.

6.5.7.5 TROPOSPHERIC PROPAGATION ERRORS

The troposphere is that portion of the atmosphere closest to the surface in which temperature changes rapidly with altitude, weather patterns are formed, and convection is active. The troposphere is generally considered to extend from the surface to approximately 10 miles or so. This portion of the atmosphere is the cause of yet another deviation from the velocity of propagation of the GPS signals in the vacuum of space. To be more precise, for GPS purposes, the "troposphere" usually refers to the effects of the atmosphere below the ionosphere which includes the neutral atmosphere up to about 30 or 40 miles above the surface. Variations in temperature, pressure, and humidity all contribute to the variation in the velocity of propagation of the radio waves in this part of the atmosphere. Unfortunately, the effects of the troposphere are not as predictably frequency dependent as are the effects of the ionosphere, and these effects can also vary widely with small changes in position or small differences in time. For example, significant changes in the water vapor content can occur over a few miles or in a few hours, and temperature inversion layers can occur at different altitudes depending on latitude, season, or time of day. Despite the difficulties, models have been developed that attempt to compensate for the effects of the troposphere on the pseudorange measurement. For precise applications, these models may require real-time meteorological data, but for most users and application, a simpler model should reduce the measurement error to about 1.0 meter.

6.5.7.6 MULTIPATH

Multipath is the phenomenon by which a signal arrives at the receiving antenna by two or more distinct paths. The multiple paths are generally due to the signal being reflected from objects such as buildings or other vehicles around the antenna, but in the case of aircraft may be from nearby reflectors such as other parts the aircraft or from distant reflectors such as the surface of the ocean or other large bodies of water. The difference in path lengths will cause the signals to arrive at slightly different times and may cause interference in the receiver which will mask the true correlation peak and cause a pseudorange measurement error. Digitally encoded signals such as GPS messages have an inherent ability to discriminate against some forms of multipath due to the chip length to which the receiver is synchronized. Any signal which arrives outside the chip length window can be easily rejected, however, an interfering signal with a short delay that arrives within the window may cause problems. The most effective means of minimizing the degradation due to multipath is through antenna beam shaping to discriminate against signals arriving from different directions and to use special care to position the antenna to avoid the possibility of reflection from nearby objects. With proper siting and antenna selection, Parkinson states that the net error to a moving user should be less than one meter, but Logsdon states a more pessimistic 12 meters for C/A code users and 1.2 meters for P code users.

6.5.7.7 RECEIVER ERRORS

Early generation GPS receivers were constructed with a single or perhaps two channels sequentially processing the required data from four or more satellites. This mechanization led to significant errors in positioning especially for vehicles in highly dynamic environments. As the size and cost of modern computer chips continues to shrink, most modern receivers have at least four and perhaps as many as eight channels processing satellite data at the same time which significantly reduces the errors associated with the receiver itself. In fact, most modern receivers use a reconstructed carrier to aid the code tracking loops which reduces errors even further. Early receiver designs were also plagued by the limited precision of the software that could run in the 8-bit microprocessors which were available. This problem has also been overcome by modern microprocessor technology which provide the required precision and calculation speeds to minimize the effects of the receiver dynamics. The net result is that a modern GPS receiver should contribute no more than about 0.5 meter error in the position uncertainty.

6.5.7.8 SELECTIVE AVAILABILITY

The accuracy of the Standard Positioning Service using the C/A code proved to be better than the Department of Defense thought it might be, so to prevent unauthorized users from obtaining too much accuracy, a feature known as selective availability (SA) was incorporated into the Block II satellites. This innovation deliberately degrades the position accuracy obtainable with the SPS by injecting timing errors in the satellite transmission sequence and/or by transmitting erroneous satellite ephemeris information in the navigation message. The policy of the DoD for C/A code accuracy as stated in the 1992 Federal Radionavigation Plan is that "SPS is planned to provide, on a daily basis, the capability to obtain horizontal positioning accuracy within 100 meters (2 drms, 95 percent probability) and 300 meters (99.99 percent probability), vertical positioning accuracy within 140 meters (95 percent probability), and timing accuracy within 340 ns (95 percent probability)." It should be noted that no information is provided on the dynamics of the errors, i.e. the values of the velocity and acceleration errors that are induced in a receiver are not stated. This policy also assumes that at least 21 satellites are available, therefore, the errors could possibly be larger than stated if multiple satellites fail and fewer than 21 are available in the constellation. Although the precise characteristics of the selective availability algorithm are difficult to determine, measurements conducted by various investigators have determined that it is generally a low frequency oscillation with a period of perhaps several minutes having a mean of zero and a standard deviation of 30 to 40 meters. SA is generated in each satellite and appears to be uncorrelated between satellites, which means that the effect on position accuracy will depend on the satellite geometry. However, it is certain that selective availability is by far the largest error component in the SPS positioning error budget.

6.5.7.9 ERROR BUDGET

Based on the above discussion, the error sources and the magnitude of the errors from these sources can be summarized in Table 1.

Table 1
Global Positioning System Error Budget

Error Source	**Predicted Error (meters)**		
	PPS	**SPS**	**DGPS**
Satellite Clock Error	3.0	3.0	0.0
Ephemeris Error	2.6	2.6	0.0
Ionospheric Delay Error	1.0	4.0	0.15
Tropospheric Delay Error	1.0	1.0	0.15
Receiver Error	0.5	0.5	0.5
Multipath Error	1.0	1.0	1.0
Selective Availability	0.0	30.0	0..0
Total UERE	4.4	30.6	1.1
Horizontal Error (HDOP = 2)	8.8	61.2	2.2
Vertical Error (VDOP = 2.5)	11.0	153.0	5.5

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11. Loran-C User Handbook, COMDTPUB P16562.6, U.S. Department of Transportation, U.S. Coast Guard, of 18 Nov 1992.
12. Global Positioning System: Theory and Applications Volumes 1 and 2, Edited by Bradford W. Parkinson and James J. Spiker, American Institute of Aeronautics and Astronautics, Inc, 1996.
13. The Navstar Global Positioning System, Tom Logsdon, Van Nostrand Reinhold, 1992.
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CHAPTER 7

ELECTRO-OPTIC SYSTEM TESTING

CHAPTER 7

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CHAPTER 7
ELECTRO-OPTIC SYSTEM TESTING

7.1 INTRODUCTION

This chapter deals with the determination of the performance of electro-optical (E-O) systems. Test techniques commonly used are presented with associated methods of data reduction and analysis.

7.2 PURPOSE

The purpose of these tests is to determine the performance of an E-O system by developing data on the characteristics of the system. The test objectives include:

1. Determination of minimum resolvable temperature or minimum resolvable contrast.
2. Determination of static and dynamic resolution.
3. Documentation of airspeed and similar installation effects on performance.
4. Validation of sensor performance parameters in tactical environment.

7.3 THEORY

7.3.1 PHYSICS

Figure 7.3.1 is the E-O system operational process. A target is in the environment along with background clutter. The electromagnetic radiation from the target and the clutter is passed through the atmosphere where it may suffer losses from water vapor and carbon dioxide molecules in the transmission path. A set of optics at the front end of the E-O system collects the radiation and focuses it on the detector. The detector produces an electrical signal based on the amount of radiation received from the target and the environment. This signal is processed and displayed to the operator. The reader is referred to suitable electro-optics texts for detailed theory of the process, references 1-9.

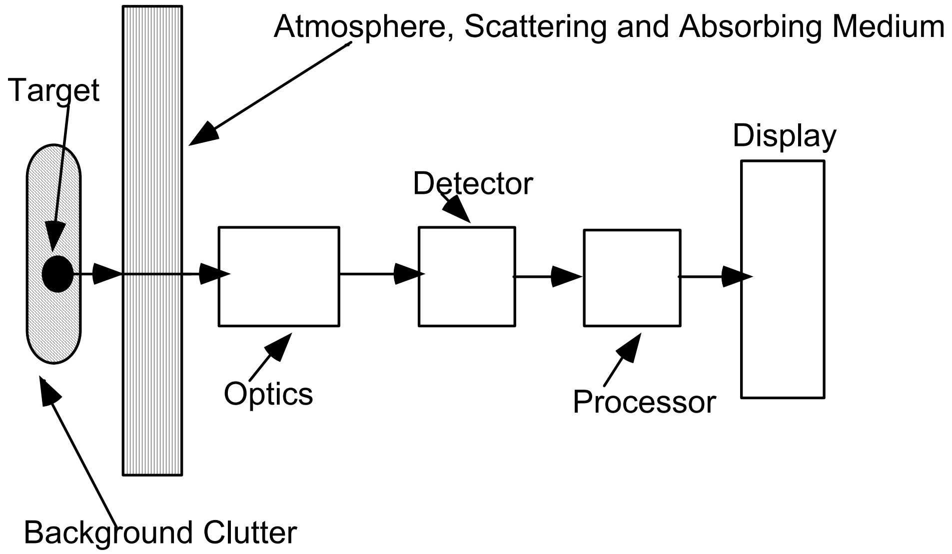

Figure 7.3.1
GENERAL ELECTRO-OPTIC SENSOR PROBLEM

For thermal radiation the sensor collects information from that portion of the electromagnetic spectrum near the red region of visible light, hence the name infrared. This region of infrared energy contains three areas of primary interest to military and civilian users. The three regions are the " .6 - 1.1 (near), 3-5 (mid wave), and 8-12 micrometer (long wave) " regions. Electro-optic systems can be designed to sense in the visible light spectrum as well. The TV camera is an example.

Plank's Law provides a relationship between the absolute temperature of a body, the wavelength of the emitted radiation, and the intensity of the radiation emitted. It is expressed as:

$$M_\lambda = \frac{C_1}{\lambda^5 (e^{\frac{C_2}{\lambda T}} - 1)} \qquad 7.3.1$$

In this expression we have the following:

M_λ = radiation emitted by the blackbody, per unit of surface area per unit wavelength. (watts/cm^2).
T = absolute temperature of the blackbody (^{o}K).
λ = wavelength of emitted radiation.
e = base of natural logarithm = 2.718.

C_1 and C_2 are constants with values based on the unit of wavelength being used. If λ is in centimeters then:

C_1 =3.741832 x 10^{-12} watt-cm^2
C_2 = 1.43848 cm-deg

The effect of temperature is observed by plotting this relationship. Figure 7.3.2 is a plot of this relation.

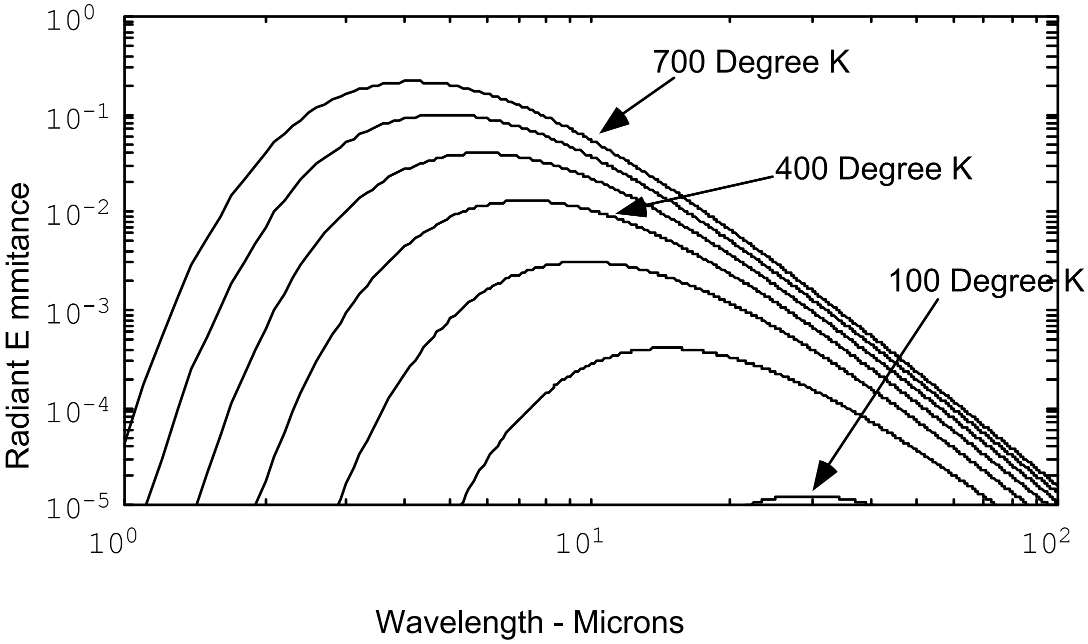

Figure 7.3.2
PLANK'S LAW

To put the data on this plot in perspective we can look at the temperature of objects with military applications. Assuming normal surrounding environmental temperature to be about 20°C to 30°C we note that objects we would like to detect have temperatures of around 300 degrees Kelvin. A look at the curves in figure 7.3.2 shows a large output from objects in this temperature range in the 8 – 12 micrometer region of the spectrum. As figure 7.3.3 shows, there is also a nice atmospheric transmission window in this region as well. Figure 7.3.3 depicts the frequency of some objects of military interest and their associated regions in the transmission bands.

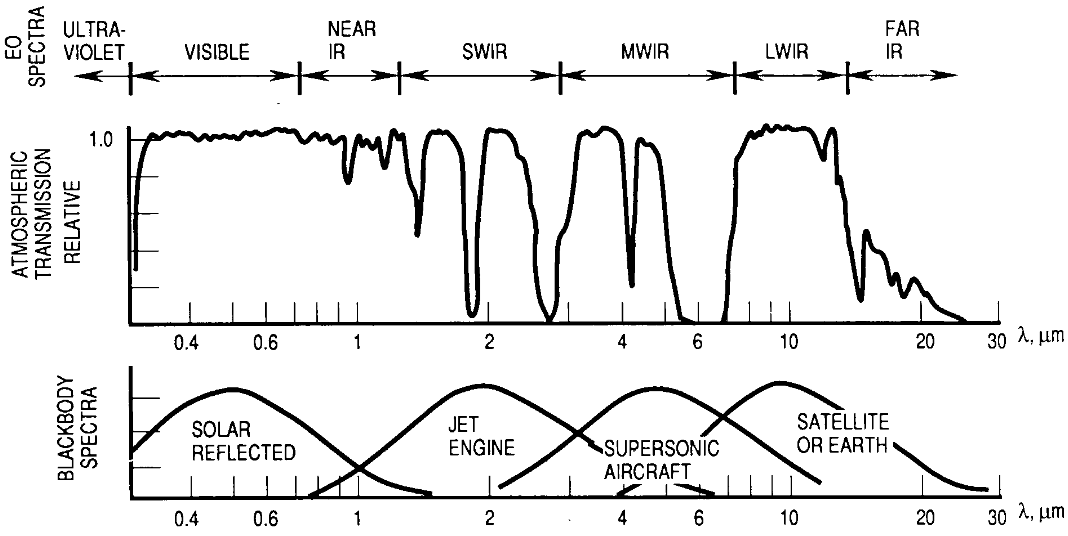

Figure 7.3.3
TYPICAL ELECTRO-OPTIC TARGET SPECTRUM[64]

The Stephan-Boltzmann law provides an estimate of the expected radiant exitance from a body at a given temperature across the spectrum.

$$M = \varepsilon\sigma T^4 \qquad 7.3.2$$

Where the following apply:

M= rate of emission per unit area (watts/cm^2)
ε = emmissivity of radiating surface
σ = Stefan-Boltzmann Constant = 5.67 x 10^{-12} (watt/cm^2 * K^4)
T = Absolute temperature (^{o}K)

Weins law relates the wavelength and temperature where maximum radiant exitance occurs.

$$T\lambda_m = 2898 \text{ (μm-K)} \qquad 7.3.3$$

Where:

T = absolute temperature (^{o}K)
λ_m = wavelength of maximum energy (microns).

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[64] Introduction to Electro-Optical Imaging and Training Systems, K. Seyrafi and S. Hovanessian, Artech House, Boston, 1993

7.3.2 ATMOSPHERIC TRANSMISSION

We must be concerned with the composition of the atmosphere, which, in turn, is a function of the meteorological conditions at the time. Particles in the atmosphere may absorb or scatter energy from our IR or visible light sources. The manner in which the various constituents of the atmosphere act on the electro-magnetic radiation is of importance in the testing of sensor systems.

Absorption of radiation is through the process of molecular resonance. When a photon strikes a molecule the molecule uses the energy to move its own electrons within their shells, thus the molecule absorbs the energy. Absorption within the atmosphere is normally not an issue for visible light radiation.

Visible light scattering is usually because of haze, fog or other larger sized particles in the atmosphere. The IR sensor will normally work in misty conditions. But when the moisture in the atmosphere starts to condense on particles to form fog, the size of the particles may be from .5 to 80 microns, and IR sensors do not work as well in those conditions. The peak of the distribution curve caused by these particles is between 5 and 15 microns. These particle sizes are comparable to IR wavelengths and the transmission of IR is greatly affected. Particle size below .5 microns is smaller than the IR wavelengths current imaging sensors use. Thus these particles (mist) have little effect on the sensor. Rain has particle sizes much larger than the IR sensor wavelengths and has a scattering effect on the IR energy. Figure 7.3.3 shows the atmospheric bands caused by the water vapor in the atmosphere.

7.3.3 FLIGHT TEST PERFORMANCE PARAMETERS

During flight and ground testing of E-O systems some key parameters are assessed quantitatively to determine if installed performance meets the specified requirements. Test techniques for these parameters and others are contained later in this document. For now we only wish to look at some basic theory on the minimum resolvable temperature, the spatial frequency curve, and sight line jitter. These parameters are commonly used in FLIR testing. Spatial resolution and resolvable contrast are the applicable visible light parameters.

A parameter known as minimum resolvable temperature difference (MRTD) is used as an IR sensor performance measure. A target of hot bars on a colder background as depicted in figure 7.3.4 may be used to make the measurement. (There are other versions of this target). Using these patterns and a variable heat source the temperature difference required to just resolve the various size targets can be determined. The plot will look much like figure 7.3.5 where we see the MRTD plotted versus the spatial frequency (related to size and spacing of the bars).

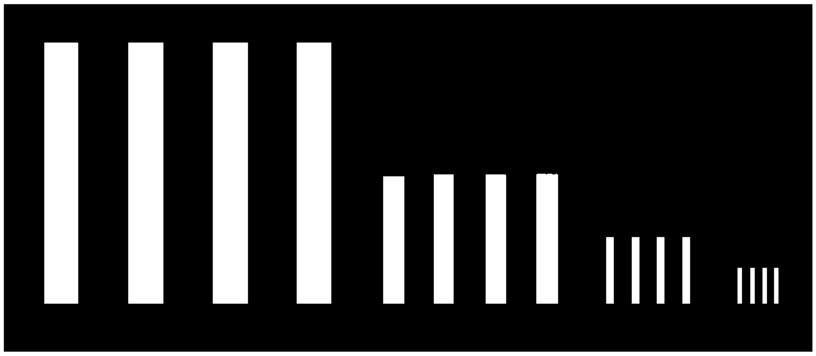

Figure 7.3.4
BAR TARGET FOR MINIMUM RESOLVABLE TEMPERATURE[65]

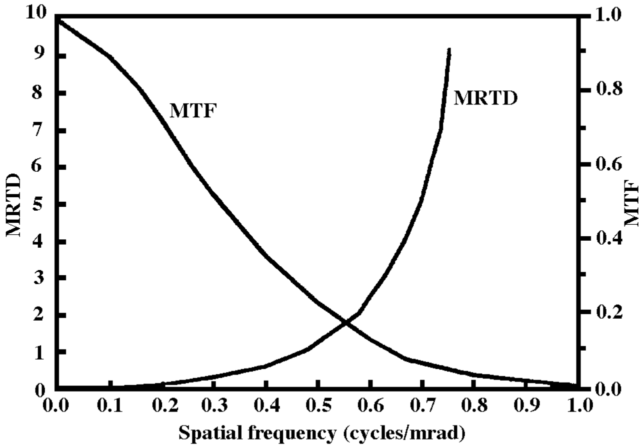

Figure 7.3.5
MRTD VERSUS SPATIAL FREQUENCY[66]

This performance measure shows both the temperature sensitivity and the high spatial frequency performance. System resolution will be the limiting factor at high frequency.

Flight and ground testing using bar targets is conducted to determine the system performance as discussed above. One of the outcomes of this testing will be a plot showing the ground and the flight resolution curves as depicted in figure 7.3.6.

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[65] Electro-Optical Systems Performance Modeling, G. Waldman and John Wooton, Artech House, Boston, 1993

[66] Ibid.

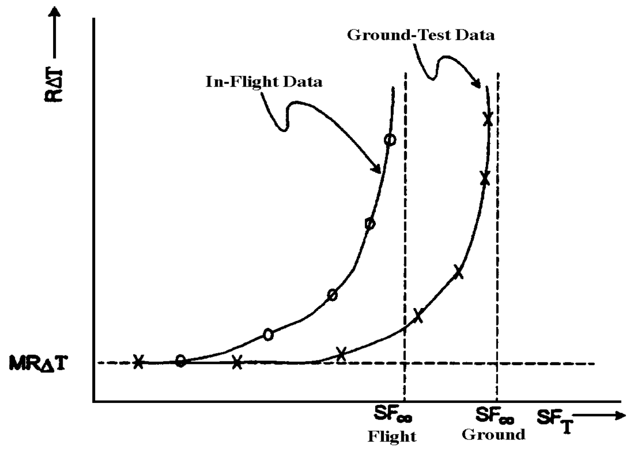

Figure 7.3.6
GROUND AND FLIGHT RESOLUTION CURVES[67]

Using the cutoff frequencies that are found from these two curves the sight line jitter is evaluated using the Philco-Ford curve shown in figure 7.3.7. This curve compares the performance of the IR sensor in a non-flight environment with its performance in the flight environment. The difference in the performance is documented as jitter caused by the installation. It is a function of things such as engine vibration, aerodynamic noise, and other similar items.

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[67] Introduction to Avionics Flight Test, AGARD Manual DRAFT, James M. Clifton, Ph.D.

Figure 7.3.7 PHILCO-FORD CURVE[68]

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[68] Ibid.

7.3.4 ELECTRO-OPTICAL TEST TARGET

7.3.4.1 TEST TARGET

Naval Air Warfare Center Aircraft Division's Electro-Optical Test Target Range is located at the Webster Auxiliary Airfield. Airborne testing is conducted in the restricted area (R4005) with control provided by Atlantic Test Range, NAS Patuxent River Approach Control, Webster Tower, and the Electro-Optic Range. The flight profile is normally from over the Bay at a heading of 252 degrees magnetic (245 degrees true). The target is located at 38^{o} 8' 53.3" N and 76^{o} 25' 22.5"W. The elevation is 25 ft. A portable target may be used which is located near this target. The coordinates are given at the time of the test.

The Electro-Optical Test Target (EOTT) is used to dynamically test airborne sensors for:

a. Spatial frequency as a function of target temperature differential.
b. Spatial frequency as a function of altitude.
c. Spatial frequency as a function of airspeed.
d. Other tests with lasers, etc.

The EOTT provides a capability to measure dynamic resolution of electro-optic sensors in a flight environment. The target frame is oriented 15^{o} from the vertical plane and is 20 ft high by 30 ft wide. The target consists of 60 elements, each 10 ft long with an equilateral triangular cross-section one foot on a side, which can be rotated $\underline{+}120^{o}$. Each of then three element faces is painted to provide a different reflectance characteristic for testing various type of sensors. The white side of the target has elements that can be uniformly heated to provide a thermal contrast with respect to adjacent elements for testing of infrared sensors. The temperature of selected panels can be controlled between 0.5°C and 10.0°C of differential temperature between the unheated and heated panels. The uniformity of selected arrays has been tested at ambient temperatures ranging from 20°F to 80°F and in winds gusting to 25knots. Temperature uniformity at low delta temperature (0.5 – 3^{o} delta C) is within 0.2°C. At higher temperature differentials (6 – 10^{o}) uniformity is within 0.5°C.

The EOTT test crew normally provides the resolution data to the test team in a finished form. They take the range data and the meteorological data and, using a curve-fitting program developed by sensor systems, they provide a computation of the spatial frequency and resolvable temperature difference curve and data.

7.4 TEST METHODS AND TECHNIQUES

7.4.1 COOL DOWN

7.4.1.1 PURPOSE AND METHOD

One of the first, most important, and easiest tests to conduct is the cool down test. Current generation IR sensor systems are cryogenically cooled to reduce the detector noise temperature and increase the detection capability of the sensor. Every time we turn the sensor on it must go through the cool down cycle. The cryogenic temperature to which the system is cooled will depend on the detector material and the cooling fluid. Common cooling fluids in use today are liquid nitrogen or argon. The test to be conducted is the same regardless of the cooling fluid or detector.

To conduct the cool down test start by going through the user manual (NATOPS) preflight procedures. At the point that the sensor system is energized a timer is started. The time from start of the sensor cool down cycle until the system is operationally ready is measured. This test is repeated as often as the system is utilized. The more data points the more accurate the time prediction will be. Visible light sensors and some newer IR sensors do not normally require cool down.

7.4.1.2 DATA REQUIRED

For each cool down test cycle the data required are:

Time – this is the most important parameter. It is what we really want to know. With this information we can determine if the cool down cycle is compatible with our current operational profiles on the equipment.

Temperature- the ambient air temperature is important. This temperature may affect how quickly the sensor cool down cycle is completed. The data will allow you to determine how the operating environment will affect the ability of the system to meet an operational requirement.

7.4.1.3 DATA REDUCTION

Data reduction will be a statistical assessment of the cool down time of the sensor and an assessment of the effect that the ambient temperature had on the length of the cool down cycle. The simple mathematical mean is usually sufficient.

7.4.2 PREFLIGHT

7.4.2.1 PURPOSE AND METHOD

Another important ground test is the preflight. This test is conducted by following the established operator manual preflight procedures. It will include all turn on and activation steps that must be accomplished to bring the system to full operation. The evaluator must follow each step completely as described in the manual. All display indications and control activation must be evaluated during the preflight test for completeness and accuracy.

7.4.2.2 DATA REQUIRED

Time- the total time to complete the preflight and have the system fully operational must be determined. This time will include the cool down and the completion of any required built in test (BIT) that must be accomplished in addition to completion of the general procedures.

Qualitative comments- comments on the ease of completing the preflight, the time required, and the feedback from the system as to its status for operation should be collected. These comments will give you the information to determine if the average fleet operator can bring the equipment to operational status in the normal time available for the type of mission the system is being evaluated to do.

7.4.2.3 DATA REDUCTION

Data reduction for this test will be to statistically evaluate the time to complete the preflight, again the basic average value will usually suffice. Also, determine the accuracy and ease of use of the procedures by the standard fleet operator.

7.4.3 BUILT IN TEST

7.4.3.1 PURPOSE AND METHOD

The effectiveness of the BIT equipment in determining the status of the system is an important test result. The best way to determine BIT performance is to use fault insertion techniques. In these tests a specific component of the system is failed (a fault inserted) and the BIT is activated for the test. The time to find the fault, the accuracy of the detection codes and the method of presentation of this information to the tester is evaluated. The measurement of BIT accuracy is a statistical test technique and will require a large sample of data to make a determination of the BIT performance.

When fault insertion is not an option during the test program, which it normally isn't at USNTPS, you can do a limited assessment that includes time to do the BIT, BIT status indication, and apparent system status.

7.4.3.2 DATA REQUIRED

Time - The time to complete the overall BIT is an important assessment. The data provides the information necessary to determine if the system can be ascertained as ready for operation with a high degree of confidence in the amount of time available during a tactical mission preflight.

Indications - The indications given to the operator by the BIT are important. The tester must evaluate the type of indication and the reliability of the indication. He can do this by comparing the BIT indications to the known performance of the system. Obviously, fault insertion will give more accurate determination of BIT effectiveness.

7.4.3.3 DATA REDUCTION

Data reduction for the fault insertion tests will be a statistical evaluation of the number of faults accurately detected as compared to the number of fault insertions. The time to find the fault, and display of the information will also be evaluated. The same type of analysis is used in the more qualitative measurement of BIT performance to the extent data are available.

7.4.4 FLIR CONTROLS

7.4.4.1 PURPOSE AND METHOD

E-O sensor controls provide the essential interface between the operator and the equipment. The controls must be evaluated for ease of use, operative sense, tactile feel, and performance during mission representative flight tasks. The test pilot/NFO must determine if the fleet user can effectively accomplish the mission using the controls provided to do the task.

7.4.4.2 DATA REQUIRED

The evaluation of the sensor controls is qualitative in nature. During every operation of the system the evaluator must determine how well the controls interface to the system. He should do these evaluations in tactical scenarios and relate the control usage to the tactical mission.

7.4.5 FLIR DISPLAYS

7.4.5.1 PURPOSE AND METHOD

The display of the sensor data to the operator is a critical element of the system performance. The usefulness of the display in all types of mission profile lighting conditions must be evaluated. The legibility of all information on the display must be assessed. The resolution of the display must be evaluated against the tactical information displayed by the system. Is the display resolution as good as the anticipated system performance? Can the operator see the display while performing mission maneuvers? The tester must answer these questions before the equipment is sent to the operational units. If a detailed technical test of the display is required members of the aircrew system team can make special measurements for inclusion in the report.

7.4.5.2 DATA REQUIRED

During the entire system testing cycle for the sensor system the evaluator will obtain information on the displays. Tests should be performed in representative environments and flight conditions. The adequacy of the size, resolution, and displayed information will be determined and noted in qualitative comments concerning the system display performance. The evaluator’s anthropometric measurements are required. Data on the refresh rate for the sensor displays and alphanumeric symbology should be recorded.

7.4.5.3 DATA REDUCTION

The tester must make sure that he/she has evaluated the displays in tactically significant environments to be sure that they will be adequate for the mission. The effect of bright sun or the overly bright glow of the display at night can make the display incompatible with the aircraft mission. Readability of all symbology and clearness of other data presented on the display must be determined by using the equipment in proper scenarios. Compatibility with night vision devices is required in most cases.

7.4.6 ALIGNMENT

The alignment of the E-O sensor is normally checked on the ground using precise measurement equipment. If the alignment is off it is normally corrected prior to continued testing. At the USNTPS the basic optical alignment of the equipment under test is assumed correct.

7.4.7 SLEW LIMITS

7.4.7.1 PURPOSE AND METHOD

The slew limits set the E-O sensor ability to track a target and the area covered while scanning with the sensor during a search pattern. The slew limits are a function of the particular installation. In addition to the sensor slew limits the accuracy of azimuth and elevation reference marks on the display and accuracy of digital readouts of azimuth and elevation can be determined. Normally we will verify these readings at 0, 90, 180, and 270 degrees relative azimuth positions and at 0, ±30, -60, -90 degrees elevation positions.

The test procedure is to mark a line on the surface under the aircraft that is parallel to the Armament Datum Line (ADL) of the aircraft. This line should extend forward and aft of the sensor turret or pod. Also, place additional reference marks perpendicular to this line at the 90 and 270 degrees azimuth positions.

Next using a plumb bob to hold an point light or IR source directly above these lines confirm the display markings and digital read out accuracy in azimuth. With the sensor in a NORMAL mode and optimized for best display, track the source as it is moved in the direction of the sensor slew limit. When the source is positioned so that the sensor reticle can no longer be moved to place it over the source you have reached the slew limit. Using the plumb bob mark the point on the surface under the aircraft where the reticle can no longer be adjusted to cover the source. This will mark the azimuth slew limit of the sensor. Repeat the test to the other side.

To obtain the elevation slew limits the test is the same. We must use some surface in front of the aircraft that is perpendicular to the ADL. We repeat the procedures with the source in the vertical plane.

7.4.7.2 DATA REQUIRED

After the slew limit has been marked right and left from the nose of the airplane the following measurements are required (See figure 7.4.1 for the detailed layout). Measure the perpendicular distance from the mark to the ADL. Also, measure the distance from the mark along the ADL to the sensor. This will enable you to use simple trigonometry to obtain the required angles. (More precise data can be found by using survey equipment). Figure 7.4.1 shows the appropriate formulation of the calculation.

For the vertical slew limit the height of the sensor from the surface below the aircraft must be measured. Next the height from the ADL corrected for the height of the sensor above the deck is measured. Finally, the distance from the sensor to the perpendicular surface is measured. The required measurements and calculation procedures are depicted in figure 7.4.1 also.

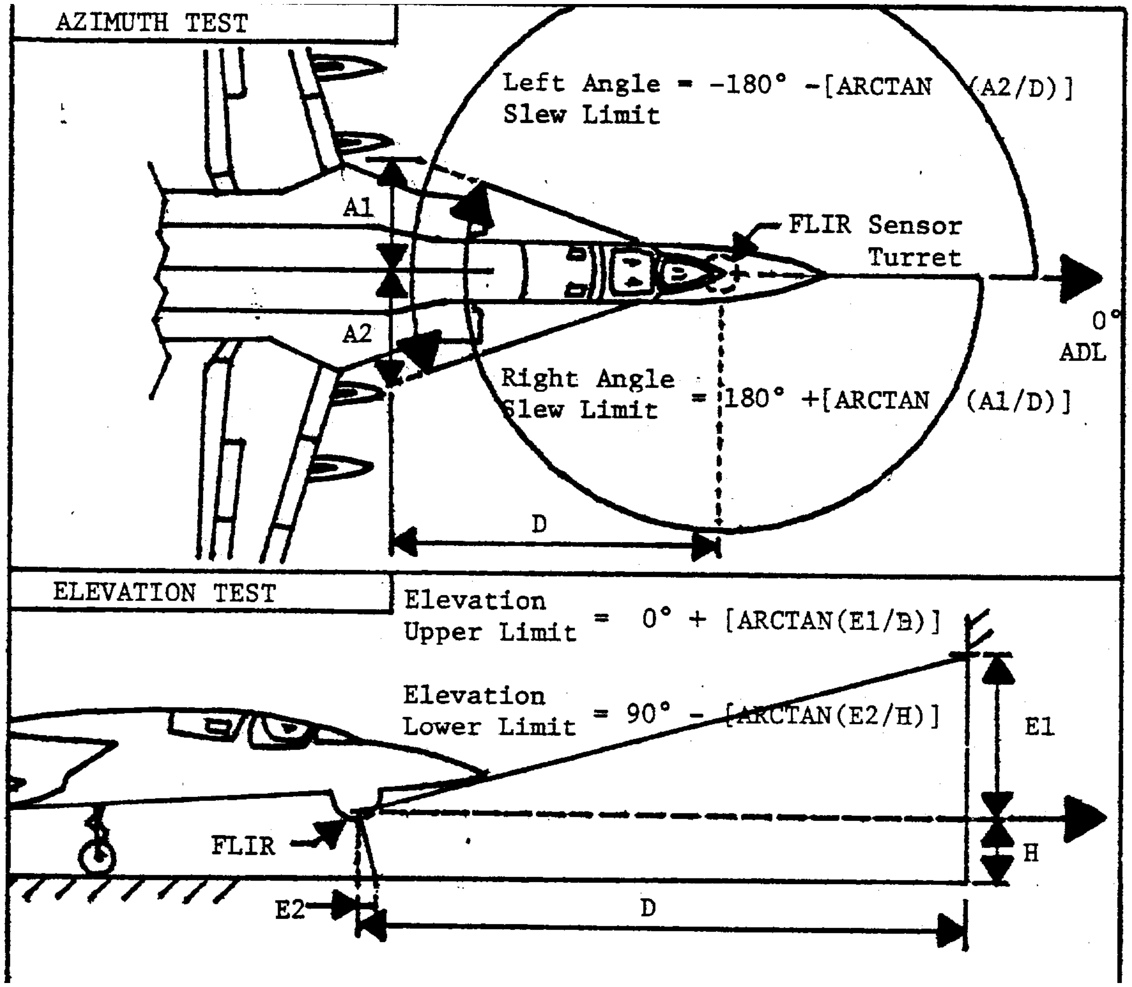

Figure 7.4.1
FLIR SLEW LIMIT TEST

7.4.7.3 DATA REDUCTION

After the data has been obtained the slew limits are calculated and compared to specification. The accuracy of the indicators is also determined and presented.

7.4.8 SLEW RATES

7.4.8.1 PURPOSE AND METHOD

The E-O sensor slew rate is determined in both azimuth and elevation. The test is normally a test of the maximum slew rate that can be generated in either the vertical or horizontal plane. It is an important parameter because it is part of the determining factor in how well the sensor will be able to track targets of interest as the airplane maneuvers. These tests must be completed in both the narrow field of view (NFOV) and the wide field of view (WFOV). The azimuth test is accomplished by slewing the sensor line of sight from 0 to 180 degrees (or other suitable relative angle). The time to accomplish the slew is measured. The test is repeated on both sides. For the elevation slew rate the test is from the 0 degrees line to -90 degrees or other suitable angle. The test is repeated in both FOV's.

7.4.8.2 DATA REQUIRED

Data required for this test will be the time from start of slew until the sensor passes through the required angle. The test may be conducted from a static start or dynamic start as long as the appropriate data entry is recorded.

7.4.8.3 DATA ANALYSIS

The data for a number of events should be collected and a statistical mean computed for each test. The computation of the slew rate is made using the formula:

Slew Rate (deg/sec)= Angular Displacement (deg)/Time (sec) 7.4.1

7.4.8.4 ERROR ANALYSIS

Error in the reaction time to the start and stop of the timing instrument can affect this test. Assuming that the reaction time to the start and stop is the same at a maximum of about 0.5 seconds the effect of the start and stop sequence should correct for the reaction time error. This, when combined with sufficient numbers of events, will give a valid assessment of the maximum slew rate.

7.4.9 SENSOR FIELD OF VIEW

7.4.9.1 PURPOSE AND METHOD

The sensor FOV test determines how much basic search area the sensor can observe at a given azimuth and elevation setting. The FOV is determined by the angular limits of the system, which may be functions of scanning mechanism or detector FOV. The measurement is required in all FOV's.

The position directly under the sensor is marked. Then the sensor is pointed to the 0 degrees relative azimuth position. A light or IR source is placed at a measured distance from the sensor on the 0 degrees reference line. The source is then moved perpendicular to the ADL until the source is positioned on the very edge of the display. The distance is measured. The test is repeated to the other side and up and down as well. Using these measurements the FOV is then calculated by simple geometric means for each FOV. Figure 7.4.2 shows an example of the procedure and the calculation.

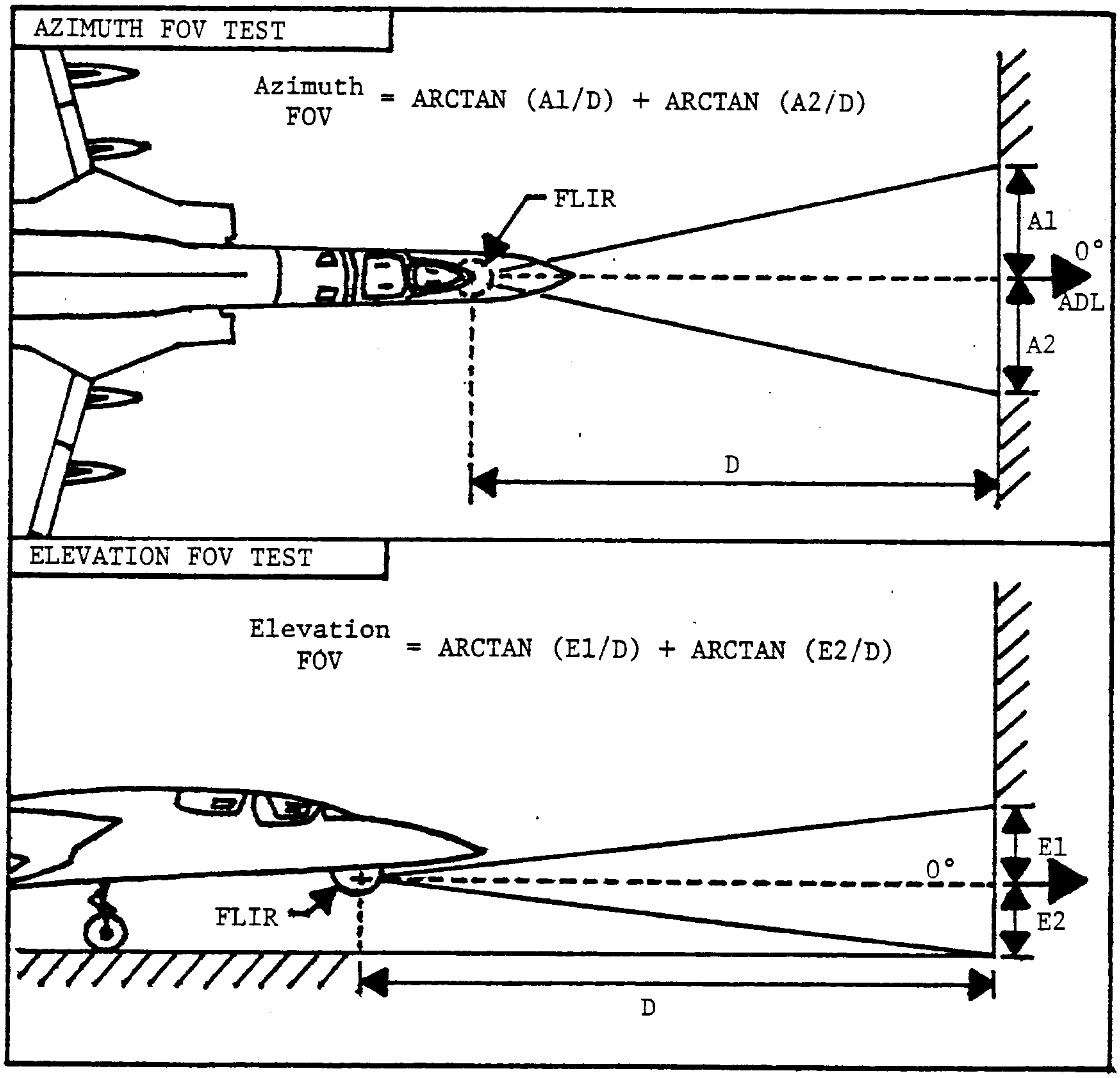

Figure 7.4.2
FIELD OF VIEW TEST

7.4.9.2 DATA REQUIRED

The data required for the test are the sensor settings including FOV for each measurement. The distance from the sensor to the source on the zero azimuth line and the perpendicular distance to the source when at the edge of the display.

7.4.10 SENSOR LINE OF SIGHT DRIFT RATE

7.4.10.1 PURPOSE AND METHOD

The line of sight drift of the E-O sensor in each FOV is needed so that we can assess the ability of the operator to use the equipment hands off. It is a measure of how much the sensor line of sight will move from the commanded position over a given time.

To measure the drift rate, we establish a reference mark on the surface directly below the sensor. Next a source is placed at a known distance from the sensor at the azimuth centerline. At time intervals (30 sec., 1 min., 5 min., 10 min. for example) a new source mark will be placed at the current apparent location of the sensor centerline. The horizontal difference between the two marks will be measured and used to compute the drift rate. The test is repeated in exactly the same manner for the elevation drift rate. Figure 7.4.3 shows the method.

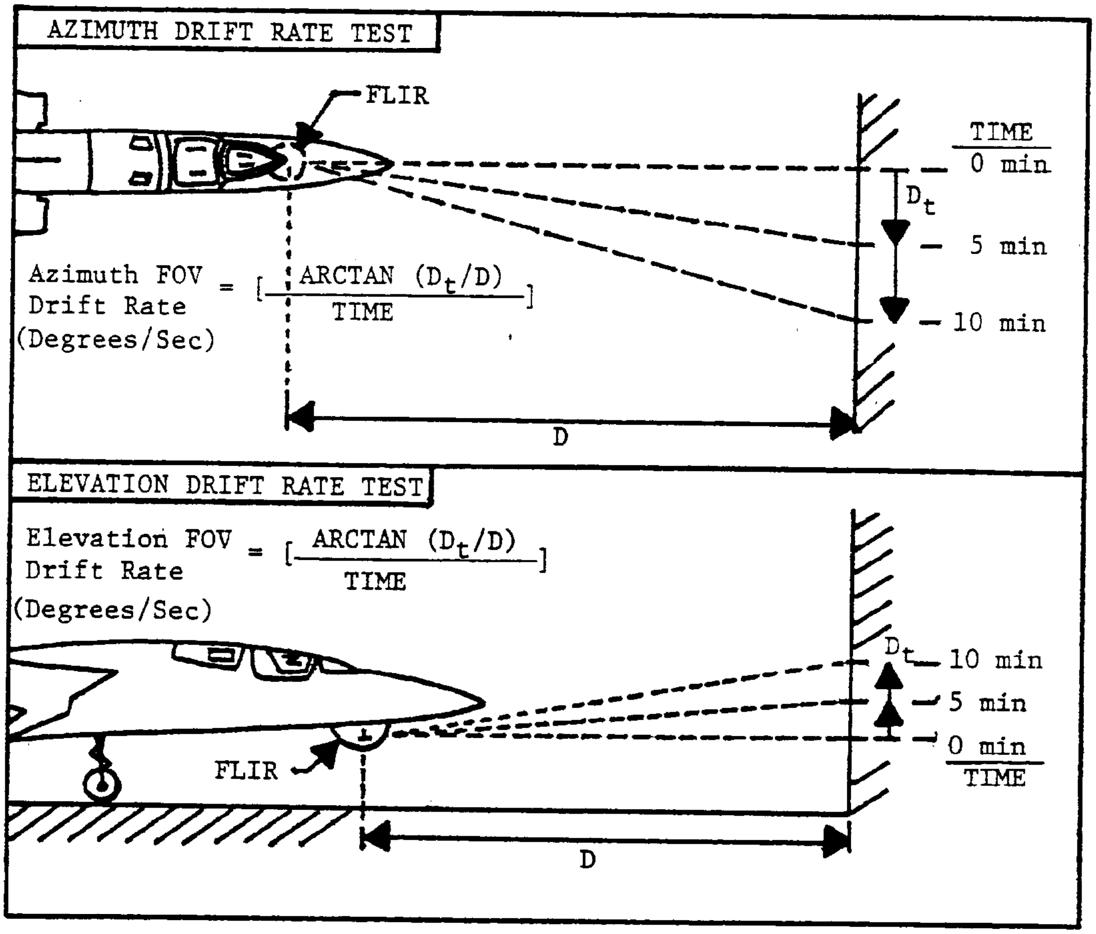

Figure 7.4.3
LINE OF SIGHT DRIFT RATES

7.4.10.2 DATA REQUIRED

The data for this test is the range along the ADL to the point source, the time and the horizontal or vertical distance the new source mark is displaced from the original source mark.

7.4.11 STATIC RESOLUTION TESTS

7.4.11.1 PURPOSE AND METHOD

The static or ground resolution tests are conducted to provide a baseline for the flight resolution tests and to establish the expected best installed performance of the sensor system. The test is conducted with the assistance of the engineers and technicians from the 4.11 systems engineering competency that operate the electro-optical test facilities. They will provide the test instrumentation and the operator to run the test equipment during the test. The test equipment for an IR sensor test includes a 180-inch collimating mirror assembly, heat sources, calibrated targets and measurement equipment. The test setup is as shown in figure 7.4.4. The test is conducted in an area where a well-stabilized temperature can be maintained for the duration of the test period. For visible light sensor test an optical resolution target is used in place of the IR target.

The targets used for the IR sensor resolution test are four bar grids with a 7:1 height to width ratio. A bar is an opening in the grid, which allows the IR source to show through to the detector. The spaces between the bars are the same size as the bars. These grids are sized to provide specific spatial frequencies for each target. For an optical test the test target may be a standard black and white line pair resolution target.

The test begins using the lowest spatial frequency target grid (largest bar width). The target temperature is incrementally increased from the ambient condition. When the system operator can first distinguish the four bars of the target the point is marked as data. This point will consist of the target size and the temperature difference between the target block and the IR source. The target array will be replaced with the next smaller in spatial frequency and the test repeated. The sequence is repeated until a target is reached that the operator cannot be resolve regardless of temperature differential being used. The data should be repeated a number of times to build a statistical confidence in the results. This test is then repeated for opposite polarity and all of the available FOV’s. Figure 7.4.5 shows an example of the ground resolution plot. From the plot an estimate of the spatial cutoff frequency for ground test and the minimum resolvable temperature differential can be obtained.

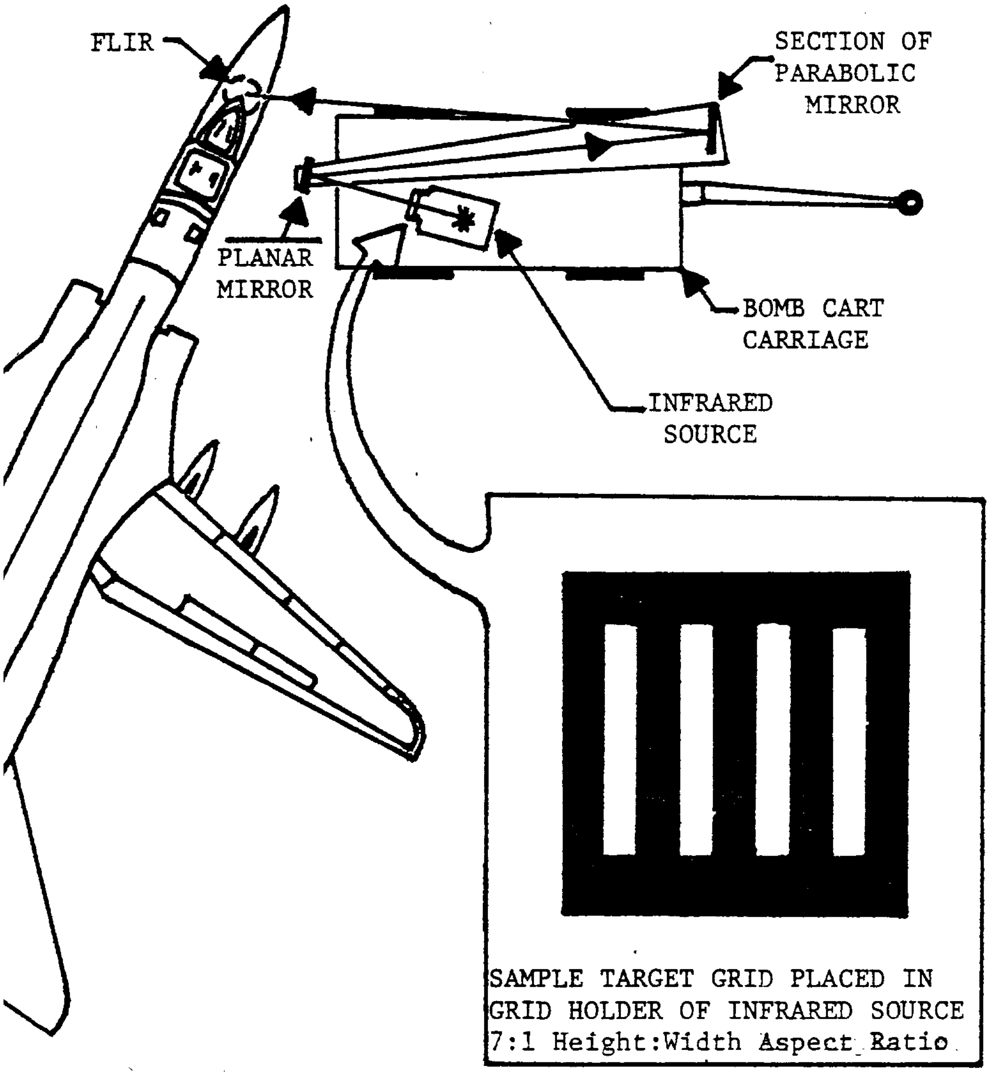

Figure 7.4.4
GROUND SOLUTION TEST

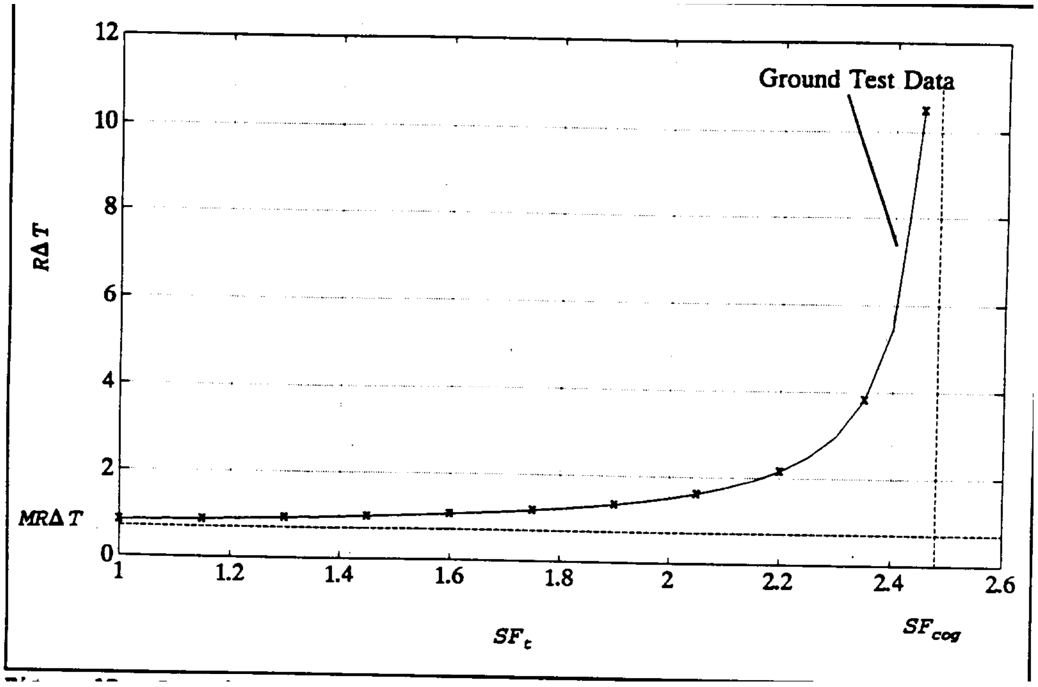

Figure 7.4.5
SPATIAL FREQUENCY VS. MINIMUM RESOLVABLE TEMPERATURE DIFFERENTIAL[69]

7.4.11.2 DATA REQUIRED

The data required for this test includes all the ambient weather conditions such as temperature and humidity plus all the FLIR settings at the time of the measurements. Normally the tester would establish a baseline and record deviation from it. The test is normally done using best possible settings so the display may be adjusted to each case. If the test is for a visible light sensor the resolution will be based on the smallest line pairs the tester can distinguish.

7.4.11.3 DATA ANALYSIS

The data is plotted as shown in figure 7.4.5. The data normally exhibits an asymptotic rise at higher spatial frequencies. This rise defines the cutoff (no longer able to resolve targets) spatial frequency of the sensor. The resolution of the system is the reciprocal of the cutoff spatial frequency.

7.4.11.4 ERROR ANALYSIS

Sources of error in the test include the effect of temperature change or wind on the stability of the test equipment. Operator consistency making the measurement from the display (not all operators make the same determination of target presence) and operator familiarity with the test techniques may influence the data collection process. Vibrations of the equipment in the testing area will have effects on the data.

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7.4.12 BORESIGHT ACCURACY

7.4.12.1 PURPOSE AND METHOD

Boresight accuracy is assumed to be the coincident alignment of the E-O sensor with other sensors on the airplane. The alignment of the sensors is important so that the crew can convert one sensor contact to another. If the radar has a target that is designated via designation cursors then the E-O sensor must be able to accurately slew to view that point.

To conduct this test on the ground the aircraft must be positioned in a location where it is safe to radiate the active sensors and where a target of known parameters can be located. For the radar to E-O sensor boresight test a target is acquired and designated with the radar cursor. The E-O sensor is then commanded to point at the designated target. The error between the two designations is noted and is the boresight error. Enough data to obtain a statistically significant sample should be collected. This test is repeated in flight to qualitatively confirm the ground test results. This can be accomplished by using targets and checkpoints that are known geographic positions and plotting the measurement data for comparison of the ranges and bearings, etc. Alignment with laser systems or other optical systems may also be established by ground tests and verified by flight tests against selected targets or the Electro-Optical Test Target.

7.4.12.2 DATA REQUIRED

The data taken is the difference in angular are linear measure between the two sensor cursors. Enough samples will be taken to give reliable indication of the relative pointing consistency of the two sensors.

7.4.13 FIELD OF REGARD

7.4.13.1 PURPOSE AND METHOD

The field of regard (FOR) test is conducted to determine how well the sensor can be employed relative to the aircraft flight path during mission representative maneuvers. The evaluation is conducted by plotting the location of points that block the sensor line of sight on a rectilinear diagram as shown in figure 7.4.6. Using the vertical and horizontal sensor scale markings, which you should have already verified, mark the corners of all obstructions on the rectilinear plot. Draw in the connecting lines and check that the sketch corresponds to the display when viewing in each sector. Label the diagram in detail, noting all obstructions.

Figure 7.4.6

Rectilinear Diagram

7.4.13.2 DATA REQUIRED

An example rectilinear plot with all the obstructions labeled is shown in figure 7.4.7.

Figure 7.4.7

Completed Rectilinear Diagram

7.4.14 STABILIZATION/GIMBAL LIMITS/GIMBAL RATES

7.4.14.1 PURPOSE AND METHOD

The stabilization of the E-O sensor is an important element of the mission effectiveness of the system. The equipment must work within the dynamic flight environment demanded by the mission tasking or it will degrade the overall system integration.

The stabilization limits and gimbal rates must be evaluated in both computer and manual modes of system operation. The selection of FOV will also affect how well the operator can employ the equipment while the aircraft is maneuvering so the stabilization tests should be done in all FOV's.

The test procedures are to:

1. Establish a test airspeed and altitude
2. Set sensor controls for optimum display and note settings.
3. Place sensor reticle over a selected target
4. Perform selected maneuvers while observing for effects of the maneuvers on the sensor display and image quality.

The maneuvers are:

1. Pull-up and Pushover to be executed from wings level attitude. The maneuver is continued to the aircraft limit or until the sensor display begins to degrade.
2. Roll maneuvers are executed as a series of increasing angle of bank turns at approximately 15 degree increments up to the aircraft limit or the sensor display degrades.
3. Right and left rudder inputs are employed. Start with half pedal deflection and increase until aircraft limit is reached or the sensor degrades. Be careful with this test. Some airplanes should not be overly stressed in yaw.
4. Coupled maneuvers are done within the test envelope limit so that an assessment of the gimbal performance of the sensor system can be made.
5. Repeat tests for other sensor modes of operation as required.

7.4.14.2 DATA REQUIRED

The data required for this test should include the sensor's operating mode with all switch positions noted. The aircraft altitude and airspeed, type of target used, and aircraft attitude at the time degradation is noted. You will need to know time to complete the maneuver and load factor to determine the effects of rate on the gimbal during the maneuvers. Finally, you must describe the type of degradation that you observed and how long the system was affected by the maneuver. This data will give you the information to make a qualitative evaluation of the stabilization of the sensor in maneuvering flight.

7.4.15 MINIMUM RANGE

7.4.15.1 PURPOSE AND METHOD

The minimum range that the operator can use the E-O sensor to track a target is significant in terms of the operational tactics developed to employ the equipment. To be able to track during an overhead pass is important in ship rigging as well as target BDA assessment or target designation for other aircraft. The goal of this test is to establish the minimum tracking range of the sensor. This minimum tracking range is usually defined by the mechanical implementation within the sensor housing and stabilization equipment.

To evaluate this minimum range, an over flight of a selected target is accomplished. The operator then tracks the target during the over flight while noting any loss of sensor presentation and also noting any changes in the image quality. Sensor transitions through the NADIR, a position at 90 degrees look down and within ±3 degrees of the Aircraft Datum Line (ADL) results in an inverted display unless special processing is done on the image. This may be a problem to the operator.

The test procedures are:

1. Establish aircraft flight profile
2. Establish sensor optimal display quality
3. Confirm NFOV setting
4. Track the target through and after the over flight to simulate the BDA assessment and confirm the performance of the system during the NADIR passage.

7.4.15.2 DATA REQUIRED

The data required for this test is mostly qualitative in nature. The aircraft parameters must be noted and the attitude at the time of any loss of track or change in picture quality during the data run must be recorded. The range to target and orientation along the ground track of the target is important as well.

7.4.16 MAXIMUM RANGES

7.4.16.1 PURPOSE AND METHOD

One of the more important of the flight tests is the determination of how well the E-O sensor can find the types of targets it is intended to find. Another is how well it provides data to the operator so he can classify the type of target displayed by the system, and if he can identify the target details after he has classified it. To accomplish this test, the system is tested against a variety of targets that represent the types of targets the sensor will be required to detect when in service.

For our testing, we will use the following definitions of the ranges stated above:

Detection range is the range at which the operator can positively discern the presence of a target on the sensor display with sufficient confidence to make a navigational correction toward the target.

Classification range is the range at which the operator can positively determine the type of target with sufficient confidence to arm the weapon system (know a warship from a merchant or a tank from a truck.

Identification range is the range at which the operator can be positive enough of the targets to commit a weapon (know it is a class of warship or a hostile threat tank vice a friendly tank).

The test must be carried out in both white and black hot polarity and against a variety of mission representative targets. The data must be repeated until a significant sample of data has been obtained to make the determination of the range for each requirement. The test should be structured to be as repeatable as possible. For example, tests could be done using the Hannibal target as the target for the sensor test. A number of test events flown toward the target area from the same heading and airspeed would be accomplished with the various ranges determined on each event. This test would be repeated on other selected targets.

1. Establish a run in heading, altitude and airspeed to the target.
2. Set the sensor to optimize the display and FOV and polarity per test plan.
3. Acquire the target, radar may be used to aid if available.
4. Determine the maximum detection range.
5. Select the NFOV if not selected and determine classification and identification ranges.

7.4.16.2 DATA REQUIRED

Aircraft parameters, sensor parameters, and the target specific data are required. Also, all weather related data is required as well.

7.4.16.3 DATA REDUCTION

The data reduction is to determine the statistical average of each of the data runs for each detection parameter. The variance caused by using different polarity and other parameter settings should be assessed.

7.4.17 AIRSPEED EFFECT ON RESOLUTION

7.4.17.1 PURPOSE AND METHOD

Most installed E-O sensor systems have specific airspeeds or bands of airspeeds where the performance is best. It would be nice if the sensor had the same performance throughout the flight regime but this is not always the case. The aerodynamic and vibration loads on the airplane cause the sensor equipment to move or vibrate within the mounts. This motion causes the sensor some loss of the ability to resolve targets. One of the primary quantitative tests done is to determine the airspeed effect on the sensor (i.e., determine the random sight line jitter). The operating airspeed band for the aircraft sensor should be such that minimal effect of airspeed is noted within the primary operating airspeed range of the aircraft. The airspeed effect test is the first of the quantitative tests accomplished using the Electro-Optical Test Target located at Webster Field. The test procedure is as follows:

1. The EOTT is set and maintained at about a 10°C differential between the target bars and background. A picture of the Webster target array is shown in figure 7.4.8.
2. The aircraft heading for the inbound leg to the EOTT is 252 degrees magnetic.

3. The airplane will be flown at a specified test altitude and airspeed comfortably above stall.
4. The sensor parameters will be optimized for best display. The test is completed in narrow field of view and in both polarities.
5. Locate the target, radar may be used or an initial mark on top and stored position might be used to aid the operator in this.
6. The evaluator will call a "mark" when distinct resolution determination is made from information presented on the sensor display.
7. The range at the time of the mark will be recorded.
8. The test is repeated at different airspeeds (increasing the airspeed about 10 knots per run).

At the completion of the events the airspeed providing best resolution will be determined. The actual resolution tests will be started using this airspeed for all flight profiles against the EOTT. (Note - this should correspond to the best range at mark if all other things are equal. Also, in a full test of a new system the airspeed effects test may require multiple flights and lots of data to quantify the airspeed resolution curve).

7.4.17.2 DATA REQUIRED

Airplane data required includes altitude, airspeed, sensor parameters and range to EOTT.

Time, space, and position data - aircraft tracking data to include range, altitude, airspeed, and deviation from track.

EOTT - Target settings

Weather data to determine atmospheric moisture, etc.

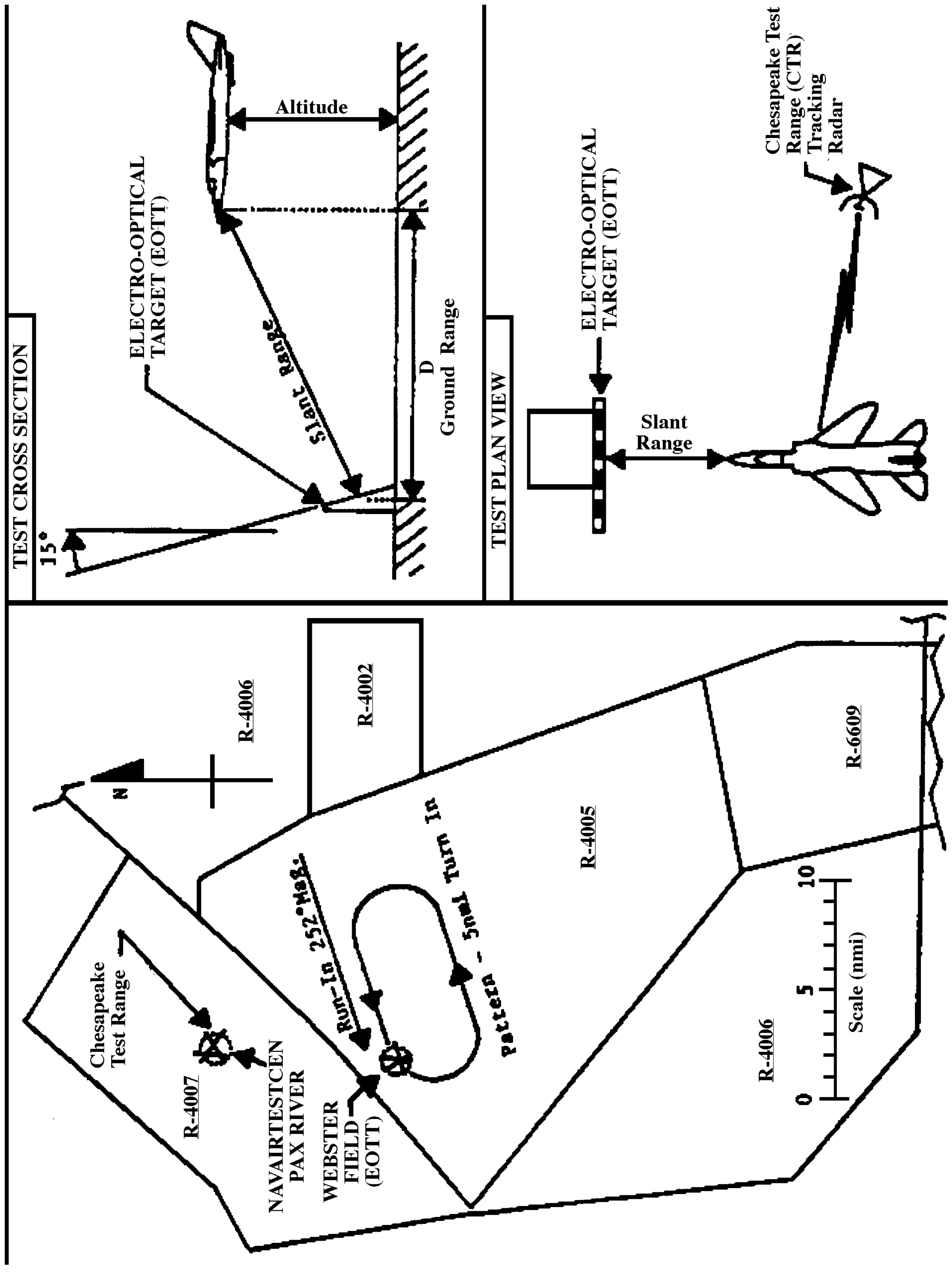

Figure 7.4.8
WEBSTER FIELD EOTT

7.4.17.3 DATA ANALYSIS

Data analysis will be to evaluate the spatial frequency determined from the target acquisition data for each pass. If all parameters except airspeed are constant then the longest-range mark will correspond to the best resolution airspeed. The actual calculation is done as follows:

$$SF = \frac{SR}{2(BW)1000} \qquad 7.4.2$$

Where:
SF = spatial frequency in Cy/mrad
SR = slant range in ft
BW = bar size of target in ft

The data is plotted as airspeed versus spatial frequency as shown in figure 7.4.9. The airspeed with the largest spatial frequency will be the airspeed of choice for the rest of the testing if it is in the normal operational range of the aircraft.

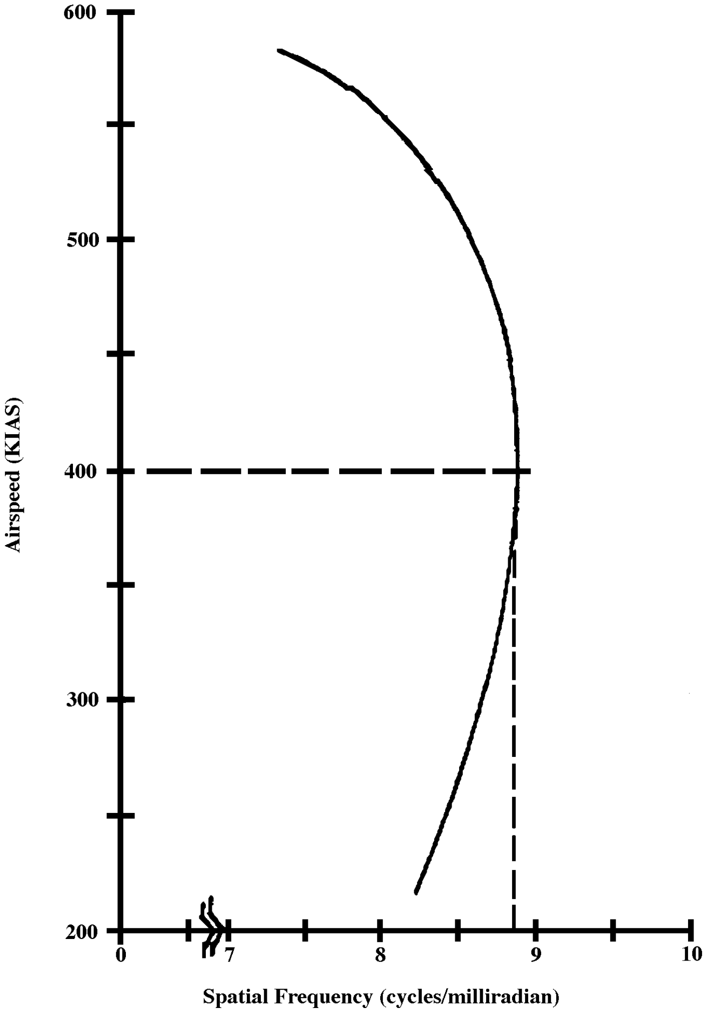

Figure 7.4.9
AIRSPEED EFFECT ON RESOLUTION

7.4.17.4 ERROR ANALYSIS

A source of error in this test will be the time delay between the called "mark" and the actual mark being noted. That will introduce a range error based on the speed of the airplane. The accuracy of other range data sources such as radar tracking accuracy or GPS position accuracy must be accounted for in the analysis

7.4.18 DYNAMIC (FLIGHT) RESOLUTION

7.4.18.1 PURPOSE AND METHOD

The dynamic resolution is the primary quantitative test done on the FLIR system. After establishing the best airspeed for FLIR performance the resolution test is done to establish the performance characteristics of the FLIR and to determine how much jitter is introduced by the installation. If cost is at issue the test can be accomplished at the best resolution airspeed. The test can be conducted at as many airspeeds and altitudes as needed to answer the performance issues for the sensor, however.

The test uses the same EOTT setup as before. Starting with the high temperature differential used for airspeed effects the temperature differential is lowered successively from pass to pass until the spatial frequency vs. temperature differential curves are fully defined.

Test procedures are the same as above with exception of the change in temperate differential between each pass. If the sensor has multiple fields of view they can usually be tested in one pass by starting with the narrowest FOV and switching through FOVs to the widest as the aircraft travels in to the target.

7.4.18.2 DATA REQUIRED

The data required is the same as that for the previous test. A mark at each point where the bars are resolved and the associated FOV is required. Atmospheric data is needed to determine the effective temperature difference.

7.4.18.3 DATA REDUCTION

Data reduction is to plot the spatial frequency versus temperature differential curve for the modes tested. The spatial frequency is calculated using equation 7.4.2. The effective delta temperature is the temperature differential adjusted for atmospheric effects. It is calculated using

$\Delta T_{EFF} = \Delta T * \tau$ where τ is the atmospheric transmission coefficient.

If ΔT_{EFF} is not provided it may be computed by first computing the atmospheric transmission using the LOWTRAN program or a suitable estimation procedure from references 2, 3, or 6. This transmission coefficient is then used to reduce ΔT to ΔT_{EFF}.

7.4.18.4 DATA ANALYSIS

Once the plot is made the minimum resolvable temperature differential can be estimated from the plot by determining where the plot intersects the temperature differential axis. The dynamic cutoff spatial frequency is determined by the asymptote to the vertical at the highest spatial frequency. Figure 7.4.10 shows an example of this plot.

7.4.18.5 ERROR ANALYSIS

Sources of error for the test are the same as those for the airspeed effects test.

7.4.19 LINE OF SIGHT STABILITY

7.4.19.1 PURPOSE AND METHOD

Determination of line of sight stability is accomplished by using data that has been previously collected. A comparison of the ground and the flight resolution data is made to determine the sight line stability. The ground and flight cutoff spatial frequencies are determined as discussed in the last section. The ratio of these values is then used in conjunction with the Philco-Ford curve shown in figure 7.3.11 to determine a numerical value for the sight line jitter. This value will be expressed in cycles per milliradian and represents the error due to vibration in the system.

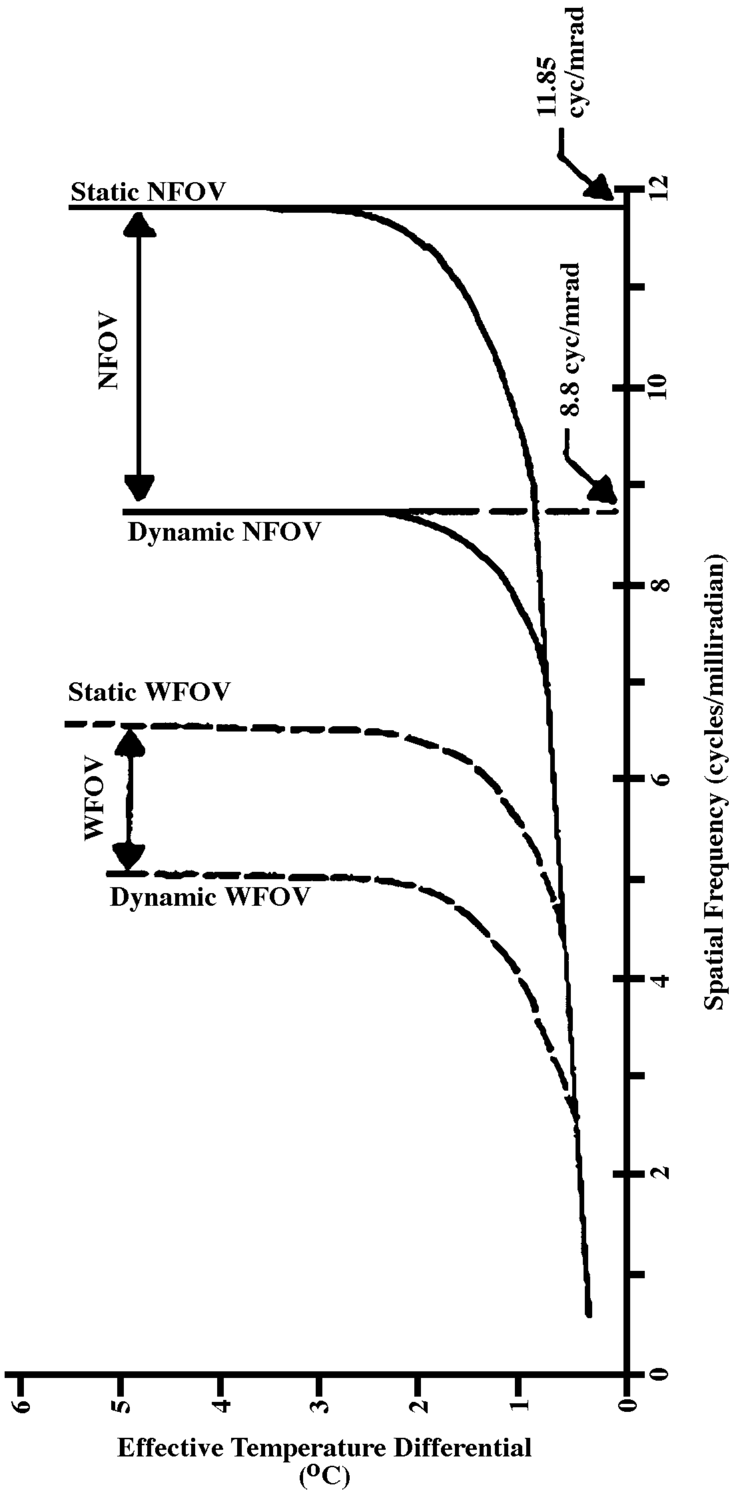

Figure 7.4.10
FLIGHT RESOLUTION DATA

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CHAPTER 8

ELECTRONIC WARFARE SYSTEM TESTING

CHAPTER 8

CONTENTS

CHAPTER 8
ELECTRONIC WARFARE SYSTEM TESTING

8.1 INTRODUCTION

8.1.1 ELECTRONIC WARFARE

Electronic warfare (EW) is defined as military action involving the use of electromagnetic energy to determine, exploit, reduce, or prevent hostile use of the electromagnetic spectrum while maintaining friendly use of the spectrum. In other words, EW seeks to insure proper performance of friendly electronic systems and deny proper performance of unfriendly systems. EW can be broken into three principal elements:

Electronic Warfare Support Measure (ESM) - gathering and immediate analysis of electronic emissions of weapon systems to determine a proper and immediate reaction.

Electronic Countermeasures (ECM) - development and application of equipment and tactics to deny enemy use of electromagnetically controlled weapons.

Electronic Counter-Countermeasures (ECCM) - actions necessary to insure use of the electromagnetic spectrum by friendly forces.

ESM is the division of EW involving action taken to search for, intercept, identify, and/or locate sources of radiated electromagnetic energy for the purpose of immediate threat recognition. The equipment associated with ESM consists of all sensors used for detecting and alerting the aircrew of enemy threats. These include radar warning receivers (RWR), missile warning sensors (MWS), and laser warning sensors (LWS). These systems detect electromagnetic energy emitted by enemy threats and display information to the crew critical in defeating or evading the threat.

ECM is defined as actions that deny the enemy use of the electromagnetic spectrum. Since total denial for all time is impossible, the primary reasons for employing ECM is to delay an adversary's response. ECM equipment consists of all countermeasure capabilities employed to defeat or evade enemy weapons systems. These include the countermeasure dispensing system (CMDS) and all deployable countermeasures (chaff, flare, towed decoys, etc.). Active jamming of RF threats for the purpose of self-defense is also considered ECM. New ECM systems are always being developed with a large emphasis placed on the development of laser system countermeasures.

ECCM, for our purposes, is considered actions taken to insure the use of the electromagnetic spectrum by friendly forces in the presence of man-made interference. This can be viewed as the enemy using ECM (jammer) against friendly EW (air-air/air-ground radar) and friendly systems countering with ECCM (filtering, frequency hopping, etc.) to retain performance of their EW system. ECCM is offensive action against the enemy's ECM capability to maintain offensive performance of friendly EW systems. ECCM is typically implemented in the EW system being exploited (i.e., air-to-air/air-to-ground radar) and involves intensive software development to filter or otherwise separate the noise induced by the jamming signal. ECCM testing is not covered in this manual as part of EW system testing.

Figure 8.1 shows areas of the electromagnetic spectrum which are frequently referred to by band designations rather than frequency. Figure 8.2 shows some of the more commonly used or known areas of the electromagnetic spectrum. Figure 8.3

presents the more common uses of the microwave spectrum. When converting from frequency (f) to wavelength (λ) and vice versa, recall that $f = c/\lambda$, where c = speed of light (≈ 3.0×10^8 m/s).

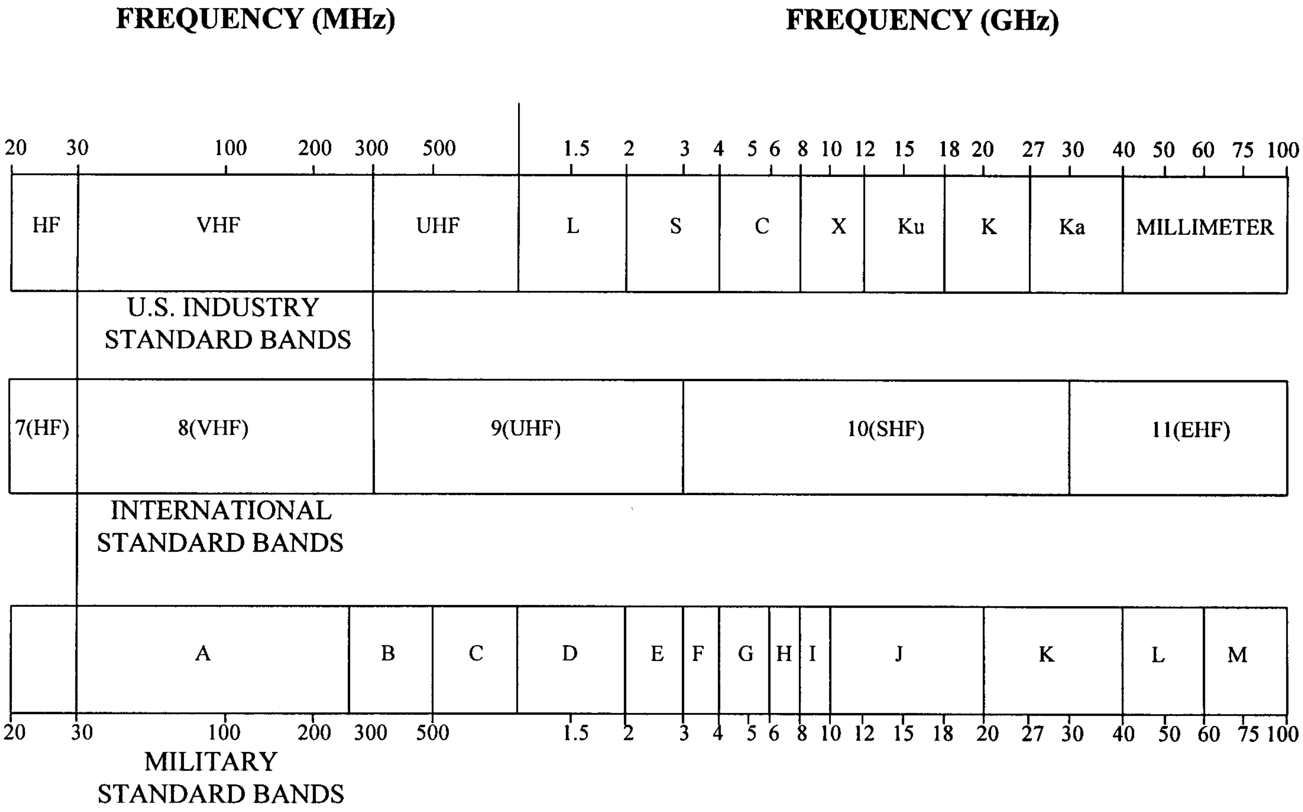


Figure 8.1

FREQUENCY BAND DESIGNATIONS

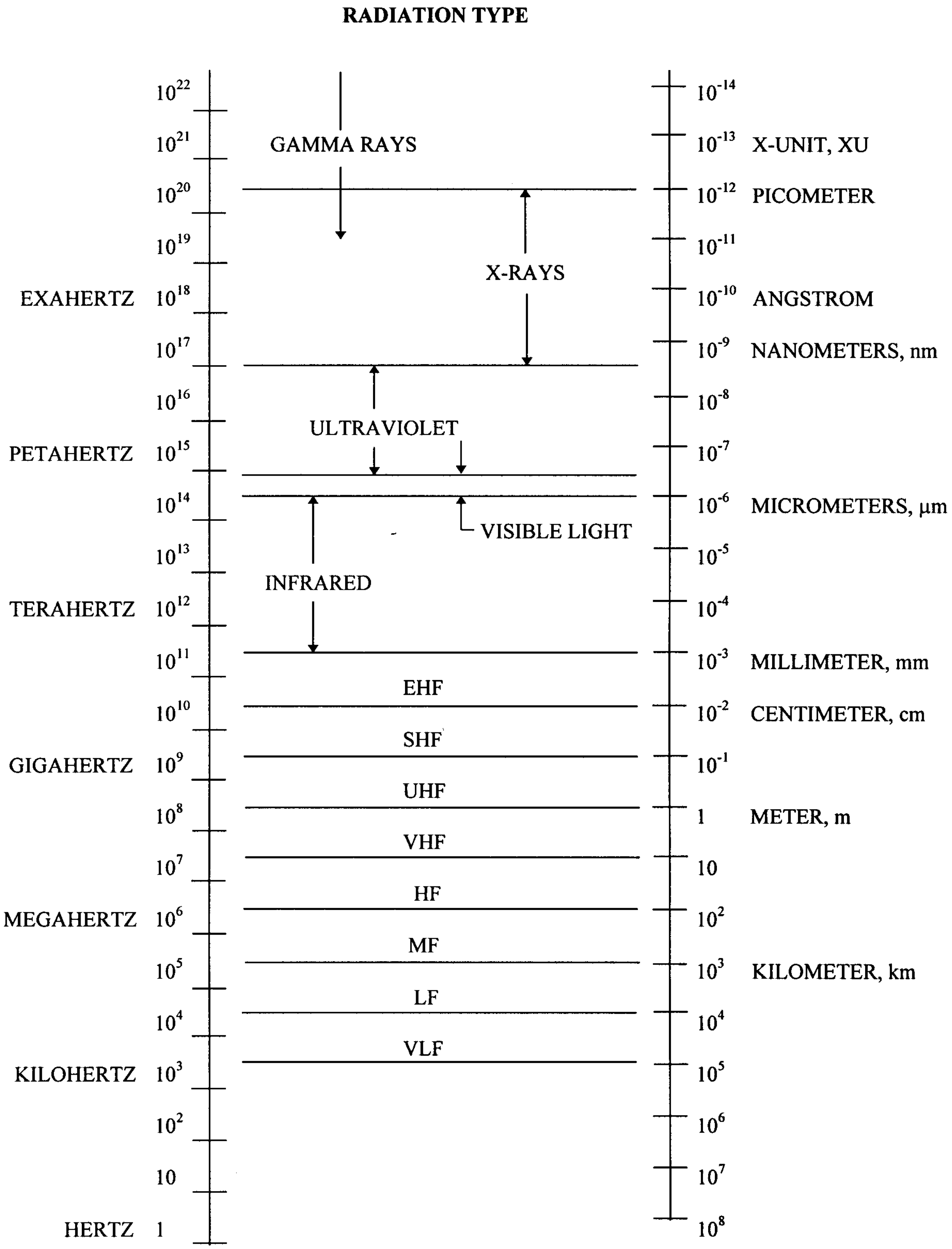


Figure 8.2

ELECTROMAGNETIC RADIATION SPECTRUM

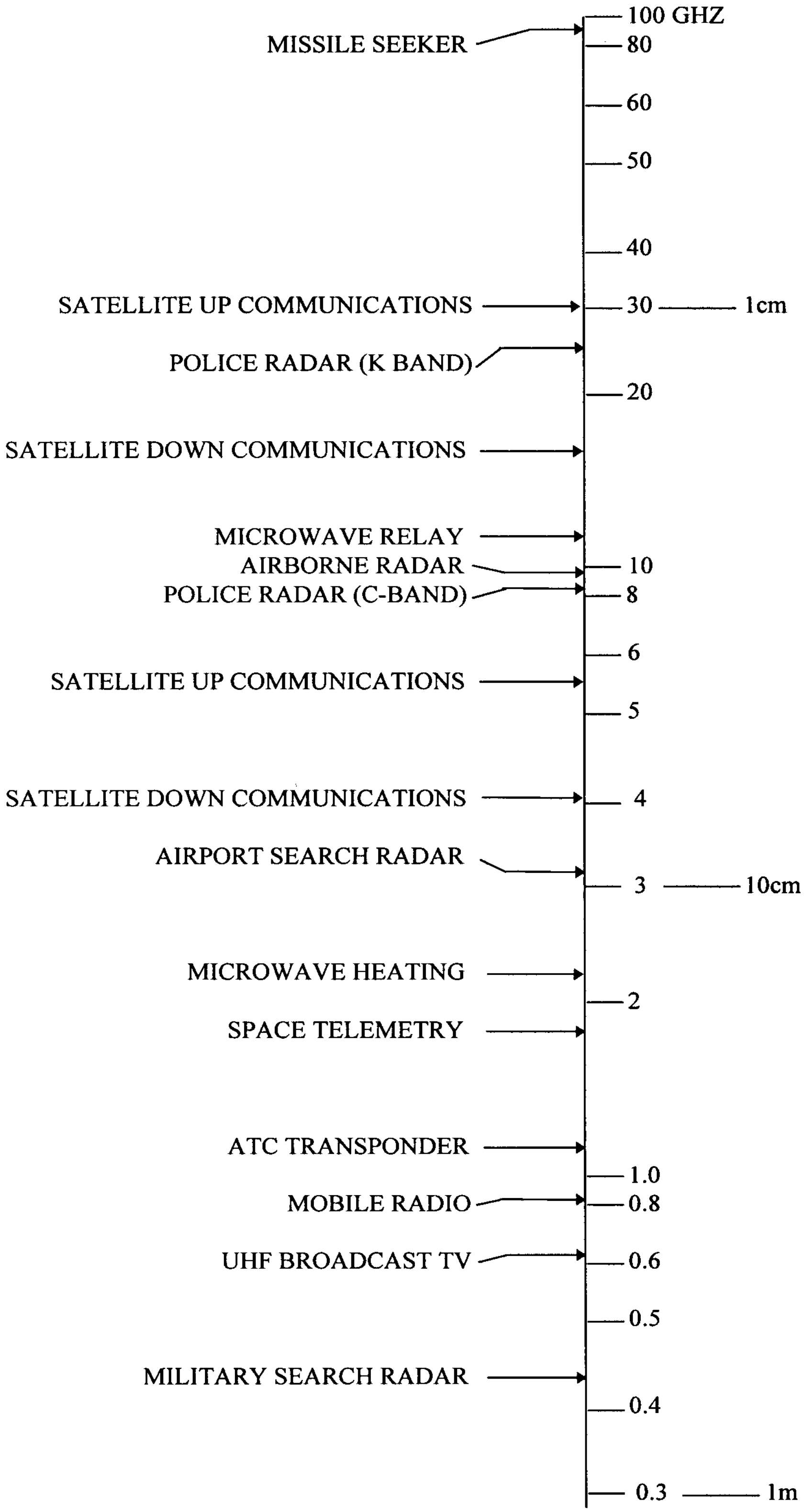

100 GHZ
80
60
50
40
30
20
10
8
6
5
4
3
2
1.0
0.8
0.6
0.5
0.4
0.3
1cm
10cm
1m
MISSILE SEEKER
SATELLITE UP COMMUNICATIONS
POLICE RADAR (K BAND)
SATELLITE DOWN COMMUNICATIONS
MICROWAVE RELAY
AIRBORNE RADAR
POLICE RADAR (C-BAND)
SATELLITE UP COMMUNICATIONS
SATELLITE DOWN COMMUNICATIONS
AIRPORT SEARCH RADAR
MICROWAVE HEATING
SPACE TELEMETRY
ATC TRANSPONDER
MOBILE RADIO
UHF BROADCAST TV
MILITARY SEARCH RADAR

Figure 8.3

8.1.2 ELECTRONIC WARFARE SUITE

The EW suite has become a critical element in all modern military aircraft and can significantly increase the survivability of aircraft engaged in hostile actions. The EW suite is a subset of the aircraft's EW system and deals primarily with the ESM and ECM components. An EW suite operates in a synergistic manner to detect, notify, and counter enemy threats, and is typically broken into four major components; each responsible for covering a portion of the electromagnetic spectrum. These components include:

a. Radar Warning Receivers (RWR) (RF spectrum)
b. Missile Warning Sensors (MWS) (IR spectrum)
c. Laser Warning Sensors (LWS)(visible and IR discrete spectrums)
d. Countermeasure Dispensing System (CMDS) (IR/RF Decoy and Jamming)

EW suites have evolved considerably over the past several decades with new and improved systems continually under development. The evolution of EW has increased the portions of the electromagnetic spectrum covered to gain advantage over enemy systems. High power, light weight, man-portable lasers are the latest and greatest technology to grace the EW arena.

The EW suite is a fully integrated system which interfaces directly with the cockpit management system (CMS), and in most cases, directly with the mission computer. In systems with automatic dispensing capabilities, this reduces the time between threat recognition and response. The EW suite itself has a primary controller and 1553 bus interface. In most systems, the radar warning receiver (RWR) functions as the primary controller and bus interface. All other systems; laser warning, missile warning, countermeasure dispensing and jamming, are controlled and report through the RWR. The RWR then reports EW status through the 1553 bus to the mission computer. Figure 8.4 shows a basic block diagram for a typical EW suite configuration.

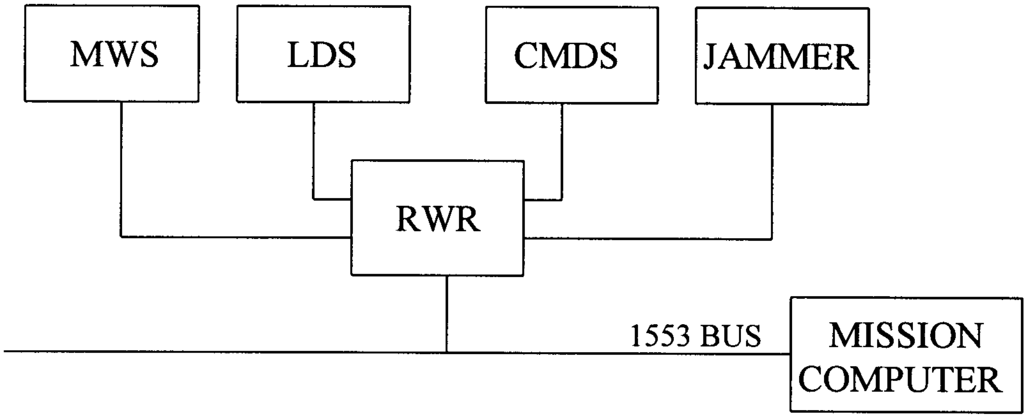


Figure 8.4

TYPICAL EW SUITE CONFIGURATION

All threats identified by the EW suite are displayed in the cockpit either through the CMS displays or a dedicated EW display. Each system varies in capability and reports information accordingly:

RWR - reports and displays bearing and type of emitter being received.

MWS - displays only quadrant information.

LWS - displays quadrant information and associated weapon system. New LWS' will have the capability of calculating bearing, range and laser frequency.

The EW sensor information is received and displayed based on prioritization in the RWR threat file memory system. The threat file memory system can be reloaded and revised to accommodate changing threat lethality and varying mission profiles.

8.2 RADAR WARNING RECEIVER EVALUATION

8.2.1 INTRODUCTION

A radar warning receiver must perform two basic tasks:

1) measure parameters of radar signals incident on the aircraft
2) analyze the measurements for appropriate response

The parameters measured and the accuracy of measurement vary from system to system, based on aircraft mission requirements, technology, and costs. The parameters available for measurement include time of arrival, pulse width, frequency, amplitude, polarization, and angle of arrival. Once the incident signal parameters are measured, they are analyzed to determine the source of the emissions. The depth of analysis varies, but usually involves comparison of currently measured parameters with threat emitter data previously collected by electronic intelligence or tactical reconnaissance missions. This data is stored in the RWR memory for comparison with incoming threat information. Such comparisons result in the identification of emitters by class (i.e., early warning, antiaircraft, surface-to-air missile) and type (i.e., SA-5, AIM-7, etc.). Finally, the identified threat and its angle of arrival are displayed to the aircrew and possibly used to control ECM systems. A typical radar warning receiver consists of four major components: antenna, receiver, processor and display. Figure 8.5 shows a basic RWR system block diagram.

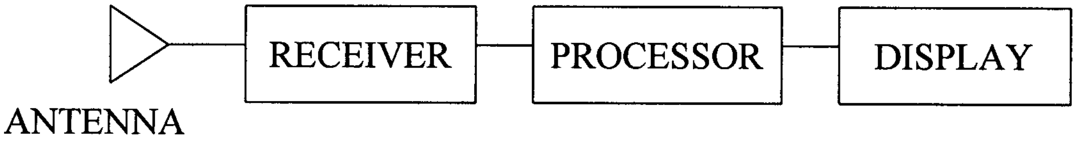


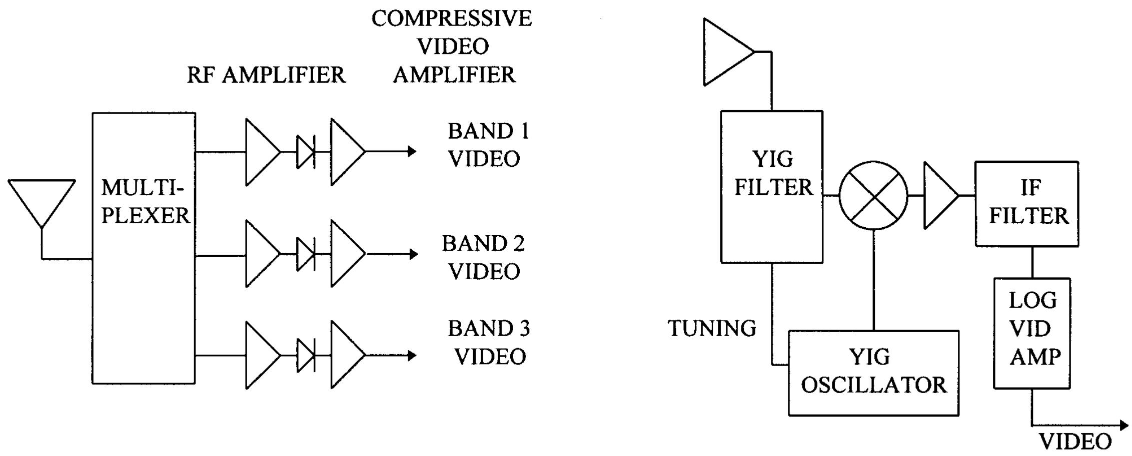
Figure 8.5

BASIC RWR SYSTEM

Major RWR system characteristics include the range of radio frequencies observed or RF bandwidth, the angular coverage provided about the aircraft, and the number and variety of incident signals which can be measured. The capabilities of receivers are highly dependent on the type of receiver design. Most receiver designs are trade-offs of several conflicting requirements. Figure 8.6 shows block diagrams of four common RWR receivers. Table 8.1 is a qualitative comparison of receiver characteristics and Table 8.2 is a quantitative comparison.

CRYSTAL VIDEO RECEIVER

YIG TUNE NARROWBAND SUPERHET



INSTANTANEOUS FREQUENCY MEASUREMENT (IFM)

WIDEBAND SUPERHET

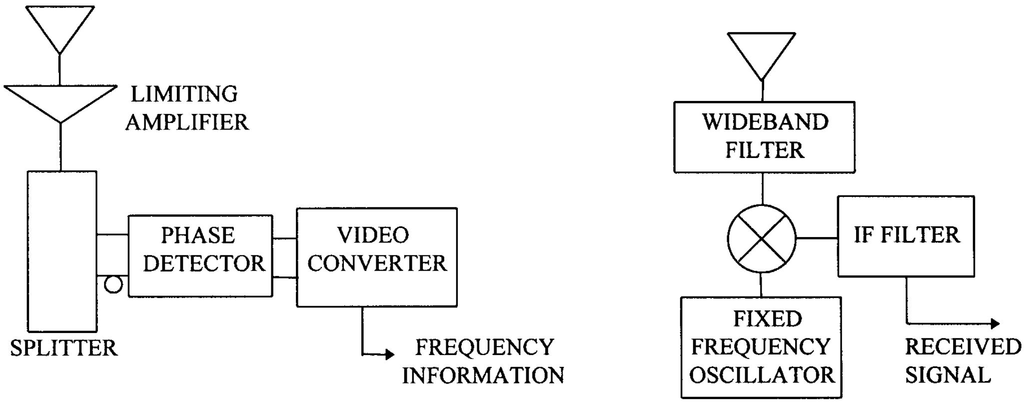


Figure 8.6

COMMON RWR RECEIVER BLOCK DIAGRAMS

Table 8.1

QUALITATIVE COMPARISON OF RWR's

	RECEIVER TYPE				
FEATURE	WIDE-BAND CRYSTAL VIDEO	TUNED RF CRYSTAL VIDEO	IFM	NARROW-BAND SUPERHET	WIDEBAND SUPERHET
Instantaneous Analysis Bandwidth	Very Wide	Narrow	Very Wide	Narrow	Moderate
Frequency Resolution	Very Poor	Fair	Good	Very Good	Poor
Sensitivity	Poor (no pre-amp) Fair (w/pre-amp)	Fair/Good	Poor (no pre-amp) Fair (w/pre-amp)	Very Good	Poor
Dynamic Range	Fair	Fair/Good	Good	Very Good	Fair
Speed of Signal Acquisition	Very Fast	Slow	Very Fast	Slow	Fast
Short Pulse Width Capability	Good	Good	Good	Good	Very Good
Retention of Signal Characteristics	Fair	Fair	Poor	Good	Fair/Good
Applicability to Exotic Signals	Poor/Fair	Poor	Good	Poor	Fair/Good
High Signal Density Performance	Poor (high false alarm rate from background)	Fair/Good	Good	Poor	Fair (Depends on Bandwidth)
Simultaneous Signal Capability	Poor	Fair/Good	Poor	Good	Fair (Depends on Bandwidth)
Processing Complexity	Moderate	Moderate	Moderate	Moderate	Moderate
Immunity from Jamming	Poor	Fair	Poor/Fair	Good	Poor/Fair
Size	Small	Small/ Moderate	Small/Moderate	Moderate	Moderate
Power Requirements	Low	Low/ Moderate	Moderate	Moderate	Moderate
Cost	Low	Low/ Moderate	Moderate	Moderate/High	Moderate/ High

Table 8.2

QUANTITATIVE COMPARISON OF RWR’s

	RECEIVER TYPE				
FEATURE	WIDE-BAND CRYSTAL VIDEO	TUNED RF CRYSTAL VIDEO	IFM	NARROW-BAND SUPERHET	WIDEBAND SUPERHET
RF Range (GHz)	Multi-Octave (0.5 - 40)	0.15 - 18 Separate	> 0.5 to 40	< 0.01 to 40	0.5 to 18
Max Instantaneous Analysis Bandwidth	Multi-Octave (to 17.5 GHz)	As high as desired w/reduction in resolution	Multi-Octave (1 octave/unit)	50 MHz	500 MHz
Frequency Accuracy	No better than analysis BW	No better than analysis BW	5 - 10 MHz	0.5% - 1%	0.5 to 3 MHz
Pulse Width Range	CW to 50ns	CW to 50ns	CW to ≈ 20ns	CW to 100ns with 20 MHz resolution	CW to 4ns with 500 MHz resol.
Frequency Resolution	≈ 400 MHz (no better than BW)	25 MHz	1 MHz	< 0.1 MHz	100-500 MHz
Sensitivity (dBm)	-40 (no pre-amp) -80 (w/pre-amp)	Better than -80 w/pre-amp	-40 (no pre-amp) -75 (w/pre-amp) 4 GHz BW	-90 1 MHz BW	-80 500 MHz BW
Maximum Dynamic Range (dB)	70	70-80	80 (w/pre-amp) 100+ (sat mode)	90	60
Tuning Time	---	50ms	---	1.0 s (1 octave)	.12 s (200 MHz Band)
Signal ID Time	100ns	50ms	2-10ms	≈ 0.1 s	---
Minimum Weight (lb)	20 (w/processor)	30	<20 (octave unit) ≈ 75 full coverage	60-75	35 (tuner only)
Minimum Volume (in^3)	300 w/processor	375	600-1000 (≈ 100 w/new technology	1500-3000	Several thousand
Minimum Power (Watts)	100 w/processor <10 w/o processor	60 w/o processor	≈ 50 (octave unit)	150	150 (tuner only)
Cost ($K)	20	50	75	125	100

Because of the large RF bandwidth the RWR must observe, the antenna is often a cavity-backed spiral antenna. Typically, four to six antenna elements, equally spaced around the aircraft, are positioned for 360 degrees of coverage and to allow for accurate determination of the threat’s angular location.

Using an example of a two antenna system, the signal from a threat is received by the two antennas with different gains and an associated phase shift (assume a planar wave) due to the difference in distance the wave travels to the two receivers. These differences result in two signals of different amplitudes and phase at the antenna outputs. The difference in signal amplitude and phase yields the threat direction.

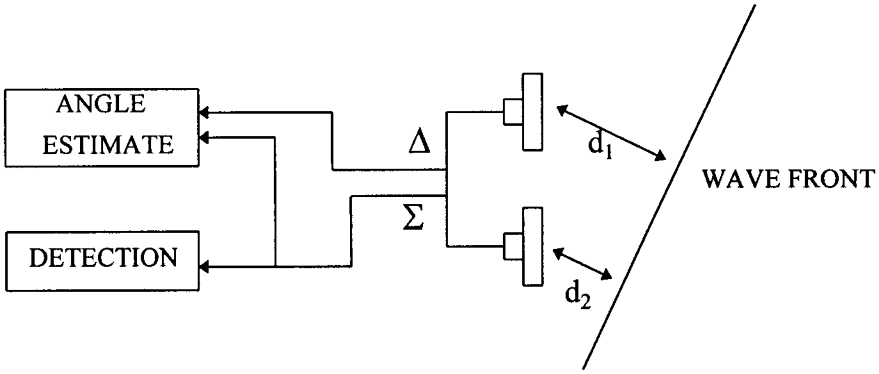


Figure 8.7

RWR DIRECTION OF ARRIVAL ANALYSIS

There are several difficulties which must be accounted for when designing, building, and testing RWR systems:

1. Detection difficulties - to avoid detection or countermeasure action, modern weapons systems signals are frequently subjected to programmed or even random changes in character (i.e., radio frequency, pulse repetition frequency, pulse width, etc.). These changes greatly compound the intercept and identification problems.
2. Wide frequency ranges to be monitored - in general, the intercept receiver must monitor a total radio frequency band. This band is substantially greater than the individual frequency ranges of the signals to be detected within this band.
3. Wide dynamic ranges encountered - the wide range in the received signal level is enormous. Because of the one-way transmission to the intercept receiver (versus the two-way action that may be required for the emitting system), signal levels are usually very high. In this case, high sensitivity is unnecessary (and undesirable because of the possible introduction of lower-level interfering signals). However, the intercept receiver may, in another circumstance, be required to intercept a low-power transmission from minor lobes of a transmission antenna and from great distance. This case requires the maximum sensitivity possible. An RWR system for general use, then, must be prepared to operate over a very large dynamic range.
4. Presence of false signals - there is always the threat of decoy signals produced by the enemy in an attempt to confuse the receiver system. This is done by subtly modifying the “fingerprint” of the emitting signal. There is also the stray RF noise produced by nonthreatening sources which are inherent in the atmosphere. While it is not the job of the RWR to make fundamental decisions in such matters, it is important that the RWR not introduce further confusion by the inability to handle the received data without further distortion or modification.

Once the signal has been received by the RWR antennas and receiver, the measured parameters are passed to a signal processor that actually identifies the emitter. The processor analyzes the large quantity of individually sensed pulses and sorts them by parameter. For example, the data passed to the processor for each detected pulse may include angle of arrival, frequency, amplitude, pulse width, and time of arrival. These items are sorted within the processor and analyzed to determine the characteristics of the RF signal incident on the aircraft. The measured characteristics are matched against previously determined threat data to obtain a "best" fit and to identify the emitter.

The processor provides its findings either to the automated controller of the ECM system or to displays for aircrew observation and action. Such displays range from a few panel lights indicating the presence and status of a threat to computer-controlled video displays. The RWR must be both ground and flight tested. The following are items which must be tested to ensure proper RWR performance and functionality. They include:

a. False Alarm and Blanking Problems
b. Antenna Coverage/Direction Finding Capability
c. Line Loss and Voltage Standing Wave Ratio (VSWR) Measurements
d. System Sensitivity/Threat Detection Range
e. Threat Identification (Emitter ID)

8.2.2 FALSE ALARM MONITORING

8.2.2.1 PURPOSE AND METHOD

False alarms in the system can be induced by extraneous noise in the aircraft wiring, interference problems between an aircraft emitter (i.e., radar, radar altimeter, etc.) and receiver, or too high a sensitivity level. False alarms must be fully investigated so that a reliable system can be developed with confidence in what is being observed by the receivers. False alarm data is collected at all times during ground and flight tests. The system must be sensitive enough to discern enemy threats while at the same time being able to filter extraneous RF which can lead to a false alarm. False alarm monitoring is extremely important when developing blanking boxes to prevent receivers from operating when on-board emitters (air-to-air/air-to-ground radar, radar altimeter, etc.) are pulsed. Unusually high false alarm rates numb the aircrew to warnings thereby decreasing the efficiency of the overall system. In a number of systems, false alarm rates have been so high that aircrew habitually turn the system off rather than endure the constant ringing of false warnings.

8.2.2.2 DATA REQUIRED

- Time: When the false alarm occurred (GPS or IRIG).
- Place/Environment: Where was the system when the false alarm occurred.
- Indications: What EW symbology was displayed as to the perceived threat.
- Aircraft Status: What other systems on the aircraft where operating at the same time (usually requires a 1553 bus recording system)

8.2.2.3 DATA REDUCTION

Data reduction for false alarms requires deductive reasoning and analysis. The difficulty is in determining, from the data, the cause of the false alarms. Any patterns seen which can be correlated to either time, place or bus traffic can be extremely important when trying to isolate the causes. Once the cause is isolated, actions such as hardware or software filtering can aid in reducing or eliminating the problem.

8.2.3 ANTENNA COVERAGE/DIRECTION FINDING CAPABILITY

8.2.3.1 PURPOSE AND METHOD

The purpose of this test is to determine the antenna coverage and direction finding accuracy of the RWR system. This test is usually conducted in-flight due to the requirement that the emitter be far enough away that the received RF wave be essentially planar. This distance is typically large enough as to make ground testing impractical. A planar wave is critical to ensure correct directional accuracy of the system. To conduct the test, a signal of known characteristics is radiated from a stationary source and received by the antennas. When the signal is detected, observations are made to verify that the RWR displays the perceived threat at the correct location on the display. When the test signal is either not detected or is detected and displayed incorrectly, the location of the source in reference to the aircraft is recorded and plotted. This process is repeated for 360 degrees around the aircraft. Data can be collected by flying clockwise or counterclockwise circles at a known distance from the emitter. Climbs and dives while maintaining the same relative heading in relation to the emitter can also be used. All data points should be repeated to account for statistical deviations and should be flown at various bank angles and pitch attitudes to ensure true mission analysis.

8.2.3.2 DATA REQUIRED

- Time: IRIG or GPS time at both the emitter and aircraft
- Aircraft Location: Exact aircraft location (GPS, INS, or laser tracker)
- Emitter Location: Surveyed or GPS equipped emitter site
- Attitude: Aircraft attitude relative to the emitter site
- Heading: Aircraft heading in relation to the emitter site
- RWR Display: Bus traffic or time synched video

8.2.3.3 DATA REDUCTION

Aircraft position relative to the emitter is determined and a straight line drawn between the two locations. The aircraft heading relative to this line should determine true direction (aircraft frame of reference) to the emitter. This is compared to the direction determined by the RWR system. The difference between the RWR determined direction and the true direction is the angular error. With a perfect installation, the angular error will equal the RWR resolution limit.

8.2.4 LINE LOSS AND VOLTAGE STANDING WAVE RATIO (VSWR)

8.2.4.1 PURPOSE AND METHOD

Line loss and VSWR measurements are ground tests which are performed to ensure that aircraft wiring does not significantly degrade the RWR system performance. Line loss and VSWR must be measured on all radio frequency (RF) lines across all frequencies considered operational and detectable by the RWR. Line losses are evaluated by injecting a signal of known amplitude into one end of the RF Line Under Test (LUT). The signal is swept over the operating frequency of the LUT and the signal level emerging from the other end is measured. After sweeping all frequencies, a plot of line loss vs. frequency is plotted. This loss adds to the minimum sensitivity of the RWR itself giving an increased minimum detectable signal level when airborne. VSWR is calculated by injecting a known signal into one end of the LUT and measuring the signal level reflected back out the same end. This is a measure of how much the transmitted power is attenuated due to reflection. This attenuation is due to a mismatch in load impedance at the end of the LUT. A plot of VSWR vs. frequency is plotted to determine the properly matched load to reduce the VSWR. A matched load is attached to the opposite end of the LUT and VSWR checked again. If the load is matched correctly, the VSWR will be minimal and should not significantly increase the minimum detectable signal level of the system.

8.2.4.2 DATA REQUIRED

- Line loss vs. Frequency
- VSWR
- Matching load impedance

8.2.4.3 DATA REDUCTION

Plot line loss and VSWR vs. frequency and determine how each effect the overall sensitivity of the RWR system. Determine if the load impedance for the RWR is correctly matched. Evaluate how the losses effect the minimum detectable signal level of the overall RWR system.

8.2.5 SYSTEM SENSITIVITY/THREAT DETECTION RANGE

8.2.5.1 PURPOSE AND METHOD

System sensitivity is a ground test which evaluates the minimum signal level detectable by the RWR and determines the system threat detection range. This check is performed to ensure the system is operating at full signal sensitivity. Test equipment capable of simulating a wide cross section of threats over a large power output is required. Pulsed, pulse Doppler, and continuous wave signals are injected into the RWR antenna ports and analyzed. The test starts with the lowest possible power output and is increased until the threat is correctly displayed by the system. The power output is recorded and subtracted from the test cable line loss to obtain the system sensitivity. This process is repeated for each threat type, each antenna quadrant, and for statistical repeatability. Threat detection range can be backed out knowing emitter power output. Flight test may be conducted to verify threat detection range and account for atmospheric variables.

8.2.5.2 DATA REQUIRED

- Threat simulated
- Minimal detectable signal level
- System Sensitivity

8.2.5.3 DATA REDUCTION

System sensitivity is evaluated to ensure proper system operation. Threat detection range is calculated for each threat based on the system sensitivity results (refer to chapter on radar theory) and the power output from each emitter. Line loss and VSWR must be taken into account when determining threat detection range for the overall system.

8.2.6 THREAT IDENTIFICATION (EMITTER ID)

8.2.6.1 PURPOSE AND METHOD

Threat identification is the ability for the RWR to identify intercepted threats by class (i.e., early warning, antiaircraft, surface-to-air missile, air-to-air radar, etc.) and type (i.e., SA-5, AIM-7, etc.). The RWR's memory system is programmed with Emitter Identification Data (EID) tables which contain characteristics of known threat emitters. Each RWR antenna port is ground tested by connecting it to a tactical electronic threat simulator capable of simulating a large cross-section of radar threats. The simulator injects a signal of known characteristic into the antenna ports and the system is evaluated for correct display symbology, audio warning clarity, time to ID, and time to announce. If a threat simulator cannot be obtained, flight test may be conducted at an EW range and the system flown against actual threat signals.

8.2.6.2 DATA REQUIRED

- Time: IRIG or GPS at the simulator and on the 1553 bus
- Threat simulator: power and frequency
- EW Display: threat identified (symbol and quadrant)
- Identification time
- Aural warning time
- Aural warning clarity (qualitative)

8.2.6.3 DATA REDUCTION

The EID table is verified for the threats simulated. Time required to identify and announce the threat are analyzed for specification and mission suitability. Audio warnings are qualitatively analyzed for clarity, brevity, and usefulness.

8.3 MISSILE WARNING SYSTEM EVALUATION

8.3.1 INTRODUCTION

The missile warning system (MWS) is designed to perform one basic task: aircrew warning of a missile launch. Once a warning has been displayed, the aircrew determines the appropriate response whether it be countermeasures dispensing, evasive maneuvers, or both. The MWS consists of several electro-optic devices which detect the infrared (IR) energy emitted by the high temperature plume of the missile's boost or ignition phase. The sensors in the MWS receive the infrared energy from the missile and translate that energy into an electrical signal. The sensitivity of the system is set at a threshold to limit the number of false detections due to normal infrared energy in the environment. The MWS is analogous to the RWR system except it operates to detect infrared (IR) energy as opposed to RF. A breakout of the optical spectrum is given in Figure 8.8 below.

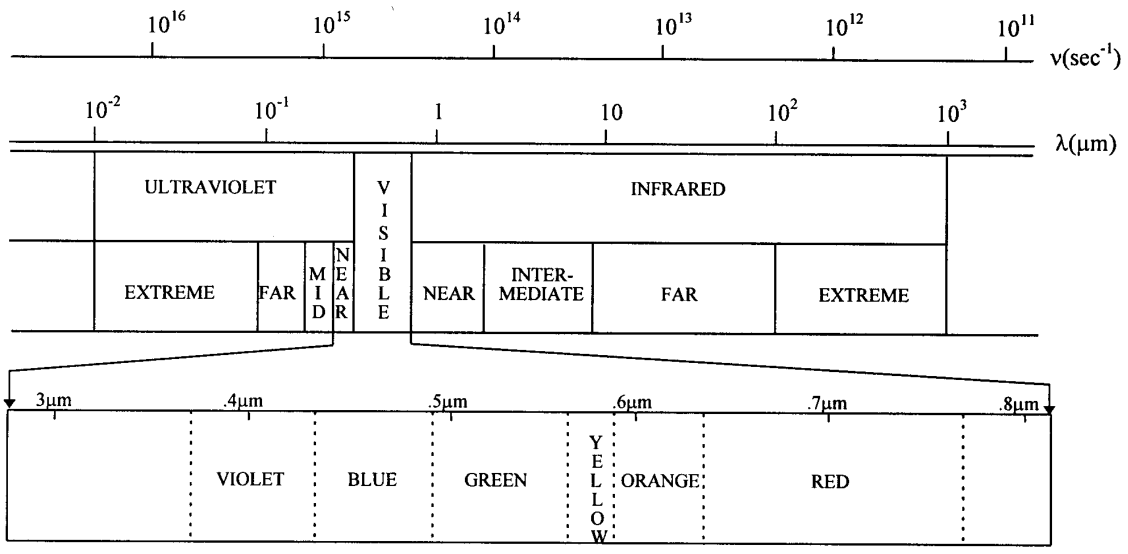
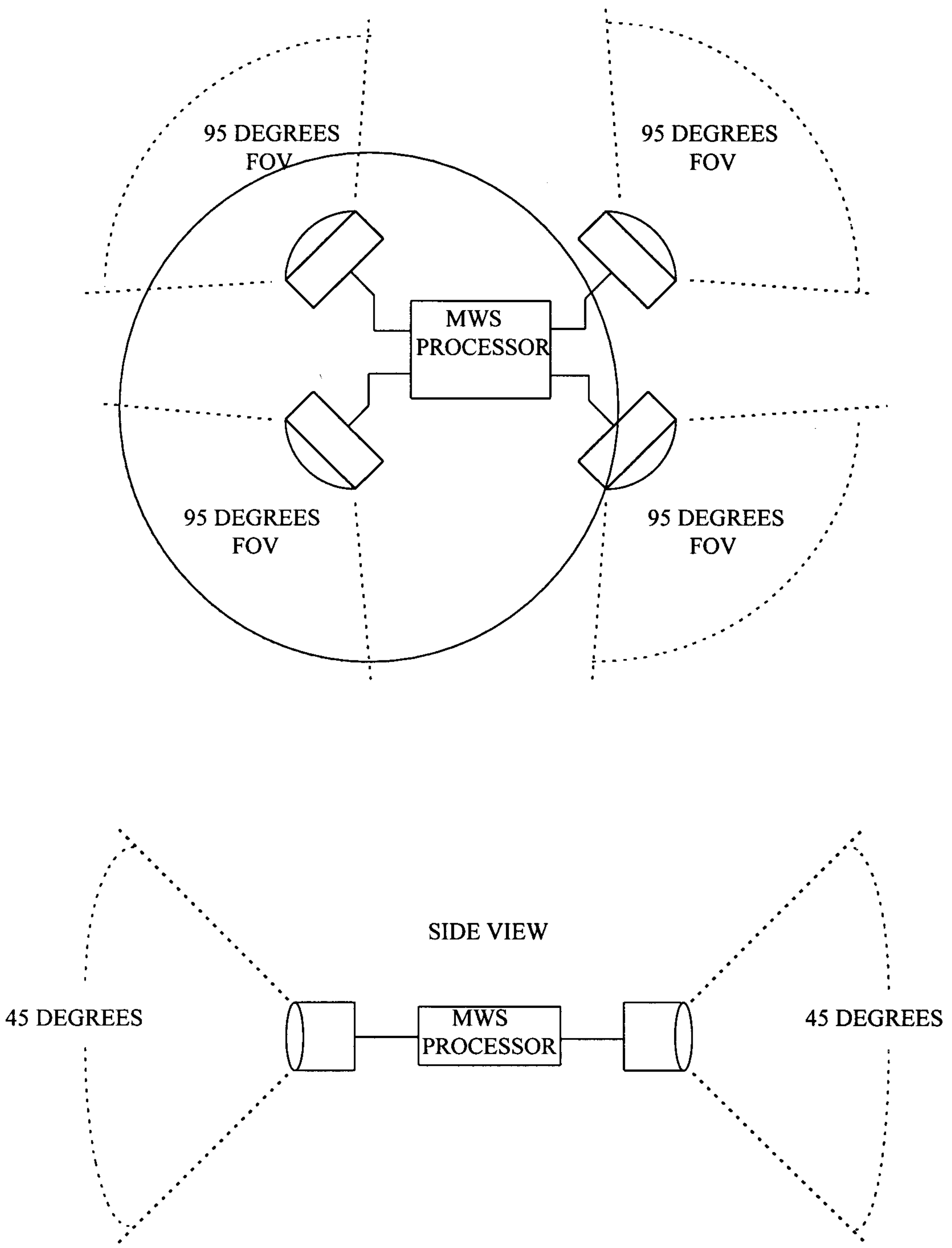


Figure 8.8

OPTICAL SPECTRUM

MWS' do not provide great amounts of information about the incoming threat as do RWR's. Current MWS' cannot identify missile class or type nor can they resolve azimuth accuracy with anything greater than quadrant (assuming 4 equi-spaced sensors) information. Instead the system provides only warning of missile launch and the quadrant (90 degrees) from which it is inbound. Typically four MWS sensors are placed at the four quadrants of the aircraft oriented to centerline similar to that shown in Figure 8.9. Each sensor is responsible for detection within its field of view (FOV). The FOV usually provides some degree of overlap with the adjacent sensor to allow for 360 degree coverage as well as coverage in the vertical. Coverage in the vertical is usually ±45 degrees of elevation. These sensors can be wired directly to the countermeasure dispensing system (CMDS) for automatic dispensing capability. Since different missiles burn at different specific temperatures (due to fuel used) and have varying burn times, new MWS' are being developed which can isolate the burn temperature and time in order to more clearly identify the type of missile launched. This coupled with the CMDS and a specified dispensing routine can greatly increase the probability of defeating a threat. Also, new MWS' are being designed which operate in association with aircraft mounted lasers. These systems use an intricate tracking system to blind IR missiles by lasing the optics in the seeker head. These new systems are not intended for discussion but are only mentioned to educate the reader of new technologies available in the future.



TOP VIEW

SIDE VIEW

Figure 8.9

MWS LAYOUT

The MWS mechanics are very similar to that of a forward looking infrared (FLIR) system as described in Chapter 6. Like the FLIR, the MWS uses electro-optic sensors to absorb infrared energy and convert it into an electrical signal, however, unlike the FLIR, their is no requirement for the MWS to convert that signal into imagery. Referring to Chapter 6, Equation 6.3.1 and Figure 6.3.2 show Plank's Law and the relationship between the absolute temperature of a body, the wavelength of the emitted radiation, and the intensity of the radiation emitted. Most missile systems have exhaust plumes that burn anywhere from 600 - 1,000 degrees Celsius. Using Plank's Law, this results in a peak radiative wavelength of between 2 and 5 microns. Knowing the energy spectrum the system is to be designed around, a detector needs to be selected. MWS systems operate with either discrete photodetectors or thermal detectors. Each has its own distinct advantages and disadvantages, however, in most MWS' the former is used more frequently.

Discrete photodetectors detect specific frequencies of IR or visible energy. Since missile plumes generally emit a peak radiative energy at a specific wavelength (i.e., 2-5 μm), a discrete detector designed to detect these frequencies can reduce false alarm rates and increase the probability of detecting a true missile launch. The disadvantage is that while a missile has a peak radiative emittance at a specific wavelength, Plank's law shows that it still emits energy across the entire electromagnetic spectrum. Discrete element detectors tend to discard all but the wavelengths they are tuned to receive. This can be a large portion of the entire energy emitted by the missile thereby decreasing their sensitivity and increasing the likelihood of missing a missile launch.

Thermal detectors detect photons across the entire electromagnetic spectrum. Although this increases the relative sensitivity of the system and the probability of detecting an actual missile launch, it also increase the rate of false alarms due to the radiative energy that exists in the atmosphere on a day to day basis. Therefore, the sensitivity of these devices must be intentionally decreased in order to reduce the false alarm rate of the system.

The MWS must be both ground and flight tested. The following are items which must be tested to ensure proper MWS performance and functionality. They include:

a. False Alarm Monitoring
b. Optical Sensor Coverage/Field of View
c. Missile Threat Identification and Location
d. System Sensitivity/Threat Detection Range

8.3.2 FALSE ALARM MONITORING

8.3.2.1 PURPOSE AND METHOD

False alarms in the system can be induced by extraneous noise in the aircraft wiring, interference with other avionics systems, or too high of a sensitivity level. False alarms must be fully investigated so that a reliable system can be developed with confidence in what is being observed by the receivers. False alarm data is collected at all times during ground and flight tests. The system must be sensitive enough to pick up the IR energy of a missile launch while at the same time not be so sensitive that the IR emitted by the background environment causes a continual false alarm problem. Just as with the RWR, unusually high false alarm rates numb the aircrew to warnings thereby decreasing the efficiency of the overall system. This is particularly true in systems which warn the aircrew of impending and possibly lethal danger. If the system is not reliable, the aircrew will not use it.

8.3.2.2 DATA REQUIRED

- Time: When the false alarm occurred (GPS or IRIG).
- Place/Environment: Where was the system when the false alarm occurred.
- Indications: What EW symbology was displayed as to the perceived threat.
- Aircraft Status: What other systems on the aircraft where operating at the same
- Time (usually requires a 1553 bus recording system)

8.3.2.3 DATA REDUCTION

Data reduction for false alarms in the MWS is exactly the same as for the RWR. It requires deductive reasoning and analysis. With the MWS the difficulty is in determining if the environment or the aircraft itself is responsible for the false alarm. Any patterns seen in relation to location, time, or system operation can be extremely important when isolating causes. Once the cause is identified, actions such as hardware or software sensitivity changes can aid in reducing or eliminating the problem.

8.3.3 OPTICAL SENSOR COVERAGE

8.3.3.1 PURPOSE AND METHOD

The MWS optical sensor coverage must be evaluated for FOV and aircraft blockage. All sensors are replaced with special video cameras which have FOV coverage identical to the MWS sensors. The cameras can be connected to television monitors and the FOV as well as any aircraft blockage recorded.

8.3.3.2 DATA REQUIRED

- Aircraft blockage
- FOV of each sensor

8.3.3.3 DATA REDUCTION

From the collected FOV data, angular coverage both in azimuth and elevation can be determined. All aircraft blockages are evaluated and a determination made as to complete aircraft coverage and the mission impact and suitability if full coverage is not provided.

8.3.4 MISSILE THREAT IDENTIFICATION AND LOCATION

8.3.4.1 PURPOSE AND METHOD

Missile threat identification (Emitter ID) and location are evaluated to determine if the system detects and displays the proper threat at the proper location. Each sensor is individually tested by connecting a hand held missile warning test set to the sensor under test and stimulating it with known patterns to determine response. The sensor is tested against all known and available threats for comparison with the emitter identification data (EID) tables. The system is evaluated for correct display symbology and location, audio warning clarity, time to ID, and time to announce. All display and bus traffic should be recorded for later evaluation.

8.3.4.2 DATA REQUIRED

- Time (IRIG or GPS)
- EW display
- Time to identify
- Time to display

8.3.4.3 DATA REDUCTION

The data is evaluated for correct threat identification and location. The EID table is verified for the threats simulated. Time to identify, display and provide aural warning of the threat are evaluated for latency and operation effectiveness. Audio warnings are qualitatively evaluated for clarity, brevity, and usefulness.

8.3.5 SYSTEM SENSITIVITY

8.3.5.1 PURPOSE AND METHOD

MWS system sensitivity is evaluated to determine the minimum detectable IR signature required to alert the system. This is critical as was discussed in the introduction 8.3.1. System sensitivity tests can be conducted using both ground and flight tests. The sensitivity on the ground is determined by injecting a low energy threat signal into the MWS sensor and increasing the energy until a detection occurs. This is repeated for each threat and determines the minimum detectable signal level. Flight test should be conducted to ensure that the environmental background does not significantly alter the system performance and that atmospheric conditions have been accounted for properly. Flight test should be conducted over a variety of terrain and from sparsely to densely populated areas. Man-made objects are typically the source of false signals so a large cross-section of man-made targets should be investigated. Flight test should also be conducted over days with large temperature differences. This testing can be done in conjunction with the false alarm testing.

8.3.5.2 DATA REQUIRED

- Time: IRIG or GPS
- EW Display: threat identified (symbol and quadrant)
- Threat Simulated: power and wavelength
- Identification time
- Aural warning time
- Aural warning clarity (qualitative)

8.3.5.3 DATA REDUCTION

The minimum detectable IR signature level is determined from the injected source signal. After flight test, a determination is made as to whether or not the sensitivity level is correct. Correct sensitivity level is determined by the number of false alarms occurring in a given time period. If the sensitivity is too low, numerous false alarms will occur and the system may be required to be corrected and the process repeated again. This is an iterative process that is complete when the false alarms are reduced to an acceptable level while not significantly impacting the detection of threat signals.

8.4 LASER WARNING SYSTEM EVALUATION

8.4.1 INTRODUCTION

Laser warning provides warning of active laser engagement with either the aircraft or the aircrew. Lasers have proliferated greatly in the last decade and are rapidly becoming the weapon of choice for poorer nations. Lasers are light, compact and simple to operate. The destructive capability behind the laser should not be underestimated. Although man-portable lasers create no structural damage, they can seriously blind or damage an aviators eyes effectively rendering the same result. Lasers are also used as guidance for weapons systems designed to engage ground or airborne targets. Laser warning systems are becoming ever more critical with the development of small high power lasers which can create irrepairable eye damage in extremely short time periods (microseconds). There are currently no countermeasures for lasers and goggles used to filter laser frequencies are the only protection for aircrews. Laser goggles can filter numerous laser frequencies, but more and more, laser goggles are becoming impractical with the development of frequency agile lasers. Filtering all frequencies used by lasers results in an opaque visor; the exact situation attempted to be corrected.

Laser is an acronym for Light Amplification through Stimulated Emission of Radiation. The physics involved with laser design and construction are quite complex and will not be gone into great detail here. It is sufficient for our purposes to learn the unique characteristics of lasers and how laser warning receivers are used to exploit these characteristics.

Lasers have several unique properties that are not typically found in nature or other man-made systems. The following are a few examples:

1. Coherency
2. Frequency/Wavelength Specific
3. Pulsed and Continuous Wave (CW) capabilities
4. Narrow Beam Divergence
5. Rapid Pulse Rise Time

Coherency: Coherency is the property of optical energy in which all photons of a specific frequency also have the same phase. This is an extremely important property of lasers. The most basic way to visual photons of the same phase is to visual a photon similar to that of a sine wave. Photons which are in phase have the peaks and troughs of the sine wave match up. Photons which are not in phase always cancel out a portion of each others energy. Natural light (i.e., sunlight, light bulbs, etc.) has little to no coherency.

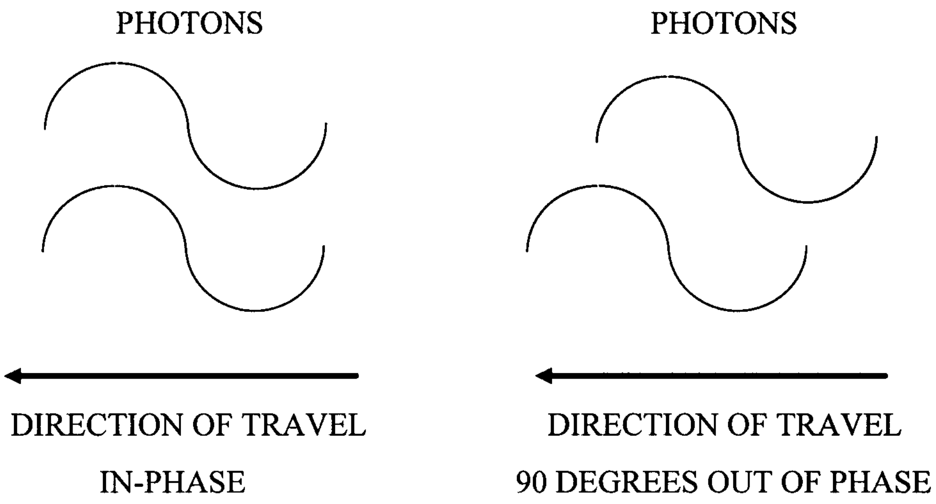


Figure 8.10

COHERENCY OF LASER LIGHT

This property can be exploited by developing a coherent energy detector. This is accomplished by developing optical filters which discriminate to 1/4 wavelength the frequency to be detected. This is the type detector used in several operational laser warning systems.

Frequency/Wavelength Specific: Frequency/Wavelength specific is the property in which only one wavelength of optical energy is emitted at any one time. Lasers by their definition operate over an extremely narrow frequency range (i.e., ± 0.1 micron $\approx 3 \times 10^{15}$ Hz). This is a quantum mechanical property of lasers inherent in their ability to operate. Laser detectors must therefore be designed to detect numerous isolated frequencies. This becomes increasingly difficult with day-to-day development of new lasers. Band detectors are therefore developed which detect optical energy across a broad frequency spectrum. Lasers are classified into bands such that each band detector may pick up a number of different lasers. Laser identification is then classified within the band which it falls.

Pulsed and CW operation: Most lasers are pulsed in order to get the maximum amount of energy on target over the shortest period of time. Continuous wave lasers do exist but their power output per time period is significantly diminished due to the long duration of operation. Pulsed operation can range from picosecond (10^{-12} seconds) PRI's out. Examples of power difference between CW and pulsed laser is as follows:

If a CW laser of 1 milliwatt is continuously lased, the power output is 1 milliwatt. However, if a pulsed laser with a 1 nanosecond pulse time and 10^3 PRF (pulsed repetition frequency of 1,000 time per second) is used for the same power laser, the effective power per pulse is 1000 watts; 1,000,000 times that of the CW laser.

Beam Divergence: Most lasers used in military applications have very narrow beam divergence. This is a measure of how much the beam spreads with distance. Most lasers diverge less than 0.1 milliradian. For a circular beam, 0.1 milliradian corresponds to an increase in radius 0.1 foot per 1,000 feet. Assuming an output spot size of 1mm^2 or less at the laser exit port, at 1nm (6,000 ft) the beam would be 0.6 feet or less in radius. This results in only 1.1 square feet of surface area. Because the laser must directly impinge on the detector for a warning, the smaller the divergence, the more difficult the laser is to detect. This is due to the fact that coherent detectors cannot detect most laser reflections. With the exception of aerosol scatter (scatter due to the atmosphere) at close range, most reflections result in the loss of coherency. Depending on the range of the target being lased, some laser detectors will detect aerosol scatter thus widening the acceptable miss distance. However, aerosol scatter at long ranges loses its coherent characteristic and therefore cannot be detected by most laser detectors. Only at short distances can aerosol scatter be detected. Likewise, once the laser impinges on the aircraft, all reflections off the aircraft tend to be noncoherent due to imperfections on the aircraft's surface. Typically, only high quality polished mirrors accurately reflect lasers without disruption to their coherency. Port scatter is typically filtered at the laser output and loses its coherency at much shorter ranges than does the aerosol scatter. Therefore, as can be seen in Figure 8.11, for small beam divergences laser warning receivers may need to be place relatively close together to ensure detection.

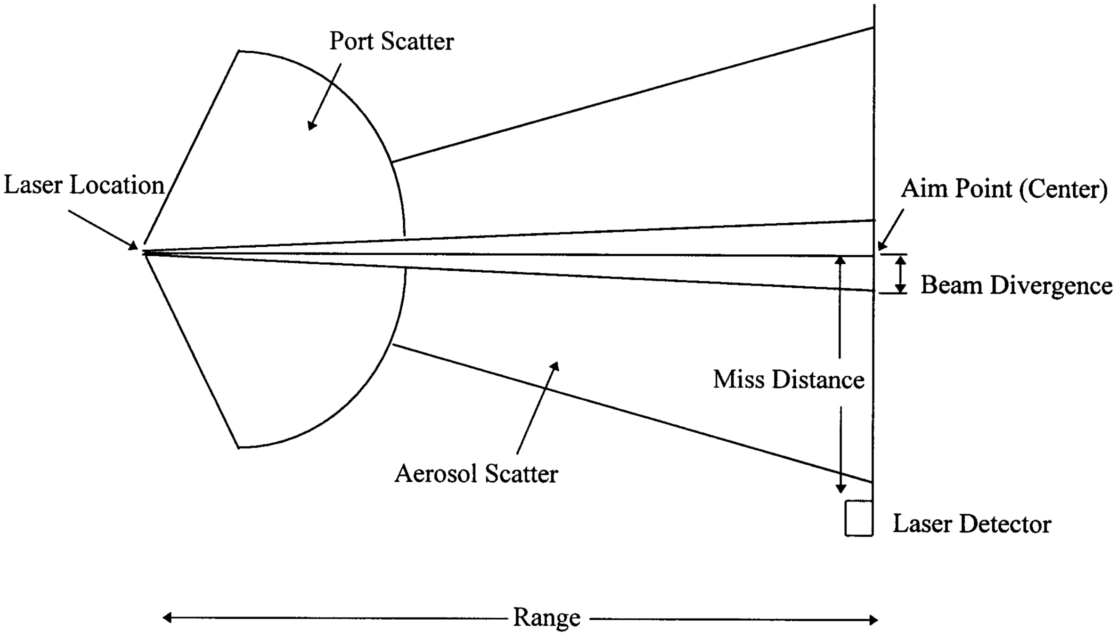


Figure 8.11

LASER BEAM DIVERGENCE

<u>Pulse Rise Time:</u> Pulse rise time is another unique property of lasers. Pulse rise times are on the order of picoseconds or shorter. Flash lamps and lasers are currently the only two optical emitters with such rapid rise times. Detectors can also be made to measure the rise time of the intercepted pulse to determine if it meets the criteria for a laser. This

is another method which has been used in the development of laser warning receivers. These types of receivers have both advantages and disadvantages. Because they no longer require the beam to be coherent, the receivers can intercept port scatter, aerosol scatter, and aircraft reflections. This requires significantly fewer detectors for complete aircraft coverage. The disadvantage is that these detectors cannot detect CW lasers thereby increasing their vulnerability to some range finders and designators. Location of the laser warning receiver on the aircraft is very similar to that of a missile warning system (MWS). Typically, four detectors are placed at the four quadrants of the aircraft with FOV coverage similar to that of the MWS. FOV is really a misnomer when dealing with highly directional weapon systems like lasers. A laser fired within the classical FOV of the detector will not be detected unless the beam impinges on the receiver. This becomes the primary factor when debating the number of sensors placed on an aircraft. Unlike a MWS which alerts to any missile launch within its FOV and sensitivity limits, whether or not the missile is directed at it, a laser warning system alerts only if the laser is aimed directly at a detector. Because of the beam divergence, lasers from long distance create the largest spot size and are therefore most likely to be detected. However, lasers from short distances, like 300 yards, may create a spot size no more than a couple square inches. This could easily miss detection. To add to the problem, the shorter the range the more dangerous lasers become. Its therefore advisable to provide coverage at the minimum range deemed operationally significant.

Military lasers are usually assigned to three categories:

1. Range Finders - Range finders are associated with anti-aircraft artillery, field artillery and mortars. A range finder can accurately determine the range of the target which can then be fed back into the weapon system for more accurate delivery.
2. Designators - Designators are used to illuminate a target so that a weapon system designed to home in on the reflected laser energy can engage the target. Designators are typically used in air-to-surface and surface-to-surface systems.
3. Beam Riders - Beam riders are an anti-aircraft weapon which use a laser for steering guidance. Beam riders are a line of sight weapon which are steered by the operator using a wide beam divergence laser. Currently there are no known countermeasures to defeat the system other than breaking line of sight with the beam riders operator.

New lasers designed specifically to blind are becoming more common, however, all the above lasers can also double as blinding lasers. Because of the relative newness of laser detecting systems, test techniques are continually being developed. Some of the most common tests for laser systems are as follows:

False Alarm Monitoring
Sensor Coverage
Threat Emitter Identification
System Sensitivity

8.4.2 FALSE ALARM MONITORING

8.4.2.1 PURPOSE AND METHOD

False alarms in the system are most commonly due to extraneous noise due to high bonding resistance. Because lasers detectors use discrimination characteristics which are not seen in nature or other man-made systems, false alarms due to environment effects are rare and can therefore be narrowed down to integration of the system in the airframe. Because of the high sensitivity to stray voltage and current, extremely low bonding resistance is required in order to obtain optimal performance from the system. This becomes exceedingly difficult when attempting to bond the system to a composite or other than metal frame. False alarms must be fully investigated so that a reliable system can be developed with confidence in the receivers ability to detect laser emissions. Unusually high false alarm rates numb the aircrew to warnings thereby decreasing the efficiency of the overall system. False alarm data is collected at all times during ground and flight tests. System false alarms must be thoroughly evaluated in flight, especially for composite airframes. Composite airframes in both fixed wing and rotary wing aircraft have a tendency to build-up static charge under flight conditions due to friction between the air and the skin of the aircraft. If bonding of the system to the skin of the aircraft results in a high resistance to ground, static arcing may occur thereby setting off false warnings. A similar circumstance can occur when testing in an electromagnetic environment. Flight conditions typically represent the worst case for developing false alarms.

8.4.2.2 DATA REQUIRED

- Time: The time the false alarm occurred.
- Place/Environment: Where was the system when the false alarm occurred.
- Indications: What EW symbology was displayed as to the perceived threat.
- Aircraft Status: What other systems on the aircraft were operating at the same time
- Time (usually requires a 1153 bus recording system)

8.4.2.3 DATA REDUCTION

Like all other sensor systems, data reduction for false alarms requires deductive reasoning and analysis. The difficulty in determining the source of the false alarm is reduced when compared to other systems due to the elimination of outside sources such as the environment. Any patterns seen which can be correlated to time, place, or bus traffic can be extremely important when trying to isolate causes. If the cause is isolated, a number of actions from decreasing the grounding resistance to software changes can help reduce or eliminate the problem.

8.4.3 SENSOR COVERAGE

8.4.3.1 PURPOSE AND METHOD

Sensor coverage for laser warning is used to evaluate FOV coverage of the sensors with respect to the aircraft, or in other words, determine the number of sensors required to provide sufficient aircraft coverage for varying ranges. It is also used to evaluate possible aircraft obstructions. As was discussed previously, FOV is really a misnomer when dealing with directional weapons like lasers. Typically the number of sensors is directly proportional to the size of the aircraft being tested. Unlike RF and IR emitters which have large propagation spheres, lasers are extremely directional and do not diverge significantly. Therefore testing should be conducted at operationally significant ranges from very close (300 - 600 ft) to relatively far (12,000 ft - 18,000 ft). Several lasers should be used and the aircraft lased from all directions and from several altitudes. Much of this testing can be conducted on the ground at zero elevation angle. Lasers are walked 360 degrees around the aircraft at several different ranges to determine vulnerabilities. This can be followed up with flight test to determine operationally vulnerable ranges.

8.4.3.2 DATA REQUIRED

- Laser Beam Divergence
- Slant Range from Aircraft
- Time (GPS or IRIG)
- Threat Display Information
- Laser Azimuth in relation to Aircraft
- Laser Aim Point
- Laser pulses vs. detector warnings

8.4.3.3 DATA REDUCTION

Data reduction is essentially the number of times, ranges, azimuth and location on the aircraft which the laser was fired and the detector did not receive. This should occur mostly at close ranges and decrease as the range increases. The end result is to find the ideal number of sensors to provide sufficient aircraft coverage and reduce the vulnerable areas to a minimum. The system is also used to compare the number of laser pulses incident on the aircraft and the number of pulses actually detected by the laser warning system. A statistical evaluation is made to determine the statistical likelihood of providing warning of a laser hit at various ranges. This information is used to determine if the sensor arrangement is adequate or if more sensors are needed to provide better coverage.

8.4.4 LASER THREAT IDENTIFICATION AND LOCATION

8.4.4.1 PURPOSE AND METHOD

As discussed previously, laser threats are currently broken into the following classifications; range finder, designator, and beam rider. The frequencies associated with each type of laser are recorded in the EW suites emitter identification data (EID) memory system and is compared to the incoming threat and analyzed for comparison. Threat identification and location are evaluated to ensure proper quadrant or azimuth location is displayed along with the appropriate threat information. This is accomplished by using hand-held threat laser simulators which can simulate actual threat systems. The laser is directed into the warning receiver and the system evaluated for correct symbology, audio warning clarity, time to ID, and time to announce. This testing is repeated for each receiver and each laser threat simulator. If threat simulators are not available, or are impractical, flight test may be conducted at an EW range and the system evaluated against actual threat lasers.

8.4.4.2 DATA REQUIRED

- Time: IRIG or GPS
- Threat Simulator: Laser type and frequency
- EW Display: threat identified (symbol and quadrant)

- Identification time
- Aural Warning time
- Aural warning clarity (qualitative)

8.4.4.3 DATA REDUCTION

The EID table is verified for the threats simulated. Time required to identify and announce the threat are analyzed for specification and mission suitability. Audio warnings are qualitatively analyzed for clarity, brevity, and usefulness.

8.4.5 SYSTEM SENSITIVITY

8.4.5.1 PURPOSE AND METHOD

LWS system sensitivity is evaluated to determine the minimum detectable laser signal required to alert the system. This can be conducted using both ground and flight tests. Ground tests use hand held lasers with filters to obtain the lower energy signals. Neutral density filters can be continually added until the warning system no longer detects the laser. This power level can then be correlated to a weapon system with a specific beam divergence and certain atmospheric conditions to determine a maximum range of detection. This is repeated for each type of threat laser to be detected. Flight test should also be conducted to ensure atmospheric conditions have been accounted for accurately.

8.4.5.2 DATA REQUIRED

- Time
- EW Display
- Energy level of laser

8.4.5.3 DATA REDUCTION

Data reduction for system sensitivity is correlating the minimum detectable signal level to a maximum threat detection range. A determination is then made as to the adequacy of the range and a decision made as to whether the sensitivity needs to be increased or is adequate for the mission. If sensitivity needs to be increased, a trade off must be made between false alarm rate and sensitivity. This may be an iterative process until a comprise is reached.

8.5 ELECTRONIC COUNTER-MEASURE SYSTEM EVALUATION

8.5.1 THEORY

The basic purpose of ECM is to introduce signals into an enemy's electronic system which degrade the performance of that system so that it is unable to perform its intended mission. It generally is not possible to inject ECM radiation simultaneously into all enemy electronic systems, and hence it is necessary to manage ECM resources so as to counter those systems which pose the greatest threats to a particular mission. The key features of ECM are jamming and deceiving. Jamming should more aptly be called Concealment or Masking. Essentially, Concealment uses deliberate radiation or reflection of electromagnetic energy to swamp the radar receiver and hide the target. Concealment

(Jamming) usually uses some form of noise as the transmitted ECM signal. Deception might better be called Forgery. Deception uses deliberate radiation, reradiation, alteration, absorption, or reflection of electromagnetic energy to forge false target signals that the radar receiver or optical systems receiver accepts and processes as real targets. Deception is most often used in conjunction with expendable countermeasures such as chaff and flares. These expendables deceive EW systems into believing a target exists where it actually does not. Although this is an extremely simplified explanation of ECM, for our purposes we will consider aircraft ECM to consist of the following:

1. Expendable flares for IR deception
2. Expendable chaff for RF deception
3. Jamming for concealment or masking

8.5.1.1 EXPENDABLE ELECTRONIC COUNTERMEASURE THEORY

Expendable ECM, as the name suggests, refers to ECM systems that are deployed only once for a limited time off-board the platform which they are designed to protect. The expendable nature of this type of ECM makes economics an important consideration in their design. To be cost effective, the life-cycle cost of the number of expendables intended to protect a platform must be less that the cost of the platform itself.

Chaff and flares are generally the most inexpensive and effective expendables. Chaff is a form of volumetric radar clutter that is composed of distributed metalized reflectors dispensed into the atmosphere to interfere with and confuse radar operation. The chaff usually consists of a large number of dipoles that are designed to resonate at the frequencies of the radars they are attempting to confuse. Flares are designed to be effective against infrared (IR) seeking missiles. They are dispensed as the missile approaches its target to capture the IR seeker's tracking system, thereby diverting the missile away from the target.

Chaff is the oldest, and still most widely used, radar countermeasure. It is generally used to protect tactical aircraft in either a corridor-laying or self-protection mode. Chaff dispensed from an aircraft at a steady rate over a fairly long period is used to form a corridor which conceals following aircraft. Self-protection involves launching relatively small quantities of chaff in controlled bursts to cause a weapon-associated tracking radar to point at the chaff rather than the protected vehicle.

When chaff is used in self-protection applications, the dispensers must be quick-reaction devices which eject relatively small quantities of chaff in controlled bursts. This is commonly achieved using cartridges fitted with pyrotechnic squibs, where the squibs are fired electrically by a programmable control unit. Self protection chaff cartridges typically contain 100 to 150 grams of chaff carried in modules of 30 cartridges. At least two modules are normally carried. Alternatively, mechanical dispensers can be used, where individual packs are ejected in short bursts from an assembly of long tubular magazines.

Flares are also one of the oldest and most widely used infrared countermeasures. It is generally used to protect aircraft against infrared (heat seeking) guided missile systems. Self-protection involves launching relatively small quantities of flares in controlled bursts to cause a weapon-associated infrared tracking system to point at the flare rather than the protected vehicle. Flares come in a variety of types, and are designed to emit a signature which will mask that of the aircraft

Expendable countermeasures are not perfect systems, in fact, there are a number of difficulties associated with expendable countermeasures. Most prevalent are the ECCM currently available to defeat basic expendable systems. Expendables are however the most widely used type of countermeasure, and arguments as to the benefit or detriment of expendable countermeasure systems will be deferred in favor of flight test discussions.

When flight testing expendable countermeasures such as chaff and flares, several types of tests must be conducted. These include:

Captive Carriage
Safe Separation
Radar Cross Section
Infrared Signature Survey
Hazards of Electromagnetic Radiation to Ordinance (HERO)

8.5.2 CAPTIVE CARRIAGE

8.5.2.1 PURPOSE AND METHOD

Captive carriage testing is conducted in order to ensure safe conduct of flight prior to any countermeasure dispensing. Captive carriage consists of mounting the dispenser and expendables on the aircraft and flying the aircraft envelope to ensure no structural integrity or adverse flying qualities are encountered. Structural integrity not only applies to the dispenser but also to any additional load factors applied to the aircraft. Handling qualities due to increased drag or loading may also impact the aircraft's ability to perform at its optimal level. Therefore, captive carriage must be performed in all areas of the envelope intended for expendable use.

8.5.2.2 DATA REQUIRED

No unique data collection or instrumentation is required for captive carriage flight test. The aircraft must be flown, in a build-up approach, throughout its flight envelope to ensure dispenser and aircraft structural limitations are not impacted. Basic handling and flying qualities should also be observed and any unusual anomalies noted. Testing should be conducted across all airspeeds, altitudes, and g-ranges of the aircraft. If no unusual affects are seen, the dispenser can be cleared for the full aircraft envelope. If any unusual or hazardous conditions are observed, restrictions may be placed on the aircraft's flight envelope while carrying the dispenser or until corrections are incorporated which alleviate the problem.

8.5.2.3 DATA REDUCTION

No data reduction required unless structural or loading issues occur. If loading problems do occur, instrumentation capable of measuring the stress and strain of the problem area may be required. This would be reduced to determine any load limiting factors.

8.5.3 SAFE SEPARATION

8.5.3.1 PURPOSE AND METHOD

Safe separation testing is conducted to ensure all expendables (chaff and flare) are safely deployed without impact to the aircraft or their effective employment. Safe separation is less critical with chaff than it is with flares. Flares have a relatively large mass which burn at extremely high temperatures. This combination provides a serious hazard to the aircraft if it were to impact a portion of the aircraft in-flight. Chaff, on the other hand, has a relatively small mass with little to no impact on aircraft safety of flight were it to impact the aircraft in-flight.

Testing must be conducted throughout the aircraft flight envelope to ensure expendable countermeasure capability throughout. Safe separation can be conducted by dispensing chaff and flares, in a built up approach, throughout the aircraft flight envelope. Dispensing should be conducted across all airspeed, altitude, and g-ranges of the aircraft. Example testing would be conducted in airspeed increments of 50 knots, altitude increments of 5,000 feet, and g-increments of 0.5g. This is however aircraft dependent. Theodolite, telemetry, or chase aircraft cameras can be used to determine aircraft/expendable clearance upon separation.

8.5.3.2 DATA REQUIRED

- Altitude
- Airspeed
- g
- Chaff type
- Flare type

8.5.3.3 DATA REDUCTION

Video tapes can be analyzed to determine chaff and flare dispensing profiles and a determination made as to the possible hazards to the host aircraft. If no hazards are observed, the aircraft may be cleared for expendable dispensing throughout the envelope. If hazards are determined or if ordinance impacts the aircraft, restrictions may be placed on the capability to dispense, or corrective actions must be taken to eliminate the hazards prior to providing clearance for full dispensing capability.

8.5.4 RADAR CROSS SECTION (RCS)

8.5.4.1 PURPOSE AND METHOD

Radar cross section is the measure of a target’s ability to reflect radar signals in the direction of the radar receiver. In simplified terms, the RCS of a target is a comparison of the strength of the reflected signal from a target to the reflected signal from a perfectly smooth sphere of cross sectional area of $1M^2$ as shown in Figure 8.12.

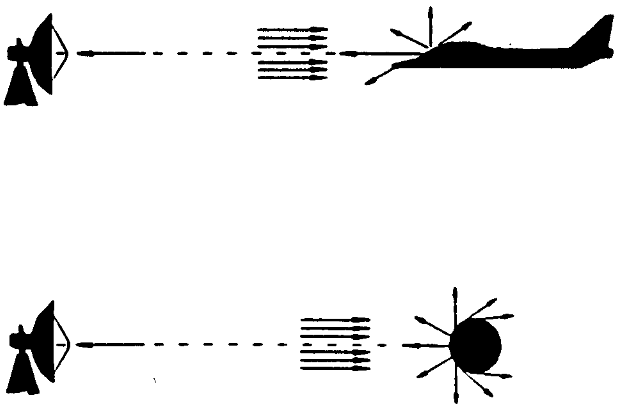


Figure 8.12

CONCEPT OF RADAR CROSS SECTION

The conceptual definition of RCS includes the fact that not all of the radiated energy falls on the target. A target RCS is most easily visualized as the product of three factors:

RCS = Geometric cross section X Reflectivity X Directivity

Reflectivity: The percent of intercepted power reradiated (scattered) by the target in the direction of the radar.

Directivity: The ratio of the power scattered back in the radar's direction to the power that would have been backscattered had the scattering been uniform in all directions (i.e., isotropically).

So, RCS is a measure of the ratio of backscatter density in the direction of the radar to the intercept power density.

The RCS of a sphere is independent of frequency if operating in the far field region (λ << Range), and the radius, $r >> \lambda$. Experimentally, radar cross sectional area is compared to the radar return reflected from a sphere which has a frontal or projected area of one square meter (i.e., diameter of about 44in) as shown in Figure 8.13.

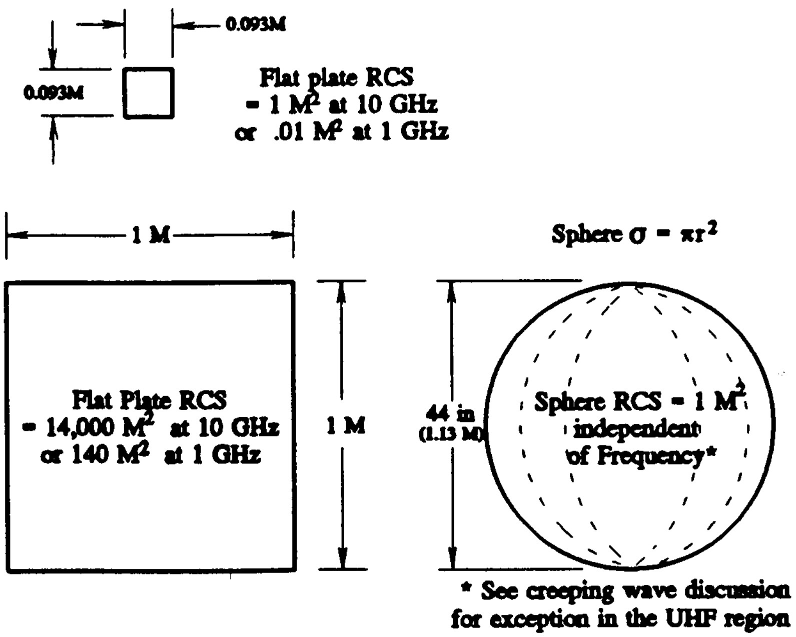


Figure 8.13

RCS VERSUS PHYSICAL GEOMETRY

Using the spherical shape aids in field and laboratory measurements since orientation or positioning of the sphere will not affect radar reflection intensity measurements as a flat plate would (Figure 8.13). The RCS of a flat plate is frequency dependent and is equal to $4\pi a^2\lambda^2$. Figure 8.14 depicts backscatter from common shapes.

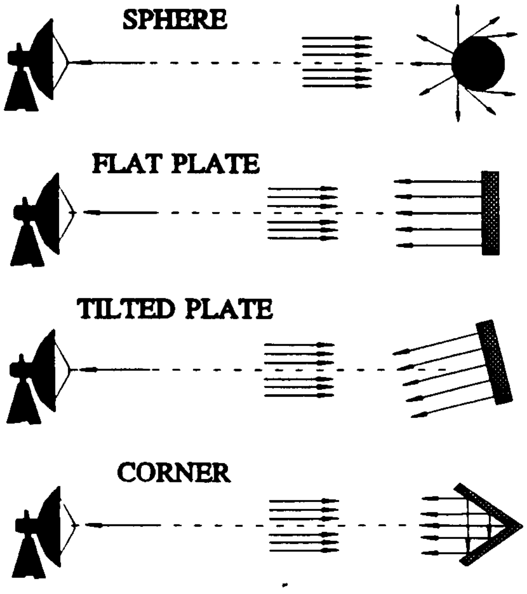


Figure 8.14

Radar Backscatter from Shapes

A flat plate perpendicular to the radar line-of-sight reflects directly back at the radar. A sphere reflects equally in all directions. A tilted plate reflects away from the radar and a corner reflects directly back to the radar somewhat like a flat plate. Figure 8.15 shows the RCS patterns of these objects as they are rotated about their vertical axes (the arrows indicate the direction of the radar reflections).

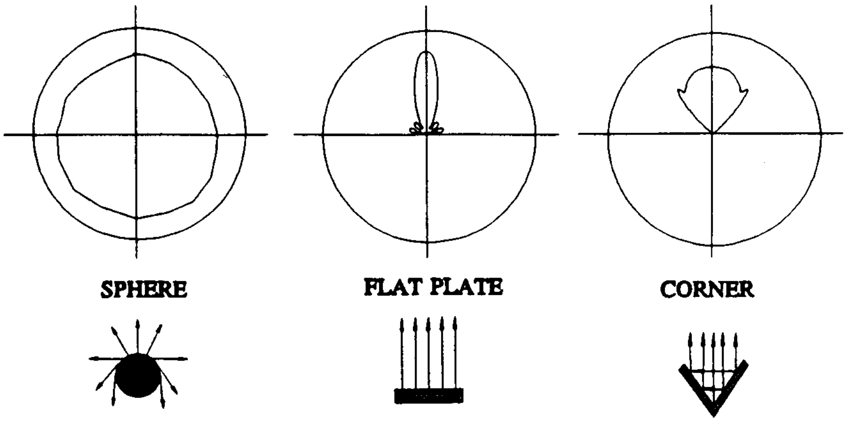


Figure 8.15

RCS PATTERNS

The sphere is essentially the same in all directions. The flat plate has almost no RCS except when aligned directly toward the radar and the corner reflector has an RCS almost as high as the flat plate but over a wider angle. Targets such as ships and aircraft often have many effective corners. Corners are sometimes used as calibration targets or as decoys.

RCS measurements must be conducted to determine the complete radar signature and vulnerability of the aircraft. RCS measurements may be conducted in one of two ways. First, a representative airframe may be placed on a pole and radar measurements taken as the aircraft is rotated on the pole. Second, measurements can be conducted in-flight. Depending on time and availability of airframes, in-flight RCS measurements are the more probable. Although flight time can be a significant cost, the availability of an airframe to strip down and place on a pole (requiring a hole in the airframe) may not be feasible.

RCS measurements must be conducted 360 degrees around the aircraft, with numerous elevation cuts, across a variety of radar frequencies. Usually elevation cuts of at least 20 degrees above and below the centerline of the aircraft are required for adequate RCS analysis. This gives some “look-up, look-down” radar signature information. These flights are typically controlled by local Range authorities. Flight profiles can either by controlled by range or flown using GPS to get the proper orientation of the aircraft with the radar emitter.

Once a complete RCS picture has been obtained, chaff dispensing may commence. Chaff dispensing is flown in very much the same way as the RCS measurements except that chaff is measured for bloom rate (how fast the chaff cloud grows) and radar reflectivity. Chaff is dispensed across the entire airspeed, altitude, and g-envelope of the aircraft and a determination made as to the best flight profile for RCS masking.

Chaff dispensing should also be tested against actual radar threats to determine the true effectiveness of masking the aircraft from radar guided threat systems. This can usually be conducted at any of the military’s EW ranges.

8.5.4.2 DATA REQUIRED

- Radar Frequency
- RCS vs. Azimuth
- RCS vs. Elevation cut
- Chaff Bloom Rate
- Chaff RCS

8.5.4.3 DATA REDUCTION

The data is reduced to determine aircraft RCS vs. aspect and a determination made as to the vulnerability of the aircraft to enemy radar. Chaff dispensing is evaluated to determine bloom rates as well as its effectiveness in masking aircraft RCS.

8.5.5 INFRARED SIGNATURE SURVEY

8.5.5.1 PURPOSE AND METHOD

Infrared signature survey is conducted to determine an aircraft's thermal signature and evaluate its vulnerability to infrared guided missile systems. This testing is very similar to that of the RCS measurements except the infrared signature survey is conducted with thermal imaging cameras to determine the hottest and therefore most vulnerable portions of the aircraft. Thermal imaging is conducted in-flight using a chase aircraft equipped with special thermal imaging cameras. The aircraft is evaluated throughout the envelope and at all engine settings. Once the imaging has been analyzed, a determination is made as to the most effective type of flare to employ as a decoy and the most effective method in deploying them (i.e., forward launching, dual launch, etc.). Flare deployment is then tested against actual airborne threats in a determination as to the effectiveness of decoying infrared guided threats. This can be conducted at any of the military's EW ranges. Video, integrated with the simulated threat missile, should be used for analysis to determine the flare's effective decoy capability.

8.5.5.2 DATA REQUIRED

- Thermal Imaging
- Engine Settings
- Aircraft flight condition
- Flare type
- Missile Video

8.5.5.3 DATA REDUCTION

Thermal imaging data is used to analyze the heat signature of the aircraft and a determination made as to its vulnerability to enemy threat systems. Flare dispensing is evaluated against the missile video to determine the effectiveness of various flares and deployment methods in decoying infrared threat systems. Much of the data analysis is qualitative in nature (i.e., very vulnerable, somewhat vulnerable, etc.). These qualitative assessments contribute to the aircraft's mission suitability determination. Known vulnerabilities, which are not feasible to change, are combined with tactics to decrease their vulnerability.

8.5.6 HAZARDS OF ELECTROMAGNETIC RADIATION TO ORDINANCE (HERO)

8.5.6.1 PURPOSE AND METHOD

Hazards of electromagnetic radiation to ordinance (HERO) testing is conducted to ensure that environments containing high electromagnetic radiation do not inadvertently detonate ordinance. In terms of chaff and flare, this is to ensure that the electrical squibs which fire the chaff and flare off the aircraft are not erroneously triggered do to the electromagnetic environment.

This testing is conducted by placing all firing devices (mainly the squibs) with empty dispensing cartridges in the aircraft while the aircraft is bombarded by electromagnetic energy of varying frequencies and power levels. If no inadvertent detonations or problems are encountered then the aircraft is cleared to operate in all electromagnetic environments tested. If problems are encountered, the aircraft is either restricted in ordinance carrying capability, restricted in operating in certain electromagnetic environments, or both until the proper shielding is employed to adequately correct the deficiency.

8.5.6.2 DATA REQUIRED

- Electromagnetic Frequencies
- Power levels
- Ordinance type tested

8.5.6.3 DATA REDUCTION

Data reduction is extremely basic if no problems are encountered. Since the electromagnetic frequencies and power levels tested should far exceed anything the aircraft will be flown in, if no difficulties are encountered, there is no effective data reduction. If problems are encountered, the data must be reduced to determine the exact frequencies, power levels, and locations which are producing the problem. Once the problem has been isolated, an analysis must be performed to determine how to shield the aircraft. If shielding is impractical or ineffective, a flight restriction may be place on the aircraft limiting its operating environment. This may include operating limitations on high electromagnetic environments such as shipboard operations.

8.5.7 RF JAMMING EVALUATION

8.5.7.1 PURPOSE AND METHOD

The most common form of ECM is active noise jamming, intended to neutralize the opposing radar or communications system completely, using either spot or barrage noise. Spot noise is used when the frequency parameters (center frequency and bandwidth) of the victim system to be jammed are known and confined to a narrow band. However, many radars are frequency agile over a wide band as an ECCM measure against spot jamming. If the rate of frequency agility is slow enough, the jammer can follow the frequency changes and maintain the effect of spot jamming. Alternately, some jammers are swept across the band of interest using spot noise to interfere intermittently with the victim system.

Barrage or broadband jamming is simultaneously radiated across the entire band of the radar or communications spectrum of interest. This method is used against frequency-agile systems whose rates are too fast to follow, or when the victim's frequency parameters are imprecisely known. In general, barrage noise requires considerably more effective radiated power (ERP) of the jammer than does spot noise for equal effectiveness. Barrage noise jamming through a radar or communications system's sidelobes is usually difficult to achieve because of the large required ERP.

The aim of deception jamming is not to swamp the victim's system with external noise so that the true signal cannot be detected, but rather to falsify deliberately the indicated system response. This technique can also be used to confuse by providing sufficient false but realistic data to the victim system as to make extraction of the valid data impossible.

The most prevalent type of jammer found operationally is the self-protection jammer. This is employed on fighter or strike aircraft which have low radar cross sections ranging from 1-10 M^2 for head-on aspects and 10-100M^2 for broadside aspects. Typical

ECM coverage is fore and aft (e.g., 60-degree cone tilted 15 degrees downward) in the regions of minimum RCS. Size and weight are limited in strike aircraft, presenting a problem in carrying ECM jamming transmitters covering the full radar band (e.g., 0.5 - 18 GHz). One solution is to use external jammer pods, which are specialized to the expected threats (frequency bands) to be countered on a particular mission. An alternative is to use an internal, power-managed ECM system which covers only the terminal threat bands (e.g. E/F, G/H, I/J bands).

Jammer flight test is conducted by operating the jammer in all modes and evaluating its effectiveness in deceiving and evading both airborne and ground based radar threats. Patterns, similar to those during RCS, are flown to evaluate the azimuth coverage of the jammer and effective operating range. The jammer should be tested at an EW range capable of producing both airborne and surface radar threats.

8.5.7.2 DATA REQUIRED

- Jammer power
- Range
- Azimuth
- Radar threat display

8.5.7.3 DATA REDUCTION

Data reduction consists of evaluating the jammers directional output power to determine its effectiveness in deceiving threat radar systems. This is accomplished using the radar range equation and solving for the power received by the threat radar system. It can be determined from this if the power is sufficient to induce effective jamming and at what range the jammer is effective. Azimuth coverage should also be evaluated to determine any vulnerabilities in the aircraft jamming coverage.

CHAPTER 9

ORDNANCE TESTING

FORWARD

This chapter was originally written by Major Doug Yurovich, USMC, in March 1992, as a Flight Training Manual for new graduates to assist their transition into ordnance flight testing, and is based on his experience as an Ordnance Project Officer with the F/A- 18 Hornet. His intent in compiling this work was to give the ordnance project officer/engineer a more expanded document to utilize for single point referencing on ordnance separation issues. **It has not been completely updated with the changes in names and locations that have happened with Navy facilities since 1982.** Though portions of this document might seem too technical in nature, (e.g., wind tunnel methods and photometric techniques), this information is necessary if one is to discuss separation issues intelligently with individuals who have been doing this type of work for years.

The basic outline for this document was taken from what used to be NATCINST 8600.1A, Sep 1989, reference 1.

The section on Aerodynamics of Store Separation originated from a article found in the Canadian Aeronautics and Space Journal, Vol. 37, No. 3, September 1991, written by F. A. Kohiyar and B. Ugolini, reference 2.

Store Separation Prediction Techniques and SECTION VI, Photometric Analysis, were taken from AGARDograph No.300 Vol. 5, *STORE SEPARATION FLIGHT TESTING* by R. J. Arnold and C. S. Epstein, April 1986, reference 3.

ORDNANCE FLIGHT TRAINING MANUAL

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SECTION I
SEPARATION TEST THEORY

1.1 Introduction. The separation of an external store of an aircraft is a highly complex phenomenon requiring detailed knowledge of the influence of the aircraft flow field upon the store, the store's aerodynamic and physical characteristics, the release mechanism used, and the physical installation of the store on the aircraft. The factors governing the motions of separation include the store's mass properties, specifically the density, center of gravity location, and moment of inertia (MI) in pitch, roll, and yaw; flight parameters such as airspeed, normal acceleration, dynamic pressure, sideslip angle, and aircraft angle of attack (AOA); aircraft design parameters such as wing/fuselage geometry, chordwise and spanwise flow, and vertical location of the stores; means of store stabilization; and ejector unit design. These factors are discussed in the following paragraphs.

1.2 Aerodynamics of Store Separation. Aerodynamic forces and moments may be classified into three categories: static, dynamic and cross-flow, as shown in Figure 1 and table I. For stores with extendible fins, the effect of fin deployment must be incorporated, as this has a significant effect on freestream static and dynamic stability.

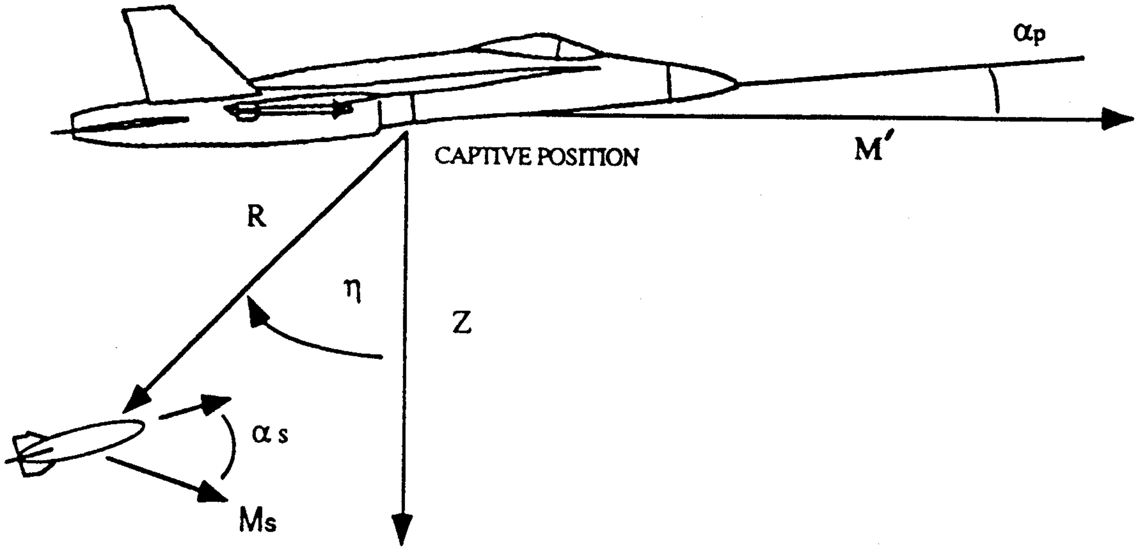

Figure 1
Aerodynamic Forces and Moments on Store

Table I
Aerodynamics Forces and Moments on Store

CATEGORIES				
COMPONENTS	STATIC		DYNAMIC	
	FREESTREAM	INTERFERENCE	(Damping)	CROSS-FLOW
Axial Force	X_f (α_s, M_s)	X_i (α_p, M, R, η)	X_q^1	-
Lateral Force	Y_f (βs, M_s)	Y_i (α_p, M, R η)	Yr^1	Y_α (α_s, M_s)
Normal Force	Z_f (α_s, M_s)	Z_i (α_p, M, R, η)	Z_q^1	Z_β (β_s, M_s)
Rolling Moment	L_f (β_s, M_s)	L_i (α_p,M, R, η)	L_p	L_α (α_s, M_s)
Pitching Moment	M_f (α_s, M_s	M_i (α_p,M, R, η)	M_q	M_β (β_s, M_s)
Yawing Moment	N_f (β_s, M_s)	N_i (α_p,M, R, η)	N_r	N_α (α_s, M_s)

Note 1: Negligible

NOMENCLATURE

L, M, N	roll, pitch and yaw moments
M	Mach number
p, q, r	roll, pitch and yaw angular velocities
R	Radial distance from store to captive position
X, Y, Z	axial, lateral and normal forces
α	angle of attack
β	sideslip angle
η	grid traverse angle from the vertical

SUBSCRIPTS

f	freestream parameter
i	interference parameter
p	parent aircraft parameter
s	store parameter

Static Forces and Moments

Freestream

Freestream forces and moments are, by definition, the baste aerodynamic characteristics of the isolated store and are functions of store incidence (angle of attack or sideslip) and Mach number. A measure of the static stability is obtained from the magnitude and sign of the variation of pitching and yawing moments with angle of attack (AOA) and sideslip, respectively. If the slope of the pitching moment curve vs. AOA is negative the store is statically stable and increasing the magnitude of the slope increases the level of stability. Similarly, the variation of yawing moment with sideslip angle is a measure of static direction (weathercock) stability; the slope of this curve, however, must be positive for static directional stability. Stores without tail fins are generally statically unstable. The restoring moments due to tail fins tend to rotate the store back into the wind, so if the fins are sufficiently large, static stability will be attained.

Interference

Aircraft-store interference effects are best obtained from wind tunnel tests, using the survey technique, which maps the by aerodynamic forces and moments at a number of pre-selected positions relative to the parent aircraft. It is generally assumed that interference varies more with vertical displacement than with axial or lateral displacement and also, that interference is independent of store attitude relative to the parent aircraft.

Dynamic Effects

For dynamic stability it is necessary to consider the motion of the body after it has been subjected to a disturbance from a state of equilibrium. If a body is stable, it will return to its equilibrium condition by a subsidence or by means of a damped oscillation. For stores, it is only necessary to consider damping in roll, pitch and yaw. These damping moments are most conveniently obtained in coefficient form.

Cross-Flow Effects

Cross-flow components are generated by asymmetric vortex shedding, which occurs on bodies of revolution at high angles of incidence, or due to rolling of the body. Vortex shedding is strongly affected by Reynolds number, turbulence, roughness and Mach number. Nose shape also effects cross flow components - blunt nose bodies have a small effect and pointed nose shapes have a large effect. The cross-flow components are:

Side force and yawing moment due to angle of attack
Normal force and pitching moment due to sideslip angle

The derivatives are generally referred to as cross-derivatives because the force or moment is due to variation of the incidence angle in the normal plane. The signs of these parameters depend on the position and strength of the vortices and can be of random sign.

1.3 <u>Store Separation Prediction Techniques.</u>

After considerable research, all of the store separation prediction techniques in use throughout NATO have already been thoroughly discussed in an array of published literature. For this reason, it was decided to present no more than an overview since this FTM is intended to be used as a guide for the new store separation officer/engineer and management personnel.

Review of Types of Prediction Techniques

Methods designed to predict store separation motion may be categorized into three broad groups: theoretical, empirical (or semi-empirical) and analogy. These three groups are distinguished by their different aerodynamic approaches. Each approach offers advantages and disadvantages to the store separation officer/engineer. The trajectory problem may be considered as two interrelated problems: aerodynamic and dynamic, that may be coupled to each other or treated separately. Generally, theoretical approaches utilize the solution of the fluid equations which can be coupled or uncoupled to solve the equations of motion. By coupling the fluid equations to the equations of motion, one can solve for the new attitude of the store at each time step in the store trajectory and then use this new aircraft/store physical relationship to calculate a new flowfield. Using the new flowfield the aerodynamics may be updated. Conversely, in the empirical approach, a specified survey of points throughout the flowfield can offer the aerodynamic information which is recalled via table look-up when the store moves to a new point (and/or attitude). More recent predictive methods offer the option of coupling or decoupling the influence of aircraft/store mutual interference at each time sup. Empirically or semi-empirically derived aerodynamic solutions are predominately used, decoupled from the equations of motion solutions. The grid data based approach is an excellent example which is discussed in a following section. Store separation prediction by analogy relies on past experience with a store of similar aerodynamic shape and mass properties and using its known separation characteristics to predict the new store's movements. Each of these generic methods will be discussed in detail, followed by sections explaining how each nation utilizes them.

Theoretical Prediction Methods

Purely analytical predictive methods used today to study store separation trajectories are applications of various paneling methods that solve the linear Prandtl-Glauert equation. A general three dimensional boundary value equation is then solved for the configuration of interest. The equation governs incompressible and linear compressible flows in both subsonic and supersonic regimes, Further, the assumption of inviscid flow applies. These panel methods differ from the more complete nonlinear potential flow formulations that govern the transonic flow regime. These nonlinear potential flow formulations (that is, transonic small disturbances and full potential flow) retain terms to improve the resolution of shock waves and to more readily determine when the equation changes its nature; that is, elliptic or hyperbolic. Although these equations are more applicable to the problems of concern in store separation testing, they are, computationally., more difficult to solve.

Paneling methods have evolved since the early seventies to the point where rather complex errors can be addressed. A major advantage of these paneling methods is that, unlike solutions of transonic full potential or other nonlinear "higher" forms of the Navier-Stokes equations, they do not require a field grid for numerical solution (much less an adaptive grid needed for trajectory studies). This frees these schemes of geometric limitations that limit the nonlinear methods to more simple configurations. Additionally, at this time, no methods exist to provide a coupled trajectory solution using these higher nonlinear schemes. Paneling-methods have evolved from earlier "lower order" versions that feature constant singularity strengths (or linear variation in one direction) on each panel. Higher order versions, such as PAN AIR are distinguished by nonconstant singularity strengths or "composite" panels that allow a linear source and quadratic doublet variation on each panel. These improvements have helped to make panel solutions less sensitive to panel spacing and density allowing more complex configurations to be studied. The use of composite panels has allowed singularity strengths to be made continuous on a configuration. This has significantly reduced the potential for numerical error, particularly for supersonic flows. A feature of PAN AIR is the implementation of the Kutta condition allowed by the use of the composite source-doublet panel. This makes the computed flowfield relatively insensitive to modeling detail at the trailing edge. The code also features an expanded treatment of wake modeling which enhances its use for lifting surfaces. The reader is referred to Reference (4) for a detailed discussion of the feature of PAN AIR.

References (4) and (5) present comparisons of PAN AIR predicted results with experiment for both subsonic and supersonic flows. Data comparisons were made at various subcritical subsonic and supersonic Mach numbers. Results show excellent agreement except in the region where nonlinear effects are to be expected. The Prandt-Glauert equation is valid for subcritical flow about slender bodies and thin wings at arbitrary subsonic or supersonic Mach numbers where flow discontinuties are not present. While PAN AIR and other paneling methods can provide trajectory solutions for relatively complex configurations in subcritical flows, numerical gridding techniques have not as yet matured.

The application of paneling methods such as PAN AIR, NEAR, Reference (6) and others can be very useful in the study of store separation characteristics as long as the limitations of the methodology are kept in mind. These codes can offer a first look at details of the flowfield that normally are not obtainable without special, costly, experimental test techniques. Additionally, the majority of "real world" store shapes are complex and pose extremely complex modeling problems. Although "higher order" panel methods may now be able to accommodate these more complex shapes and configurations (such as multiple stores carriage), these real world configurations only further aggravate the nonlinear aspects of the aerodynamic problem.

A first step in investigating a new store for release characteristics lies in understanding the store's freestream aerodynamics. Preliminary trajectories can be computed for the store using this data with flow angularity or with grid data from very similar stores (if available) to determine if more elaborate testing is necessary. Preliminary data can possibly be acquired by examining the freestream aerodynamic data from similarly shaped stores. The Office for Aircraft Compatibility (OAC) and the Arnold Engineering Development Center (AEDC) have jointly developed a freestream stores aerodynamic data management system that contains over sixty stores with a wide variety of characteristics. This system is automated for data retrieval with a number of features for manipulation of the data. The data base is described in Reference (7). The data base has proven invaluable in a number of instances in supporting first order trajectory studies on short notice.

A number of semi-empirical aerodynamic estimation codes are used in conjunction with the freestream data base. These codes augment experimental data or provide a first order estimate when data are not available. These codes continue to be improved and currently those most used are DLCODE Reference (5), MISSILE DATCOM Reference (8), NSWC and NSRDC Reference (9). These codes are used to produce freestream aerodynamics to be used with flow angularity and grid data as inputs to six degree of freedom trajectory programs. The codes require geometric inputs and arc relatively simple to use depending on the program. In addition, AEDC has developed an executive selection program that assesses up to eight separate estimation programs with logic designed to select the particular code that can best compute a particular aerodynamic coefficient for the geometry and Mach number/angle of attack range of interest. Most semi-empirical codes are relatively simple to use for first order estimates of release behavior. Higher order solvers (such as paneling methods) or Euler solvers, are more difficult for the using engineer to apply. However, many are evolving rapidly into more user-friendly codes. Until these codes are generally available, semi-empirical estimation codes will continue to be used and improved.

Before closing this section on theoretical methods, it should be noted that Reference (4) indicates that methods which make use of panel surface geometry are under development for solving nonlinear transonic problems. Many believe that codes with a transonic panel" method may be available in the future. The geometric versatility of such a paneling method may make this approach, in some cases, very competitive with future more elaborate nonlinear solutions that will use field grids. Further, the rapidly accelerating capability of Computational Fluid Dynamics (CFD) is being turned to solution of the transonic store separation problem. Basic research is well underway in the USA, in the academia, and in aerospace companies around the world. The USAF's Armament Laboratory has chosen the Euler formulation as the solution algorithm. This avoids the limiting assumptions of small disturbances and the restrictions of slender body store and relative weak flowfield gradients. The Euler algorithm will be solved numerically using a contour-conformal grid scheme that has the advantage of flexibility in concentrating the grid in an area of the flow where strong gradients occur and is applicable to any aircraft/store configuration: single and multiple stores carriage, slender and non-slender bodies, and arbitrary shapes will also be incorporated. Additionally, dynamic grid concepts will be applied to the store separation problem. Contour conformal grids will be allowed to dynamically adapt to the movement of the store as it separates from the aircraft. Currently, the grid generation and Euler solving computer program have been derived by the Armament Laboratory and are being checked out using simple store shapes. Dynamic gridding algorithms are just now being developed. Wind tunnel testing designed to provide data for method validation will be performed over the next several years. Near term, the development of transonic surface paneling" methods will significantly aid the study of transonic store separation as higher order solvers continue to be developed. Yet, for the foreseeable future, empirically derived data will continue to be a principal source for the "aerodynamic" solution of the separation problem.

Empirical and Semi-Empirical Methods

Despite the recent advances in computational techniques, wind tunnel testing is, and will remain for several years to come, the most reliable prediction technique that can address the transonic store separation problem. Wind tunnel testing techniques used in understanding store separation events are well known. References (10) through (14) present a concise review of the various techniques and, therefore, are reviewed herein only briefly.

Selecting the approach for the store configurations of interest to yield the most reliable and cost effective data is the most important consideration in planning a wind tunnel test. However, designing a test to acquire data that may be later extended to other configurations, or utilized beyond its initial intended purpose, is another very important consideration. Some wind tunnel testing techniques obviously offer this advantage while others do not.

There are basically four wind tunnel methods that continue to be used to predict store separation trajectories. In the US, all four techniques have been used in support of a variety of programs. These four techniques are: Captive Trajectory System (CTS), Grid (flowfield data base), Flow Angularity (flowfield data base) and Freedrop.. In addition, two other more recent wind tunnel based techniques are discussed that offer alternative approaches. These arc: Installed Carriage Loads Derived Grid flowfield and the Influence Function Method.

CAPTIVE TRAJECTORY SYSTEM (CTS):

Within the United States there are five wind tunnels equipped with articulated dual sting arrangements that support CTS testing. Of these five tunnels, four are transonic tunnels while the other is a supersonic tunnel. Practically all of the store separation testing performed by the USAF is accomplished in the AEDC four foot transonic wind tunnel (called 4T). The principle of the CTS is essentially common to all wind tunnels. The AEDC 4T facility is typical and can be used to cite advantages and disadvantages. The articulated dual sting arrangement used for store separation studies is no more than a system that supports the aircraft model on one sting, with limited movement, while the store model with an internal balance is mounted on a separate sting capable of commanded movement in all six degrees of freedom. Aerodynamic forces and moments on the store are measured by an internal strain gauge balance that may measure from five to six force and moment components. The aerodynamic data measure by the balance is fed to a computer during the test run. These forces and moments are combined with other required data such as store mass property characteristics (weight and center of gravity), ejection forces, rate damping forces and moments of inertia, which are not measured and which are needed to solve the equations of motion and predict the store's next position relative to the aircraft for a simulated increment in time. Through a closed loop system, the new position in time is fed to a positioning device which then commands the model sting to move to a new position in the tunnel. The cycle is then repeated automatically to obtain a complete trajectory.

CTS offers the primary advantage of most closely measuring the actual forces and moments (within general wind tunnel constraints) during the store separation trajectory that are the result of the store's actual attitude and position. Furthermore, within the assumption of quasi-steady flow that is common to all wind tunnel testing of this type, CTS can more closely simulate factors such as varying aircraft load factors and maneuvers, varying ejection force parameters, varying store thrust and a variety of other parameters that obviously other methods, such as freedrop, cannot. Its advantages over other methods that "aerodynamically" map the flowfield (such as grid and flow angularity) is that it measures the aerodynamic forces and moments at the precise point in the trajectory, and at the precise calculated attitude of the store. This technique provides the most accurate experimentally determined aerodynamic dare for a position in the trajectory; but has some dramatic limitations.

CTS is not designed to provide the user with a useful data base for examining a large number of individual trajectories off-line. This off-line capability is needed to understand the sensitivity of store release to many different variables such as Mach number, angle of attack, changes in store mass and inertia characteristics, fin deployment times, aircraft dive angle (load factor), ejection performance, and many other parameters that require many individual simulations. These large numbers of simulations cannot be economically completed in the wind tunnel. Although CTS can offer the advantages of an "on-line" trajectory simulation that can shorten analysis time (given the existence of models and a timely entry in the wind tunnel), this can be offset by an even more far ranging requirement for an aerodynamic flowfield data base that can be used in the future. Future development or product improvement may alter mass and inertial characteristics of a store or other important variables. These changes and the effect they would have on the separation trajectory would be very difficult to isolate using CTS data from a previous configuration. Furthermore, no capability would exist to match predictions to actual flight test conditions. This tool would be required in order to identify potential design changes that may become apparent during flight testing. CTS data acquisition can also be hampered by hardware problems. The dual sting arrangement has been designed to terminate the trajectory whenever the store or sting contacts the aircraft. For some aircraft/store configurations and stores that exhibit large angular motions, the trajectories may be terminated too quickly before any useful data can be acquired. While this is not an insurmountable limitation, the separation engineer must be ready to alter trajectory data inputs during the wind tunnel test to assure longer trajectories for better study or live with the short trend trajectory information available from the test runs. Practical limitations on CTS equipment in the past has resulted in trajectories being terminated due to the linear motion of the store sting positioning device. Recent improvements made by AEDC in the software that controls the CTS apparatus motion allows the C TS movement to more closely parallel the actual store trajectory. This has significantly reduced the occurrence of premature termination of trajectories due to sting/store grounding. Again however, CTS trajectories for stores that exhibit larger angular motions may still terminate too soon to provide useful data.

GRID:

The CTS can be used to provide wind tunnel data in the CTS mode or the and mode. The grid mode is essentially a flowfield technique in that that store sting is positioned automatically to preselected and preprogrammed positions and attitudes with respect to the aircraft model. The store/balance combination then measures aerodynamic coefficient data at each point. During testing of this type, a matrix of coefficient data is obtained through a region of the aircraft flowfield that can be expected to encompass the subsequent trajectory path for a particular configuration. The measured values represent total aerodynamic coefficients of the store as a function of the store's position and attitude at a particular point in the aircraft flowfield By subtracting the store's freestream aerodynamic coefficients (measured for the same store model at the same attitude outside the flowfield of the aircraft) from the total aerodynamic coefficients, a set of interference aerodynamic coefficients can be calculated as a function of position and attitude within the aircraft flowfield The matrix of interference coefficients becomes a data base available for subsequent trajectory calculations. These interference coefficients are recombined with freestream aerodynamic data during each time step of a trajectory calculation to determine a total aerodynamic coefficient applicable for that store's position and attitude within the aircraft flowfield

The basic advantage that the grid technique offers is its implicit versatility for future studies. On-line wind tunnel test time required for computation of trajectories using the full CT S mode is not used in the CT S grid mode to c gather a larger aerodynamic data base that can be used for further studies later. A larger, more comprehensive, set of trajectories can be generated more economically and efficiently by allowing the store separation engineer the flexibility of careful study of trajectory sensitivity to various parameters outside of the high cost environment of the tunnel test section. For certain configurations such as stores with deployable fins, this approach may be far more economical and much more practical than a comprehensive CTS test of a model with changing configurations.

For a given aircraft/store configuration the aerodynamic loads acting on the store are functions of the aircraft Mach number, angle of attack and sideslip angle, and the store's relative position and attitude with respect to its carriage position. A comprehensive set of aerodynamic interference coefficient data as functions of all these variables would require a lengthy wind tunnel test program as well as a trajectory generation computer program set up to sift through all of the data for the appropriate values and to interpolate or extrapolate as necessary. Such a program would require a high speed computer with a large storage capacity. The apparent disadvantage of the grid technique in requiring a data sift program can be offset by judiciously selecting what grid data needs to be taken. Reference (15) describes a joint wind tunnel study between the OAC and AEDC This study concluded that interference aerodynamics varies considerably more with vertical displacement than with lateral or longitudinal displacement and that store orientation in an axis within the grid volume generally has a minimal (second order) effect on the interference aerodynamic coefficients. In some instances of stores with large planform areas, a second order influence of store pitch on the interference coefficients may become important. References (13) and (15) e' -`d on the significance of the study on planning a grid wind tunnel test for a new store. experience with limited and testing though, has demonstrated excellent correlation with full CTS trajectories for most store separation studies conducted over the past several years by the OAC

A number of references are listed in the work mentioned above which substantiate the use of limited grid for complex aircraft flowfield and store shapes. Additionally, there are a number of techniques that have evolved over the years that can aid the store separation engineer in optimizing a grid survey. In the case of multiple carriage racks, the displacement for stores ejected at an angle from the vertical may be easily estimated and the resultant trajectory used to define the vertical and lateral displacements at desired grid points. Careful attention to structuring the configurations to be tested and the order in which they are tested can help to streamline testing by treating each side of the aircraft model as a separate flowfield This allows the store separation engineer the ability to minimize tunnel shutdown, model changes, and start up times during a test.

FLOW ANGULARITY:

A second commonly used method for determining interference flowfield aerodynamics is the technique known as flow angularity. Aerodynamic data is normally obtained by using a velocity probe attached to the CTS sang apparatus in place of the store/sting combination. The velocity probe is then used to measure velocity components at various locations in and around the aircraft flowfield within a volume that is expected to included the store's anticipated trajectory. From this information, local flow angles of attack are determined generally at the nose and tail of the store. This information is used with freestream lift curve slope data to generate the interference coefficients rather than measuring the interference coefficients themselves. Two approaches are generally employed when utilizing a velocity probe. The first approach, as discussed in References (13) and (16), is to measure flowfield effects with the store installed in its carriage position. The second approach is to measure the initial store loads along the centerline of the store as if it were installed on the aircraft. Although neither approach is a true representation of the interference flowfield both can provide a first order answer to store trajectory studies. The first approach incorporates a partial influence of the store upon the interference flowfield while the second approach may be more versatile in dealing with a larger class of stores of various shapes and planform areas. The greatest advantage of this second approach is its adaptability to providing quick answers for stores that have not been wind tunnel tested. Using this approach however, requires a thorough understanding of the freestream aerodynamic characteristics for the store in question, including the relative contribution of the nose and tail segments. This data can be acquired from wind tunnel testing or approximated by aerodynamic estimation computer codes. Normally, the variation of aerodynamic forces with angle attack and center of pressure area is required. This methodology generally allows a greater degree of flexibility in modeling the interference flowfield interaction due to fin control surface motion of fin deployment for complex stores. This is the case for modeling the damping of free floating control surfaces (such as canards). A detailed description of the approach can be found in Reference (13). It may be noted that although the normal approach for acquiring flow angularity data is through the use of a velocity probe attached to the CTS sang, some work has been done to explore the use of a laser doppler velocimeter in measuring local transonic flowfields. The real advantage in using the velocimeter lies in removing any physical interference attributed to the probe itself Finally, techniques have been developed for extracting flow angularity data from grid data for certain stores. By using measured freestream aerodynamic data, one can extract local flow angles and produce a data base of local flowfield angles that can be used to solve the aerodynamic interference problem for other stores. A newer technique that will be discussed later is an extension of the flow angularity approach.

INFLUENCE FUNCTION METHOD (IFM):

Since wind tunnel testing still offers the most accurate method for addressing store release problems, the large number of store/aircraft and flight conditions involved in certifying stores mandates that methods be developed to improve the cost-effectiveness of wind tunnel testing by extending test data beyond the stores to which the testing was initially geared. The flow angularity technique discussed previously has been recognized for some time as a useful approach for this reason. The Influence Function Method IFM described in References (17) and (18) is a natural extension of this method from two store elements (nose and tail) to any number of store elements - with some important differences. The flow angularity technique uses freestream values of the normal force coefficient slope and angle of attack for the nose and tail plus assumed locations of the nose and tail centers of pressure to calculate moment coefficients. The IFM determines these coefficients by traversing the store model through a known flowfield longitudinally, aft to forward, where the local angle of attack is known. At each point in the traverse, the aerodynamic forces and moments are measured generating a series of equations. By matrix inversion, the influence functions themselves are calculated and the store is calibrated to a known flowfield Conversely, a "calibrated" store can be passed through an unknown flowfield to determine the local flow angle along a tranverse line during a wind tunnel test to solve for the unknown flowfield In completing this method, the store of interest can then be immersed in this flowfield analytically along that tranverse, having been calibrated previously to a known flowfield The aerodynamic coefficients can then be solved by matrix multiplication. This methodology has been successfully used for supersonic flowfields with excellent results for single carnage stores at various vertical distances from the parent aircraft. Investigation of the technique's application to subsonic flows is still underway, as is also the extension of the technique to the other aerodynamic coefficients (yaw and roll). Preliminary findings tend to indicate comparable results can be achieved for subsonic flows.

The obvious disadvantage of the IFM lies in the calibration of the store in question. The general approach for supersonic conditions would be calibrating the store experimentally by passing it through a known flowfield such as an oblique shock wedge flow. The requirement for a wind tunnel test is an obvious disadvantage. Calibration using analytically derived flowfields produced by paneling methods such as PAN AIR has generated accurate influence function calculations. Reference (19) (unpublished) has also demonstrated the reasonability of using semi-empirical aerodynamic estimation programs, such as DL CODE, that have been modified to superposition simple flowfields on the store model within the code. Using the same traverse logic calculations of the influence functions were made using the code generated coefficients. Reference (19) reports very good agreement with other calculations of influence functions and subsequent comparisons of trends in predicted and measured aerodynamic coefficients for a GBU-15 store in an F-15 flowfield A disadvantage in this particular approach, lies in the fact that such prediction codes have inherent limitations in predicting shock strengths. Consequently, local flow angles may show large discrepancies in these regions.

FREEDROP:

The fourth empirical wind tunnel method in use today is the freedrop method, also called dynamic drop. In this approach, scale store models, constructed to obey certain similarity laws, are released from the aircraft model in the wind tunnel. High speed orthogonal photography is used to record the event. The film is read to extract time position data that can be used to understand the separation events and to assess the relative risk of flight testing. Static aerodynamic forces and moments acting on the store are properly scaled when the model geometry and flowfield are matched to full scale flight conditions. The accelerations of the store model will be similar if the total forces and moments, mass, center of gravity, and moments of inertia are also properly scaled. IN achieving this scaling, the model is scaled to one of three scaling laws: heavy, light, or Froude. Selection of the most suitable scaling law depends on the nature of the separation problem, those parameters of particular interest to the store separation engineer (which needs to be accurately known) and the capabilities of the facilities available.

Reference (12) outlines the dynamic scaling principles involved in freedrop testing. Proper sealing requires linear geometric scaling of aircraft and store models from full scale to model scale. Also required is linear and angular acceleration matching for both aircraft and store models. Relationships for the ratio of model scale and full scale values for time, velocity, Mach number, moments or inertia, ejector forces, and related parameters are calculated as power functions of the scaling factor.

If compressibility and viscous effects are matched, then aerodynamic coefficients are matched between model and full scale. These premises lead to the scaling relationships that arc known as Froude scaling: so named because the velocity scaling is equivalent to the hydrodynamic Froude number. The reduced Mach number at model scale resulting from Froude scaling, however, generally only insures aerodynamic coefficient equality for low subsonic (less than 0.8 Mach) full scale flight conditions.

Assuring that the aerodynamics are properly matched requires that Mach number be matched at the expense of another parameter. Those techniques that maintain Mach number equality are known as "heavy" and "light" scaling. Heavy model scaling results in an increased velocity requirement over that of Froude scaling and with all else being equal, the required mass of the model is larger than that required for the Froude scaled model. Because the velocity ratio has been relaxed, heavy scaling fails to account properly for induced angle of attack or aerodynamic damping effects on angular motions. Similarly, linear motion is also affected by induced angle of attack variances. The amplitude of angular motion will be too large due to under damped motion.

Light model scaling can be used when proper angular motion response is of major importance. Light model scaling is so named because the mass ratio is maintained to that of Froude scaling and retains the velocity ratio simulation along with Mach number by assuming that the gravitational constant within the wind tunnel test can be arbitrarily increased. In reality, the gravitational constant within the wind tunnel cannot be changed. The deficiency in the required gravitational acceleration called for by light model scaling can be corrected by artificial means. The use of magnetic fields or use of the aircraft model sting apparatus to accelerate the aircraft model away from the store at store release and the use of increased ejection forces are typical methods that can be used.

Of the various scaling laws, heavy model scaling, is the predominant method used by most agencies throughout NATO. Because of the low subsonic requirement for Froude scaling, the method becomes unsuitable for the majority of work that centers around transonic flowfields While heavy model scaling results in under damped angular motion of the store during separation, the trend usually results in a conservative approach to safe separation studies. References (10) and (20) generally indicate that heavy model scaling agrees favorably in angular motion in full scale trajectories and very well in linear motion since the ratio of aerodynamic forces to gravitational forces is maintained. Light model scaling generally results in deficient vertical store separation distances while agreeing much closer to full scale trajectories in angular motions. Reference (11) reports that a correction to vertical acceleration can be made by altering the ejector force. This requires some a-priori knowledge of the flowfield that can be used to tailor this technique to the test. For highly complex configurations where little or nothing can be realistically assumed about the flowfield such a technique would not be very useful. Consequently, the literature surveyed tends to recommend heavy model scaling as the preferred method for most modern day studies.

Selection of the appropriate sealing method is dependent on the separation problem and the experience and preference of the using engineer. However, dynamic drop offers certain advantages and disadvantages in comparison to other trajectory acquisition methods. Realistic considerations need to be understood in deciding whether this approach over another is advisable. Reference (12) elaborates on these factors in detail. Some advantages and disadvantages of using freedrop are summarized in the following paragraphs.

Freedrop testing generally offers the best (if not the only) approach where model size or shape precludes a suitable store-balance-sting combination design. Modifications to the rear part of store models to accommodate stings can alter the store aerodynamics (such as static margin). freedrop testing eliminates this problem. In eases where stores are required to be released from internal aircraft bays, freedrop testing can offer the best solution to the problem. freedrop is particularly suitable for unstable stores where tumbling motion can be continued without the constraint of CTS sting limitations/mechanical constraints Finally, freedrop testing allows studying multiple stores releases from racks in- the ripple mode.

The greatest disadvantage to freedrop testing lies in its cost and the rather limited use of the data for future study. Data reduction is also a lengthy process. The nature of freedrop testing is such that the store is usually destroyed. The model is normally captured in screens after release but only to salvage the model for refurbishing for later testing and to prevent wind tunnel damage. Normally, one model is used for each drop. The cost of model fabrication may easily reach a sizable percentage of the total test cost. Tied also to the cost is the feet that the tunnel is shutdown after each drop in order to retrieve models and reload the aircraft model with new store models. Normally, one to two drops are made per hour, and while "air on" time is short, tunnel occupancy is considerably lengthened. Incidentally, the model screens generally increase required tunnel total pressures and hence, increased power costs for higher Mach numbers.

Model fabrication particularly with heavy model scaling, can be difficult in obtaining the correct scale of moments of inertia, weight, and center of gravity simultaneously. The requirement to use high density materials such as tungsten, gold and other expensive metals or alloys can drive costs up further, plus create fabrication problems. Engineers should consider allowing a tolerance in modeling the store mass properties - saving design time and the possible selection of less costly materials and machining. Ejection mechanisms can similarly produce problems in modeling. Testing may not be possible with certain full scale ejection forces due to practical limitations in model ejector designs.

Finally, a fundamental shortcoming of freedrop is its inability to address releases under active guidance or with axial thrust. Furthermore the method is not particularly suited to maneuvering release or diving flight although methods have been developed for correcting vertical and axial displacements due to the load factor and bank angle associated with the maneuver (Reference (21)). Summarizing freedrop methods (particularly using heavy model scaling laws) produce very good agreement with full scale trajectories and in some cases offer the only viable experimental technique. The technique has major drawbacks in the costs associated with this type of testing, the unsuitability of the data for future study, and its limitations to certain types of separation problems.

Note on Model Scale for Wind Tunnel Testing:

Perhaps the single most prominent problem associated with wind tunnel trajectory testing techniques lies within the realm of model scaling. Generally, the wind tunnel test approach is valid for the simulation approach in use today. Under the assumptions of quasi-steady flows, the aerodynamic behavior of the store within the flowfield is tempered only by Reynolds number and the fidelity of the model and support system to produce as near as possible the full scale external store shape. Realistically, however, the high cost of wind tunnel testing favors the smaller tunnels and consequently, the CTS and grid testing approaches used by the OAC have been designed around a 5% scale collection of store models. This standardization of scaling has contributed to a substantial savings in model fabrication costs since many store programs involve many different aircraft types. It may be noted that the OAC also maintains 5% models of practically all inventory USAF fighter aircraft. The F- 111 model is the only one which is not standardized. It is a 4.7% model and this does cause store model problems. Five percent scaling is suitable to the AEDC 4T tunnel but creates a challenge in minimizing loss of store detail at this scale. For example, sophisticated guided bombs possess antennae umbilical fittings, conduits, and other protuberances that are extremely difficult to model at this scale. More importantly, these same types of stores may have lifting surfaces with airfoil shapes. Modeling of these surfaces is often restricted to net plates with shaped leading and trailing edges. Correct alignment of these surfaces is also difficult at these scales. Additionally stores with canards or other control surfaces designed to "trail center" or "float" freely during carriage and the first few seconds after release before being engaged are extremely difficult to model effectively. The engineer often must assume the worst case condition exists with these surfaces locked. Alternatively, freestream data collected for a larger scale model may be incorporated to estimate the deflection of these surfaces within the aircraft flowfield. Mating some store models to the sting balance combination may become very complicated at 5% scale. Often some modification has to be made to the store afterbody to be able to accept the balance. Furthermore, sting interference effects on store aerodynamic characteristics, particularly at transonic Mach numbers for stores with boat tail after bodies, can be significantly affected by sting-to-model base diameter ratio. While these effects can be alleviated somewhat by prudent sting design, there are important model design considerations that the using engineer should keep in mind when dealing with small model scales. Testing has shown that attention to minute model detailing to the maximum extent can improve small scale results with regard to full scale or flight test results. Details such as store openings, swaybrace appendages on suspension equipment, vortex generating devices, and antennae can impact results significantly. The model scale clearly has an impact in store balance selection. Small scale stores may preclude full six-component balance installation and often four or five component balances are used instead (usually excluding roll moment and or axial force). Consequently, to provide fully accurate coefficient information, the missing data must be supplied from external sources. The difficulties encountered at small scale can be offset by testing the store in freestream at the largest scale possible. Interference aerodynamics are obtained from the flowfield determined coefficients by subtracting the freestream aerodynamics for the same small scale store at the same attitude. Consequently, the effects of loss of model details are removed from the interference aerodynamics.

Analogy Methods:

Clearance of a store can often be approached from an analogy standpoint; that is, when similarly shaped stores that have been previously flight tested and for which the preponderance of data show that from similarity the new store can be tested in a low risk manner. In these instances, a number of store characteristics are compared between the two stores - the new store and the store that has already been tested - and a conservative buildup flight test program is accomplished. The analogy is established on the basis of mass and physical similarity between the two stores including the planform areas. Freestrearn aerodynamic data is generally compared between the stores and if experimental data is not available, aerodynamic estimation codes are used to generate a comparison. Since the missing data is normally the interference flowfield effects, in attempting to establish the analogy one should consider differences in where the two stores are positioned in the flowfield This is to say that the location of each store's lifting surfaces at various locations in the flowfield should be noted as well as the similarity in the store suspension system. A primary consideration is any variation of store center of gravity relative to the ejection force. Imparted ejection moments should compare favorably both in magnitude and direction. Six degree of freedom simulations without flowfield data can be executed with important aerodynamic coefficients varied parametrically - but caution should be exercised in evaluating the results. Using the approach successfully is predicated on sound, well documented historical data in the form of flight test reports. The propagation of analogies based on other analogies should be avoided. It is best to base each analogy clearly upon well documented, hard test results and data. Obviously, the basic advantages this method offers is a minimal cost program for generating a flight clearance by circumventing the cost and lead time required for wind tunnel testing. The technique is best suited to minor design changes for previously cleared stores, or for stores of similar shapes. For an agency like the OAC or AIR-530, that processes over hundreds of flight clearances each year, the use of analogy techniques have proven an effective approach when properly applied. The greatest disadvantage is in the relative risk, the relative increase in flight testing, and the amount of judgment and experience that must be relied upon in deciding upon the approach for a particular problem.

Specific Techniques Used by the NATO Nations:

In order to determine what techniques were being used in the nations outside the US, the original authors visited several government and industry organizations in other NATO nations and found that, in essence, all the techniques used in the US are being used by other countries; at least to some degree. Some real innovative application of proven techniques were uncovered, such as the method of actually measuring captive store loads during flight testing and then using data to perform six degree of freedom trajectory calculations (Netherlands), and the development of an Accelerated Model Rig (AMR) for accurate freedrop wind tunnel testing (United Kingdom). The original authors found that the well documented wind tunnel techniques such as grid survey and freedrop are being used; however, not as extensively as theoretical methods. In the US the reverse is true (at least presently). That is, in the US, the wind tunnel based methods are extensively used.

At this point, it is useful to outline the techniques and methods used by several of the NATO nations and the reasons why they selected the particular technique. The purpose of this section is to serve as a basis for stimulating officers/engineers and managers in various government and industry organizations to use the AGARD channel to submit and disseminate additional information on internal capabilities, techniques, and procedures for use by the aircraft/stores compatibility community.

United States (US):

The OAC has established informal guidelines in deciding what techniques are best suited to a particular store separation problem. Generally, since most stores are carried in complex configurations, and released from multiple carriage racks at transonic speeds, experimentally determined flowfields is the preferred methodology. In fact, before proceeding any further, it may be stated, based on a review of OAC records over the last several years, that wind tunnel based prediction techniques have been used in the following proportions: CTS - 15% grid - 70%, flow angularity -10% and freedrop - 5%. the original authors informally polled AEDC personnel and were told that CTS was used 50% of the time, grid and flow angularity was used 359£ of the time and freedrop was used 15% of the time. These percentages give a good indication as to the degree the various techniques arc used by industry and government throughout the US.

By using the experimentally derived flowfield approach, a general flowfield data base is continually expanded to include additional stores and aircraft. The OAC has developed an extensive data base for the F-15 and F-16 aircraft. Data exists in both grid and flow angularity format. As a cost savings measure, the grid is normally acquired in the limited gride mode described in an earlier section. During each test, however, the Limited grid is compared with selected full CTS trajectories to verify the grid data base. For stores of large planform area, the store grid is acquired both as a function of vertical distance from the captive position and the pitch attitude of the store. Generally, freestream data for each store is acquired at the same scale as the flowfield grid, but for stores with complex shapes, larger scale data is acquired if at all possible. The consideration here is primarily the availability of funds to cover the cost of wind tunnel testing. Stores such as bomb racks and fuel tanks that have a pivoting release mechanism cannot be practically tested using CTS Only for these type situations is the freedrop method used. When freedrop testing is performed, heavy scaling is used.

Analytical methods are currently-restricted to single carriage stores at speeds outside the transonic flow region (Mach number less than 0.9 and greater than 1.1) For this reason, analytical methods are not routinely used. Analogy methods are used extensively. Analogy methods are supported by an extensive flight test data based and computer simulations using appropriate data when necessary. Every available source of information is cross-referenced when exact aerodynamic data is not available.

The six degree of freedom computer program is the mechanism used to actually calculate store separation trajectories. The program used by the OAC is fully documented in Reference (22) and (23). The program uses a look-up format for all required input data such as ejection force, flowfield store mass properties, aircraft flight conditions and so forth. The program is an adaptation of the DDI-MODS modular trajectory simulation developed by Litton Systems. It has been extensively modified to suit the special purposes of the OAC For example, the program can be used to address maneuvering release of stores with post aircraft maneuvering. Output from the program is in a multifaceted digital format; however, computer generated plots are the primary means for analyzing store separation trajectories. The computer graphics program is fully described in Reference (24). Incidentally, computer graphics portrayal of store separation trajectories provides the store separation engineer with a valuable analysis tool. The engineer is able to quickly "see" the trajectory instead of having to analyze "mundane" data plots. Practically every organization is now using computer graphics in some form or the other. The rapidly expanding field of computer graphics offers ever new opportunities for enhanced analysis.

As will be mentioned in some detail in the next section, the scope of the flight test program, at least in the US, is largely influenced by safety of flight, cost, and time factors.

A very real problem in store separation today is multiple bomb rack jettison. Associated with every employment envelope established for stores is a jettison envelope for the rack from which the stores are released if the rack itself is jettisonable. For example, CVER, MER 10 and TER-9 multiple bomb racks are jettisonable. Jettison of racks can be very dangerous. It would be very expensive to wind tunnel and/or flight test all possible combinations of rack/store configurations that could be encountered. For example, the normal release sequence for the six stores from alternates from aft to forward rack stations. If for example, a malfunction occurs as stores are released, leaving three stores forward and two stores aft, one store forward and no stores aft, and so forth, and the pilot is now forced to jettison the rack with remaining stores, one can see that separation can be quite a problem due to the unusual aerodynamic arrangement and large off-center weight. Since racks are normally only jettisoned in an emergency there is little incentive to spend any more money and time than is necessary to establish a benign safe jettison envelope. Because bomb racks are very narrow, use of the CTS is generally precluded due to sting mounting incompatibilities. As a result, wind tunnel testing has, in the past, resorted to freedrop testing. Unfortunately, this approach does not satisfy the economic considerations when dealing with the scope of the problem. Consequently, a technique for establishing a more efficient return on, generated data and allowing more flexibility in studying rack jettison questions was needed by the USAF. As a result, the OAC developed a technique called the Multi-Carriage Bomb Rack Jettison Computer Simulation Techniques (MST). The technique is documented in Reference (25). The technique offers a method for predicting the trajectories of bomb racks which are of low density, are aerodynamically unstable, and have wide center of gravity and moment of inertia variations. All of these characteristics contribute to coupled angular motions. Because of the complex nature of the problem, it can best be solved experimentally.

The MST acquires total flowfield aerodynamic coefficients from two sources. First, the rack with attached stores is mounted on an instrumented pylon (internal pylon balance) and aerodynamic data are obtained for the total installation in the captive carriage position. Next, freestream aerodynamic data for the rack/store configurations are obtained using a larger model scale to facilitate sting installation. Once this data is obtained, it can be subsequently used in support of this type of work or other aircraft. These data form the starting point for determining captive carriage interference aerodynamic coefficients. Interference coefficients are decayed exponentially with vertical distance with respect to the pylon. The resulting data is used in a six degree of freedom computer program, along with other necessary input data to obtain rack trajectories. The technique has been validated with freedrop tests for a variety of rack configurations and Mach numbers with very good correlation. This technique is very useful for subsonic flow, but does not agree as well for supersonic flows where more complex patterns of shock flow exist. Some a-priori knowledge of the flowfield is needed to establish decay constants through previous tests and extensive freestream data is needed. This is the principle disadvantage to the technique. Yet, it does provide more data versatility than the freedrop method, and gathers installed loads data in the process which may be useful for later studies.

United Kingdom (UK):

During the visit to the UK, the original authors visited with representatives from several agencies and organizations, all of whom are actively involved in store separation and each of which utilizes one or more techniques.

Aeroplane and Armament Experimental Establishment (A&AEE) Boscombe Down

Aircraft/store certification requirements emanate from the Royal Air Force (RAF) and are submitted to the Ministry of Defense/Procurement Executive (MOD/PE), who processes validated requirements to the (A&AEE) (A&AEE) evaluates the requirement and assesses whether flight testing can be performed without the need for analyses or wind tunnel testing, or if flight testing can be dispensed with and the requirement met by analogy to an already certified aircraft/store configuration. Usually flight testing is required! In fact, even for analogy situations, flight testing is usually performed to demonstrate satisfactory store separation at the comers of the night envelope. When analyses or wind tunnel testing is deemed necessary, (A&AEE) solicits assistance from aerospace firms or other government organizations through MOD/PE Upon receipt of predicted store separation characteristics, (A&AEE) formulates the night test plan and conducts the testing. The initial test point is selected on the basis of judgment and experience. Subsequent test points are based on results of predictions and actual results after each test mission. (A&AEE) utilizes externally mounted cine cameras to record store separation trajectories. Cine film is reduced using a photogrammetric data reduction program called ATRAJ While this system has worked well in the past, (A&AEE) has taken the initiative to develop a video camera system. The system (the first of its kind seen by the original authors) offers to revolutionize data gathering for compatibility testing and will be discussed in a subsequent section.

Royal Airplane Establishment (RAE), Bedford

RAE Bedford is not directly involved in aircraft/stores compatibility testing. In the original authors view, RAE can be likened to the US's National Aeronautics and Space Administration (NASA). They have their projects and flight test resources. They perform basic research, concept evaluations, and system assessments (RAE Bedford developed the first Heads Up Display). RAE Bedford has taken a leadership role in the UK in developing theoretical prediction techniques for store separation. Techniques are then made available to industry and government in the UK

RAE Bedford has developed a store prediction technique called RAENEAR (an improvement of the NEAR technique). This technique is a panel method and is valid for stores with circular cross sections. RAENEAR calculates the flow field, calculates store loads, and uses the equations of motion to calculate the trajectory. Advantages of RAENEAR are that it is cheap (does not require expensive wind tunnel testing) and quick; although the definition of "quick" is relative. At the present time, each run requires several hours of computer time. A disadvantage of RAENEAR is the limitations of aerodynamic theory (particularly in the transonic Mach regime and at high angles of attack) which impacts prediction accuracy. RAE Bedford acknowledges that theoretical methods are far from being reliable enough to dispense with wind tunnel techniques. However, they are convinced that with RAENEAR critical configurations, speed regimes, areas of difficulties, and so forth, can be evaluated at less cost than by only performing expensive wind tunnel testing. RAENEAR is fully described in Reference (26) and an overview of RAE Bedford prediction methods is contained in Reference (27).

British Aerospace (BAe) Brough

BAe Brough uses both theoretical and wind tunnel techniques to predict store separation trajectories. Both RAENEAR and SPARV, Reference (28), theoretical techniques are used. BAe Brough is enhancing RAENEAR by improving its computational efficiency and accuracy, improving modeling and aerodynamics, and extending its applicability to non-circular ejected stores, Reference (29). SPARV, is a panel program which calculates store forces and moments at any position in the trajectory and then uses a Runge Kutta iteration to predict the movement of the store. BAe Brough states that the method is still in its infancy and will be improved by incorporating semi-empirical techniques such as cross-flow drag and viscous effects. They feel that SPARV, is better than the simpler RAENEAR because of the greater potential for extension as modeling techniques for panel methods improve. SPARV, is applicable to complex geometries and, hence, can easily handle effects of geometry changes. The SPARV, program has been validated to some degree by comparing predictions with flight test results. BAe Brough states that a shortage of high quality flight test data has been a major stumbling block in investigating the relative merits of various prediction techniques. Turning to their wind tunnel capabilities, BAe Brough operates a blow-down tunnel with a 0.68 square meter test section. The relatively small size of the tunnel dictates use of small models on the order of 1130 scale (they have 1/28.5 scale Hawk aircraft, 1/30 Buccanner and Harrier aircraft, and 1/30 scale Tornado aircraft). Because of small tunnel size, the freedrop technique is preferred and its use has been optimized for their blow down tunnel.

BAe Brough has evaluated the pros and cons of the various scaling methods and selected light model scaling. To compensate for the gravitational deficiency associated with this scaling method, a unique Accelerated Model Rig (AMR) was developed. The function of the AMR is to accelerate the model of the aircraft upwards during store separation. Using a 1/30 scale model, the AMR accelerates the aircraft upward 29g during store separation. This 29g coupled with the 1g natural gravity field approximates that which would occur in an ideal 30g field. The upward acceleration of the model can be maintained for about 20 milliseconds (an additional 20 milliseconds is allowed for deceleration to rest) which equates to 0.6 seconds full scale. This is adequate for most stores to leave the near field of the aircraft. Correction of the gravitational deficiency using the AMR accounts for the largest (first order) error associated with light model scaling. The other source of error is the induced incidence of the aircraft as a result of its upward acceleration, and the induced incidence of the store as a result of the gravitational deficiency. To minimize errors from this source, BAe Brough has devised the technique of adjusting the pitch rate of the ejector. The validity of the AMR has been estate; shed by virtue of good comparison of predicted/actual store trajectory results. Data comparisons are presented in Reference (30) along with a detailed discussion of the AMR design and construction details.

Although BAe Brough has a viable AMR system, several improvements are planned. For example, the ejection force simulation will be improved and end of stroke velocities will be measured using a laser doppler technique. Trajectory analyses will be enhanced by implementing a data reduction system that is similar to the US's Graphic Attitude Display System (GADS) used for Cine camera film reduction. GADS will be discussed in a subsequent section. Use of this type of data reduction system in a wind tunnel application would be entirely new. It may be noted that at the present time, Cine film is reduced using either a one or two camera solution. BAe Brough is looking into ways of changing the aircraft incidence during aircraft acceleration (perhaps with a microprocessor controlling the parent aircraft rack and pinion system). This would eliminate the need for adjusting the ejection force/moment. Lastly, they are evaluating increasing the maximum wind tunnel operating stagnation pressure from 4 to 9 atmospheres. This would have the effect of increasing Reynolds Number (RN) to 1/4 to 1/5 of full scale values. A final thought on the AMR system. It may be noted that the system can only be used for single store releases due to the short time available for accelerating the parent aircraft model. However this has not proved to be a serious limitation for BAe Brough since most of the releases that they are required to support are single releases.

BAe Brough also operates two other wind tunnels in support of store separation testing. The Open Jet Wind Tunnel (2x2 foot test section) is used for free drop testing. Light model scaling without gravitational correction is used. For l/7 scale (typical) the acknowledged trajectory error is about one meter vertically at 0.5 seconds with an induced incidence error of about one degree at Mach 0.5. Multiple store releases are made in this tunnel. Use of heavy model scaling was considered, and rejected, because of the need to increase store density to high values that required models to be constructed from exotic (and expensive) materials, and the need for high ejection forces.

The BAe Brough Low Speed Wind Tunnel is a continuous flow tunnel with a seven by five foot test section (velocities up to 250 ft/sec). freedrop testing in this tunnel uses Froude scaling due to low Mach requirements. Normal model scales range from 1/10 to 1/12. Testing this tunnel is primarily devoted to evaluating emergency jettison of stores during take-off and landing conditions. The reader is encouraged to read Reference (38) which describes in some detail the store separation methods used in the UK. Intuition, RAENEAR light model testing, and the AMR are all discussed in this reference.

Aircraft Research Association (ARA)

ARA is an independent cooperative research and development organization set up in 1952 by 14 UK aerospace firms. It is non-profit and is not government owned. ARA operates two continuous and four intermittent wind tunnels. The focal point of store separation activities is the 9 by 8 foot transonic wind tunnel (up to Mach 1.4). ARA utilizes freedrop testing using light model scaling (with a simple vertical displacement correction factor incorporated into final reduced output data to account for the gravitational deficiency).

ARA operates a Two Sting Rig (TSR) which is similar to the US's CTS The TSR is described in Reference (31). The TSR is used in either the trajectory or the grid mode. This system was validated in 1978 by comparison with flight test data and a US CTS The TSR can be used up to Mach one. Typical model scale is 1/10. Position accuracy is advertised as plus/minus 0.05 inches and 0.15 degrees.

ARA is very active in theoretical prediction methods. They believe that these methods are needed to complement wind tunnel work. ARA has used the Nielsen method (Reference (32)) and validated it to high subsonic Mach. The method is used to support wind tunnel studies before actually conducting testing. ARA is convinced that in the future there will be an ever increasing use of theoretical methods to complement wind tunnel testing. Incidentally, ARA used the Nielsen method to optimize lateral spacing of stores on a Twin Store Carrier (TSC). Because of these studies, subsequent wind tunnel testing was much reduced in scope had studies not been performed. The reader is encouraged to read Reference (33) which fully describes store separation testing at ARA ARA's opinion as to the advantages and disadvantages of mathematical modeling, TSR, and freedrop are all discussed in this Reference

Netherlands (NL):

The original authors visited the National Aerospace Laboratory (NLR) which is a government subsidized organization. NLR has extensive store separation prediction and test capabilities for aircraft used by the Royal Netherlands Air Force (RNLAF). They have a complete NF-5 and F-16 capability. NLR is the recognized authority on compatibility matters in the Netherlands, and accordingly, the (RNLAF). relies on NLR for technical expertise. Basically, the (RNLAF). provides NLR with their certification requirements and NLR then performs compatibility analyses, and formulates and orchestrates flight testing which is performed by the NRLAF.

NLR can predict store trajectories using theoretical, grid, flow angularity and freedrop methods. When wind tunnel testing is required, NLR prefers use of the grid method. This is because, as mentioned in an earlier section, grid data can be used off-line to perform trajectory analyses. Trajectories are calculated using a six degree of freedom computer program called VORSEP. VORSEP accepts aerodynamic parameters as inputs. The model can be operated in two ways: (1) to predict store trajectories when aerodynamic coefficients are obtained from theoretical studies, wind tunnel tests, or from tests with the NLR full scale captive store load measuring system (described in subsequent paragraphs), and (2) to determine aerodynamic coefficients from store trajectory data measured in a wind tunnel or from full scale store separation tests. In these cases the model initially uses predicted coefficients to produce a predicted trajectory and the coefficients are adjusted until the predicted and actual trajectories coincide. VORSEP, the NLR panel method, and other prediction techniques used by NRL are fully described in References (34) and (35).

In addition to the above, NLR has developed, and validated, a unique, full scale flight test captive store load measuring system. This system consists of a support structure suspended from a bomb rack, a five component load measuring balance, and a replaceable store shape (which is made as light as possible to minimize inertia. forces). The system is designed so that in-flight airloads may be measured with the store in a captive carriage position and in a displaced position (with a spacer placed between the store and the carriage rack). The basis for selection of this nominal offset value was NLR studies which show that interference aerodynamic forces decay rapidly to small values by the time one store diameter is reached. This correlates with USAF results. The system has been validated on the NF-5 using a number of low density store shapes such as the BLU-1. NLR experience is that store separation trajectories based on flight test full scale captive loads are far more accurate than theoretical or wind tunnel based predictions. Incidentally, NLR believes that this system is particularly suited for their use since the NF-5 carries stores on parent pylon and on multiple carriage racks and many stores are of the low density, unguided, variety. The NLR captive store loads measuring system is fully described in Reference (36). AS a follow on activity,, NLR is developing a self-contained instrumentation package that will allow tests on normal operational aircraft. The present system must be used on a specially instrumented aircraft since data is recorded on the aircraft.

When a new certification requirement is received by NLR an assessment is made to determine if the store can be certified by analogy. NLR acquired an extensive aerodynamic data based for stores certified on the NF-5 by the airframe contractor. This data base is very important to NLR and serves as a basis for analogy type certifications. If a new store fits within the analogy criteria, no further analyses are performed and flight testing may or may not be conducted. If an analogy does not exist, store trajectories are initially predicted using the NLR panel method. Results are used to identify safe, marginal, and unsafe areas of the flight envelope. If results show safe separation throughout the flight envelope, no further analyses are necessary and flight testing is conducted only as necessary to validate predictions. If results show marginal or unsafe areas of the flight envelope, NLR may request that the (RNLAF). first perform flight testing using the captive loads system. NLR reports that three missions are usually required to gather store airloads data for each configuration (one mission with the store in the captive carriage position and two missions with the store in displaced position). Store airloads are subsequently used in six degree of freedom computer program to predict store separation trajectories. NLR reports excellent agreement between predictions and actual results. In fact, data contained in Reference (37) show that for LAW-3 and BLU-1 stores, trajectories predicted using the captive load system compared very well with actual results. On the other hand, predictions based on the NLR panel method and wind tunnel data did not compare nearly as well (particularly in the pitch plane). In view of proven results, NLR naturally attaches high confidence to predictions using the captive store loads measuring system. This system has enabled store separation flight testing to be performed with lower risk and fewer missions than would otherwise have been possible. It may be noted that NLR starts flight testing at a point judged to be very safe (based on experience). If there are any significant differences between predicted and actual results, carriage loads are extracted from actual results and used to update predictions. This process is continued until separation envelope goals have been achieved.

Before closing this section it should also be noted that NLR has developed their own data reduction program, called MILLIKAN, to support store separation flight testing. The program converts store images on movie film to six degree of freedom digital data. This program uses a single camera solution. The MILLIKAN, system is fully described in Reference (38).

Canada (CA):

The development of a Canadian Forces (CF) store separation prediction and test capability has been rather recent; yet, the CF has already developed a baseline capability along with plans for further growth. Historically, the CF certified stores on their aircraft by analogy to stores certified on another country's aircraft or by performing night tests. The problem with the analogy method was that the CF frequently found that another country's flight envelopes were too restrictive for their use. As no pre-flight prediction techniques existed, the CF resorted to brute force flight testing. The CF found that this type of testing was too expensive, too time consuming, and too resource expensive for their purposes.

The above operating procedure might have remained unchanged were it not for the decision to enhance the CF-5 external stores capability. The CF-5 program provided the opportunity for the CF to develop and acquire a prediction and test capability. The CF (through DFTEM 4-4, CF office of primary responsibility for stores compatibility) were aware of, and liked, the manner in which stores were being certified by the (RNLAF). on the NF-5 with the assistance of NLR This stimulated the CF to establish an in house prediction and test capability utilizing Canadian industry (Canadair LTD) in conjunction with the government's National Aeronautical Establishment (NAE) High Speed Aerodynamics Laboratory and the Aircraft Engineering Test Establishment (AETE). Initially, the CF established a joint Canadair/NLR effort to certify the SW-25 and BL-755 stores on the CF-5. During this program, Canadair obtained NLR prediction methodology and AETE developed instrumentation and test techniques.

The first in-house application occurred in 1978 when the CF was tasked to certify the LAU-5003 rocket launcher (with various weight warheads) on the CF-5. Canadair performed preliminary trajectory analyses using their store separation model to determine critical configurations and to form a basis for establishing a flight test plan. During AETE flight testing (using an instrumented captive airloads measuring system like that used by NLR actual results were compared with predictions and, where necessary, predictions were upgraded before proceeding to the next test point. Following successful completion of the program, LAW-3 and LAU-5002 rocket launchers, AIM-9 missiles, and an airborne instrumentation pod were certified by purely analytical means saving the CF substantial funds, time, and resources.

The Canadair store separation model is described in Reference (39). This program is written in Fortran specifically for use on Canadian computing facilities. Basically, it is a modular six degree of freedom program so that it can be used to support any compatibility program (its use is limited to unpowered axi-symmetric stores). It consists of a MAIN program which utilizes store and aircraft mass and geometric input data an calculates and tabulates the actual trajectory. Subroutines consist of ATMOS which processes altitude and velocity parameters, LIFT which processes store and aircraft aerodynamic parameters as a function of flight condition, EJECT which converts ejection forces into store forces and moments, AERO which calculates total freestream plus interference, or freestream plus captive) store aerodynamic loads during the trajectory, and PLOT which plots the trajectory. In LIFT< the aircraft angle of attack remains constant during store separation; in EJECT, ejection force "recoil" is included. Forces are varied from pylon to pylon in AERO, captive store loads are decayed to freestream by the cube of the aircraft wing aerodynamic chord. In addition, the simplifying assumption is made that store freestream and interference forces can be treated independently. Accurate inputs to AERO are obviously the key to accurate trajectories. AERO can accept experimental, theoretically derived, or captive store airloads measured with an instrumented store (this has been done successfully at AETE).

In the theoretical area, the NAE initiated a multi-faceted effort to develop and purchase computer prediction codes and to acquire and fabricate wind tunnel equipment to support store separation programs. Several codes are in use and development to generate store freestream aerodynamic forces. The Jorgesen code is used to predict forces and moments on slender bodies up to 180 degrees alpha (subsonic and supersonic). This code is based on slender body and cross flow theory and has been extended for use up to Mach three; a code termed AKCAX is being developed to predict the freestream pressure distribution and drag for slender bodies at zero degree alpha and to predict side force at high alpha. The Mendellhall code is used to predict freestream forces and moments on wing/body/tail store configurations up to 35 degrees (subsonic and supersonic). This code is based on lifting surface theory which utilizes vortices shedding from the body nose and the wing edges. Plans are to acquire a crossflow code to be able to predict freestream forces and moments (subsonic and supersonic) up to high alpha. Interference forces and moments on a store as it translates through the aircraft's flowfield are predicted subsonically using the three dimension NLR panel method and transonically using the equivalence rule/cross flow developed by NAE and solved by the NLR panel method. This method is characterized by short computer times. The Dillenius code is used to predict store captive loads. RAENEAR (valid for stores with circular cross sections) and NEAR (not limited to circular cross sections) prediction programs are also in use. Present plans are to compare predictions with flight test data to assess prediction accuracy.

It is clear from the above that the CF has developed, and is enhancing, their prediction capabilities to support current and future efforts such as for the CF-18 aircraft/stores compatibility program. Current plans are for a contractor to perform trajectory predictions and provide flight test support for initial baseline store configurations. This will establish a data base for the CF and put the CF in a posture to perform follow on certification efforts totally in-house beginning in 1986. Along these lines, the CF is already planning on obtaining their own 6% CF

18 wind tunnel model. The reader is encouraged to read References (40) to (44) which describes in considerable detail Canadian store separation methodologies and capabilities.

France (FR):

During their short visit to France, the original authors visited Avions Marcel Dassault-Breguet (St. Cloud). Dassault has extensive prediction capabilities utilizing both wind tunnel based grid, freedrop (using light model scaling), Captive Trajectory System CTS methods, and theoretical methods. Because of the wind tunnel's high cost, and the ability to perform parametric studies and pre-flight comparative analyses, theoretical methods are preferred.

The aircraft flow field is theoretically predicted: subsonically, using the singularities method with a distribution of sources, sinks and vortices on the aircraft surfaces and divided into a large number of elements (this method requires high computing time); and supersonically, using the finite difference method (which assumes isentropic flow and does not consider shocks).

When wind tunnel testing is performed, the French industrial wind tunnels are used. A configuration analysis is performed to determine which test techniques should be utilized. For example, is the store stable or unstable, low or high density, located adjacent to another store, high or low wing/tail aircraft configuration, speed regime, and so forth? Subsequently, physical and mechanical limitations of the wind tunnel and limitations associated with the test technique itself are evaluated, and based on results, a test technique (grid, CTS or freedrop) is selected. A recent application of in-house capabilities has been in support of the Mirage F-1 program. Store separation wind tunnel testing, using 1/15 scale models, was performed. Dassault reported large yaw differences between predicted and actual results. In the wind tunnel, the missile nose yawed inboard whereas in flight, the missile did not yaw at all. This was surprising, but not new, as similar anomalies were noted by the Air Force during wind tunnel testing performed in support of the A-7D flight test program.

Germany (GE):

The original authors visited Dornier at Friedrichsafen and MBB at Ottobrunn during their short visit to Germany. These firms perform compatibility analyses and testing under contract to the German government. For aircraft in the development phase, the German procurement office contracts for the aircraft and this contract includes the stores the aircraft must carry and release (baseline stores). During the development phase, firms normally perform extensive wind tunnel testing to optimize the shape of the aircraft to ensure successful integration of baseline stores. These test results are reviewed by the German government representative (military certification agency BWB-ML). On the basis of the test results, BWB-ML issues a preliminary flight test authorization as necessary to conduct the next mission. Without a clearance from BWB-ML the firm is not allowed to fly. If a new certification requirement is validated for an existing (inventory) aircraft, BWB-ML decides whether the German government test center will, or can, handle the task alone. Normally, if there is no need to modify the aircraft, BWB-ML decides that the German test center will perform the test. In this event, the test center engineers write a proposed test plan and discuss the test plan with BWB-ML. If BWB-ML concurs, they issue a flight authorization to the test center to allow testing to start. Again, after each mission, BWB-ML reviews results and, upon program completion, issues the final certification which allows the German Air Force to fly within the certified envelope.

Two examples may serve to illustrate the operating relationship of BWB-ML with respect to the firms. In the first case, there was a requirement to establish an Alpha Jet emergency jettison envelope for a twin store carrier loaded with stores. The contractor recommended that wind tunnel testing be performed before initiating flight testing. BWB-ML determined that flight testing could be initiated without wind tunnel testing, and this is in fact what was done. In another example, for a major new missile certification effort on the F-4, MBB predicted missile separation characteristics BWB-ML then reviewed these calculations and issued a flight clearance to the German test center. After each mission, results were used to upgrade the calculations for the following mission. In this example, BWB-ML made the determination that a joint firm/government participative program was in the best interest of Germany.

MBB: MBB uses SSP (Store Separation Program) code which relies on flow fields, captive loads, free flight aerodynamics and ERU-characteristics all determined either by theory or by experiments. In development since 1974, this code has been used to evaluate most clearances needed for the Tornado fighter aircraft where it has been used to optimize the minimum release intervals for multiple bomb releases. For retarded bombs, the intervals were nearly halved by this theoretical optimization and successfully flight tested within the operation envelope. The MBB-SPP has recently supported multi-firings of the Tornado/MW-1 ammunition. References 4547 present an excellent discussion of the MBB-SSP methodologies.

Dornier: Dornier employs a variety of prediction techniques such as grid, free drop, and theoretical. Theoretical techniques and free drop appear to be the centerpiece of Dornier's methodology. Although a store data base is maintained, theoretical store separation predictions are always made, even if a new store is analogous to a certified store. Dornier has had good success using theoretical methods and free drop which are documented in References (48) and (49). An interesting application described to the original authors was in support of a tow target system. Problems were being encountered during target tow. The system was modeled mathematically and parametric studies were performed which identified a fix. The fix was implemented, tested, and proved successful during subsequent flight tests.

High confidence is placed on the accuracy of predictions using wind tunnel methods. However, wind tunnel testing is rarely used due to high cost. In fact, it is the original authors' understanding that the wind tunnel is used only when there is an order for a production aircraft to support the high cost of testing. If wind tunnel testing is performed, free drop and grid (particularly for missiles) methods are used. Dornier examined use of light, heavy, and Froude scaling. Heavy model scaling is preferred although light model scaling is used for low density unstable stores. Judgment is used in selecting the best scaling method for the applicable task at hand.

1.4 Release Methods. Two methods of releasing a store will be examined. They are the nonejected release (gravity drop) and ejected release. To analyze the release, imagine an airplane loaded with stores, flying in stabilized, level flight. The lift equals the weight of the aircraft and the stores, and the thrust equals the drag. To achieve the necessary lift, the airplane is at a certain AOA Also, the sum of the aircraft pitching, rolling and yawing moments is equal to zero.

Gravity Release. In the ideal gravity release, as soon as the suspension hooks open, the store is pulled free of the aircraft by gravity and accelerated toward the earth. The thrust on the aircraft accelerates it forward away from the store, resulting in a satisfactory separation. However, in an actual release, especially with multiple stores, the movements of the aircraft and stores prior to and at the moment of release, can result in an unsatisfactory separation. After the first store is released from one side of the airplane, the drag on that wing is decreased and a slight yawing moment will be induced on the airplane. The decrease in weight on that wing will also cause a rolling moment with subsequent yaw due-to-roll With the release of the stores, there may be a CG shift. The CGT shift can cause a nosedown or nose up pitching moment on the airplane. These three moments and the associated angular accelerations can cause the airplane to rotate toward subsequent released stores. This problem is compounded as dive angles arc increased, because the separation force due to gravity is proportional to the cosine of the dive angle in straight-path dives, thereby decreasing as dive angle increases. Thus, a stable low-drag store could continue to fly in close proximity to the airplane.

Ejected Release. To overcome the above problems, a device was designed that would eject the stores from the rack. These ejector racks were designed with electrically actuated cartridges that supply energy to the ejector units. With these racks, even at very high dive angles, a separation force will be exerted on the weapon to push it away from the aircraft; however, the motions and reaction forces of multiple racks and airplane structure (such as wing twist and flex) can negate the benefits of ejected releases. As each store is released from the rack, the rack undergoes a reactive motion such that the rack is flexing in a direction opposite to that of the ejection velocity. This motion can yield a negative or zero separation velocity with respect to the aircraft. The ideal ejection velocities from a rigid MER/TER ejector (MAK-79) are only 6 ft/sec (for a 500 lb bomb) and just 4 ft/sec in the vertical direction for the shoulder stations. Currently, the CVER, BRU-33A/A, used in conjunction with the F/A-18, employs an ejection velocity of roughly 20 ft/sec statically. Due to rack dynamics, the ejection velocity imparted onto the store is roughly 10 ft/sec, with a 500 lb store. With the previously mentioned small ejection velocities (4 and 6 ft/sec), small motions of the very flexible multiple racks can cause poor separation.

1.5 Release Maneuvers. There are four basic types of release maneuvers: straight-path dive, curvilinear dive, dive-toss, and lateral toss.

Straight-Path Dive. In a straight-path dive delivery, the aimpoint reticle is initially placed below the target and is allowed to track toward the target while the dive angle is maintained constant (g = cosine dive angle). The straight path dive is illustrated in figure 2. The forces resulting from this type of delivery are illustrated in figure 3. It should be noted that the gravity portion of the separation force is a maximum (equal to the weight of the store) at O-degree dive angle and is zero in a 90-degree dive. A further item of interest is that studies at NAVWPNCEN China Lake indicate that pilots usually establish more g than the cosine of the dive angle when attempting a straight-path dive. During the NAVWPNCEN tests, the normal g measured during dives that experienced pilots considered to be 45-degree straight-path dive deliveries varied from 0.8 to 1.2, with no releases at the calculated straight-path value of 0.7g. This phenomenon will provide increased bomb-to-aircraft separation and should result in improved separation characteristics with reduced bomb-to-bomb and bomb-to-aircraft interference.

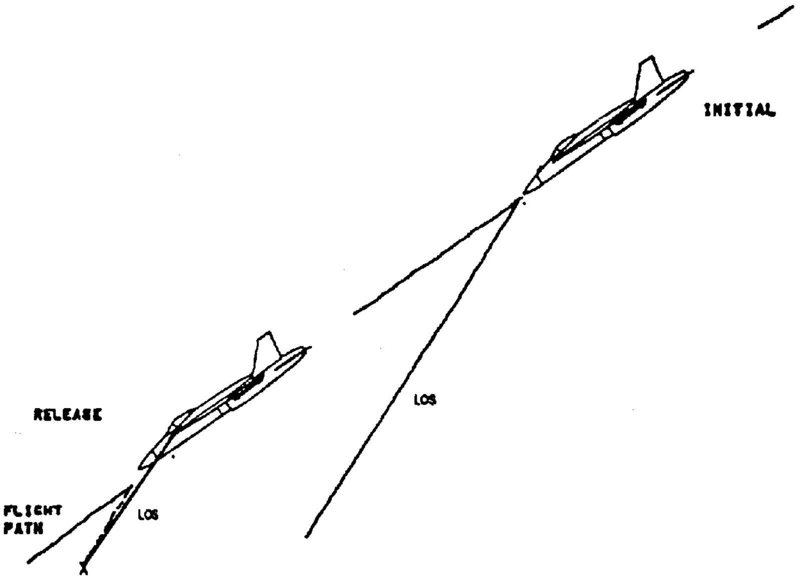

Figure 2
Straight Path Drive

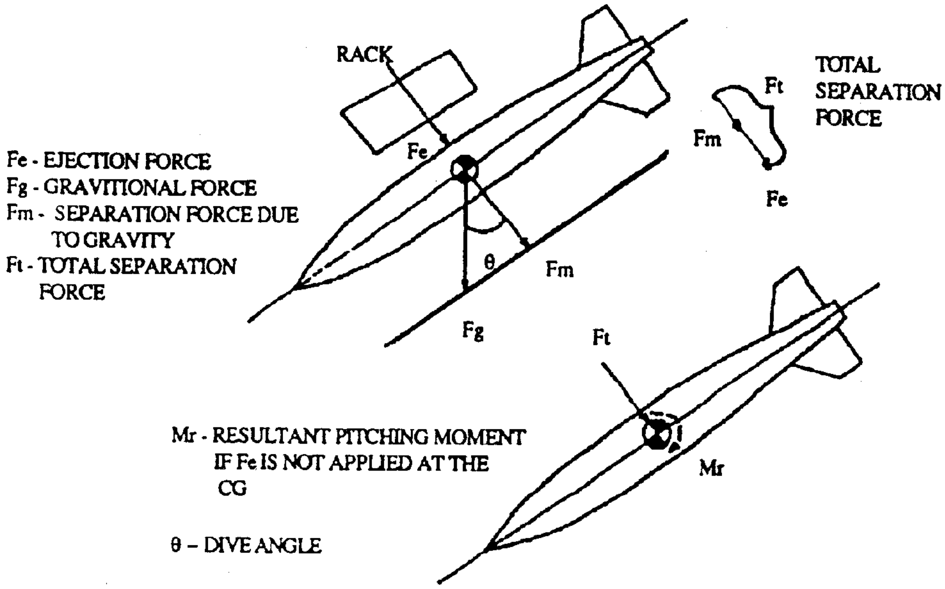

Figure 3
Bomb Forces

<u>Curvilinear Delivery</u>. In the curvilinear delivery, the reticle is placed on the target and held there throughout the dive. This results in the aircraft following a downward curving path as depicted in figure 4. The curvilinear delivery results in a reduction in the gravity portion of the separation force to a state below that realized in a straight path dive delivery of comparable dive angle. This reduces the resultant separation force, all other dive parameters being equal. Because of the resulting reduction in safe separation, this delivery method is not authorized.

Note that a late tracking correction to push the pipper down to the target may produce a curvilinear flight path at release.

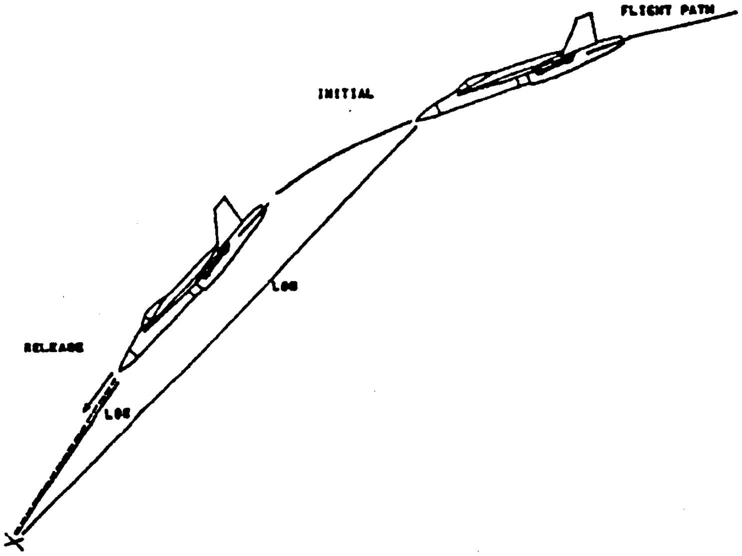

Figure 4
Curvilinear Delivery

Dive Toss. In the dive toss delivery, the aircraft is established in a dive directed at the target (essentially zero sight angle). At a predetermined altitude, a pull-up (usually 4 g's) is commenced. The weapon is released after a computed number of degrees of pitch change and the aircraft continues the pull until the dive recovery is completed (figure 5). The process of determining a dive toss release point has been mechanized within the ballistic computers of modern tactical airplanes to allow a wide amount of latitude in commit dive angle, altitude, airspeed, and normal acceleration. The dive toss delivery improves the separation characteristics by reducing the time the weapon is influenced by the disturbed airflow around the racks, pylons, and airframe. During bomb releases at high g loading, excess lift will exist on the aircraft from the instant the bomb load is released. Thus, the maximum allowable g at release must be limited to provide sufficient structural margin to absorb this resultant g jump. Adequate planning to account for this phenomenon during dive toss deliveries is essential for safe test work

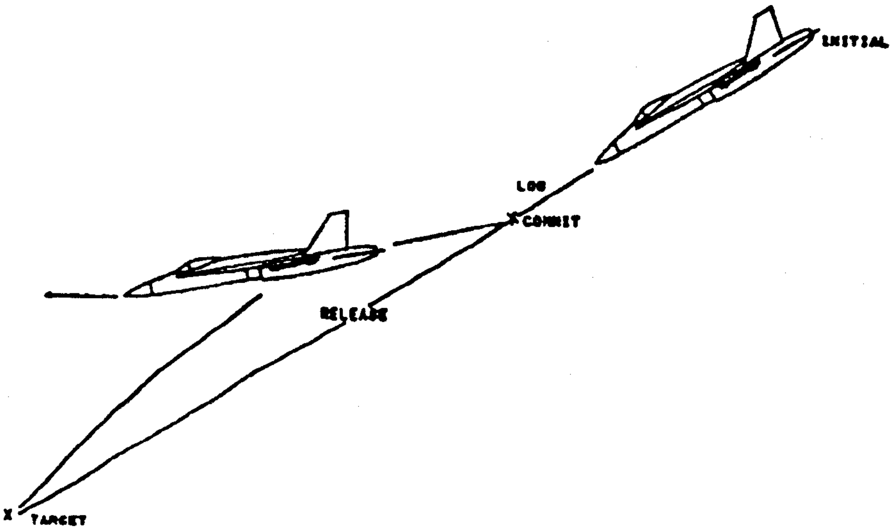

Figure 5
Dive Toss

Lateral Toss Bombing (LTB). LTB is a delivery method designed for low altitude release of low drag (unretarded) weapons. In the maneuver, the airplane approaches the target at a low altitude with an azimuth offset. The pilot performs a high g turn (90 degree bank), pulls through the target, and releases the weapon as the solution cue crosses the target. The maneuver can be accomplished in level flight or a shallow dive. The high g turn required to avoid the fragmentation pattern greatly reduces the time the weapon is influenced by the disturbed airflow, similar to the dive toss delivery, and provides improved weapon separation characteristics. Altitude loss can be expected because the vertical lift is reduced when the airplane bank angle is increased. As with dive toss deliveries, g jump will occur, and adequate planning is required to avoid overstressing the airplane. Weapon-to-airplane collision is not usually a problem during LTB; however, bomb-to-bomb collisions may occur during multiple weapon releases.

1.6 Bomb-to-Bomb Collisions. Bomb-to-bomb collisions frequently cause bomb-to-aircraft collisions and may cause fuze function and detonation after fuze arming. Prevention of bomb-to-bomb collisions is usually accomplished by specifying a minimum release interval (MRI). The type delivery, design of the weapon, and design of the aircraft are all factors which combine to dictate the safe MRI. The effects of delivery maneuvers on bomb-to-bomb collisions parallel those on bomb-to-aircraft collisions. Compared to straight-path deliveries, the dive-toss and lateral toss deliveries provide the greatest bomb-to-bomb clearance for a given release interval and the curvilinear release the least.

1.7 Store Design Effects. The store's inertial and aerodynamic characteristics are important parameters in achieving a safe separation. For good separation characteristics, a store should have a high density (i.e., the weight of the store should be relatively high and the maximum lift low to provide a minimal aerodynamic pitching moment). The store should also have a large degree of static stability. Folding fins can be used to increase tail volume on stores if large fixed fins will interfere with carrying weapons on multiple racks.

Moment of Inertia. The MI of a store, measured in slug ft2, is another important parameter. Application of the equations of motion to the store after release shows that the angular acceleration of the store is inversely proportional to the MI. The larger the MI, the slower the angular rotation; a fact which will allow the store to fall a greater distance before it reaches its greatest angular displacement. This will allow the store to move well away from the aircraft before it can rotate (yaw or pitch planes) into contact with the aircraft.

Center of Gravity. The location of the stores CG with respect to the ejector foot position is also quite important. If the CG is significantly forward or aft of the ejector foot, the store will be given an initial pitch rate on ejection. Newer bomb racks have been designed to reduce this initial pitch rate by incorporating two ejector feet. The pitch rate imparted is inversely proportional to store mass moment of inertia In addition, the store's dynamic stability will affect the resultant aerodynamic pitching moment and may produce more rotation (store aerodynamically unstable) or stop the pitch or yaw rate if the store is stable.

1.8 Aircraft Design Effects. The aerodynamic design of the aircraft and the location of the stores on the aircraft have a very large effect on separation. Phenomena encountered during testing are presented in the following paragraphs.

A-6 Airplane. The A-6 airplane has a very large forward fuselage which necks down fairly rapidly to its narrowest vertical and lateral cross section just aft of the centerline station. As the air flows along the tunnel between the engine nacelles underneath the airplane, the Bernoulli effect produces a low pressure area which causes stores released from the centerline to be pulled upward toward the airplane. The low pressure area causes light stores loaded on inboard wing stations to crisscross underneath the airplane. The less dense the store, the greater the effect the low pressure area has upon it.

A-7 Airplane. The A-7 airplane generally displays good stores separation except from the inboard shoulder stations on multiple racks. The design of the A-7 creates a low pressure area along the sides of the fuselage, which tends to pull bombs in toward the fuselage and causes bombs from opposite wings to cross beneath the fuselage increasing the probability of bomb-to-bomb collision and bomb-to-aircraft collision, particularly with the low horizontal tail. This fact severely limits the loads authorized for release and increases the release intervals that may be used on the A-7.

AV-8B Airplane. The AV-8B's unique V/STOL design creates several phenomena which cause problems relating to stores separation and weapon system accuracy:

a. The engine exhaust nozzles are located immediately forward of and below the wing leading edge and below the midpoint of the wing root on both sides of the fuselage. The engine exhaust flow magnifies the effect f the normal low pressure area along the sides of the fuselage and creates a condition which causes low drag stores to cross beneath the fuselage, increasing the probability of bomb-to-bomb collision. This effect is negligible for high drag stores, probably because they decelerate out of the aircraft's flow field much more rapidly than low drag stores.

b. The intermediate and outboard pylons are cantilevered forward of the wing leading edge while the inboard pylons are located under the wing This configuration allows the intermediate and outboard pylons to absorb some of the ejection energy at bomb release by twisting about the attachment points, effectively reducing the total velocity imparted to the store. This results in the stores from these stations following different trajectories than those from the inboard stations. Bombs from the outboard stations tend to drift outboard rather dramatically after release, causing uneven bomb spacing at ground impact.

c. The AV-8B wing is composed almost entirely of composite materials and while stronger than a conventional metal wing, is generally not as stiff. This allows an increase in wing flexure at weapon release, thereby absorbing some of the ejection energy, as well as affecting wing motion during subsequent releases. This effect, called wing recoil, can cause either an increase or decrease in resultant store ejection velocity depending on the direction of wing motion at subsequent store releases. This phenomenon increases the probability of bomb-to-bomb collisions after release and results in uneven ground impact spacing.

d. The effects described in the previous two paragraphs combine to produce store end-of-stroke ejection velocities that are not only unique to each aircraft station, but vary with store mass, aircraft dive angle, airspeed, and load factor at weapon release. To correct for these effects, the AV-8B stores management system varies the actual weapon release intervals between stations as delivery conditions change to achieve even ground impact spacing and to provide the interbomb spacing requested by the pilot.

F-14 Airplane. The design of the F-14 airplane introduces several problems relating to stores separation.

a. The tunnel created by the engine nacelles requires that the opening of Snakeye fins be delayed until the bomb has cleared the bottom of the nacelles.

b. The location of bomb stations forward of the engine inlet requires the use of fuze arming methods that do not employ Fahnestock clips or pull-out arming wires. All arming hardware must go with the bomb and not be retained in the arming solenoids.

c. very short release intervals between stores at high subsonic Mach numbers, the flow field which a store senses appears to be disturbed by the release of subsequent stores, resulting in unpredictable motion for initial stores released in a ripple delivery.

d. The outboard forward weapons rail stations of the F-14 are located immediately aft of the environmental control system air inlets. At high subsonic and transonic airspeeds, the spill-over from these inlets impinges on any stores carried on the outboard forward stations. This spill-over flow induces very strong nose outboard yawing motions for the stores loaded on these stations. The motions are so strong that the tail of the released store often yaws inboard and strikes the adjacent loaded weapon.

F/A-18 Airplane. The F/A-18 airplane is the Navy's first tactical airplane to provide a capability for supersonic carriage and release of conventional weapons. The carriage equipment supplied with the F/A-18 to achieve safe separation at these flight conditions includes pylon racks, VERs and CVERs, which incorporate dual ejectors with high ejection velocities (20 P]sec for a 500-pound bomb).

a. One adverse feature of the VER/CVER is that its high reaction loads and the resulting dynamic motion of the composite wing, pylon, and VER/CVER cause the ejector pistons to strike the bomb at an off center angle thereby imparting an initial rolling motion to the bomb. In addition, the airflow between two bombs loaded on the same VER/CVER.

b. Separation tests of MK 80 series weapons have exhibited a high percentage of unstable bombs at airspeeds above 0.85 IMN, especially from the two inboard wing stations where airflow around the fuselage and into the engine intakes adds to the magnitude of weapon roll and yaw. This airflow pattern has resulted in numerous bomb-to-bomb collisions from all wing stations and missile pitchup/bobble from the inboard wing stations during missile release tests.

c. The F/A-18 has a very low horizontal stabilizer that extends laterally to a point in line with the outboard pylons. This geometry has prevented the clearance of aft ejecting SUU-25 flare dispensers because of stabilizer strikes.

S-3 Airplane. The design of the S-3 airplane presents several specific problems relating to store separation.

a. There is no method provided to enable the noncomputed (off-line) release of multiple stores in a train delivery. Noncomputed multiple store deliveries require individual pilot-initiated actions. On-line (computed) releases are selected in yards. This exception to the conventional use of release intervals in milliseconds or feet frequently causes confusion. Weapon system on-line MRI is imbedded in the system software and is not accessible by the aircrew.

b. A tunnel effect is created through the open bomb bay doors and severe internal bomb bay turbulence is created with the bomb bay doors open at airspeeds greater than 375 KIAS. This turbulence can create low pressure areas inside the bomb bay resulting in "floating" stores inside the bomb bay after release and unpredictable store separation characteristics. Onboard cameras will probably record noticeable skin rippling, bomb bay and landing gear door chatter, and possible lifting of leading edges on aft avionics bay access panels.

c. Bombs (particularly MK 82's) released from the bomb bay can separate in a tail down attitude. This is acceptable as long as the bomb transitions smoothly to a nose down attitude after clearing the bomb bay. Due to lack of a mission requirement, retarded weapons are not authorized for release from the bomb bay in a nonretarded mode.

d. Rotational acceleration has been observed with bombs released from the bomb bay stations resulting in a "coning" effect and store-to-store collision inside the bomb bay. These characteristics are particularly prevalent for MK 82 bombs released at airspeeds in excess of 375 KIAS.

e. Bombs released from the bomb bay at airspeeds above 400 KIAS in 45-degree (0.7 g) dives have been observed to momentarily follow (“tailgating”) the aircraft flight path phenomena.

P-3 Airplane. The design of the P-3 airplane creates the following store separation phenomena.

a. A tunnel effect through the open bomb bay doors and severe internal bomb bay turbulence is created when the bomb bay doors open at virtually all air speeds. This turbulence can create low pressure areas inside the bomb bay resulting in “floating” of stores inside the bomb bay after release and unpredictable store separation characteristics. Due to the width and length of this bomb bay, occasionally yawing of bombs within the bomb bay should be anticipated.

b. Rotational acceleration has been observed with bombs released from the bomb bay stations resulting in a "coning" effect and store-to-store collision inside the bomb bay. This phenomenon is most prevalent with the MK 82 bomb.

c. Premature deployment of MK 15 fins while inside the bomb bay has been observed and has resulted in store-to-store collisions. This phenomenon is caused by bomb bay turbulence.

d. Large stores, e.g., torpedoes and torpedo-sized devices, having a high mass moment of inertia (100 to 126 slug ft^2) released from the bomb bay can exhibit moderate nose or tail pitch down just after release and commence yawing immediately after clearing the bomb bay doors. Although no store-to-aircraft collisions have been observed or recorded, the test engineer should be aware that the possibility exists.

e. The same large stores of the previous paragraph, when released from adjacent wing pylon stations (e.g., 12/13 or 14/15), have also demonstrated moderate nose or tail pitch down just after release and commence yawing after clearing the aircraft. No store-to-aircraft collisions have been observed or recorded.

f. Bombs (particularly MK 82) released from the bomb bay can separate in a tail down attitude. This is acceptable as long as the bomb transitions smoothly to a nose down attitude after clearing the bomb bay. Retarded weapons are not authorized for release from the bomb bay in a nonretarded mode. This restriction is dictated by store delivery criteria, not store separation characteristics.

g. A 250 KIAS maximum release airspeed restriction is placed on the launch of sonobuoys and sonobuoy devices from the three internally loaded, pressurized, CAD fired sonobuoy chutes and the single internally loaded gravity (free fall) chute. The following problems with the internal launch mechanisms should be anticipated:

Low ejection velocities (less than 18 ft/sec) from the internal pressurized tubes can result because of the sonobuoy striking the outer door lip.

Low ejection velocities from any of the internal launchers will result in at least the air retardation parachute and possibly the sonobuoy body contacting the lower fuselage between the launch tube and just aft of the radome area. An occasional sonobuoy strike on the port sonobuoy receiver antenna can also occur because of the low ejection velocities

SH-3 Helicopter. SH-3 separation tests should anticipate the following problems with the 12 internally loaded, gravity type sonobuoy launcher chutes:

a. With the main cargo door open, the air-flow (up to 45 mph) across the sonobuoy launcher areas will result in an occasional inadvertent separation and retardation parachute deployment inside the cabin, which results in a hung store if launch is attempted.

b. An occasional windflap strike against the tail wheel of the SH-3 helicopter can be anticipated, but damage is unlikely.

c. The sonobuoy release solenoids do not always relatch after sonobuoy release and should be checked prior to loading the next sonobuoy.

SH-2 Helicopter. With the SH-2 helicopter design, the following separation problems can be anticipated with the 15 externally loaded, CAD-fired sonobuoy launcher chutes:

a. The SH-2 sonobuoy launch assembly is not equipped with a positive antirotation lock and the sonobuoy launch container (SLC) may be loosened by normal aircraft vibration.

b. The SH-2 is the only ASW helicopter with the tail rotor on the port side of the aircraft, and occasional SLC styrofoam cushions and spacers have been observed passing between the tail pylon and tail rotor.

SH-60B Helicopter. The design of the SH-60B helicopter presents problems with the pneumatic sonobuoy launch assembly.

a. Any SLC except the LAU-126/A must be inspected to ensure that the vinyl seals on the breech end of the SLC are ruptured prior to loading in the launcher assembly. Failure to rupture the vinyl seals can result in damage to the launcher pneumatic pressure tubes and injury to aircrew.

b. It is possible to obtain a false lock indication when mating SLCs to the launcher assembly. Failure to correctly seat and lock the SLC into the launcher will result in the sonobuoy partially separating from the helicopter at launch and possibly striking the helicopter when it does loosen completely. A false lock could also result in inadvertent loss of the sonobuoy in flight, thereby endangering personnel on the ground/deck.

c. On those SH-60B helicopters equipped with a third (Penguin missile) pylon, the bottom two rows of sonobuoy launch tubes must not be used and should have a blankoff plate installed.

SH-60F Helicopter. After launching a sonobuoy from one of the six internally loaded gravity type launch chutes and prior to reloading the launcher, it is necessary to verify that the outer doors are fully closed and the manual release handle is in the locked position to prevent an inadvertent release of the sonobuoy.

Special Helicopter Considerations. Typically stores have been designed for fixed wing aircraft an adapted for late use on helicopters. Structural problems associated with these stores include those caused by cantilevering the stores out away from the helicopter fuselage (accentuated by any maneuvering flight), potential sympathetic vibration frequencies between the load (or load combination) and helicopter, and any reaction load caused by the store jettison. Effects on aircraft performance can also be dramatic with large decreases possible, due to the extra weight and drag of the external stores. Flying qualities can also be detrimentally affected (especially by the larger stores) due to lateral load imbalances caused by asymmetric jettison or release of stores, aircraft center of gravity shifts, or potential blanking of aerodynamic surfaces. An additional concern of droppable stores is the incompatibility between the stores fragmentation patterns and the host helicopter's speed and altitude capabilities.

1.9 Interference Effects. Large variations in separation characteristics will occur with varied load configurations and mixed weapon loads. At present, there is no suitable analytical method to accurately estimate the flow pattern effects on adjacent stores. This problem is compounded by the variation in flow caused by changing the release sequence or by the effect of spanwise flow on swept-wing airplanes. The spanwise flow imparts a lateral moment or sideslip to wing stores. The flow varies with adjacent store type, release sequence, and airspeed. The end result is that separation characteristics vary from station to station on the airplane and from station to station on multiple racks. Stores mounted behind other stores may tend to remain in the wake behind a forward store during low g releases. The inability to analytically determine separation characteristics requires that high-speed camera coverage be used to analyze store separation.

1.10 Control of Separation Characteristics. Control of aircraft delivery parameters can be used to improve poor separation characteristics. Improvement can usually be gained by:

a. Decreasing release indicated airspeed or Mach (refer to paragraph 3.5 for details)

b. Increasing ejection velocity (if store pitch rate is not also increased).

c. Increasing normal g at release (except for very low density stores like empty rocket pods).

d. Decreasing the dive angle (which increases the normal g for both straight and curvilinear dive deliveries).

Improvements gained through most of these parameters restrict delivery tactics and are generally undesirable. However, the test plan for separation testing should begin with the ideal combination of these factors and methodically progress to the desired limits.

SECTION II
PROJECT PLANNING

2.1 Introduction

2.2 Research

Past NAWCAD Projects
Defense Documentation Center
Air Force
Naval Air Systems Command

Field Activities
  NAWCWD China Lake, California
  NAVSWC Dahlgren, Virginia
  NAVSWC White Oak, Maryland
  NAWCWD Point Mugu, California
  WPNSTA Earle, Colts Neck, New Jersey
  NAVWPNSUPPCEN Crane, Indiana
  DTRCEN Carderock, Maryland
  NAVWPNEVALFAC Albuquerque, New Mexico

Technical Manuals
Contractor

2.3 Test Requirements

Test Matrix
Reduced Testing
Wind Tunnel Results

2.4 Cost Estimates

Aircraft Utilization Costs
Aircraft Cameras
Range Cameras
Store Preparation
Aircraft Preparation
Aircraft Loading
Carrier Suitability
Material Costs
Training/Travel
Contracts
Management

SECTION II (Cont'd)
PROJECT PLANNING

2.5 Test Plan Preparation

Test Plan Format and Approval
Clearances
Scope of Tests
Method of test
Special Precautions

SECTION II
PROJECT PLANNING

2.1. Introduction. A well-developed test plan is the most valuable tool available to the project officer/engineer. It should provide the information necessary to execute a program to all aspects of a particular weapon system on a timely basis and at the least cost. The plan provides milestones, serves as a vehicle to disseminate information, allows for detailed accounting of all costs and requirements, and permits the project manager to foresee problem areas. For these reasons, the time required to formulate a complete test plan is well spent. Initially, the project team will typically become embroiled in a frantic period of work unit development, AIRTASK writing, and the development of funding and schedule options. Once these items have been successfully navigated, the serious work of detailed test plan development will begin. The following sections provide general guidelines for the formulation of a complete, effective plan. In addition, a project planning checklist is provided as Appendix C to facilitate thorough planning and to help the project officer/engineer get started on the most time critical items first.

2.2 Research. The purpose of research is to:

a. Gather information, specifications, previous test results, and technical knowledge that will aid in establishing the approach to testing.

b. Avoid costly duplication of effort by NAWCAD or another facility and to use previous results when possible.

Past NAWCAD Projects. The file of old reports and the film library in the Ordnance Systems Department, Strike Aircraft Test Directorate, should be examined for work related to the project at hand. Copies of old test plans, reports, and messages are useful in planning, and a review of related film is essential The reports are filed in chronological order and film is catalogued by aircraft and ordnance type.

Defense Documentation Center (DDC). DDC should have files of previous written works on the hardware being tested if the item is not totally new to the RDT&E community.

Air Force. The increased multiservice use of weapons and aircraft provides other sources of information. Eglin Air Force Base, Florida (ADTTW) will provide reports and information on Air Force RDT&E work. Frequently, the cognizant Air Force project officer can be consulted for assistance and data on Air Force projects.

NAVAIRSYSCOM. The NAVAIRSYSCOM may provide information from contractors or other facilities. The appropriate project engineer or class desk should be consulted.

Field Activities. Frequently, NAWCAD will begin project work after another activity has completed R&D on the hardware being tested. The major activities and their areas of interest are:

NAWCWD China Lake. The NAWCWD has a number of laboratories and a large staff dedicated to weapon development. In addition, NAWCWD provides the only overland ranges for missile firings. The NAWCWD conducts aircraft software testing and is responsible for testing fuzes.

Naval Surface Warfare Center (NAVSWC), Dahlgren, Virginia. NAVSWC Dahlgren is responsible or Hazards from Electromagnetic Radiation to Ordnance (HERO).

Naval Surface Warfare Center (NAVSWC) Det. Silver Spring Maryland. NAVSWC Silver Spring is responsible for developing fuzes and mines and holds technical information on all these devices in use by the Navy. NAVSWC/Silver Spring also has facilities for wind tunnel testing.

Pacific Missile Test Center (PACMISTESTCEN). Point Mugu, California. PACMISTESTCEN is responsible for the development of missiles and is the cognizant activity for some bombs, rockets, and other ordnance items

Naval Weapons Station (WPNSTA) Earle. Colts Neck. New Jersey. WPNSTA Earle is the cognizant activity for ordnance handling equipment.

Naval Weapons Support Center (NAVWPNSUPPCEN]. Crane. India. NAVWPNSUPPCEN Crane is the lead activity for pyrotechnics, flares, markers, and smoke signals.

David Taylor Research Center (DTRCEN), Bethesda, Maryland. DTRCEN has facilities for wind tunnel testing.

Naval Weapons Evaluation Facility (NAVWPNEVALFAC), Albuquerque New Mexico. NAVWPNEVALFAC is responsible for verifying and publishing all checklists and technical manuals.

Technical Manuals. All ordnance equipment require technical manuals, checklists, and instructions for use that are normally prepared by the contractor or during R&D. Weapon functions, wiring, fuzing, loading, and handling information are provided by these manuals. The manuals and checklists should be used and validated during tests.

Contractor. The contractor or developer of a weapon may be consulted concerning weapon design and configuration. Permission must be obtained from NAVAIRSYSCOM to use contractor-supplied information and/or support, since this support may not be available without cost to the Navy.

2.3 Test requirements. Once the background research is well under way, the planning team (project officer and engineer) should begin to list the tests required to provide a thorough and safe build-up to the desired endpoints. Section III contains the specific test requirements for various types of ordnance. Test requirements should be screened while doing the initial research to determine the technical information needed to test the item. After this information has been gathered, the preliminary test plan may be formulated.

Test Matrix. The test matrix is the basic table listing each event required during the evaluation. All information concerning configuration, test parameters, fuzing, and hardware requirements will eventually appear in the test matrix. The completed matrix will provide the sequence of events, the number of flights, ground tests, and stores required.

Reduced Testing. The general approach to separation testing, discussed in Section I, which attempts to isolate the separation variables will require many test flights and stores and requires a very conservative buildup process. Most stores, however, have similarities to previously cleared weapons, and comparative analysis may allow a substantial reduction in the flights required. If the store has been cleared from other aircraft, analysis may indicate the critical release conditions for the aircraft under test. The test program would then validate the predicted store behavior with a minimum number of flights and then proceed quickly to a determination of the separation characteristics near the critical conditions with fewer build-up releases The same procedure applies when the store is physically and aerodynamically similar to previously cleared stores. In addition, the limits which will be recommended by NAWCAD must be safely exceeded by a small margin during testing; however, the testing must not exceed interim limits provided by the AIRTASK and clearance message.

Wind Tunnel Results. Normally, contractors or developmental agencies will provide results of wind tunnel studies for new stores. When this information is not available and it is required for the safe execution of a test program, DTRCEN or NAVSWC/Silver Spring may be contacted to provide wind tunnel data. The cost and delay involved will preclude this procedure for many programs, but may be justified by the high risk or uncertain characteristics of some stores. When tunnel studies are available, releases may be planned to verify tunnel data If the tunnel results prove sound, some test releases may be eliminated by extrapolation of wind tunnel and flight results. However, in no case should critical release points be flown without a thorough build up to the flight regime approaching the endpoint.

2.4 Cost Estimates. Once the test matrix has been completed, the project officer/engineer should contact representatives from each of the support activities to begin detailed test planning and to request an itemized cost estimate for work to be done. A written estimate should be obtained which includes work day labor requirements and rates, flight hour costs for the specific aircraft involved, material costs for special brackets and fittings which must be manufactured, travel, training, documentation, report writing costs, and incidental expenses. An overall cost estimate for the project should be compiled and the final cost briefed to the program's NAVAIRSYSCOM sponsor. The following paragraphs provide basic guidelines and approximate costs for typical test program items.

Aircraft Utilization Costs. Flight hour costs for the aircraft are generally the major source of expenses for the test program. Current flight hour rates may be obtained from the Operations Department of the directorate which maintains the applicable aircraft. Do not forget to include the cost of chase aircraft, if they will be required. Also, some directorates may charge for ground test hours that use an aircraft. Ground test rates may be as much as half the flight hour rate. An additional cost equal to 15% of the flight hour costs should be added to cover reflys or airborne aborts for weather, maintenance, etc.

Aircraft Cameras. The work day estimate for aircraft cameras includes the cost of film, film loading/unloading, camera installation, and film processing. It does not include special costs for wiring or camera installation at unwired locations on the aircraft. A typical cost is 9 work hours/camera/flight. Of this cost, 45% is labor and 55% is material. Current estimates may be obtained from the Airborne Instrumentation Department, RD. An additional cost equal to 30% of the camera costs should be added to cover reflys and aborts.

Test Range Costs. Range camera and radar coverage costs are based on the number of cameras desired per flight. The following are:

a. Baseline: 103 work hours/flight hour.
    - radar, controllers, safety, computer.
    - 50% labor, 30% material, 25% in-house contract.

b. Two cameras (film and video): 39 work hours/flight hour.
   - 50% labor, 50% material.

c. Three theodolites (film only): 55 work hours/flight hour.
   - 50% labor, 50 material.

d. Two rawindsondes 23 work hours/flight hour. -35% labor, 65% material.
   50% labor, 50 % material.

e. Two balloons: 9 work hours/flight hour.
   -.45 % labor. 55% material.

f. Target support: 23 work hours/flight.
   - 100% in-house contract.

These estimates include radar and theodolite operations only. Data assessment and data reduction, if required, must be added to these estimates. Current work hour requirements may be obtained from RD when specific needs are known. An additional cost equal to 30% of the range costs should be added to cover reflys and aborts.

Store Preparation. The cost of store preparation, instrumentation, painting, rack installation, and wing adapter installation will depend on the particular requirements of the test. Again, written estimates of work-hour requirements must be obtained from the cognizant cost center.

Aircraft Preparation. Preparation of the aircraft includes installation of wiring and hardware, test of systems, and configuration changes. The cost will depend on the particular requirements of the test. Estimates must be obtained from the cognizant cost center.

Aircraft Loading. The cost of loading is based on the average number of stores per flight. The time for different stores varies and will include any special fuzing, parachute installation, and arming procedures.

Carrier Suitability (CVS). Exact cost must be determined through consultation with the CVS Department of SA. Typical requirements are 90 work hours per event with 20 events being the normal number required. Of this cost, 25% is labor and 75% is material. In addition, an average of 5 flight hours must be included in the cost estimate to cover a typical CVS "shake" profile.

Material Cost. Material cost for fabrication of adapters, fittings, or other hardware must be obtained from the cost center involved. Cost of stores, fuzes, launchers, and other standard Navy hardware must be included for all programs starting in FY90.

Training/Travel. The cost of special training for aircrews, ordnance, and/or maintenance personnel must be considered. Normally, this includes TAD and travel costs. Current rates and allowances may be obtained from the Business Resources Department travel clerk.

Contracts. The cost of in-house contractors must be included in the project cost

Management Funds must be available for department management and secretarial staff.

2.5 Test Plan Preparation. Work assignments are generated in a variety of ways at many facilities within the RDT&E community. The project will usually fall into one of the following categories:

a. Monitor tests conducted at other facilities

b. Contractor demonstrations

c. Navy Technical Evaluation (i.e., DT-II and beyond)

d. Service suitability (BIS trials)

In the above categories, the effort, coordination, and procedures differ. However, the scope and purpose of the test program must be defined before a plan can be formulated. The project officer must know exactly what to test and the limits of responsibility. Generally, the scope of a test is defined by the AIRTASK; however, the project officer may be required to provide a recommendation to NAVAIRSYSCOM for program definition prior to AIRTASK release. As problem areas are found, the scope may be enlarged to investigate anomalies which develop with the test item.

Test Plan Format and Approval. With research completed, the purpose and scope of the proposed tests defined, and the test matrix complete the project team can begin drafting the formal test plan. The format of the test plan will be in accordance with that described in NAWCINST 3960.1A. The test plan must be submitted through the department head for approval by directorate management. After department head approval, the test plan will normally be scheduled for presentation at a test plan review board which will be attended by directorate management, operations, and safety personnel. The submitted plan must include the detailed test procedures to be followed and all the test points to be evaluated. The approved plan constitutes official NAWCAD permission to continue with the project. Amendments to the test plan must be approved by directorate management. Minor deviations to the test plan may be approved by the department head within the constraints of the test plan.

Clearances. Tactical manuals provide clearance information and, when correlated with the test matrix in old reports, can provide documentation of prior separation work. In no case, however, should actual test work be completed prior to receiving a clearance message from NAVAIRSYSCOM (AIR-530) for the current project. If the intention is to test beyond the initially cleared limits or the clearance envelope is to be released in increments, then an amended test plan with those new test matrix points must be approved once clearance for those points is received.

Scope of Tests. The test matrix may be used to compile the total number of stores, fuzes, adapters, and other assorted hardware required. In addition, the test loads, configuration, and test envelope may either be included in the test matrix or as separate tables in the scope of tests section of the test plan. A listing of the applicable test standards including specifications and a reference to the definitions of the deficiency classifications should also be included in this section.

Method of Test. The method of tests section should include a description of the build-up program as well as a detailed discussion of the methodology to be used to fill the test requirements. The required sequence of test events should provide for methods to reduce flight and store requirements by combining test phases and events when possible. At all times, ground and flight safety must be an integral part of the plan. The method of test will also contain a description of instrumentation requirements and the data reduction and processing equipment and procedures to be used.

Special Precautions. A safety checklist in the format specified for the directorate providing the test aircraft must be included in the test plan and reviewed with the test crew prior to each project flight. As part of this checklist, a thorough review of the applicable portions of NATOPS should be undertaken.

SECTION III
TESTS AND TEST METHODS

3.1 Introduction

3.2 Assembly and Loading Tests

3.3 Fit Tests

3.4 Captive Carriage Tests

3.5 Separation Tests

Test Build-up
Level Releases
Dive Releases
Release Intervals
Miscellaneous
Specific Separation Considerations

3.6 Cluster Bomb Units

3.7 Dispensers

3.8 Fire Bombs

3.9 Aircraft Guns

Reliability and Maintenance Record
Maintenance Procedures
Boresight Procedures
Ground Tests
Cook-off
Gas Concentration
Hangfire and Double Feed
Engine and Airframe Compatibility
Air Firings
Ballistics and Dispersion
Articulated Gun Systems

3.10 Rockets

Ground Tests
Static Firing
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SECTION III (Cont'd)
TEST AND TEST METHODS

3.11 Missiles

Ground Tests
Flight Tests

3.12 Flares

Safety Considerations
Ground Tests
Flight Tests

3.13 Torpedoes

Ground Tests
Static Releases
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Flight Tests

3.14 Sonobuoys

Safety Considerations
Countermeasure Devices
Ground Tests
Static Firings
Flight Tests

3.15 Miscellaneous Stores

Ground Tests
Flight Tests

SECTION III
TESTS AND TEST METHODS

3.1 Introduction. The tests and test methods typically required during an ordnance evaluation arc described in this section. An orderly progression of these events is necessary to preclude errors which affect the validity of subsequent test results and safety. This section provides guidelines for the conduct of tests for fit, compatibility, carriage, separation, and store specific test considerations.

3.2 Assembly and Loading Tests. Many weapons will be tested without the benefit of proven assembly, loading, rigging, and checkout procedures. Therefore, it is mandatory that the project officer/engineer obtain thorough training and indoctrination for ordnance personnel. This training must include proper installation of store assemblies, fuzes, initiators, igniters, fins, lugs, adapters, parachutes, arming wires, and other associated hardware. Detailed records must be established to verify the specific combination of hardware that was used on each weapon. Procedures for handling, storing, and using both inert and live ordnance must be established, and personnel must be indoctrinated in all aspects of use of the store. Loading information for weapons already introduced into the fleet may be obtained from applicable conventional weapons loading manuals. Checklists for an Air Force designed weapon may be obtained from the Munitions Test Division, Compatibility Section, Eglin Air Force Base, Florida

3.3 Fit Tests. Fit tests involve loading the store on the aircraft stations to be tested and checking for adequate fit, clearance, and freedom from interference with all possible combinations of weapons and racks. Specific areas to check include:

a. Store lugs not compatible with rack suspension hooks.

b. Sway bracing inadequate due to fit or store rigidity.

c. Clearance between adjacent stores and between the store and aircraft must be measured and photographed. In some cases the fit may be satisfactory for carnage, but not for release.

d. The clearance distance between the store and ground must be measured or calculated with struts and tires both compressed and flat. Consider takeoff rotation, catapult tracks, arresting gear clearance, and flap, speed brake, aileron, and gear door clearances. All clearances must be measured at the most critical condition. Movable aircraft surfaces should be positioned so that the most critical geometry is achieved and then the store should be loaded. Clearances are specified in MIL-1-8671B and MIL-STD1289A; however, judgment must be the overriding factor exercised in unspecified areas or where the specification details do not directly apply.

e. The electrical compatibility of the power supply, rigging, bails, and harnesses must be verified.

f. Consider weight restrictions for all loading configurations of the store.

g. Compatibility with weapons handling equipment should be evaluated by Systems Engineering Test Directorate.

3.4 Captive Carriage. A captive carriage test is a test of store compatibility with the aircraft in night and is usually conducted prior to the first separation flight. These tests ensure minimum acceptable structural integrity of the store as well as acceptable aircraft stability and control during a flight that is within the aircraft and store limits. All stores shall have captive carriage tests except those stores that have been previously tested within the desired limits. The following captive carriage sequence should be followed wherever possible:

a. Study the results of the fit tests and then establish the stations and racks on the test aircraft on which the test stores are to be carried.

b. Verify that the CG and drag count are within limits for the night.

c. Provide the schedule coordinator with captive carriage test requirements (i.e., type of test, aircraft, number and locations of stores, flight conditions, camera/range coverage, etc.). If the test stores are to be carried "piggyback" on some other project flight, one of the two test plans must reflect the configuration.

d. Specify the type of handling equipment to be used so that the ease of loading can be determined. Witness the loading of stores and verify the loading procedures (i.e., proper installation of fuzes, arming wire, sway brace pads, etc.).

3.5 Separation Tests. The number of separation test flights and how quickly the envelope can be expanded are dependent on the desired clearance limits, past separation tests on the same or similar stores, the type and number of aircraft to be cleared, and the type delivery maneuvers and MRI that are desired. Generally, separation envelopes should be expanded as far as possible to allow for the development of new tactics and to provide maximum flexibility in the introduction of new delivery maneuvers. In all cases, the separation characteristics will be successfully demonstrated beyond the limits that will be recommended; however, the stated clearance limits assigned by AIR-530 must not be exceeded during the test points or during dive recoveries with hung stores. Stores should be cleared to the following limits when possible:

a. Maximum Airspeed

    (1) Carriage - Limits of Basic Airplane (LBA)

    (2) Release - LBA

b. Acceleration

    (1) Carriage- LBA

    (2) Release - Maximum LBA but at least 4.0 g (fixed wing airplanes) Minimum LBA but at least 0.5 g

c. Maximum Dive Angle - 60 degrees

d. MRI - To the minimum release interval possible for the aircraft release system.

The desired separation limits may be stated in the AIRTASK particularly if tactical employment of the store does not require a large separation envelope. Separation envelopes from multiple racks may be smaller than from parent racks, and mixed loads, downloads, and

MRI must all be investigated for optimum combinations to expand the envelope as far as possible.

Test Buildup

Level Releases. During build-up releases for untested stores, the first release should be a single-store, level delivery from parent racks at an airspeed near that for maximum range. This airspeed should provide low induced drag for the wing; and, consequently, the local flow angularity will be low. This speed also provides low dynamic pressures and will allow an examination of the basic weapon dynamic behavior during separation. Aircraft bomb racks are usually oriented to provide zero store AOA at maximum range airspeeds. Level releases will then be made at incrementally higher and lower airspeeds until maximum and minimum speed limits are approached. The separation characteristics, as affected by the aircraft flow field variation with airspeed, may be determined from a comparison of separation photography at each airspeed. Variations in store pitch and yaw will indicate the release conditions when the combination of store dynamics and flow field interaction may become critical. The same build-up should be used for releases from multiple racks; however, once store motion is seen to be similar to releases from parent racks, many data points may be omitted until the critical release is approached. During level multiple releases, a preliminary investigation of MRI may also begin. Particular attention should be given to the motion of stores from MER shoulder stations. These are the stores most likely to produce bomb-to-bomb collisions, particularly inboard shoulder stores near the fuselage. On swept-wing airplanes, forward MER stores are subject to upwash and spanwise flow which increase in intensity at high AOA's. These factors may be critical for determining the safe jettison limits of individual stores and loaded multiple racks.

Dive Releases. An investigation of the variation in separation characteristics with dive angle should then begin. As dive angle is increased, the component of gravity normal to the Armament Datum Line (ADL) decreases and thereby reduces the net separation force. Therefore, as dive angles increase, aerodynamic forces and store dynamics begin to have a greater influence on separation characteristics. An examination of level releases should indicate the airspeed for greatest and least airflow influence on store motion. The airspeed for least aerodynamic influence should be used for the first release at each dive angle. Incremental increases in airspeed may be used to reach the desired maximum release airspeed. Again, MRI should be considered during multiple releases at each dive angle. The rate of increase of incidents of erratic store motion govern the rate at which dive angle build-up may occur. With good separation during level, high-speed releases, and good separation during a 30-degree dive at maximum release speed, increments of 15 to 20 degrees may be used to increase dive angles up to a maximum of 65 degrees (5 degrees in excess of the desired 60 degrees maximum recommended limit). If separation characteristics are good at all airspeeds in level flight and low dive angles, only the maximum release airspeed need be tested at each increased dive angle. If a dive angle is reached where store motion begins to vary from the established baseline, smaller increments in dive angle increase should be used. This will permit a controlled approach to the critical release condition and allow a prediction of potentially unsafe releases.

Release Intervals. Demonstrated safe releases from multiple racks will then be followed by reduced release intervals until the critical MRI is determined. Obviously, the critical MRI at 60 degrees will be larger than that at 20 degrees. Tactical manuals usually give the MRI only for the steepest dive and highest release airspeed combination. If a requirement for a shorter MRI is dictated, further testing may be conducted to determine the MRI at smaller angles. In this event, the recommended clearance would specify the small envelope caused by using an MRI lower than that for the highest recommended dive angle.

Miscellaneous. During any build-up program, it is essential that photographic coverage be reviewed before the next flight. This allows the determination of critical areas as they begin to appear and will reduce the chances of making an unsafe release. .technique that allows g effects to be investigated independent of dive angle effects involve the use of the bunt maneuver. This is accomplished in near level night by pushing forward on the control stick until a lower g condition (normally 0.5 g) is obtained. The 0.5 g is then held constant during store release. In most cases, if the bunt maneuver is performed satisfactorily at the most critical conditions (i.e., maximum airspeed and minimum g), the tests can proceed to a dive angle which corresponds to the g level tested. The test conducted at the actual dive parameters is more critical, since the component of gravity accelerating the store away from the aircraft is g cos B. Immediately after release in a bunt maneuver in near level flight, the component of gravity accelerating the store away from the aircraft is approximately 1.0 g.

Specific Separation Considerations. The following additional items influence separation and should be considered during planning and testing:

a. Retarded and nonretarded releases will require different MRI.

b. Aircraft armament system functions dictate whether MER/TER/ITER hooks should be open or closed on empty stations.

c. Facing shoulder stations may be downloaded to improve separation characteristics. The effect of a reduction of total number of stores must be weighed against the tactical gain due to improved separation, a larger envelope, and reduced MRI.

d. An additional hazard during separation is weapon hardware that is released, ejected, or otherwise separated from the store after release. The hazard may be to the releasing aircraft or to other aircraft in formation.

e. Fuze function during bomb-to-bomb collisions is unsatisfactory. Live fuzes in inert weapons, with a minimum arming delay selected, should be used to evaluate this possibility.

f. Arming wires, pull-out plugs, and umbilical separation should be recorded by high-speed photography to test for interference on store motion, impingement on aircraft surfaces and damage to plugs, bails, connectors, and fairings.

3.6 Cluster Bomb Units (CBU). Fuze function timing is critical with this weapon, and is normally tested in conjunction with separation testing. The fuze function time is correlated with release altitude to allow opening at a specific altitude above ground level. Range camera coverage and down looking aircraft cameras are often the only suitable methods for observing fuze function. Theodolite or 16mm range camera coverage should be used in an attempt to observe fuze function that does not cause CBU opening. AIRTASK requirements to determine bomblet impact patterns will necessitate the use of a land range, probably NAWCWD, China Lake. The CBU usually releases bombs or bands during opening, which may create a hazard to other CBUs or to the aircraft.

3.7 Dispensers. Dispensers have unique separation problems with aft fired or released parachute retarded flares, sonobuoys, etc. These stores must satisfactorily clear all aircraft MRI at smaller angles. In this event, the recommended clearance would specify the small envelope caused by using an MRI lower than that for the highest recommended dive angle.

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Specific Separation Considerations. The following additional items influence separation and should be considered during planning and testing:

a. Retarded and nonretarded releases will require different MRI.

b. Aircraft armament system functions dictate whether MER/TER/ITER hooks should be open or closed on empty stations.

c. Facing shoulder stations may be downloaded to improve separation characteristics. The effect of a reduction of total number of stores must be weighed against the tactical gain due to improved separation, a larger envelope, and reduced MRI.

d. An additional hazard during separation is weapon hardware that is released, ejected, or otherwise separated from the store after release. The hazard may be to the releasing aircraft or to other aircraft in formation.

e. Fuze function during bomb-to-bomb collisions is unsatisfactory. Live fuzes in inert weapons, with a minimum arming delay selected, should be used to evaluate this possibility.

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3.7 Dispensers. Dispensers have unique separation problems with aft fired or released parachute retarded flares, sonobuoys, etc. These stores must satisfactorily clear all aircraft surfaces. Of particular concern are high and mid-wing airplanes with low horizontal stabilizer, ventral fins, and low aft-mounted speed brakes. In addition, the following problems have been identified during past tests:

a. Incomplete evacuation of tubes may require jettison of a partially expended pod. The reliability of the dispensing function should be included in the tests by tabulating data on unexpended submunitions.

b. Cockpit indicators of dispenser status should be thoroughly evaluated for reliability and the accuracy of indications.

c. The electrical power requirements of the dispenser may be excessive under certain conditions. A complete evaluation will require thorough ground testing of power distribution requirements under high electrical load conditions.

d. The minimum airspeed required for satisfactory dispenser functions is a prime test item. Some dispensers may require a minimum dynamic pressure to satisfactorily dispense the stores.

e. Most chemical agents are very corrosive and the effect of the agent on the bomb rack or other airplane surfaces must be thoroughly evaluated for stores which dispense chemicals while remaining attached to the aircraft. Some require that the dispensing airplane be washed immediately after flight.

3.8 Firebombs. Firebombs, with the exception of the finned Air Force firebombs, are unstable stores having unpredictable store motion after release. They are normally carried and released from parent racks. At the time of this writing, MK 77s were in the process of being dropped off the F/A-18 and CVER. Delivery from steep dives is undesirable due to the poor ballistics, but a level delivery is usually satisfactory at medium airspeeds. The most critical separation problems for firebombs involve strikes against adjacent stores, racks or pylons during release. Ground handling, safety, fuzing, and leakage of the mixture should be thoroughly tested.

3.9 Aircraft Guns. Aircraft guns are unique test items in that the pressures, vibration, recoil, and rate of fire impose severe loads on the aircraft and on the guns themselves. Wear and erosion of parts and high rates of fatigue failure require that tests of aircraft guns go far beyond functional tests. The following paragraphs outline a desirable sequence of events during testing.

Reliability and Maintenance Record. Logs should be established to document rounds loaded, rounds fired, type ammunition and links, and malfunctions. Malfunctions should be recorded with the part number, cause of failure, rounds fired before failure, and length of all bursts preceding failure. Malfunctions include material failures, jams, double feeding, hangfires, and cook-offs. Frequent measurements should be recorded to determine the wear and erosion patterns and parts life.

Maintenance Procedures. Maintenance and loading personnel must be properly trained before testing begins. All technical information must be obtained and studied, and prescribed procedures must be meticulously adhered to during tests in order to validate the suitability of the procedures and the guns. Recommendations for changes to maintenance and operating procedures should be made when appropriate. Safety precautions should be carefully analyzed for completeness and applicability.

Boresight Procedures. should be completed Prior to the commencement of the test program and at frequent intervals thereafter. The boresight procedure should be simple, quick, and should not require elaborate equipment. Tests should include boresight checks frequently enough to determine when and why the boresight was degraded. This would particularly apply during carrier suitability and shipboard operations.

Ground Tests. Initial ground tests should include firing-in and boresight checks using TP or ball ammunition. Subsequent flight tests should also include firing HEI and other types of ammunition to ensure their compatibility. Live ammunition will normally be fired in the Chesapeake Bay or W108. During ground tests, the following parameters should be documented:

a. Cyclic rate

b. Recoil forces

c. Temperatures in gun compartment

d. Dispersion

e. Projectile drop

f. Temperature and pressure at appropriate locations near the muzzle blast

g. Gun gas concentrations

h. Projectile tangential velocity (throw) from Gatling type guns

Verification of RADHAZ susceptibility by NAVSWC Dahlgren and susceptibility to cookoff, gas explosions, hangfires, and double feeds should be determined during ground tests; however, aerodynamic effects on gas accumulation and muzzle blast must also be determined during air firing.

Cook-off. Particular attention should be paid to the cook-off susceptibility of new gun installations. Cook-off normally occurs if an unfired round is not cleared following a prolonged burst which heats up the chamber. The uncleared round may then absorb sufficient heat to spontaneously fire after a period of a few seconds or minutes. Other causes of cook-off would include fires and oil or hydraulic leaks that ignite at operating temperatures in the gun compartment and raise the chamber temperature to the cook-off level. Proper design of the gun compartment should isolate the aircraft from the gun sufficiently to preclude serious damage to the aircraft during gun malfunction, and should preclude the collection of powder residue, flammable liquids, and explosive gas concentrations.

Gas Concentration. Tests should include sampling the gas concentration in the gun compartment. Gun gas concentrations of 12.5 percent to 74.2 percent by volume are sufficient to cause an explosion with the possible loss of the aircraft. During ground and air tests, initial bursts should be of short duration to allow a close monitor of gas build-up. Purging, although usually better during air firing, is affected by power setting and altitude. Sampling methods include the use of vacuum bottles and electronic counting devices.

Hangfire and Double Feed. Hangfire results from the slow functioning of the cartridge firing train that may allow the extraction of the round before obtaining deflagration of the propellant. Double feed is a mechanical extraction problem whereby a fresh round is fed, into the chamber against the unextracted preceding round, Both failures can cause high order explosions in the gun compartment with extensive damage to the aircraft. Until system reliability is confirmed, precautions must be taken to protect the aircraft and personnel from explosive malfunctions.

Metal shielding, sandbags, and the removal of unnecessary equipment and personnel during firing are mandatory precautionary measures.

Engine and Airframe Compatibility. The initial testing of new gun installations may reveal problems with engine flameout, compressor stall or damage, and airframe damage due to blast and explosion of brass and links. Items of particular susceptibility to damage include pylon doors and latches. Muzzle gas ingestion by aircraft engines is frequently a problem. The predicted dispersion pattern of gases should be carefully considered during ground tests and thoroughly evaluated during air firings. Engine and intake duet instrumentation will be required to properly document gas ingestion problems.

Air Firings. The airborne testing should determine that the gun installation can successfully operate throughout the aircraft envelope. Aircraft engine problems may be prominent at high altitude and either low or high AOAs depending on the location of the gun installation. Mechanical feed problems will usually become apparent during high g conditions while firing long bursts. During air firings, a build-up of burst length is recommended to reduce the possibility of explosive gas concentrations. Although ground tests may not reveal gas accumulation. aerodynamic effects may cause the pooling of gases in openings and compartments near the gun installation.

Ballistics and Dispersion. Ballistics and dispersion data may be required on some new installations. The Air-Launched Ballistics Section should be consulted to determine what data are required and how they should be compiled.

Articulated Gun Systems. Articulated systems historically consisted of turreted and crew gun systems. These gun systems allow off-axis fields of fire and present the same basic and testing concerns as fixed forward firing guns in addition to unique flying quality effects created by the off-axis recoil loads (typically yawing or pitching moments) and travel stop requirements to avoid shooting part of the aircraft structure or rotor disc for helicopters. An additional consideration for articulated guns is the requirement to fully test for detrimental effects upon aircraft utility systems (hydraulics, electrical, pneumatic, etc.) when operating turreted systems at peak demands (maximum slew rates plus firing for example).

3.10 Rockets. The Navy currently employs 2.75 and 5 inch air-to-surface rockets. The 2.75 inch rocket is fired from a 7 or 19-round launcher. The 5-inch rockets are fired from a 4-round launcher. A primary area of concern for testing is to ensure that the launcher is HERO safe. When the launcher HERO susceptibility has been established, ground tests may beam.

Ground Tests. Initial electrical checks should be performed to ensure that there are no stray voltages, and that the electrical continuity of the rocket adapter harness is satisfactory. The pod and airplane intervalometer should be tested for pulse interval and pulse width as prescribed by maintenance directives. All safety devices should be tested to ascertain their effectiveness. During ground tests, the ease of handling, loading and unloading, and maintenance of the pod should be evaluated. Of primary interest is the possibility of damage to either the pod or to rockets during handling. Damage may cause catastrophic failure of the pod or rocket motor, and the handling equipment and procedures should be carefully evaluated during all phases of the tests. The procedures for the assembly of the rockets, loading, wire cheeks, arming and dearming should be carefully followed and validated. Normal weight, CG, and MI data should be taken at all possible launcher loading configurations using a variety of warheads.

Static Firing. Upon satisfactory completion of the ground tests, static ground firings should be conducted to evaluate launcher performance. These static firings should be conducted on the rocket test stand maintained by the SA Ordnance Firing Tunnel before static aircraft firings are conducted. Pertinent considerations include blast and heat damage, functional reliability, intervalometer functionality, the proximity of rocket exhaust to the engine, and rocket motion leaving the tubes. Rocket overlap when leaving the launcher will probably lead to collisions and erratic rocket behavior in flight. An interval of greater than 35 milliseconds will ensure that there is no overlap between departing 2.75 inch rockets. If nose and tail fairings are interchangeable, the pod should be fired through both fairings to determine the probability of FOD to the aircraft or engine, and the effects on rocket motion during separation. During static firings, it is imperative that safety be maintained. This includes readily accessible fire fighting equipment in position to protect the aircraft and test personnel. This is particularly true when teeing new rocket motors, launchers, or warhead configurations.

Flight Tests. Flight testing should include the jettison of full, empty, and partially fired pods, as well as a determination of the rocket and launcher performance throughout the desired flight envelope. Usually, jettison tests will be performed in conjunction with inflight firing tests in order to reduce the total number of test flights. Completely inert rockets should be used for jettison tests if at all possible. Jettison of rocket pods is normally done at I g because of the aerodynamic and inertial characteristics of the pod. Increasing g does not enhance the separation characteristics of empty rocket pods since the AOA increase with g produces aerodynamic loading that forces the pod into the aircraft during jettison. Pod CG may become critical as partially filled pods are jettisoned. The marking of pods will aid in documenting weight and CG during jettison tests. Firing tests should begin with single rocket firing and progress to single full pod firing using the intervalometer on the pods (if asymmetric thrust on the aircraft is not critical). These firings should take place throughout the intended envelope covering the dive angles, airspeeds, and accelerations at which the launcher should function. When single pod, ripple fire has been thoroughly tested, the firing of multiple pods from aircraft parent stations and TERs at minimum intervals should be conducted to verify functional reliability of the pod-aircraft system and aircraft asymmetric thrust characteristics During all in-flight rocket firing tests, continuous aircraft engine ignition should be used (if available). Rocket exhaust effects on engine performance must be evaluated and, if adverse, special instrumentation will be necessary to document engine performance. Photographic coverage at 400 fps is vital in an early evaluation of rocket exhaust patterns and effects.

3.11 Missiles. The material contained in paragraph 3.10 is also applicable to missiles, although testing for missiles also includes tests of the complicated guidance and control units. Missiles generally require a launcher or adapter assembly, and electrical and functional tests are more elaborate; thus, the following paragraphs apply in addition to paragraph 3.10.

Ground Tests. The launcher or adapter should be checked for alignment, ease of installation, and physical compatibility with the aircraft. Fit tests for missiles must thoroughly evaluate fin and canard clearance at all positions for both carriage and separation. Adjacent station loading should be evaluated for fit and for the susceptibility of adjacent stores to damage from the exhaust plume. HERO tests are essential for missiles, and missile electrical power requirements should be evaluated for overload potential and the possibility of operation and jettison using the aircraft emergency power supply.

Flight Tests. Because of the larger propulsion systems and relatively long range of missiles, the following considerations apply:

a. Aircraft engine performance is more likely to be affected, particularly when missiles are fired from fuselage-mounted launchers and at high altitudes and low indicated airspeeds.

b. The long range of missiles may require the use of W108 for firing tests.

c. A chase airplane is mandatory when testing missiles from single engine airplanes and for clearing the impact area.

d. Instrumentation to document the thermal conditions aft of the launcher is usually necessary for large missiles. This can be in the form of thermally sensitive tape or thermocouples.

e. The effects of rocket ignition without separation as well as the probability of occurrence of this event should be determined. Flying qualities may be seriously affected; therefore, jettison capabilities must be sufficient to allow emergency jettison of the missile in the event of improper ignition/separation.

f. If the missile can be used at night, the effects of missiles exhaust plume on pilot vision should be determined.

g. Severe structural loads on launchers and adapters are possible during launch. The magnitude of these loads should be determined.

3.12 Flares. Flares may be either parachute retarded or nonretarded (cartridge or decoy type). They may be carried either internally in dispensers or on multiple bomb racks. Large aircraft use dispensers that are integral to the airframe and loaded from within the aircraft during flight (e.g., P-3). All flares are high yield pyrotechnic devices and require extreme care in their handling and use.

Safety Considerations. Some flares, such as the MK-45, have a live ejector and are ejected from the canister with considerable force. A light pull force is sufficient to actuate the ejector mechanism, so these tests must be done carefully. LUU-2 series flares do not forcibly eject the can and require that a minimum of 100 pounds pull be applied to the parachute riser to ignite the flare. The area behind the dispenser should be clear of personnel and equipment and appropriate fire fighting equipment should be at hand. High density/low pressure water fog is the most satisfactory method of extinguishing flares since magnesium generates oxygen to support combustion. Purple K will smother a flare eventually, but large quantities of water will more quickly reduce the temperature below the combustion point. Burning flares may be safely moved away from the aircraft by using the parachute as a tow line; however, the flare canister should not be touched. Flares should be rigged and handled strictly in accordance with current technical directives. Rigging procedures should be verified during g testing. If possible, safety pins or clips should remain installed until the flare is dropped : dispensed. The safety device, if installed, must remain with the flare at least until the aircraft is prepared to taxi or launch. Additional considerations provided during tests conducted from cargo or patrol type aircraft include:

a. For large parachute flares equipped with a safety pin, pull the safety pins with the flare positioned to eject overboard if a malfunction occurs.

b. Flares not actually being used should be stored and secured away from the test area of the aircraft. Provisions for jettison of the entire load of flares should be considered.

c. No excess personnel should be allowed aboard the aircraft

Ground Tests. In addition to fit and compatibility tests, flare dispensers should be tested for reliability, operation, and electrical continuity. Damage to flares from the ejection force should be analyzed and the time required for activation, ignition, burn, and parachute operation determined. The loading procedures for flares should also be evaluated.

Flight Tests. Initial flight tests will involve a determination of separation characteristics in level flight at intermediate airspeeds, then the normal progression to the desired limits can be performed. During separation tests, additional data should be obtained on the timing of actuation, burn, etc. Jettison tests with full, empty, and partially filled dispensers should be conducted in a manner similar to jettison tests of rocket pods. The effects of adjacent stores on flare separations from bomb racks and ejector foot damage to flare casings should be considered during tests for flares not using dispensers, and the jettison of multiple racks with flares must be tested to determine their jettison limits. Throughout the flight test program, a healthy respect for the danger associated with flares and their extreme susceptibility to the local flow field must be maintained.

3.13 Torpedoes. The Navy currently uses the MK46 and MK-50 torpedoes equipped with air launch accessories. Both torpedoes are carried in the bomb bays of P-3 and S-3 series aircraft and on external pylons of SH-2, SH-3, and SH-60 series helicopters. The variety of air launch accessories (suspension bands, air retardation parachutes, arming wire configurations), torpedo models and detailed requirements to correctly assemble torpedoes for each aircraft requires that project officers, engineers, and technicians thoroughly research the SW512-AO-ASY-010 Torpedo Manual. Incorrect mechanical alignment or assembly of the air launch accessories can result in damage to torpedo fin assemblies during loading and collision with aircraft surfaces during launch.

Ground Tests. Electrical release and control checks and aircraft preparation should be performed in accordance with the applicable Weapons/Stores Loading Manual prior to loading torpedoes. During ground tests, an evaluation should be made of torpedo-to-aircraft clearances, compatibility of the torpedo suspension lugs with the aircraft bomb rack, and routing of the lanyards. If testing an umbilical cable, an evaluation should be made of the torpedo and the aircraft to determine mechanical fit, ease of connection. unusual routing or bending of the cable, and to ensure that the umbilical will separate at the correct angle from the torpedo at launch. If testing the aircraft torpedo presetter system, a presetter test set and torpedo emulators should be used to verify the conditioning signals through the umbilical cable and to the bomb rack. This step is important because some torpedo operating modes require delays between the receipt of presetting signals and actual launch/release of the torpedo.

Static Releases. Static releases should be performed to verify arming wire separation, preset operation and that physical interference between the torpedo and bomb rack does not occur. Static releases should be conducted such that the torpedo is dropped on a soft surface, such as a mattress or styrofoam pads, that will prevent the torpedo from being damaged. Additionally, the suspension bands must be safety wired to prevent suspension band operation. Only qualified personnel should be allowed in the area of the release until the safety bolts are reinstalled in the suspension band lugs.

Flight Test Preparation. Prior to flight testing, each torpedo must be weighed, have the CG location determined, and have a record made of the serial/lot number on the torpedo and the air accessories. Torpedo weight and CG are extremely important because water entering the cavities during prior tests can result in significant changes in weight and CG. Because the air accessory systems NAWCAD uses for most tests are production assemblies recording the serial/lot number of the components of the air accessory systems will allow an accurate reporting of failures of those systems.

Flight Tests. Flight testing should include normal and jettison releases. During normal release, an evaluation will be made of the separation of the suspension bands from the torpedo, air retarder deployment, and the torpedo water entry angle. The MK-46 torpedo is restricted to water entry angles between 25 and 60 degrees. The MK-50 torpedo is protected by a frangible nose cap and can withstand water entry angles up to 90 degrees. When jettisoned, all components of the MK-46 torpedo air accessory system should remain with the torpedo. When jettisoned, all components of the MK-50 torpedo air accessory system should deploy as in a normal release. Instrumentation for all flight tests should include onboard high-speed cameras, a safety chase aircraft with photographer onboard, and theodolite coverage for real time analysis of each event. Additionally, the test torpedoes should be recovered for inspection and subsequent use. The theodolites or 35mm range cameras will assist the recovery crews in locating the torpedo by providing the position of water entry.

3.14 Sonobuoys. The Navy currently uses the A-size sonobuoy (36-inch length and 4.875 inch diameter) as the standard air launched acoustic sensor. There are, however, other sizes of sonobuoys that are popular due to increased flexibility in selecting the quantity and type of sonobuoys that can be carried. These sonobuoys are identified as A/3, A/6, etc., with the "A" denoting the same diameter as an A-size sonobuoy and the number being the ratio of its length (e.g., A/3 is a sonobuoy 1/3 the length of an A-size sonobuoy or 12-inches long).

Safety Considerations. As sonobuoys become more sophisticated there is need for a larger and more stable power source to support newer technology. Lithium sulfide and lithium chloride batteries are currently the only power sources capable of supporting these sophisticated sonobuoys. The majority of sonobuoys the ordnance engineer is required to handle will be either mass models or dummy models, neither of which contain a battery. All of the sonobuoys that would normally be equipped with a lithium battery will be marked with appropriate warning labels, e.g., CONTAINS FLAMMABLE EXPLOSIVE, CONTAINS TOXIC MATERIAL, or FLAMMABLE SOLID. Extreme care must be exercised when handling the full up rounds. Although lithium battery technology has many improved safety features, the mishandling of these sonobuoys can result in personnel injury and death. It should not be assumed at any time that a dummy sonobuoy is 100 percent safe. P-3 aircraft are prohibited from carrying lithium-powered devices inside the cabin unless key members of the aircrew are equipped with quick donning oxygen breathing masks. There are no restrictions for the helicopters since maximum ventilation of the cabin area can be achieved by simply opening the main cabin cargo door.

Countermeasures Devices. A series of countermeasures devices (CMD) have been developed that look like sonobuoys; are shipped, stored, and launched from SLCs; and are compatible with the sonobuoy launch systems of all ASW aircraft. The difference between a sonobuoy and a CMD is that the CMD contains explosives that are intended to disperse the CMD payload over a very wide area The explosive material ranges from a few grams of Tetryl or Primacord to the equivalent of a 71mm mortar shell The design incorporates as many safety features as possible. All CMD currently in the Navy inventory use an out-of-line firing train and delay elements to achieve the maximum distance between the CMD and the releasing aircraft and still maximize the effect of the CMD payload.

Ground Tests. For all ASW aircraft that have a CAD-launched sonobuoy system, electrical release and control checks and aircraft preparation should be performed in accordance with the Weapons, Stores Loading Manual prior to loading the sonobuoy SLC. Prior to loading SLCs into the SH-60B pneumatic launcher and in addition to the aforementioned procedures, the test team should ensure the pneumatic system is completely vented so that no pressure remains in the system. All ground safety override systems should be checked for correct operation. If the store to be tested requires special handling procedures different from, or in addition to, those procedures required for sonobuoys, a special Loading and Handling Checklist should be drafted and approved through the SA Ordnance Systems Department. During ground tests, the ease of inserting the SLC into the launcher assembly should be evaluated. Pay special attention to how well the windflap remains attached to the sonobuoy when the sonobuoy is removed from the SLC and loaded into the launcher tube during fit tests on aircraft with launch systems that do not use SLCs.

Static Firings. When a site to conduct ground launches of sonobuoys has been chosen, the area around the test should be cordoned off and safety observers positioned to keep nontest team personnel away from the danger areas. Ground launches of sonobuoys from P-3 and S-3 aircraft can safely be conducted on the ramp by positioning the sonobuoy launcher over the dirt or grass area at the ramp edge. The pit in front of the SA Firing Tunnel can also be used for these tests. Ground sonobuoy launches from the SH-2F and SH-60B helicopters will be conducted on the ramp. A special catcher box, located at RW, has been built specifically for the lateral (horizontal) launch systems of these aircraft. Ground launches of sonobuoys from the SH-3H and SH-60F are not required due to the benign separation characteristics, gravity launch only capability of the launch chutes and lack of any potential for physical interference in a static environment.

Flight Tests. There are three different types of flight tests recommended for sonobuoy/CMD which will use four different range facilities depending on the nature of the test. For routine separation tests to evaluate separation characteristics, any free area of the Chesapeake Test Range can be used. Clearance from the test aircraft is documented using onboard camera systems to record data points. For tests of new sonobuoys/CMD, sonobuoys/CMD from new manufacturers, sonobuoys/CMD with modifications to the air retardation system, or when the release airspeed is questionable, Hooper Target should be used with range camera coverage to allow the test team to monitor each release in real time. For separation tests of sonobuoy/CMD for which recovery of the units for analysis is required or when live CMD are being tested, the Army's Harry Diamond Test Range, Nanjemoy, Maryland should be used This is the only land range close to NAWCAD certified for small explosives and with sufficient area to allow aircraft maneuvering when airspeed is an important variable in the tests. For support of CMD developmental/TECHEVAL testing for which radar cross sectional (RCS) data are required, the Naval Research Laboratory (NRL) range facility at Chesapeake Beach, Maryland must be used.

3.15 Miscellaneous Stores. Drop tanks, cargo carrying pods, and liquid filled stores all present unusual separation problems due to variable CG locations and weights and slashing dynamics for partially full liquid - filled stores in addition to the normal problems associated with large diameter, poorly stabilized, and/or low density stores.

Ground Tests. In addition to fit and compatibility tests, these stores should undergo an extensive ground ejection test program to measure store pitch rates and vertical separation velocities for the full range of all possible CG locations and weights. These data should then be used to select the store loadings for the flight test program.

Flight Tests. Any store that has a variable weight or CG during flight must have its separation capabilities evaluated for all adverse conditions. Using the testing methodology of paragraph 3.5 and the test results of the ground test, the flight test program should approach the more hazardous store configurations with caution. Testing of liquid filled stores may proceed from the use of a nonsloshing model to an actual liquid fill with the proper ullage. A careful analysis should be made to select representative test points and avoid testing all possible situations over the airspeed range.

SECTION IV
RANGE SUPPORT AND INSTRUMENTATION

4.1 Introduction

4.2 Chesapeake Test Range

4.3 Real-Time Processing System

4.4 Target Support Section

4.5 Optical Tracking Section

4.6 Mechanical Design and Fabrication

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4.8 Target Ranges

Hooper Island Target
Hannibal Target
Bloodsworth Island
Warning Area W108
Other Ranges
SEPTAR

SECTION IV
RANGE SUPPORT AND INSTRUMENTATION

4.1 Introduction. RD is responsible for providing targets, target range airspace, realtime computation and telemetry support, time and space position, information, and aircraft instrumentation. These responsibilities are divided among the following: the Chesapeake Test Range (CTR), Real-Time Processing Section (RTPS), Target Support Group, Mechanical Design and Fabrication Section, Optical and Radar System Group, and Airborne Instrumentation Department. The services provided by each of these sections pertinent to ordnance testing and targets available in the local restricted areas are discussed in the following paragraphs. In addition, ordnance specific test equipment can be fabricated by the Ordnance Electrical Laboratory (O&E) of the SA Ordnance Systems Department. The O&E Lab section head should be consulted to determine what in-house test equipment can be supported prior to consulting outside sources.

4.2 Chesapeake Test Range. CTR is responsible for range control and tracking within the Patuxent restricted areas. This includes range clearance of surface units with the support of the surface search radar groups and deconflicting air traffic in conjunction with NAS Patuxent Air Operations. CTR provides range control and communications including range safety, vectors, and coordination with the optical tracking systems. CTR can also provide coordination with aircraft operating off shore in the W- 108 and W-386 operating areas via a data link with NASA Wallops.

4.3 Real-Time Processing System. RTPS includes seven project engineering stations, each equipped with computers, recorders, CRT displays, and strip charts. Each station can support an individual aircraft operating simultaneously with the other stations. The stations can each support 512 measurements per aircraft with a throughput of 50,000 samples per second. The four older stations are equipped with four strip chart machines, each with eight channels. The new stations feature CRT displays which provide a three dimensional aircraft representation similar to a heads-up display format, plus two CRTs for out-of-limits measurement checking, and two CRTs for bar graphs. The new stations are MIL-STD-1553 data bus compatible. In addition to fixed site testing at NAWCAD, RTPS can operate from, or link with, remotely located ground sites or the UC-880 airborne telemetry system also maintained by RD.

4.4 Target Support Section. This section maintains the targets already in position in R 4005 North and South (Hooper and Hannibal targets), prepares and instruments targets required for specific tests (e.g., Tomahawk target support) and maintains and operates remotely controlled boats and dune buggies used for moving target tests. The remotely controlled boats operate on the Chesapeake Bay in the vicinity of R-4005N, and the dune buggies are normally operated at Webster Field.

4.5 Optical Tracking Section. Theodolite tracking is available from five tracking stations located along a 15-mile strip from NAWCAD to Point No Point. Photographic coverage of weapon separation and tracking to impact requires both theodolite and radar support. Theodolite coverage provides triangulation information for impact spotting and subsequent ballistics information as well as real-time video regarding weapon separation, fuze arming, canister opening and fin deployment.

4.6 Technical Design and Fabrication. This section of RD is responsible for building fixtures, special adapters, and wiring harnesses required for project work and equipment installation when suitable equipment cannot be provided by the project equipment manufacturer.

4.7 Airborne Instrumentation. The instrumentation needed for ordnance testing generally consists of a camera control panel or a magnetic tape recorder showing indicated airspeed, normal acceleration, event marking and any parameter deemed necessary to document actual release conditions. Onboard high-speed cameras are required to show separation, motion of the store, and arming wires and pullout bail functions. Accumulation of vibration stress, electrical or thermal data will require an oscillograph or magnetic tape with appropriate pickups. The Airborne Instrumentation Department can install, maintain, and repair these types of equipment.

4.8 Target Ranges. Patuxent area target ranges should be scheduled through Patuxent Air Operations or CTR Central Schedules at least a week prior to the desired flight tests. The following paragraphs provide information on each range. Target locations and airspace assigned are depicted in Appendix D.

Hooper Island Target. Hooper Island Target, Figure 1, Appendix D, is located at 5.8 miles on the 142 radial of the Patuxent VORTAC. This target is used primarily for determining weapon delivery accuracy and can be used in making individual drops of practice bombs or single firing of 2.75-inch rockets. This target should not be used for large weapons unless the objective of the test justifies the possible damage to the target. Runs are made from south to north under radar control to remain over water at all times. Hooper Target is scheduled through the ATR Central Schedules Office. Airborne control is provided by ATR, "Echo Control".

Hannibal Target. Hannibal Target, Figure 2, Appendix D, is a scuttled merchant ship, located 19 miles on the 149 radial of Patuxent VORTAC. Ball gun ammunition, rockets and bombs with inert warheads, inert flares, and other inert stores may be fired, dropped, or jettisoned on this target. Pilots are responsible for thoroughly clearing the target before release. Frequently, small boats are in the target area or tied up alongside. NAS Air Operations (via tower) should be notified if the target is not clear and low passes over the target have no effect in clearing the small boats from the range. Runs are made on east/west headings with turns to remain south of the target or as directed by Patuxent Approach Control. Radar control is not normally provided but is available on request. Hannibal Target is scheduled through NAS Air Operations (Approach Control).

Bloodsworth Island. Bloodsworth Island, located in R-4002, Figure 3, Appendix D, is used for live drops. Range scheduling is provided by the ATR Central Schedules Office. A maximum of 500 pounds of live ordnance is authorized to be dropped on any one pass. Particular care must be taken to ensure that the aircraft will not fly over Deal Island or any other populated area while making live runs. The normal pattern at Bloodsworth Island is from east to west with left-hand turns to remain south of Bloodsworth while on the down-range heading. Although this is a restricted area, small boats may be very close to the Island and the pilot should make low passes around the island to clear the area thoroughly. Patuxent River Approach Control monitors the use of the Bloodsworth Island impact area and, if it is not being used, permission can be obtained from Approach Control for strafing and rocket runs. All NAWCAD pilots must be aware that this live ordnance drop area is used frequently by surface ships for gunnery and should not be overflown if advisory has listed it as a hot area.

Warning Area W108. Warning area W108 is located over the ocean southeast of Cape Henlopen, Delaware. This area is normally used for air-to-air gunnery arid missile firing, but is available for air-to-surface ordnance when required. Live ordnance drops require clearance from FACSFAC, Norfolk, DSN 433-1217. A message request must be submitted at least 1 week in advance listing the ordnance to be dropped and the specific drop area. Live ordnance drops beyond the 100 fathom curve will require special clearance from FACSFAC to preclude interference with the surface hydrophone net. Responsibility for assuring that the drop area is clear rests solely with the pilot. Warning area W108 is scheduled through NAS Air Operations.

Other Ranges. Some projects may require facilities not available at NAWCAD because of local restrictions or requirements for large areas and specialized services. Additional services may be found at:

Warren Grove, Pennsylvania
Lakehurst, New Jersey
PACMISTESTCEN, Point Mugu, California
NASA Range at Wallops Island, Virginia
White Sands, New Mexico
Eglin AFB, Florida
NAS Key West, Florida
Fort Bragg, North Carolina
Dahlgren, Virginia
San Clemente Island, California
Harry Diamond Test Range, Nanjemoy, Maryland
NRL Chesapeake Beach, Maryland
NAVWPNCEN, China Lake, California

SEPTAR. The MK-35 SEPTAR is a remote-controlled 55-foot fiberglass boat with a normal speed of 25 knots, but capable of 40 knots. The SEPTAR boat can be augmented to simulate most high speed surface craft. Electro-optical displays and laser measuring equipment can also be provided. No ordnance should be dropped directly on the SEPTAR, but towed targets can be provided for weapons scoring. The SEPTAR normally operates in the Hooper target complex, but can be operated anywhere on the CTR.

SECTION V
FLIGHT TEST PROCEDURES

5.1 Introduction

5.2 Store Preparation

Weight and Center of Gravity
Painting
Ordnance Stowage and Handling

5.3 Aircraft Preflight

5.4 Flight Test Preparations

5.5 Flight Data Cards

5.6 Flight Brief

5.7 Area Clearance

5.8 Target Procedures

5.9 Supersonic Tests

5.10 Hung Ordnance

5.11 Stabilization

5.12 Chase Aircraft

5.13 Flare Procedures

5.14 Postflight

5.15 Ordnance Incidents/Accidents

SECTION V
FLIGHT TEST PROCEDURES

5.1 Introduction. Information contained in this section describes typical flight test preparations and procedures. It is offered as an addition to material found in the NAS Air Operations Manual, NASINST 3710.5. Aircrew and engineers should review their Operations Manual in detail while preparing for flights involving the restricted areas, mine and torpedo drop zones, and ordnance handling areas.

5.2 Store Preparation. The type of tests and documentation required for analysis govern the amount of store and aircraft preparation required. Preparations will normally include consideration of the following items.

Weight and Center of Gravity. For separation testing, NAVAIRSYSCOM requires the actual weight, moment of inertia, and CG of stores and suspension equipment be determined. These data can be used for correlation with expected separation characteristics. Erratic store behavior may be related to off-design CG location. Specific data requirements for formal reports include:

a. Weight of the store, launchers, and racks.

b. Moments of inertia (Myy, Mzz, and sometimes Mxx).

c. Distance in inches from CG of the store to the bomb rack ejector foot.

d. Distance between suspension lugs.

e. For suspension systems with variable lug attachments, the distance in inches from the forward aircraft suspension lug to the nearest store suspension lug.

The following information should be written on each store in a location that is accessible during preflight to allow the specific weapon characteristics to be tracked.

a. Weight

b. Center of gravity from forward lug

c. Moment of inertia (if desired)

d. Serial number

In addition, firing tunnel personnel should maintain a list of these parameters to allow the correlation of store serial numbers with the weapons.

Painting. Requirements for painted stores vary, but generally originate from the need for ballistic data or to aid in observation of store motion or function. Ballistic data compilation requires that all theodolites track the same store, usually painted a distinctive color different from the other stores for test points involving multiple drops. Store roll information can be ascertained from film if stores are painted in a checkered or lined pattern. Frequently, an identification mark will be required to distinguish between different fuzes loaded or unloaded canisters, or other store features that are not readily apparent in film coverage.

Ordnance Stowage and Handling. Inert and live ordnance, live ammunition, and pyrotechnics shall be stowed in appropriate magazines at the NAS Weapons Division in the limited quantities required to support current projects. Loading will be conducted on the south ramp area of Hangar 201 when possible; however, the other ramps adjacent to Hangars 201 and 115 may be used if necessary. All forward firing ordnance will be loaded on the east ramp of Hangar 201 with the aircraft spotted such that it faces the breakwater. Final arming and dearming of forward firing armament will be conducted at the designated arming areas depicted in Figure 4, Appendix D. Handling and stowage of all ordnance will be in accordance with the procedures contained in current ordnance publications, notices, and instructions and will be conducted by designated NAS Weapons Division ordnance personnel. The varied and sometimes unusual nature of the ordnance used at the NAWCAD requires that aircrew and supervisory personnel continually monitor ordnance for safety, compliance with directives, and to foresee Hazards from Electromagnetic Radiation to Ordnance (HERO).

5.3 Aircraft Preflight. The preflight prior to ordnance testing consists of the usual preflight items in accordance with NATOPS and the additional items required by the particular test. In general, the project officer or engineer should carefully inspect store integrity, the ejector mechanism, sway bracing, configuration, instrumentation power cables, film remaining, and any peculiar features of the store being tested. In addition. the aircraft should be meticulously inspected for dents. scratches. holes. and other external damage, and each site of such damage marked and noted for postflight inspection.

5.4 Flight Test Preparations. The flight crew and engineers must be thoroughly prepared prior to conducting ordnance tests. This includes a thorough knowledge of the project equipment, range areas, and test points to be flown. The following paragraphs provide a basic guide for preparation for test flights.

a. Review the test plan and prepare a detailed flight card.

b. Thoroughly brief all personnel involved with the flight. Include range operations, ordnancemen, chase crew, and appropriate operations and maintenance personnel.

c. Review aircraft limitations and procedures for in-flight damage assessment and landing emergencies.

d. Inspect the loaded aircraft to assure proper suspension, electrical connections, and instrumentation readiness. A large proportion of airborne malfunctions are caused by improper rigging and loading.

5.5 Flight Data Cards. The following information should be depicted on the flight data card: the load, release sequence and parameters, trim conditions, desired sideslip and AOA, armament and instrumentation switch set-up/operation, communication frequencies, and the aircrew data requirements. In addition, the card should contain space for recording qualitative comments, flight data, and sufficient information to permit the correlation of recorded data and film. All information must be clearly and logically presented Figure 5, Appendix D is a sample data card that contains the normal information provided.

5.6 Flight Brief. The flight brief is probably the single most critical event performed during the flight test preparation phase. Countless hours of research, test planning and instrumentation/range support work can be squandered by a poor flight brief. If all your tolerances are not conveyed to the test crew, you may very well expend your extremely limited stores and flight time funds and never get the data needed to clear the store to the desired endpoint. As such, the initial flight briefs should be well prepared and rehearsed, and a review board conducted with the project officer prior to the real thing. Sample briefing guides are available in the SA Operations Office.

5.7 Area Clearance. Clearance into the appropriate restricted area will be requested from Advisory Control. Advisory will request the aircraft type, time in the area, the target to be used, and altitude requirements while on target. For operations on Hooper target, the flight will then be cleared to Echo Control and given a working frequency. Echo Control will establish radar contact once airborne, and vector the aircraft to set up for the data runs.

5.8 Target Procedures. The controller will confirm the intended dive angles, type of entry, altitudes for roll in, timing of calls for standby and release, and the drop sequence prior to the first run. Practice runs may be made at the discretion of the test crew until they are comfortable with the profile. Normally, the roll-in altitude will be 15,000 feet for dive angles 30 degrees or less and 20,000 feet for dive angles greater than 30 degrees. The dive entry may be made either by a 0 g pushover or by rolling inverted, pulling to the desired dive angle, and then rolling to the upright position. The controller will give 10 second and standby calls prior to the execution of the entry. These methods are the most precise techniques for establishing dive angle under positive control. Practice runs should be used to establish the power setting required to reach the release parameters at the desired release altitude. The standby call or "Cameras on. call will be given by the controller 2,000 feet prior to reaching the release altitude for dive releases, followed by the "marl`" call indicating arrival at the release altitude. A normal recovery or abort should be commenced at this call. The release altitude should have been programmed to permit a dive recovery with all stores retained to allow practice runs and cover hung store contingencies, and it is imperative that recovery be initiated at this planned altitude. A right turn to downwind heading will follow the recovery, and the controller's appraisal of the maneuver will be given on the downwind leg. Carriage of all ordnance, live or inert, should be carefully planned to remain over water whenever possible. Takeoff an landing will normally require a deviation from the normal pattern in order to remain clear of populated areas.

5.9 Supersonic Tests. The high-speed performance of new attack aircraft has created a requirement for supersonic separation testing. Onboard camera coverage and ground image tracking from RD theodolites are normally used as a real-time monitor of weapons separation characteristics. in addition, theodolite cross-coverage of impacts at Hooper target are required to complete weapons delivery accuracy tests. Profiles have been developed that reduce sonic boom disturbances to populated areas surrounding the inshore operating area. These profiles are held by the SA Ordnance Systems Department. The basic test procedures are as follows: Aircraft will be flown to the roll-in altitude under close control by CT R Echo Control. Holding for sequencing will be conducted at subsonic airspeeds At the roll-in point, the aircraft will execute a positive g roll-ahead to place the aircraft in the desired dive angle on the run-in heading. Adjustments in dive angle and heading will be made by the pilot. Power will be adjusted to obtain and maintain the desired mach. Following release, power will be reduced to idle and a 3 g pull executed until reaching a -45 degree flight path angle, then the pull is reduced to 2 g until subsonic mach is reached at approximately -30 to -20 degree FPA. Once subsonic, the pullout will be completed and the aircraft will climb back to the roll-in altitude (or level off for rendezvous and RTB). These procedures are optimized for F/A-18 dive releases. Other types of release or aircraft will require a modification to the procedure. In all cases, it is important to minimize the supersonic boom.

5.10 Hung Ordnance. Hung ordnance is defined as any store or weapon that remains with the aircraft after an attempted release. Approaches with hung ordnance should use a straight-in entry clear of populated areas. The tower must be advised of an intent to land with hung ordnance at least 10 miles from the field. When returning with captive or hung ordnance, the pilot should remain with the aircraft until qualified ordnance personnel arrive, and dearming is complete.

5.11 Stabilization. All test work requires that some degree of stabilization exists at the desired data point. During separation testing at high dive angles, stabilization is difficult to attain. The airspeed will be increasing and must be controlled so that the airplane will reach the desired release altitude at the correct airspeed. The power setting required should have been determined during practice runs. If the pilot or controller feels that the dive angle is incorrect, the run should be aborted. Late dive angle corrections will invalidate the release acceleration and may cause an unsafe release if a pushover is made. In no case should the pilot attempt to directly control the acceleration to obtain that desired at release during a straight path dive. If dive angle is correct and the airplane is trimmed for the release airspeed, the desired acceleration will be attained.

5.12 Chase Aircraft. Chase aircraft should be used on all critical separation tests, particularly if multiple runs at successively higher airspeeds are to be made on one flight. The test aircraft should be carefully observed during weapon release and inspected between runs to detect damage caused by bomb-to-aircraft collisions. In no case should the test flight be continued following an actual store-to-aircraft collision. The chase and test crews will be the clearing authorities for subsequent runs if there is any concern about whether a collision has taken place. Most requirements do not require the chase aircraft to be flown in extremely close proximity to the test airplane. During both the roll-in and in the run, the chase aircraft should fly a loose position abeam the test airplane at a distance of 200 500 feet. Duplication of the roll-in maneuver will allow the chase aircraft to find and maintain a safe position. While positioned to the side and slightly stepped down, the chase pilot should be able to observe erratic store behavior and predict a collision if more critical release conditions are subsequently to be reached. The chase pilot should be thoroughly familiar with the flight characteristics and procedures for the test aircraft so that if damage occurs he can assist the test crew during recovery. The chase crew should be thoroughly briefed on the conduct of the flight, desired chase position, release sequence, and store characteristics. It is imperative that the preflight briefing include a description of the predicted flight path of the store(s) to be released. Previous tests have shown that the chase pilot may not be able to maneuver quickly enough to avoid store-to-chase aircraft collision. A two-place aircraft serves as an excellent photography vehicle and can provide coverage from many angles, but photographic coverage is always to be considered of secondary importance to the safety of night responsibilities of the chase crew.

5.13 Flare Procedures. Flare releases require more elaborate planning than other types of ordnance since flares are subject to drift and are particularly capable of starting fires on impact. All flare releases must be planned to allow flare burnout prior to impact. A forecast of wind at each 1,000 feet of altitude should be obtained to permit a prediction of the flare track after release. The release point must be planned to allow for drift during fall and still ensure impact in the water in the drop area Warning area W108 may be used if the required release altitude is too high to permit an accurate prediction of the flare track. For all flare or pyrotechnic drops, the pilot must observe the impact to ensure that the store landed in the water. Incidences of flares impacting land must be reported immediately by radio to base.

5.14 Postflight. Upon return from separation flights, the aircraft should be carefully inspected for signs of damage, arming wire retention, and overstress. Onboard camera film should be reviewed prior to the next flight. The next section will highlight data reduction techniques for cameras.

5.15 Ordnance Incidents/Accidents. Ordnance incidents or accidents should be handled in accordance with OPNAVINST 3750.6, OPNAVINST 4790.2, and NAVORDINST 8025.1.

SECTION VI
PHOTOMETRICS

6.1 Data Reduction Techniques for Cameras

6.2 Photogrammetric Techniques

6.3 Photo Imaging Techniques

6.4 Photo Chase Techniques

6.5 Comparing Actual Test Results With Predictions

SECTION VI
PHOTOMETRICS

6.1 Data Reduction Techniques for Cameras

Techniques Available

If cameras, whether video or film, are used to obtain slow motion views of the store during separation from the aircraft, then this optical data must be reduced to angular positions and displacements versus time for comparison to predictions. Basic to this solution is the knowledge of the camera's position in relation to the store being released. If the camera's distance and angular position relative to the store are accurately determined, and a known point or distance on the aircraft appears in every frame of the camera's view, then a mathematical solution may be obtained for successive positions of the store during separation. This mathematical solution lies at the heart of every data reduction technique now available. How this solution is obtained varies considerably from technique to technique. The earliest solution used for store separation data reduction involved a purely mathematical triangulation process. Although the actual program developed by different agencies or nations varied in name, they could all be described by the term "photogrammetry" or a photogrammetric solution of the time-space position problem. Photogrammetric techniques require complex accurate painting patterns on both the store and portions or the aircraft, as well as manipulation of the data obtained in complex equations. Later improvements of these photogrammetric techniques lessened or eliminated some of the painting patterns, and simplified somewhat, the data manipulations.

In the late 1970's, the United States Navy developed a photo-imaging technique called the Photo Data Analysis System (PDAS). This provided a major improvement over photogrammetric techniques in that no special paint pattern of either the store or the aircraft was required. PDAS did, however, require the purchasing of some unique data reduction hardware and the training of personnel to operate the equipment. After the one-time purchase of equipment, PDAS provided a significant reduction in the time and cost for data reduction. It also provided an improvement in data accuracy. PDAS has since been widely used by both the Navy, Air Force and several US aircraft companies. Because of its inherent advantages in low cost and quick data turn-around a group was formed in the US to seek improvements to the PDAS. In the mid 70's, efforts resulted in a second generation photo-imaging technique called Graphic Attitude Determining System (GADS). It too required the purchase of a unique machine for data reduction and the training of operators, and has been in use at Eglin AFB for several years.

Another type of data reduction technique allows the viewing cameras to be located on a photochase aircraft instead of on the releasing aircraft. This technique, called CHASE by its developers at McDonnell Douglas Aircraft Company is highly complex, requires an inordinate amount of pre-flight calibration efforts and many baseline camera runs. But, CHASE does completely free the release aircraft from camera carriage, and the actual reduction of data is relatively straight forward Because of its complexity it would be of use only to large, well funded flight test organizations. It offers an excellent quality alternative to the more conventional data reduction techniques. In the following paragraphs, each of these data reduction techniques will be discussed in more detail.

6.2 Photogrammetric Techniques

By far the most commonly used technique for the reduction of movie camera film is the photogrammetric method. It is used by virtually every government agency and industry within NATO. Although the detailed description of each nation's, or each company's, use of the photogrammetric technique varies, the basic method remains the same. In this method, both the store being released and the aircraft pylon are painted with a background color and a contrasting color pattern of dots whose positions are accurately known with respect to some specific point. Size and color of the dots are not fixed; they are optimized for accuracy and ease of film reading however, a minimum number of dots must be visible at all times in the film. Onboard camera lenses are selected so that both the store being released and part of the aircraft's adjacent structure (such as the pylon) are visible on the film. After the release, each frame of the onboard gathered movie film is processed through a film reader manually. These data, along with a series of geometric and physical constants, such as location of the reference dots with respect to a specific position, camera location and lens focal length, are input to a computer. The computer is programmed solve the equations of motion and defines the store trajectory, printing out angular and linear motions as a function of time. Although a two-camera solution is preferable, a one-camera solution can be used most of the time and will provide accuracies of about + 2 inches for displacements and + 2 degrees for angular motions. The photogrammetric computer program requires starting estimates of the store and a camera orientation with respect to the aircraft. A final iterated solution is then obtained which achieves convergence for even poor starting values. After the first frame, the program employs previous frame results as the estimate for the succeeding frame. Because of this, wing flexure and vibration are automatically eliminated. The computer is programmed to print out the trajectories in both tabular and plotted format, so that a direct comparison may be made between predicted and in flight trajectories.

Variations of the basic method, which are widespread include the use of a geometric paint pattern on the store instead of rows of dots, the elimination of painted dots or references on the release aircraft, and the automatic reading of the film by machine. A good basic description of the photogrammetric data reduction process may be found in Reference (51). Utilizing the improvements mentioned earlier, several agencies have been quite successful in the employment of the photogrammetric technique. Any reader desiring to learn more about the employment of this technique should consult the NLR report at Reference (50). It is a basic handbook for the user of the technique and is an excellent source document. Another excellent source document for the reader who wishes to delve deeply into the actual mathematical representations of the equations of motion is the NLR report at Reference (52). Reference (53) contains a description of an automated film reader which asserts that it is ten times faster and seven times more accurate than manual film reading. It is a computer controlled system specifically designed for the analysis of pictoral data. This system reduces the data reduction time, a major drawback of the basic photogrammetric process.

An interesting report on the inherent accuracy of a single-camera photogrammetric solution to the store separation problem is given in Reference (54). In this report, an actual store (an empty rocket pod) was set up in a hangar on very accurate mountings and then, using a surveyor's transit, was moved through a known set of displacements and angles, being photographed at every step using a 35mm camera. The resulting 35mm slides were then used as the frames of a movie would be and run through the photogrammetric computer solution of the equations of motion. Over 900 photos were taken and processed, and both the accuracy of the photogrammetric method and optimum camera angles for obtaining best solutions were established

6.3 Photo Imaging Techniques

PDAS

The first major alternative to photogrammetric data reduction techniques was developed by the US Navy in the 1960's and, as mentioned earlier is called PDAS. It offered the major advantages of not requiring any painting of the store or aircraft, reduced data reduction time, and enhanced accuracy. The USAF also adopted this method in the early 1970's in support of the A-10 and F-15 store separation flight test programs. On the one program, the A-10, because of the large number of aircraft pylons (eleven) carrying stores, many hundreds of stores would have had to be painted with a highly accurate paint pattern if the usual photogrammetric technique had been used. Because of the accuracy of painting required, the lack of adequate painting facilities, and the large number of store: involved, just painting the stores would have taken months. By adopting the PDA; technique, flight tests were simplified and a large cost and time factor was eliminated.

PDAS utilizes an image matching technique to obtain spatial position and orientation of photographed objects with respect to recording cameras. It consists of projecting each frame of the onboard flight gathered data film through an optical system into a high resolution video camera and displaying the resulting image on a television monitor located on an operator's console. Another high resolution video camera is positioned near the console to view an exact scale model of the store. The store model is mounted on a remotely controlled six-degree-of-freedom model positioner mechanism. The video signal from this second television camera is fed through a video mixer and the resulting image is simultaneously displayed on the same television monitor as that from the data film. The operator can adjust the position and orientation of the store model through the use of a set of levers on the console. The store model is adjusted by the operator until the image of the store on the positioner is exactly superimposed on the image of the store from the data film (a process similar to using a camera range finder). Once the two images are exactly aligned and superimposed, the operator presses a button which transfers the encoded frame count and position data to a computer data card. Each frame of the film is similarly reduced, until a card deck is generated. This deck is input to a computer program - just as in the photogrammetry process - to solve the spatial relationships. The output from the photo-imaging technique is a set of tabular data and selected plots which accurately define the store separation trajectory to compare directly with predictions. This technique produces extremely accurate data (A 0.1 foot for displacement and + 1.0 degree for angles). Because PDAS does not require painting of the stores, the overall cost of data reduction is less than one-half the cost of data reduction using photogrrammetry.

At the time the USAF decided to adopt the PDAS technique, only two systems exited -one at the Navy Pacific Missile Test Center, Point Mugu California, and the other at the Naval Weapon Center, China Lake, California. The system at Point Mugu was chosen for the A-10 and F-15 programs. The PDAS lives up to every expectation. During the course of the A-10 and F-15 programs, improvements in output data format were made. Specifically, pictorial computer-generated trajectories were created. Data reduction time was indeed shortened, and the data quality for several hundred store releases over a two year time span was excellent. As the PDAS became used in quantity, even the cost per run of reduced store separation data was lowered to a value significantly lower than that of a comparable photogrammetric trajectory. A complete detailed description of the Point Mugu PDAS can be found in Reference (55).

GADS

Although the USAF and US Navy were well satisfied with the results from PDAS, both services recognized that considerable improvements could be made - particularly with the availability of powerful, mini-computers. As a result, a working group was formed to incorporate all these desired improvements into a specification, and this specification was then offered to industry (in 1978). The GADS, which emanated from this specification, was purchased and installed at Eglin AFB, Florida; where it has been used for store separation data reduction activities in hundreds of tests. It has proven to be a major improvement to the PDAS technique. Unlike the PDAS, which requires an exact scale model of each store to be placed on a manually operated positioning system, the GADS uses a self-control computer to generate a video image of the outline of the store, thereby eliminating both the mechanical positioning system of PDAS and the manufacture and storage of the exact scale models of the stores. The GADS also incorporates a much improved joy-stick-operated store image manipulation system, thereby making the operator's task easier and quicker.

6.4 Photochase Techniques

The above techniques all require cameras to be mounted on the aircraft releasing the stores. They also all depend for their accuracy in the exact knowledge of the geometrical relationship (angles and distances between the cameras and the store and the reference points). It was, therefore, quite a revelation when, in 1975, the McDonnell Douglas Company announced the development of a technique that positioned the cameras not on the release aircraft, but on the photochase aircraft! Since the exact distance between the photochase aircraft and the release aircraft could never be ascertained. The general testing community looked upon this new technique with great skepticism. However, the system, appropriately termed "CHASE", was proven during F-15 flight testing. A complete description of the technique can be found in Reference (56). The technique proved to be very successful. Primarily through the results of some innovative mathematics, elimination of all assumptions. and very precise optical calibrations. However, it also proved to be a highly complex and demanding system to operate. It is still used upon occasion, but is not known to have been taken up by other testing organizations.

Consideration for Selection the Right Technique

There is one factor which must be stressed here. All of the methods described provided accurate and useful quantitative data, both in tabular and plotted format. We have run comparisons of the methods by processing the same film strip from a particular store release and comparing the output plots. No useful purpose could be served by presenting the comparison in this report as the superimposed data results in essentially the same line. This brings us to an important conclusion. We have examined several methods of reducing flight test data, the kinds described above, and others developed by various airframe manufacturers. All of them are inherently accurate enough to provide good, usable data. The degree of mathematical accuracy attained is not as important as how many of the error-causing factors are accounted for by the method, and whether the factors are compensated for or corrected. Data reduction accuracies of + 2 or 3 inches and degrees can be absolutely adequate if the error-causing factors are corrected for. Of all the error-causing factors, the ones which seem to be the most important (and most difficult to correct) involve those connected with the camera optics. Errors caused by lens/camera alignment, calibration, internal manufacturing aberrations and uncertain optical centers are among the most important. Although great care must be exercised in developing a data reduction method which properly accounts for as many of the error-causing factors as is possible, equal care must be used in insuring that the method does not introduce other, larger errors through the human factor. A method which requires an inordinate amount of human input and manipulation of data prior to and during computer reduction is extremely prone to errors, particularly if no built-in-test features are incorporated.

From this discussion, one can see that there is no "right" or "wrong" technique. The right technique is the one that best fits the users requirements. The photogrammetric method requires no initial one-time outlay of funds for expensive data reduction equipment, but does require more time (both computer run time and work hours). It could be the "right" selection if store separation tests are not performed in large numbers. If the testing organization is a major activity, constantly producing large numbers of tests and data, then the purchase of the data reduction machine can be amortized over the large number of tests. In such a case, even with the cost of equipment, photo-imaging can provide data much quicker and at lower cost.

A word about video data processing. All the discussion above has assumed that the store separation data was acquired by 16mm movie film cameras. If, however, digital television cameras replace movie film cameras as the onboard data gatherer, then the reduction of this data offers even more alternatives. First, since the data is already in video format, a step in the GADS could be skipped (conversion from photograph to video) at a considerable cost savings and simplification. Also, the reading of the video data, since it was initially gathered in digital format -could be processed electronically. And, since this video image is now being superimposed by the GADS on another computer generated video image of the store, all this could conceivably be processed by computer with no manual manipulation. This would indeed be an order of magnitude increase in the state of the art, and is not out of the realm of the foreseeable future.

6.5 Comparing Actual Test Results With Predictions

This section describes the basic approach used to compare actual night test results with predictions during store separation testing and how subsequent night test points are adjusted based on this comparison. Also discussed is an approach for performing "brute force" testing where one does not have any predictions per se (no analyses) - night testing is planned and conducted based on expected store separation characteristics. Clearly, brute force testing must only be performed by experienced personnel to minimize potential safety of night hazards. In brute force testing, the experience and judgment which come with experience are essential ingredients to a successful program

Iterating Between Flight Test and Analyses

There are generally two levels of comparison. In the first level, flight test six degree of freedom digital trajectory data (obtained from GADS or another data reduction system) are compared with digital predictions at each test point. If actual results (based on judgment) do not closely match predictions, subsequent test points may be adjusted from the original test plan. Between each test point, the predicted collision boundary is recomputed and adjusted to reflect actual test results to that point. This process is performed between each test point and, as a result, the confidence as to the accuracy of the final collision boundary will ultimately approach 100%. Incidentally, before proceeding any further, the reader is reminded that the above process is also performed for store yawing and rolling motions. The process for these motions is identical to the pitching motion and is, therefore, not presented herein. For illustrative purposes, store pitching motion seems to be the easiest to describe, and this is why it was chosen.

In the second level of comparison, predictions in a graphical format are compared with actual test results in a qualitative manner. The engineer compares predictions (normally generated using a computer graphics program) with the store separation trajectory obtained directly from the onboard movie film. In this method, the film is not reduced using GADS or any other processing system. If in the engineer's judgment the actual store separation trajectory closely matches predictions, the next test point is performed. While this method requires an experienced engineer, it has been used with remarkable success. With proper training, one can generally do a very good job in estimating store angular motions at various estimated linear positions. By eliminating the data reduction step entirely, testing may be accelerated by a factor of two to three from one to two missions a week to at least five missions a week. The cost savings gained by eliminating the data reduction step is not a factor, the time savings is.

There is an intermediate level of comparison between full data reduction of onboard movie film and no reduction at all that is worth mentioning. The authors have frequently been in situations where no data reduction system is available (or one can assume that the GADS or another system being used has broken down), and yet testing must go on. But at the same time, store separation motion is of concern to the engineer, and some hard data is needed to compare with predictions. In such a case, the film is commonly projected frame by frame on an appropriate blank piece of paper. The pylon and store are sketched in the captive carriage position as references. Then the film is simply advanced a specific number of frames (a stop action projector in conjunction with time-coded film is always used) and by tracing around the projected store image, the store is sketched in the new position. This process is continued to the extent necessary. When the store is in the captive carriage position it is usually very easy to locate its center of gravity. An important point is that displacement and angular values are always calculated with respect to the initial captive carriage position so a cumulative built-in error is not established. While all of the aforementioned discussion might appear simplistic to the reader, it must be emphasized that this method has been used successfully on innumerable occasions as an expediency when there is no other way to obtain hard data.

Brute Force Testing

In the previous section the authors discussed an approach for continuing testing when actual results do not match predictions. In this section an approach will be discussed for performing testing when no predictions exist at all. However, first some boundaries must be placed on what is defined as brute force testing. In the truest sense of the word, brute force testing would be to perform testing for a previously untested store without any prediction of what might happen. The authors would never perform such brute force testing since it would violate al' of our requirements to maintain high safety of flight criteria What is meant when brute force testing is referred to is the structuring and conduct of testing with a solid foundation based on past experience with similar stores and/or aircraft. The simplest example of "brute force" testing would be a store that is analogous to one that has already been night tested and certified in the aircraft flight manual. Assume that the MK 82 low drag general purpose bomb (LOOP) with conical fins is certified on the A-7 and it is desired to certify the same bomb with retarded fins. They weigh about the same and are approximately the same length. A review of the free-stream aerodynamic characteristics of the two bombs would show that the MK 82 with the retarder fin (Snakeye) closed is slightly less stable than the MK 82 LDGP. Because of the relatively minor aerodynamic, physical, and geometric differences, the two bombs are considered analogous. Accordingly, without the benefit of hard predictions, but with the knowledge of the demonstrated separation characteristics of the MK 82 LDGP bomb, a brute force flight test would be performed for the MK 82 Snakeye.

The way time and money may be saved using the brute force method can best be illustrated with a few examples. During the initial test program of the MK 82 bomb on the A-7, extensive wind tunnel testing was performed using the CTS method, and then trajectories were validated by performing five release missions which cleared the store throughout the desired flight envelope (speed up to 500 knots and dive angles up to 60 degrees). By using the brute force method the MK 82 Snakeye was cleared (with the fins closed) in four missions. Even if time consuming wind tunnel and/or off-line analyses were performed prior to flight testing, it is doubtful that more than two missions would have been cut from the program. In all likelihood, only one mission would have been cut from the program. Between each mission, onboard film was reviewed quantitatively and since actual results matched expectations, testing was continued to a successful conclusion. Next, brute force testing was used to clear the MK 82 Snakeye for releases with the fins open. In this mode, a lanyard is extracted from the band which holds the fins closed and frees the fins to open after stores release. If CTS or grid wind tunnel testing were performed, a model of the store with the fins closed would be used first.

Then, at the appropriate distance corresponding to the desired lanyard length, the tunnel would be shut down and a model with the fins open would be substituted. This is a time consuming and somewhat inaccurate process in that the transition of the fins between closed and fully opened is not tested. The time for this to occur on the real bomb varies with airspeed. At low speeds, the fins open only partially, and at high speeds the fins open fully, with attendant differences in the bomb's drag characteristics. Finally, if the lanyard length is changed, the wind tunnel data is compromised since in the wind tunnel only one lanyard length is normally simulated. For these reasons, it is easier to just go out and flight test (presuming we have experience with the functioning of the MK 82 Snakeye as a result of flight tests on another aircraft). An initial lanyard length is selected to allow the store to fall a safe distance below the aircraft. Sometimes a ground static ejection test is performed for the purpose of defining optimum lanyard lengths. Testing is begun at an aggressive speed since the store would already have been cleared with the fins in the closed mode. During the course of testing, the lanyard length may be adjusted, as needed. This was required during A-7 testing because fin opening at high speeds resulted in a flow disturbance over the aircraft's horizontal tail causing a severe aircraft reaction on the order of +5 to +7 "g"s. Accordingly, the lanyard length was adjusted until this problem was eliminated. To this day the original authors are convinced that this problem would never have been uncovered during wind tunnel testing or during off-line analyses.

Another area in which brute force testing is used almost exclusively is in support of store separation from multiple bomb racks, and from multiple pylons in the ripple release mode. Except in the case of guided stores (e.g., the GBU-8, 10, and 12), practically all unguided Stores (e.g. the MK 82 LOOP, CBU-58, and MK 20) are operationally required to be released in the ripple mode. The reason for this is quite clear one must release a large number of unguided stores, centered on the target to increase the probability of target kill. Ripple release would not be a problem from a store separation standpoint were it not for the fact that, as a general rule, stores are required to be released in the minimum interval possible. Most multiple bomb racks such as the MER-10 and TER-9 can function (that is step from rack station to station) down to intervals as low as 50-70 milliseconds. In addition, most USAF aircraft can step from pylon-to-pylon in 20-30 milliseconds. These are small intervals that have large store separation ramifications. Unfortunately, the original authors do not have confidence in the ability to model rack dynamics and store-to-store interference during ripple release, both of which can significantly affect store separation characteristics. Multiple bomb racks such as the MER- 10 are quite flexible. This flexibility results in different effective ejection forces at each of the six rack stations. On one ground ejection test, six MK 82 inert bombs were ejected from a MER-10 at a low ripple release interval. From high speed photography, individual store ejection velocities were measured. Because of rack flexibility, velocities varied from a maximum of eight feet pa second down to zero (the rack actually bent away from the store, and imparted no ejection force). Static ejection testing provides the force at each station for use in predictions but lack the effect of aerodynamic forces. Unfortunately, the force further varies with the weight of the stores loaded on the rack. The other major area mentioned earlier that causes considerable problems during ripple release is store-to-store interference. It should be readily apparent that when two stores are released from tandem (one behind the other) rack stations (as from a MEA-10), the store released from the forward station disrupts the flowfield (in an unknown way) for the store released from the aft station immediately behind. When A-10 testing was being performed, it was found that stores released from the forward MER-10 stations separated with a strong nose-down pitching motion which caused the stores to translate rapidly aft resulting in nose-to-tail collisions with stores released from the aft MER-10 stations. The aft stores separated with a very mild nose-down pitching motion, and hence, little aft movement in the near field of the aircraft. The difference in the relative drag between the forward aft stores stores to the magnitude of the nose-down pitching motion was directly responsible for the collisions. However, predictions, using the grid method, showed that the aft stores would separate with the same nose-down magnitude as stores released from the forward stations. The reason the aft stores did not pitch nosedown as predicted was due, in our view, to the disturbed airflow caused by the forward separating stores. Using brute force, various combinations of interval and speed were tried and a combination that was acceptable for operational use was never found. That is, the low interval desired could never be successfully achieved at a high release speed. As a result of these tests, the MER-10 was never certified on the A-10. As the reader can see, this can be a significant problem. Because of the unpredictable effects in situations similar to the above, the original authors would tend to rely on the brute force method. Our usual approach is to begin reduced interval testing at the end point condition where stores separation in the single mode has already been demonstrated. For example, on the A-10 safe release of the MK 82 LDGP bomb from the MER-10 was demonstrated at the maximum desired speed of 420 knots in a 60 degree dive in the single mode. Then, at that same speed, releases were performed at progressively reduced intervals until the minimum interval was reached. Had a problem been encountered, airspeed would have been reduced and then testing would have been resumed at the last successful interval. This type of process should be continued until enough data are acquired to formulate a certification recommendation. In the case of the A-10, the authors had a choice of a 420 knot speed (with an interval which was determined to be-too high for operational use) or a lower airspeed (which was also determined to be too low for operational use) with the minimum interval desired. The A-10 operational community did not want to back off from their requirements in terms of needing high speed and low interval and, therefore, as mentioned earlier, the MER-10 was deleted from the aircraft. To show how totally dependent store separation is on the aircraft's flowfield, it may be useful to mention that low interval releases of MK 82 LDGP bombs was demonstrated on the F-15 at speeds up to 700 knots without a single problem!

In addition to releases from an individual multiple bomb rack in the ripple mode, the store separation engineer must also consider possible store-to-store interference when releasing stores from multiple pylon stations. Most tactical aircraft have many pylons and these are normally all loaded with stores which are then released in a predetermined sequence from pylon-to-pylon. The A-10 has eleven pylons, the A-7 and F-16 have six, the F/A-18 has five, and the F-15 has three air-to-ground pylons, so the possibility of store-to-store contact is always present; particularly when stores are loaded and released from multiple bomb racks such as the CVER, MER-10, and TER-9 where shoulder stores are ejected at an approximate angle of 45 degrees from the vertical. It was mentioned in an earlier section that on the A-7, stores released from the aft inboard station of a MER-10 have a strong tendency to translate inboard towards the fuselage. Accordingly, stores released from these stations must be closely monitored. In short, it should be apparent that with thirty-two bombs released in a minimum interval, some store-to-store conduct is likely to occur. The best way to establish the presence or absence of store-to-store contact with specific intervals is by brute force testing. Once a safe interval has been established, then a full-up ripple release test where stores are released from all pylons can be performed as a demonstration. However, there is no need to release, in a case such as that on the A-7 configuration, all thirty-two bombs on every mission.

SECTION VII
TEST STANDARDS

7.1 Introduction

7.2 Store Installation and Separation

7.3 Guns

7.4 Rockets

7.5 Missiles

7.6 Pyrotechnics

7.7 Other Documents

SECTION VII
TEST STANDARDS

7.1 Introduction. This section lists the applicable specifications for each type of aviation ordnance. These are general specifications and will be superseded by any specific specification published for the particular weapon undergoing test. In addition, the deficiency classifications published in NATCINST 5213.3F should be used during technical evaluations to categorize mission specific deficiencies. In some cases, modifications to the Definitions of Part I, II, and III deficiencies will be approved, particularly for ordnance testing where compatibility may be restricted to small test envelopes or where comparison tests are performed on several variations of similar systems. The following specifications are grouped by the type of test or ordnance they are pertinent to.

7.2 Store Installation and Separation

a. MIL-A-8591, Airborne Stores and Associated Suspension Equipment, General Criteria for

b. MIL-B-81006, Bombs Free Fall Demonstration of Dispersion, Requirements for

c. MIL-D-8708, Demonstration Requirements for Airplanes

d. MIL-D-23615, Design and Evaluation of Cartridge Actuated Device

e. MIL-D-81303, Design and Evaluation of Cartridge for Stores Suspension Equipment

f. MIL-I-8671, Installation of Droppable Stores and Associated Release Systems

g. MIL-L-22769, Launcher Weapons Airborne and Associated Equipment, General Specifications for

h. MIL-M-81310, Technical Manuals and Checklists

i. MIL-T-7743, Testing Store Suspension Equipment, General Specifications for

j. MIL-T-18847, Tanks, Fuel, Aircraft Auxiliary, External Design and Installation of

k. SD-24, Specification for Design and Construction of Aircraft Weapon Systems

7.3 Guns. The following specifications should be checked for compliance when testing aircraft gun installations:

a. MIL-A-2550A-2, Ammunition and Special Weapon - General Specifications for

b. MIL-I-8670, Installations of Fixed Guns and Associated Equipment in Naval Aircraft

c. MIL-STD-637, Machine and Automatic Guns and Trainers through 30mm

7.4 Rockets. The following specifications should be checked for compliance when testing aircraft rockets:

a. ML-L-22769, Launcher Weapons, Airborne and Associated Equipment, General Specifications for

b. ML-P-24014, Preclusion of HERO to Ordnance, General Requirements

c. MIL-T-8676, Testing of Aircraft Rocket Launchers

7.5 Missiles. The following specifications apply to tests of aircraft guided missiles and should be tested for compliance:

a. MIL-D-8684, Data and Tests, Engineering Contract Requirements for Air Launched Guided Missile Systems

b. MIL-D-18243, Demonstration of Guided Missile Weapons Systems, General Specifications for

c. MIL-E-25366, Electrical and Electronic Equipment and Systems, Guided Missiles, Installation of, General Specifications for

d. MIL-M-8555, Missile Guided, Design and Construction, General Specifications for

e. MIL-M-8856, Missile Guided, Strength and Rigidity Requirements

f. MIL-S-23069, Safety Requirements, Minimum for Air Launched Guided Missiles

g. MIL-W-8160, Wiring Guided Missiles, Installation of, General Specifications for

7.6 Pyrotechnics. Pyrotechnic devices should be tested against the following specifications:

a. MIL-I-8672, Installation and Test of Aircraft Pyrotechnic Equipment in Aircraft, General Specifications for

b. MIL-R-22449, Requirements (Certification) for Pyrotechnic Items

7.7 Other Documents. Appendix A includes a reasonably complete listing of other documents which apply to the design and testing of aircraft raft and aviation associated equipment.

SECTION VIII
PROJECT MANAGEMENT

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PROJECT MANAGEMENT

8.1 Introduction. Project management and report writing can be the easiest phases of an evaluation if a thorough and well-organized project notebook is maintained. Unfortunately, they are usually the most frustrating and time-consuming items due to missing data, project passdowns, and inadequate planning in assuring mission relation and conclusion statements arc written as part of the daily flight reports. Detailed instructions regarding the requirements of interim reports, quick response reports, and the NAWCAD final report are contained in NAWCINST 5213.3F. This section is devoted to a discussion of project notebook organization and daily or weekly management tools.

8.2 Project Notebook. The project notebook should be used as a day-to-day record of the progress of the project. It is invaluable as an aid to turn over the project to another officer/engineer and during report writing. The format and organization of the notebook may vary, however, the following minimal information is essential.

Background. The background should briefly describe the history of the project up to the beginning of planning at NAWCAD. Pertinent technical information, references, photographs, and personnel cognizant of the test item should be included.

Planning. All detailed information upon which the test plan is based should be recorded in the notebook for future reference and for the information of relieving project managers. This includes any test plans written for previous phases of a multiphase evaluation.

Chronology. The notebook should provide a concise, thorough diary of all occurrences during the project. This will include telephone calls, correspondence, and daily flight reports of findings throughout the test program. The daily night reports should be thorough and have mission relation information and the conclusions of the night crew who actually fly the tests.

Technical Information. Publications, drawings, specifications, films, and other pertinent information generated during the test program should be included in the notebook as a reference for subsequent review.

Results. Though not required, a conclusions section devoted to a categorical listing of outstanding deficiencies will aid immensely in reviewing program status when you get a call from your NAVAIRSYSCOM sponsor. Be sure to also include the viewgraphs, slides, and oral presentation notes prepared during the program to help organize your thoughts and reduce the briefing material preparations required for final oral reports.

8.3 Work Unit Management Information Report. Each week a Work Unit Management Information Report categorized by unique serial number (the last four digits of the job order number) will be received for each project assigned to the department. This report lists the charges against the project by each of the authorized (and possibly unauthorized) cost centers. The printout is issued on Thursday for the charges made the preceding week. Through this report, the project engineer/officer can locate cost centers that are erroneously charging against their project. The report can also be used to monitor the financial health of the project. With weekly financial reports, the project engineer/officer can determine if his funds will last for the whole project, if they are getting the planned amount of work accomplished for the level of expenditure, and if the level of expenditure correlates to the planned time schedule.

8.4 Additional Funding. If, during the course of the project, it becomes necessary to request more money, there are several steps that need to be taken to procure the additional funds. When it becomes obvious that the project will require additional funding, the project engineer/officer should first contact his cognizant engineer at the facility for which he is doing the project (NAVAIRSYSCOM, NAVWPNCEN, PACMISTESTCEN, etc.). In most cases, a telephone conversation will be sufficient to acquire the additional funds; however, occasionally the cognizant engineer will require a formal message or letter request. If the cognizant engineer cannot provide additional funds, work on the project must be stopped until some decision can be made to resolve the funding difficulty. After the increased funding has been agreed upon, there will be a waiting period of 2 to 4 weeks before official notice of additional funding is received. If the funds have not arrived after the normal waiting period, the project engineer/officer should call the Directorate's Budget Analyst to determine if notification has been received. If it has, the analyst can assist in timely processing of the necessary paperwork to expedite processing. Once the funds have arrived and are processed through the Comptroller's Office and Staff, the project engineer/officer can then proceed to complete the project. If the funds have not been received by the Comptroller's Office, then a follow up call to the NAVAIRSYSCOM sponsor will be required.

8.5 Expired Funding. Sometimes, because of delays in the project, it becomes necessary to request an extension to the expiration date of the money. This request is started by contacting the Directorate's Budget Analyst. Requests should be made at least 1 month before the expiration date.

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APPLICABLE DOCUMENTS

The following is a list of documents relating to various aspects of the design of aircraft stores and suspension equipment and to aircraft/store compatibility. The documents are listed for reference. The latest issue available should be utilized.

Military Specifications

1.	DOD-D-1000B	Drawings, Engineering, and Associated List
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5.	MIL-A-8870	Airplane Strength and Rigidity Vibration, Flutter, and Divergence
6.	MIL-A-8870A	Airplane Strength and Rigidity Flutter, Divergence, and other Aeroelastic Instabilities
7.	MIL-A-8871A	Airplane, Tests, Strength and Rigidity Flight and Ground Operations
8.	MIL-A-8892	Airplane Strength and Rigidity, Vibration
9.	MIL-A-8893	Airplane Strength and Rigidity, Sonic Fatigue
10.	MIL-A-22550C	Ammunition, General Specification for
11.	MIL-B-5087B	Bonding, Electrical, and Lighting Protection, for Aerospace Systems
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14.	MIL-C-81511E	Connector, Electrical, Circular, High Density, Quick Disconnect, Environmental Resisting and Accessories, General Specification for

15.	MIL-C-81582B	Connector, Electric, Bayonet Coupling, Umbilical, General Specification for
16.	MIL-C-83125	Cartridge for Cartridge Actuated/Propellant Actuated Devices, General Design Specifications for Military
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23.	MIL-D-23615B	Design and Evaluation of Cartridge Actuated Devices
24.	MIL-D-81303A	Design and Evaluation of Cartridges for Stores Suspension Equipment
25.	MIL-E-5400T	Electronic Equipment, Aerospace, General Specification for
26.	MIL-E-6051D	Electromagnetic Compatibility Requirements, Systems
27.	MIL-E-7080B	Electric Equipment, Aircraft, Selection and Installation of
28.	MIL-E-8189H	Electronic Equipment, Missiles, Boosters and Allied Vehicles (Inactive)
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30.	MIL-F-8785 C	Flying Qualities of Piloted Airplanes
31.	MIL-F- 15733	Filters Radio Interference, General Specification for
32.	MIL-F-83300	Flying Qualities of Piloted V/STOL Aircraft

33.	MIL-G-46858A	Guidance and Control Systems, Missileborne, Remote Control (Command) Guided Missiles, General Specifications for
34.	MIL-H-8501A	Helicopter Flying and Ground Handling Qualities, General Requirements for (AF use MIL-F-83300)
35.	MIL-I-8670A	Installation of Fixed Guns and Associated Equipment in Naval Aircraft
36.	MIL-I-8671C	Installation of Droppable Stores and Associated Release Systems
37.	MIL-I-8672B	Installation and Test of Aircraft Pyrotechnic Equipment in Aircraft, General Specifications for (Asg)
38.	MIL-I-8673	Installation and Testing of Aircraft Flexible Weapons Systems
39.	MIL-I-8677	Installation of Armament Control Systems and Associated Equipment in Naval Aircraft
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44.	MIL-M-8090F	Mobility, Towed Aerospace Ground Equipment, General Requirements for
45.	MIL-M-8555C	Missile, Guided, Design and Construction, General Specification
46.	MIL-M-8856A	Missile, Guided, Strength and Rigidity, General Specification for
47.	MIL-M-9977 G	Manual, Technical and Checklists, Munitions Loading Procedures, Nonnuclear and Nuclear (Aircraft)
48.	MIL-M-81310C	Manual, Technical, Airborne Weapons/Stores Loading (Conventional and Nuclear)

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54.	MIL-R-22449	Requirements (Certification) for Pyrotechnic Items
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71.	MIL-STD-220A	Method of Insertion-Loss Measurement
72.	MIL-STD-320A	Fuze Explosive Component Terminology, Dimensions and Materials
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75.	MIL-STD-454J	Standard General Requirements for Electronic Equipment
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92.	MIL-STD-882B	System Safety Program Requirements
93.	MIL-STD-1289A	Ground Fit and Compatibility Tests of Airborne Stores, Procedure for
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95.	MIL-STD-1319A	Item Characteristics Affecting Transportability and Packaging and Handling Equipment Design
96.	MIL-STD-1374A	Weight and Balance Data Reporting Forms for Aircraft (including rotorcraft)
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99.	MIL-STD-1512	Electroexplosive Subsystems, Electrically Initiated Design Requirements and Test Methods
100.	MIL-STD-1553B	Aircraft Internal Time Division Command/Response Multiplex Data Bus

Naval Air Systems Command

1.	AR-S	Microelectronic Devices Used in Avionics Equipment, Procedures for Selection and Approval of
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5.	AR-34	Failure Classification for Reliability Testing, General Requirements for
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Other Applicable Publications

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6. SD-24 General Specification for Design and Construction of Aircraft Weapon System - Vol I Fixed Wing Aircraft Vol 2 Rotary Wing Aircraft

7. NAVSEA OP-4 Ammunition Afloat

8. MIL-HDBK-235 (Navy) Electromagnetic (Radiated) Environment Considerations for Design and Procurement of Electrical and Electronic Equipment, Subsystems and Systems Part IA

9. NAT-STD-3441 Airborne Stores for Fixed Wing Aircraft and Helicopters, Design of (Edition 4)

10. NAT-STD-3556 Aircraft Stores Ejector Cartridge (Edition 2)

11. NAT-STD-3558 Locations for Aircraft
Electrical Control Connection for Aircraft Stores
(Edition 3)

12. NAT-STD-3575 Aircraft Stores Ejector Racks
(Edition 2)

13. NAT-STD-3605 Compatibility of Mechanical
Fuzing Systems and Arming Devices for
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Aircraft/Stores Compatibility and Pilot Escape
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Command Engineering Design Handbook,
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Electromagnetic Radiation to Ordnance (HERO
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LIST OF ABBREVIATIONS AND ACRONYMS ASSOCIATED WITH TEST AND EVALUATION WORK

A&AEE	Aeroplane and Armament Experimental Establishment
AAB	Aviation Armament Bulletin
AAC	Aviation Armament Change
AAW	Antiair Warfare
ABC	Advanced Blade Concept
ACL	Automatic Carrier Landing
ACLS	Automatic Carrier Landing System
ACM	Air Combat Maneuvering
A/D	Analog to Digital (Converter)
ADI	Attitude Direction Indicator
ADF	Automatic Direction Finder
ADL	Armament Datum Line
ADP	Automatic Data Processing
AEDC	Arnold Engineering Development Center
AF	Audio Frequency
AFB	Airframe Bulletin
AFC	Airframe Change
AFCS	Automatic Flight Control System
AGARD	Advisory Group for Aerospace Research and Development
AGL	Above Ground Level
AGM	Air-to-Ground Missile
AHRS	Attitude Heading Reference System
AIM	Air Intercept Missile
AIMS	Automatic In-Flight Monitor System
AM	Amplitude Modulation
AMCS	Airborne Missile Control System
AMR	Accelerated Model Rig
AMTI	Airborne Moving Target Indicator
AMTT	Airborne Moving Target Track
ANFE	Aircraft Not Fully Equipped
AOA	Angle of Attack
AP	Armor Piercing
APT	Armor Piercing Tracer
APU	Auxiliary Power Unit
ARA	Aircraft Research Association
ASCU	Armament Station Control Unit
ASE	Automatic Stabilization Equipment
ASW	Antisubmarine Warfare
ATCRBS	Air Traffic Control Radar Beacon System
ATDS	Airborne Tactical Data System
ATRAJ	Photogrammetric Data Reduction Program
AVB	Avionics Bulletin
AVC	Avionics Change or Automatic Velocity Correct
AWDS	Automatic Weapons Delivery System
AWHE	Armament Weapons Handling Equipment
BAT	Boresight Acquisition and Track
BDHI	Bearing Director Heading Indicator
BDU	Bomb, Dummy Unit

BIS	Board of Inspection and Survey
BIT	Built-In Test
BITE	Built-In Test Equipment
BLU	Bomb, Live Unit
BSU	Bomb, Stabilizer Unit
BUSS	Buoy Underwater Sound Source
BW	Bandwidth
CAD	Cartridge Actuated Device
CAINS	Carrier Aircraft Inertial Navigation System
CASS	Command Activated Sonobuoy System
CATCC	Carrier Air Traffic Control Center
CBU	Cluster Bomb Unit
CCU	Central Computer Unit
CFD	Computional Fluid Dynamics
CFE	Contractor Furnished Equipment
CG	Center of Gravity
CMD	Countermeasures Devices
CNI	Communications, Navigation, Identification
CODAR	Correlated Detection and Recording
CORDS	Coherent on-Receive Detection System
CORE	Coherent- on- Receive
CPU	Central Processing Unit
CRT	Cathode Ray Tube
CSD	Constant Speed Drive for Generator
CTS	Captive Trajectory System
CVER	Canted Vertical Ejector Rack
CVS	Carrier Suitability
DAMTI	Digital Airborne Moving Target Indication
DARPA	Defense Advanced Research Projects Agency
DASH	Drone Antisubmarine Warfare Helicopter
DBS	Doppler Beam Sharpening
DDD	Detail Data Display
DDI	Digital Display Indicator
DDPS	Digital Data Processing System
DIANE	Digital Integrated Attack Navigation Equipment
DIFAR	Directional Lofar System
DME	Distance Measuring Equipment
DMTI	Digital Moving Target Indication
DOP	Development Options Paper
DR	Dead Reckoning
DRO	Destructive Readout (Computer Memory)
DSB	Double Sideband
DSC	Data Support Center (P-3C)
DT	Developmental Testing
DVARS	Doppler Velocity Altimeter Radar Set
EARS	Enemy Airborne Recognition System
EBR	Ejector Bomb Rack
ECD	Estimated Completion Date
ECM	Electronic Countermeasures
ECP	Engineering Change Proposal
EER	Explosive Echo Ranging (JULIE)

EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMV	Electromagnetic Vulnerability
EPP	Emergency Power Package
FAE	Fuel Air Explosive
FDI	Flight Director Indicator
FDS	Flight Director System
FFAR	Folding Fin Aircraft Rocket
FIM	Fault Isolation Meter
FLIR	Forward Looking Infrared
FLOLS	Fresnel Lens Optical Landing System
FM	Frequency Modulation
FOD	Foreign Object Damage or Foreign Object Debris
FOM	Figure of Merit
FPA	Flight Path Angle
FPS	Frames Per Second or Feet Per Second
FSK	Frequency Shift Key
FTA	Fast Time Analyzer
FTC	Fast Time Constant
FTP	Fly to Point
FW	Force Warfare Aircraft Test Directorate
g	Acceleration (in units of 32 ft/sec2)
GADS	Graphic Attitude Determining System
G&C	Guidance and Control
GCBS	Ground Control Bombing System
GFE	Government Furnished Equipment
GOR	General Operational Requirement
GP	General Purpose
GPS	Global Positioning System
GSE	Ground Support Equipment
HATS	Helicopter Attack System
HART	Hypervelocity Aircraft Rocket, Tactical
HE	High Explosives
HEI	High Explosive Incendiary
HERO	Hazards of Electromagnetic Radiation to Ordnance
HSD	Horizontal Situation Display
HSI	Horizontal Situation Indicator
HUD	Heads-Up Display
HV	High Voltage
IF	Intermediate Frequency
IFF	Identification Friend of Foe
IFM	Influence Function Method
IFPM	In-Flight Performance Monitor
IHAS	Integrated Helicopter Avionics System
IHFAS	Integrated High Frequency Antenna System
ILS	Instrument Landing System
IMMT	Integrated Maintenance Management Team
IMN	Indicated Mach Number
IMS	Inertial Measurement Set
INS	Inertial Navigation System

IP	Initial Point
IR	Infrared
ISD	Initial Search Depth
ISLS	Interrogator Side Lobe Suppression
ITER	Improved Triple Ejector Rack
AIWT	Integrated Weapons Team
JEZEBEL	Passive Underwater Detection
JULIE	Explosive Echo Ranging
KCAS	Knots Calibrated Airspeed
KIAS	Knots Indicated Airspeed
KTAS	Knots True Airspeed
LAAV	Light Attack ASW Vehicle
LABS	Low Altitude Bombing System
LAMPS	Light Airborne Multipurpose Support
LAU	Launcher
LBA	Limits of Basic Airframe
LF	Low Frequency
LGB	Laser Guided Bomb
LLLTV	Low Light Level Television
LOB	Line of Bearing
LODUS	Low Data Rate UHF Satellite
LOFAR	Low Frequency Analysis Recording
LOP	Line of Positipn
LORELI	Long Range-E\cho Location Indicator
LOS	Line-of-Sight
LRU	Line Replaceable Unit
LTB	Lateral Toss Bombing
LTH	Light Turbine Helicopter
MA	Master Arrn
MAD	Magnetic Anomaly Detection
MCS	Mine Countermeasures
MDS	Minimum Discemible Signal
MECH	Mechanical
MER	Multiple Ejector Rack
MF	Medium Frequency
MFD	Multifunction Display
MK	Mark
MI	Moment of Inertia
MOAT	Missile Onboard Aircraft Test
MODEM	Modulator-Demodulator
MPCD	Multipurpose Color Display
MPD	Multipurpose Display
MPH	Miles per hour
MRI	Minimum Release Integral
MSL	Mean Sea Level
MST	Multi-Carriage Bomb Rack Jettison Computer Simulation Technique
MTBF	Mean Time Between Failures
NATOPS	Naval Air Training and Operating Procedures Standardization
NAV/COM	Navigator/Communicator
NNSS	Navy Navigational Satellite System (Transit)

NONSTOP	See TEMPEST
NORO	Nondestructive Readout (computer memory)
NPE	Navy Preliminary Evaluation
N/T	Nose and Tail
NTDS	Naval Tactical Data System
NVG	Night Vision Goggles
NWDS	Navigation Weapon Delivery System
OAC	Office For Aircraft Compatibility
OBC	Onboard Checkout
OR	Operational Requirement
OT	Operational Testing
OTPI	On Top Position Indicator
PAM	Pulse Amplitude Modulation
PARAMP	Parametric Amplifier
PBRA	Practice Bomb Rack Adapter
PCM	Pulse Code Modulation
PCR	Program Change Request
PDAS	Photo Data Analysis
PEP	Peak Envelope Power
POSE	Peculiar Ground Support Equipment
PM	Phase Modulation
PMBR	Practice Multiple Bomb Rack
PPM	Pulse Position Modulation
PRF	Pulse Repetition Frequency
PRO	Projection Readout
QRC	Quick Reaction Capability
RAENEAR	Store Prediction Technique
RAST	Recovery Assist, Secure, and Transverse System
RAT	Ram Air Turbine
RATCC	Radar Air Traffic Control Center
RAWS	Radar Altimeter Warning System
RD	Range Directorate
R&D	Research and Development
RDT&E	Research, Development, Test, and Evaluation
RDY	Ready
REWSON	Reconnaissance, Electronic Warfare, Special Operations, and Naval Intelligence Processing System
RHAW	Radar Horning and Warning
RF	Radio Frequency
RFI	Ready for Issue or Radio Frequency Interference
RENA	Radio Frequency Noise Analyzer
RMS	Resource Management System or Root Mean Square
RPL	Ripple
RSLS	Receiver Side Lobe Suppression
RTB	Returnto Base
SACK	Semiautomatic Checkout Equipment
SAD	Submarine Anomally Detection
SAR	Synthetic Aperture Radar or Search and Rescue
SAS	Stability Augmentation System
SCAC	Submarine Classification Analysis Center

SCNS	Self-Contained Navigational System
SCNS-WP	Self-Contained Navigational System, with Provisions for Short Range Station Keeping
SE	Snakeye or Shielding Effectiveness
SEAM	Sidewinder Expanded Acquisition Mode
SEC	Support Equipment Change
SED	System Effectiveness Demonstration (IHAS)
SEFF	Snakeye Free Fall (unretarded)
SEHD	Snakeye High-Drag (retarded)
SELD	Snakeye Low-Drag (unretarded)
SERET	Snakeye Retarded
SHF	Super High Fre~guency
SIDS	Shrike Improved Display Systems
SIF	Sdecive Identification Feature
SINCO	Autonecics Synthetic Referenced Coherent Radar
SINS	Ship's Inertial Navigation System
SKU	Station-Keeping Unit
SLC	Sonobuoy Launch Container
SLT	Sonobuoy Launch Tube
SMC	Stores Management Computer
SMS	Stores Management System
SOFA	Surveillance of Friendly Aircraft
SONO	Sonobuoy
SOR	Specific Operational Requirement
SOS	Sound Surveillance System
SPARV	Panel Program Calculating Store Forces and Moments
SPL	Source Power Level
SRAB	Short Range Antenna Boresight
SRO	Switch Readout
SRS	Sonobuoy Referencing System
SRSK	Short Range Station Keeping
SRTC	Search Radar Terrain Clearance
SSB	Single Sideband
SSE	Special Support Equipment
SSP	Store Separation Program Code
STBY	Standby
STD	Standard
SUS	Sound Underwater Signals
SUU	Suspension Unit
TA	Terrain Avoidance
TACAMO	Take Charge and Move Out
TACAN	Tactical Air Navigation
TACSATCOM	Tactical Satellite Communication
TCG	Time Code Generator
TCPPI	Time Clearance Plan Position Indicator
TEMP	Test and Evaluation Master Plan
TEMPEST	Secure Communications Radiation Environment
TER	Triple Ejector Rack
TF	Terrain Following
TFD	Tactical Flight Director
TFR	Terrain Following Radar

TGT	Target
TID	Tactical Information Display
TP	Thermally Protected or Target Practice (projectile)
TRN	Train or Terrain Reference Navigation
TSC	Tactical Support Center
TSR	Two Sting Rig
TOR	Tentative Operational Requirement
TWS	Track-While-Scan
UHF	Ultra High Frequency
UHT	Unit Horizontal Tail
UR	Unsatisfactory Report
VAST	Versatile Avionics Shop Test System (AN/USM247)
VER	Vertical Ejector Rack
VORSEP	6 Degree of Freedom Computer Program
WDA	Weapons Delivery Accuracy

PROJECT PLANNING CHECKLIST

1. Upon notification from NAVAIRSYSCOM of program intent:

    a. Begin project notebook.
    b. Contact other personnel/agencies for background and technical information.
    c. Contact other NAVAIRTESTCEN activities which will participate in testing.
    d. Rough out a test matrix.
    e. Request cost estimates from NAVAIRTESTCEN activities.
    f. Input workload management information into CT-30 data base system.
    g. Fill out work unit request and forward to NAVAIRSYSCOM sponsor, including ordnance requirements.
    h. Begin test plan writing.

2. Upon notification of work unit approval:

    a. Submit ordnance requisition.
    b. Request clearance from AIR-530.
    c. Finish writing test plan and have it reviewed to department head level

3. Upon receipt of work unit, funding and clearance message:

    a. Ensure funding documents are forwarded to comptroller's office for assignment of a job order number.
    b. Schedule and present test plan at directorate Test Plan Review Board.

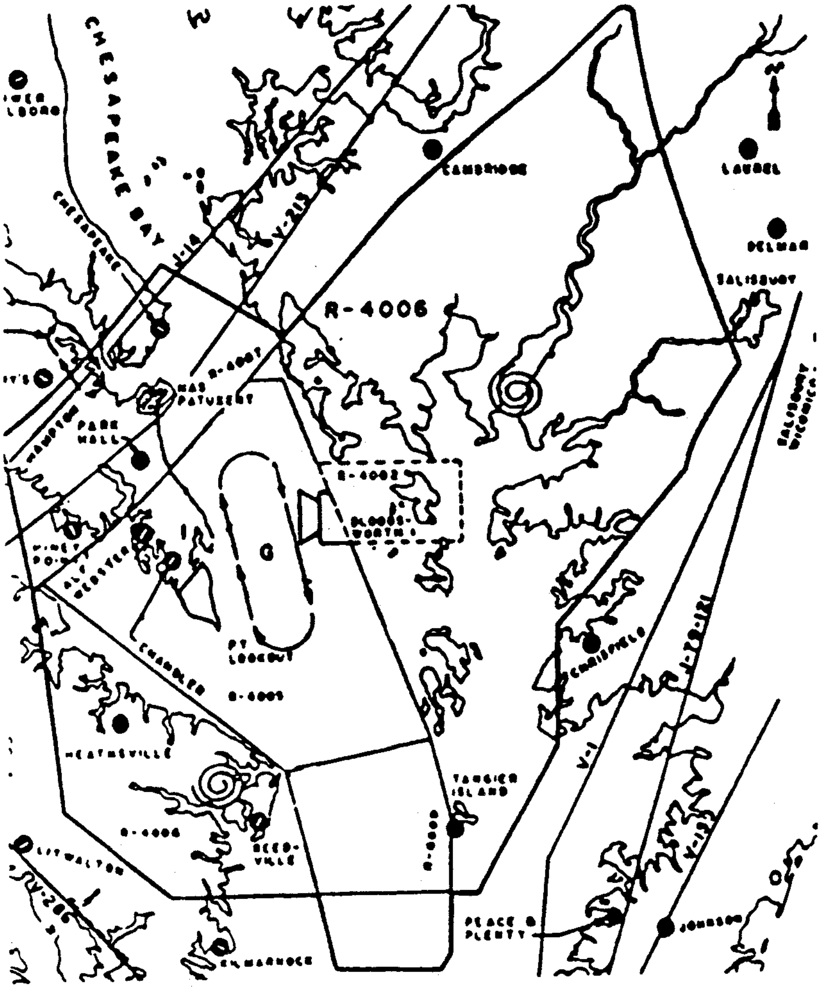
4. Upon test plan approval:

    a. Authorize cost centers to begin work. (1) Install instrumentation. (2) Install project equipment.
    b. Perform ground tests including safety of highs inspection.
    c. Schedule range and chase support.
    d. Conduct night operations/collect daily reports.
    e. Coordinate data reduction.
    f. Publish interim reports.

5. Upon completion of testing:

    a. Publish quicklook message.
    b. Publish final report.

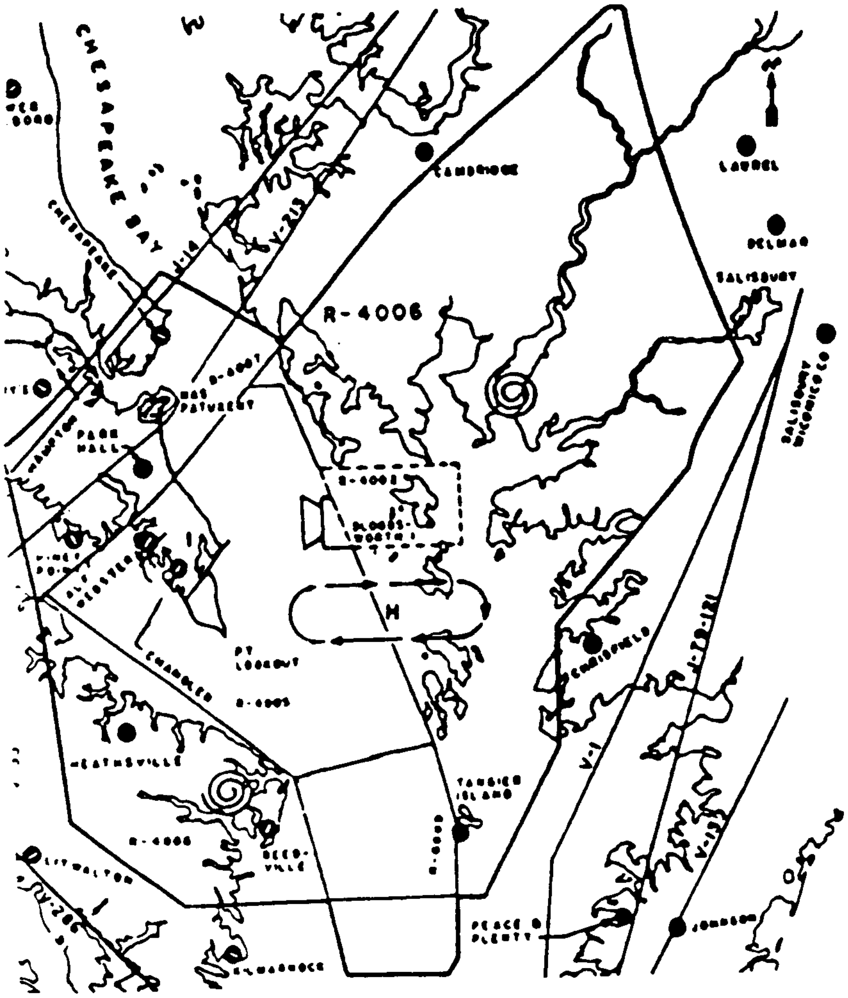
HOOPER



Location:	R-4005N CH 123 R-145/6.1 DME LAT N 3813.0/LONG W 7618.8
Description:	Raft attached to central platform surrounded by four pilings. Bombs on raft only.
Ordnance Allowed:	Inert Bombs
COMM:	Echo Control Freq as assigned by advisory
Run-in HDG:	340 deg T

Figure 1

HANNIBAL



Location:	R-4005S CH 123 R-152/19.1 DME LAT N 3802.4/LONG W 7609.4
Description:	Ship with Buoys 150 yds to NE and SW
Ordnance Allowed:	Inert Bombs, Fammo
COMM:	Request exclusive use with advisory BTN 8/9
Run-in HDG:	As desired, the ship is anchored bow north

Figure 2

CHAPTER 10

NIGHT VISION DEVICES

CHAPTER 10

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CHAPTER 10
NIGHT VISION DEVICES

~~10.1~~10.1 INTRODUCTION

Night Vision Devices (NVDs) fall into two primary categories: image intensifier (I^2) systems, including Night Vision Goggles (NVGs), and thermal imaging systems, including Forward Looking Infrared (FLIR). With the advent of NVD technology, the United States Armed Forces have achieved a significant advantage in warfighting capability. These systems have provided the capability to “see-at-night” and “fight at night” by passively capturing infrared (IR) electromagnetic energy in different spectrums and providing images for viewing, acting as “windows” to see into the night. The Persian Gulf war validated the use of these devices, playing a major role in the rapid defeat of Iraq. U.S. Air Force Major General Buster C. Gloson summed up the importance of NVDs when he said, “always remember that the Gulf war began, was fought and was won at night”. The successful integration of NVDs into an aircraft requires a multi-disciplined, technical effort to maximize sensor performance, human factors and mission utility, while minimizing interference due to internal and external Infrared IR aircraft emissions. Successful Test and Evaluation of an integrated NVD must include the evaluation of each of these performance and interference parameters.

10.2 PURPOSE

This manual will cover the ground and flight-testing techniques currently used to test NVDs and Night Vision Imaging System (NVIS) cockpit compatibility at the U.S. Naval Test Pilot School. The techniques are applicable in the test work done on programs at the Naval Air Warfare Center Aircraft Division (NAWCAD). For the purposes of this chapter, NVDs will refer to any device utilized by aircrew to image terrain for navigation and pilotage at night that are displayed to the aircrew on a helmet or on a Heads Up Display (HUD). NVGs specifically refer to helmet mounted image intensifier systems that operate in the near IR region. Most of the techniques discussed in this chapter apply to NVGs and NVIS cockpit compatibility. Electro-optic NVDs that operate in the mid and far IR region can be tested utilizing some of the techniques described in this chapter along techniques described in Chapter 7, ELECTRO-OPTIC SYSTEM TESTING. Systems that employ sensor fusion of near and either mid or far IR may need to conduct a combination of both ELECTRO-OPTIC SYSTEM TESTING and NIGHT VISION DEVICE TESTING.

~~10.3~~10.3 THEORY

~~10.3.1~~10.3.1 IMAGE INTENSIFIER THEORY

Image Intensifiers, or I^2 tubes, provide light amplification by intensifying the existing light and displaying that scene for the user. Although the intensification process results in considerable amplification of the existing scene brightness, the quality of the NVG image degrades as the ambient light level decreases. Therefore, most NVGs are limited to operation at or above overcast starlight conditions.

Figure 1 depicts the spectrum of energy associated with moonlight and starlight and the relative spectral reflectivity of vegetation and cloth. One important aspect of this figure is that starlight has more energy in the Near IR portion of the spectrum than it does in the visible portion of the spectrum. Another important fact is that both vegetation and cloth are better reflectors of Near IR energy than of visible energy. Both of these factors were considered in the early NVG design efforts. The result is a system that operates primarily in the visible to Near IR spectrum.

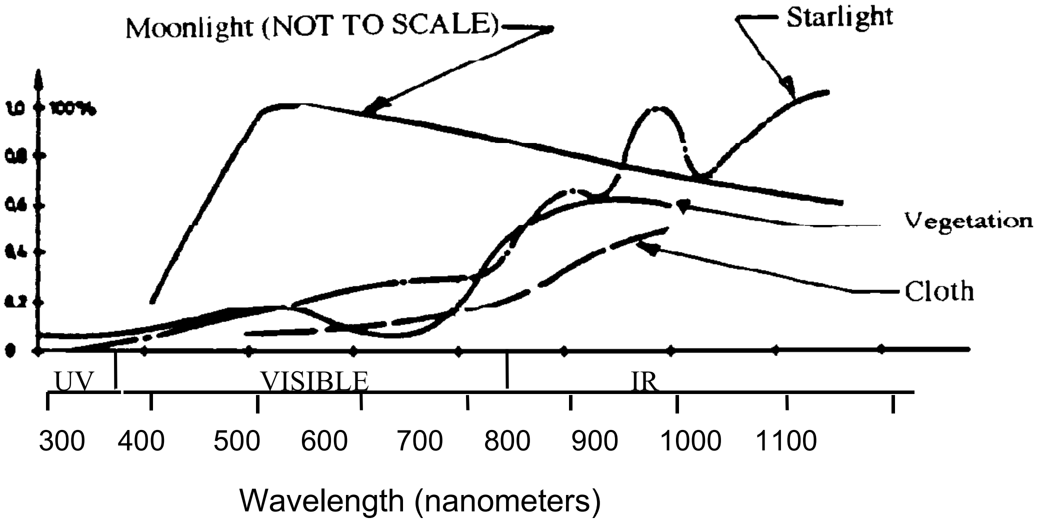

Figure 4

Night Sky Spectral Energy & Selected Spectral Reflections

The modern I^2 tube used for military applications is the Generation (Gen) III I^2 Tube. Figure 2 depicts the four basic components of the Gen III I^2 tubes. The first component is the Gallium Arsenide (GaAs) photocathode which produces photoelectrons when struck by visible and Near IR photons from the scene. The photoelectrons are then accelerated into the second component, the Micro Channel Plate (MCP), which contains millions of channels lined with ion charged lead that release thousands of electrons for every incident photoelectron from the photocathode. Following the primary intensification in the MCP, the resultant electrons are accelerated through a voltage to, the third component, the phosphor screen. The I^2 phosphor screen works just like the phosphor in a TV screen. Incident electrons interact with the phosphor, which then releases visible energy. Most I^2 tubes use P-22 or P-43 phosphor resulting in a monochrome green output. The fourth component prepares the image for viewing.

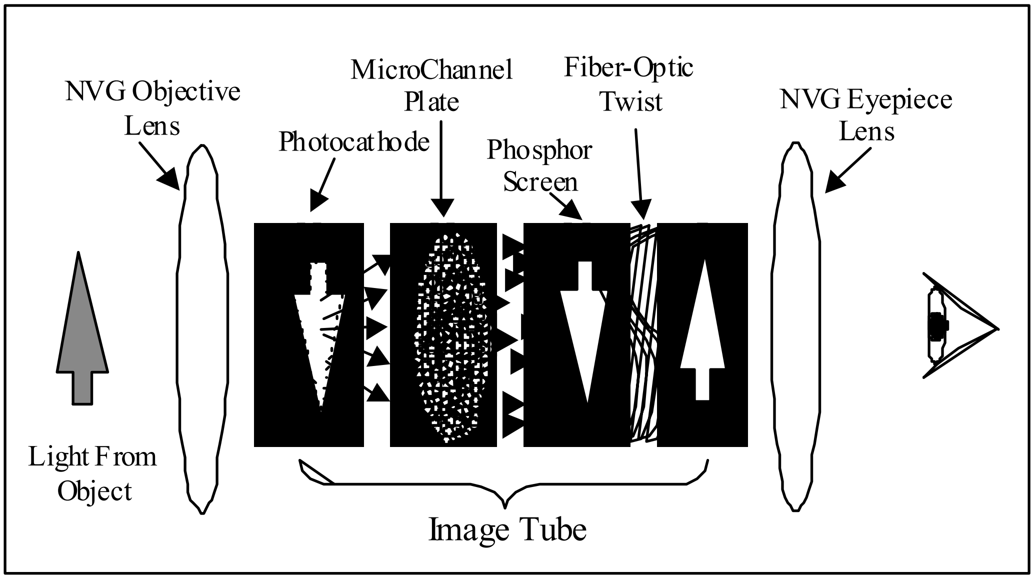

Figure 5

Illustration of Image Intensifier Tube

Figure 3 pictorially shows the two basic types of NVGs. Type I, direct view or Anvis style, NVGs employ a fiber optic twist, which rotates the image 180 degrees to prepare the image for viewing. Type II, combiner type or Cats Eyes style, NVGs use combiner optics to rotate the aided image and combine with the unaided image to produce a superimposed image for viewing.

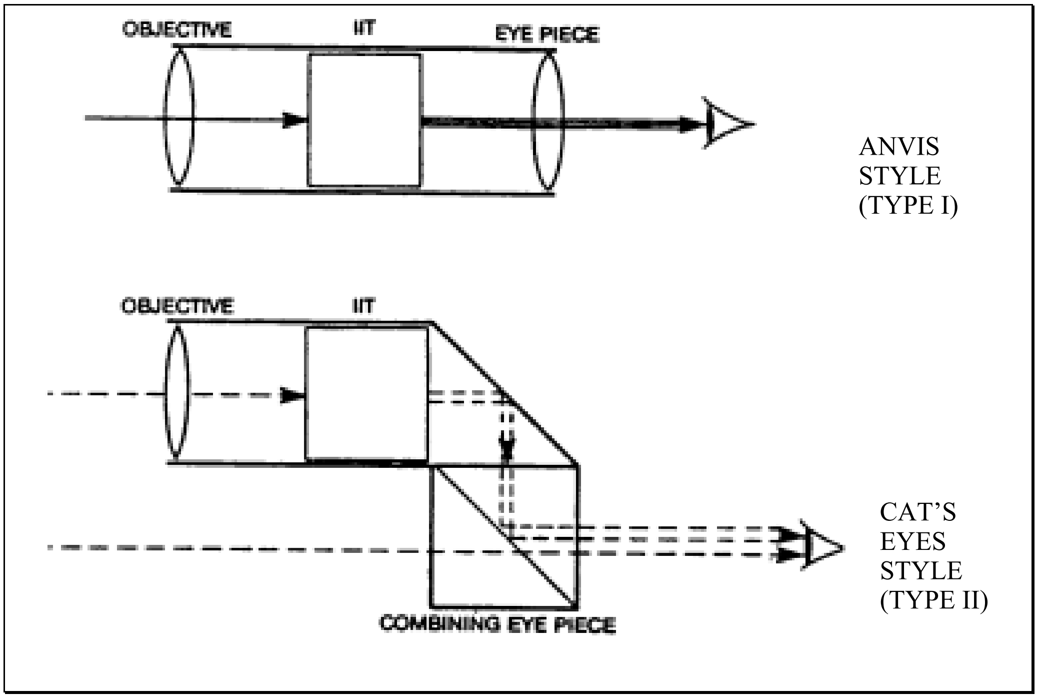

Figure 6

Direct View (ANVIS) & Combiner Type (Cats Eyes) NVGs

10.3.2 NIGHT VISION IMAGING SYSTEM (NVIS) LIGHTING COMPATIBILITY

In order to fly with light image intensifier sensors mounted on the helmet, the aircraft cockpit lighting must be compatible with and not adversely affect NVG performance. Modern Gen III light intensifier devices are sensitive to electromagnetic energy from the 500 to 900 nanometer wavelengths, which includes much of the visible light spectrum (380 -760 nanometers). Therefore, lighting in the cockpit in this region can adversely affect the performance of the goggles. The NVG response is similar to the way the human eye responds with too much interior light inside a car while driving at night. The incompatibility reduces the gains of the intensifier tubes, severely degrading the NVG performance.

In 1986, a joint military specification, MIL-L-85762, "Lighting, Aircraft, Interior, Night Vision Imaging Compatible," was approved to resolve cockpit lighting problems and provide performance requirements and testing methodology to ensure effective and standardized aircraft interior lighting. In order to resolve compatibility issues with minimal performance effects, both the aircraft and the NVGs are required to meet the standards of MIL-L-85762.

To develop a NVIS compatible aircraft cockpit, engineering compromises are made to both the crew station and to the image intensifiers to optimize performance. NVIS compatibility is partially achieved by incorporating a filter in front of the NVG objective lens. The spectrum response of the typical Gen III image intensifiers and the three types of NVG filters, (Class A, Class B, and Leaky Green) are shown in figure 4. The Class A filter allows all the Near IR energy into the NVG while blocking most of the visible spectrum below 625nm. This means that a cockpit with properly filtered blue and green lights will not interfere with the operation of the NVG. Most military rotary wing platforms use Class A NVGs and blue-green cockpit lighting. NVG manufacturers responded to the requirement for color displays in the cockpit by developing Class B filtered NVGs. The Class B NVG allows all the Near IR energy to reach the photocathode while blocking most of the visible energy below 665nm. This allows properly filtered yellow and red sources to be part of the cockpit without causing degradation to NVG performance. Most TACAIR platforms use Class B NVGs. Class A and Class B filters are sometimes commonly referred to as “minus-blue” filters. The final NVG filter is known as the Leaky Green Filter. While the Leaky Green Filter mimics the bulk of the Class B response, it was designed to allow some of the energy from the Heads Up Display (HUD) to pass through the NVG for viewing by the aircrew. This was accomplished with a small notch in the green part of the spectrum around 550nm. Prior to the development of the leaky green filter, most TACAIR platforms were limited to the use of combiner type NVGs. Combiner devices (like Cats Eyes) allowed the aircrew to view the intensified outside scene overlaid onto the direct view of the HUD through the combiner lens. The use of a leaky green filter removes the requirement for combiner optics and decreases the overall complexity of NVGs used in HUD equipped aircraft. Understanding the filtering associated with each NVG is critical to understanding any problems that may arise during testing.

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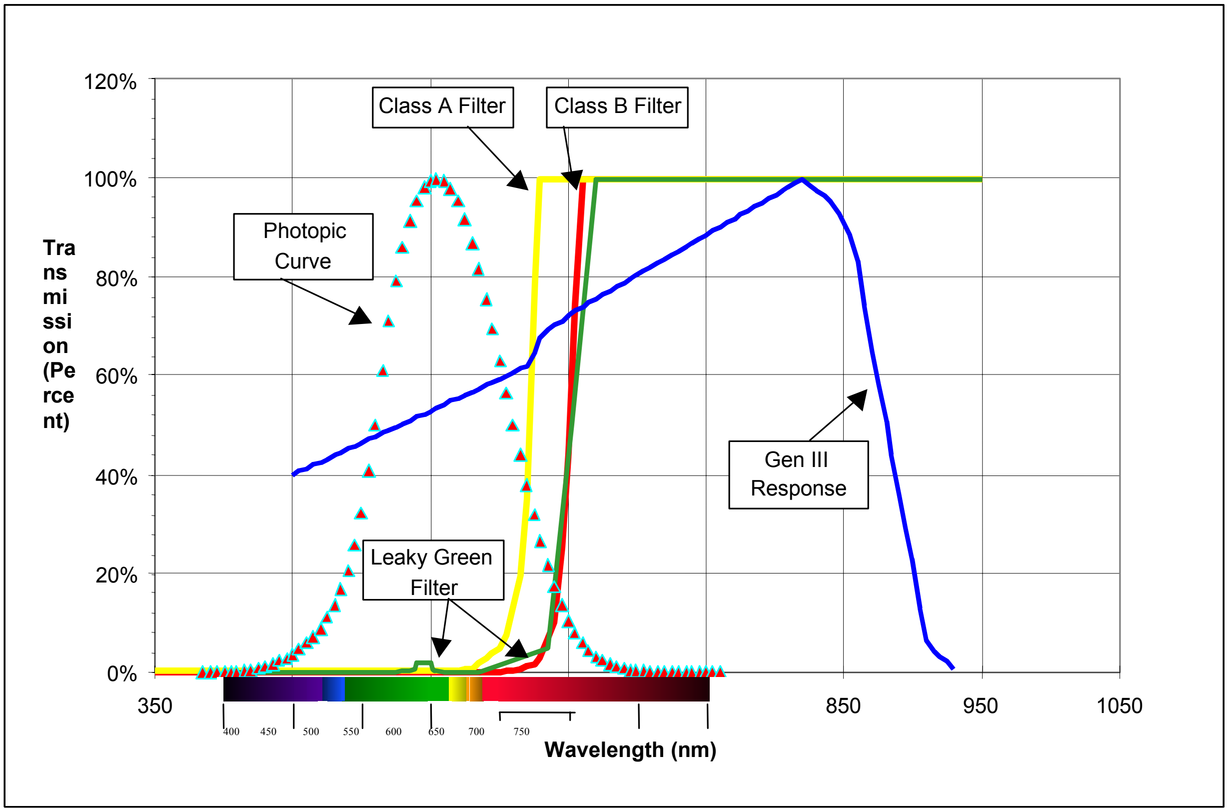

Figure 4

Photopic and NVG Related Spectrum

By itself, NVG filtering can not mitigate the interference from a standard cockpit lighting group. As shown in Figure 4 all visible light is not filtered from the NVGs; therefore, cockpit lighting requires filtering. Compatible cockpit lighting should not be viewable through the NVGs. Since most incandescent and some LED lights emit significant near IR energy, these devices must be filtered to remove as much of the offending near IR energy as possible. A perfect cockpit would be one where the lights in the cockpit are invisible through the NVG, but could be placed at a reasonable intensity so that they could be easily viewed while looking under the NVG.

MIL-L-STD-85762 goes into great detail to describe the requirements for designing and testing a NVIS compatible cockpit, including lights, displays, legibility, readability, luminance, illuminance, chromaticity, and reflections. Brief definitions of the terms used extensively in the specification are provided to better understand the specification requirements.

During NVIS laboratory and ground testing, light is measured using either a spectroradiometer or photometer. Photometric measurements are in line with the response of the eye. Therefore, two different color sources with the same output in photometric units will appear to be similar in brightness. Radiometric units are an absolute measure of brightness. Luminous flux is the amount of light flowing through a given area in a given time, expressed in lumens (lm) for photometric measurements and Watts (W) for radiometric measurements. The relationship between lumens and Watts as a function of wavelength, which is based on the average response of the human eye, is shown in figure 5.

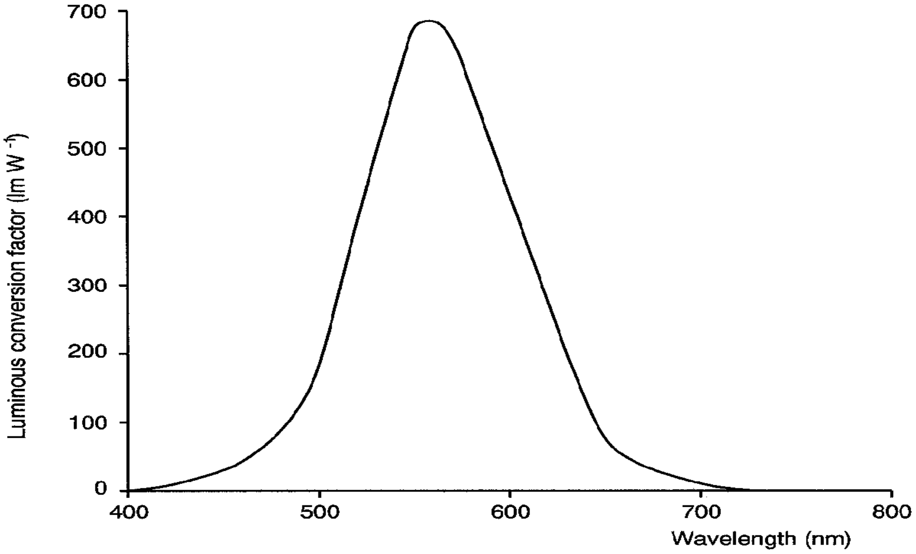

Figure 5

The Relationship between Lumens and Watts as a Function of Wavelength

Illumination is the amount of light that is received by a given surface area, not the amount reflected or being emitted. Illumination is expressed in lux, which is lumens per square meter or in foot-candles, which is lumens per square foot. Irradiance is the radiometric term for illumination, which is expressed in Watts per square meter. Light intensity from a point source is defined in lumens per steradian (sr), which is also known as candela (cd), or Watts per steradian. Since the light from the point source diverges so does the flux as it fills the same angular spread instead of the same area. The steradian is the solid three-dimensional angle where the subtended area of a sphere's surface is equal to the radius squared. The term luminance in photometric terms (candela per square meter) and radiance in radiometric terms (Watts per steradian per meter squared), account for the distance the light source travels. Another photometric term for luminance is foot-lamberts (fL) which is candelas per square foot. NVIS radiance accounts for the spectral response of the light source in relation to the response of the Night Vision Goggles. NVIS Radiance is a radiance measurement weighted to the response of the NVG. In this respect NVIS Radiance is similar to Luminance in that luminance is a measure of electromagnetic energy weighted by the response of the human eye. Since a high power infrared source will be invisible while a low power green source will be easily seen by a human observer, luminance measurements are required to determine how bright an object will appear to the human eye. Likewise, NVIS Radiance measurements are used to determine how bright a source will appear when viewed through a Night Vision Goggle. And, since there are two basic filter types for NVGs, MIL-L-85762A describes both Class A NVIS Radiance and Class B NVIS Radiance. (Do not confuse NVIS Radiance – i.e., NVG weighted radiance - with standard radiance which is an absolute measure of the total energy emitted from a source.

10.4 NIGHT VISION GOGGLE AND NVIS LIGHTING TEST METHODS AND TECHNIQUES

Night Vision Goggle performance in the presence of NVIS Cockpit lighting is evaluated in three successive phases. Phase I is the laboratory testing of both the NVGs and the individual displays and cockpit lights. Phase II is ground testing which brings the NVGs together with the displays/lights in the applicable aircraft. And, Phase III is flight testing which is designed to evaluate benefits and limitations associated with the operation of the NVGs and lighting in the mission environment. The primary items to be evaluated are NVG performance, NVIS lighting performance, associated human factors characteristics, and mission utility. The Test and Evaluation program at the U.S. Navy Test Pilot School generally focuses on the Phase III flight test activities and qualitatively incorporates the same aspects of Phase I and Phase II during pre-flight and ground evaluation. When a new night vision device or a new cockpit display is introduced, all three phases – laboratory, ground, and flight-testing are accomplished to ensure the safety-of-flight for the new aircraft configuration. Before flight-testing is conducted, ejection capability, windburst protection, and laser eye protection are evaluated in separate laboratory facilities.

The goal of a NVD test program is to evaluate the NVD aided and unaided mission suitability and total system performance including NVD and cockpit lighting under a full range of ambient lighting conditions.

The sections that follow describe each test phase with emphasis on Phase III flight-testing.

10.4.1 PHASE I - LABORATORY TESTING

10.4.1.1 NIGHT VISION GOGGLE LABORATORY TESTING

Prior to ground and flight testing, every new Night Vision Goggle is subjected to a battery of laboratory tests designed to document each major performance characteristic. NAWCAD NVG testing is performed in the Night Vision Device and Cockpit Displays. Laboratory is configured to evaluate Night Vision Goggle Performance in the areas of:

- Field-of-View – including evaluations of exit pupil and eye relief
- Resolution – peak resolution and resolution as a function of light level
- Gain – as a function of light level
- Spectral Response – versus wavelength of energy from Ultraviolet to Near IR
- Current Draw – maximum current required from the batteries
- Weight – component and system level.

Each characteristic is compared to the manufacturer's specifications in order to determine specification compliance. Analysis is performed using historical data to determine areas of improvement and/or degradation between existing NVGs and the current NVG under evaluation.

10.4.1.2 COCKPIT DISPLAY LABORATORY TESTING

Whenever possible new transparencies, displays, filters, and light elements are evaluated in the NAWCAD Transparencies and Cockpit Lighting Laboratory of the Human Engineering Applications Branch. This laboratory is configured to evaluate display, filter, and transparency (windscreen/canopy) performance in the areas of:

- Luminance – including peak & minimum luminance, as well as luminance uniformity
- NVIS Radiance– per MIL-L-85762A (energy "seen" by the NVG)
- Colorimetry – specification compliance for color as well as display uniformity
- Contrast – as a function of display brightness
- Daylight Readability – a measure of the ability to use the display in daylight
- Filter Transmissivity – characterizing both display and lighting filter transmission
- Transparency Transmissivity – characterizing the photopic and Near IR transmission.

As was the case with the NVG laboratory evaluations, each display/transparency characteristic is compared to the manufacturer's specifications in order to determine specification compliance. Analysis is performed using historical data to determine areas of improvement and/or degradation between existing items and the current item under test.

10.4.2 PHASE II - GROUND TESTING

Prior to the issuance of a flight clearance for any new Night Vision Goggle or NVIS Cockpit display the ground and flight-testing is conducted. Although the primary emphasis of the U.S. Navy Test Pilot School has been toward NVG and display flight testing, several aircrew from the Test Pilot School have participated in formal NAWCAD night vision ground testing. Paragraph 10.4.2.1 describes the NVG portion of the ground test and 10.4.2.2 describes the cockpit displays and transparencies portion of the ground test.

10.4.2.1 NIGHT VISION GOGGLE GROUND TESTING

Prior to flight testing, every new Night Vision Goggle undergoes ground testing designed to evaluate the performance of the NVG in the applicable cockpit environment. NAWCAD NVG ground testing is performed in the Aircraft Test and Evaluation Facility (ATEF) using personnel and equipment from the Night Vision Device and Cockpit Displays Laboratory as well as the Transparency and Lighting Laboratory. ATEF provides a light-tight hangar environment with a controllable ambient light level. This is accomplished with a night sky simulation system, which allows resolution targets to be set at representative levels between overcast starlight and full moon conditions while the cockpit is subjected to light levels that simulate the night environment.

Aircrew and engineers participate in the ground test phase, which normally includes:

- Familiarization – including display functions and new NVG configurations
- Instrument/Display Scan – through the NVGs to determine obvious problem areas
- Reflection Scan – viewing the transparencies (canopy/windscreen) to determine where reflections are most prevalent
- Display/Instrument Readability Assessment – when viewed under the NVGs or through the NVGs in the case of HUD evaluations
- Night Adaptation Impact – evaluating the ability to night adapt in the NVG environment
- Bar Chart Resolution – evaluating the limiting factors affecting visual acuity of the aircrew while viewing the resolution test chart within the cockpit environment.

With the exception of the Bar Chart Resolution Tests, the other NVG ground test items listed above are self-explanatory. The following paragraph describes bar chart testing and the data reduction associated with the ground test results.

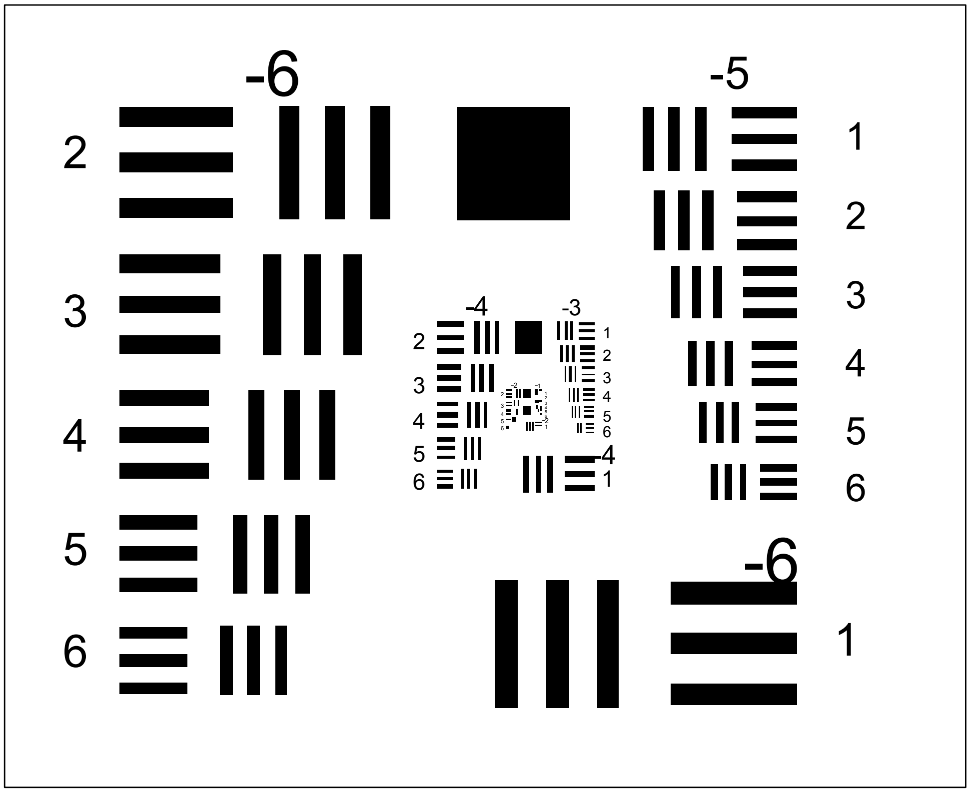

Figure 6

USAF 1951 Resolution Test Target

Figure 6 shows the USAF 1951 Resolution Test Target. This target is often called the “tri-bar” target due to the fact that each element within the chart includes three horizontal and three vertical bars. The Group number is located at the top of each block of elements and the element number is located on the side. Each element in each group has a specific bar separation distance allowing the test team to calculate minimum angular resolution for a specific set of NVGs in a specific environment. The process includes taking a baseline measurement (from a known distance) outside the cockpit at each known ambient light level. For each measurement the test team looks for the smallest element on the bar chart which can be resolved. Resolving an element means that the test personnel can see the separation between each of the vertical and horizontal bars in that test element.

Once a resolution measurement has been taken, it is necessary to perform several calculations in order to determine the angular performance of the NVG as well as the effective visual acuity of the aircrew using NVGs in that environment. Effective visual acuity is like normal human visual acuity (i.e., 20/20, 20/40, etc) except that effective visual acuity is measured through the NVG. (Note that the calculations to follow require a precise measurement of the distance between the observer and the resolution test target).

NVG resolution is usually expressed in cycles per milliradian (cy/mr). The resolution calculations start at the bar chart where each element represents a resolution measured in line-pair per millimeter (lp/mm) and calculated as follows:

$$R = 2^{(G+((E-1)\ /\ 6))}$$

R = Chart resolution in lp/mm
G = Minimum resolvable Group number
E = Minimum resolvable Element number

Then resolution at the NVG in units of cycle per milliradian can be calculated as follows:

$$Sr = (R * D)$$

Sr = NVG System resolution in cy/mr
R = Chart resolution in lp/mm
D = Distance from NVG to chart (meters)

Finally, system resolution can be converted to effective visual acuity using the following equation:

$$VA = 34.384\ /\ Sr$$

VA = Human equivalent Acuity denominator (i.e. 20/VA)
Sr = System Resolution in cy/mr

The effective visual acuity for each display/lighting configuration should be compared against the baseline visual acuity (taken outside the aircraft) to determine whether or not the cockpit lighting degrades the performance of the NVG.

Any problems identified during the ground tests should be compiled and evaluated to determine if any safety of flight issues need to be solved before proceeding to the flight test phase. Any key issues noted during the ground tests should be identified for further evaluation during the flight test phase.

The following tests are required during ground testing:

- Windscreen transmissivity – various angles, spectral measurement
- HUD Transmissivity – where required
- Display NVIS Radiance – as a function of wavelength
- Display & HUD absolute luminance – for each color and the background
- Spectral radiance – measurements of each type of indicator
- Daylight Readability – for each display/instrument.

10.4.2.2 QUALITATIVE GROUND TESTING OF NIGHT VISION GOGGLES

Qualitative Ground testing of NVGs and NVIS cockpit compatibility should be conducted in the aircraft prior to flight. An initial familiarization should be conducted in a dark area of the field in order to acquaint the evaluator with the system under test in the aircraft with engines running, lights out, and wearing full survival equipment. Human factors assessment, lighting compatibility, windscreen/canopy field-of-view, and field of regard testing provide a natural build up prior to flight test.

Human factors assessments should include adjustment capability, neck strain, image quality, and capability to don and remove the goggles. Qualitatively, if the NVGs bloom or respond to a light then that light is not compatible. Assessment lighting compatibility tests should be similar to the laboratory evaluation.

Measurements of canopy and windscreen compatibility should be measured from each crew station at direct and oblique angles, mapping the entire canopy. Qualitative evaluations should include a ground test with the canopy open and closed to observe any degraded performance

Like most Electro-Optic systems, two very important parameters of Night Vision Goggles are Field of View (FOV) and Field of Regard (FOR). The aided FOV of the NVGs is defined as the angular measurement in degrees of the intensified image seen from the optimum focal point. The unaided FOV is defined as the area of vision other than the intensified image with the NVGs mounted. Field of Regard is a less obvious concept, but realizing that NVGs are sensors much like a FLIR system, FOR is the area usually depicted on a rectilinear plot where one can rotate the head and view the helmet mounted intensified image. The difference between aided FOR and unaided is where the NVGs (head) can rotate and the eyes can look around in the unobstructed FOV. During ground and flight testing the FOV can be estimated using known cockpit angular measurements. Field of Regard can only be measured in the aircraft with flight gear and restraining devices on. This will vary with neck flexibility of each aircrew. The effective FOR should account for torso and head movement, and take into consideration any restrictions preventing full head movement with NVDs mounted on the helmet

In a perfect world, display ground testing in the aircraft would be primarily used to ensure that the laboratory results are equivalent to the results obtained when the display is integrated into the aircraft. However, laboratory testing can not always be accomplished, and therefore, in-aircraft measurements must be taken to ensure that the cockpit is in compliance with the design specification. Any problem areas found during ground testing should be identified for further evaluation during the flight tests.

10.4.3 PHASE III - FLIGHT TESTING

Night Vision Goggle flight testing at the U.S. Navy Test Pilot School and NAWCAD are similar and usually result in qualitative evaluations of system performance. As with most flight test programs there are work-ups associated with NVG flight testing. In general high ambient lighting flights are flown before low ambient lighting flights. Flight paths are chosen so that flat terrain is present before mountainous terrain, and high altitude evaluations are performed prior to the low altitude evaluations. A typical NVG related flight test program will include: high altitude cruise, Air-To-Air assessments, low-level navigation, Air-To-Ground assessments, and section maneuvering. During each portion of the night-vision-related flight test the aircrew should evaluate the applicable items from the following list of critical performance issues:

- Pre-flight/sensor performance – ensure system under test is suitable and consistent
- Human factors – NVG comfort, usable field-of-view, ease of operation
- Sensor performance – ability to detect and identify a target at various light levels or with various cockpit configurations
- Display/HUD usability – the ability of the aircrew to read displays/HUDs in any desired mode while using the NVGs
- Warning/Caution Compatibility – is aircrew attention properly drawn to the warning indicator when NVGs are in use
- Fault detectors
- External Lighting Considerations – is the external lighting adequate for formation flight and does the standard lighting interfere with the operation of the NVGs
- Cockpit performance when NVGs are not in use – ability to use the cockpit during daylight operations and unaided night operations
- Overall Mission Utility – how does this system affect the aircrew's ability to successfully complete the mission.

The following sections describe how the critical performance issues should be evaluated during each flight profile.

10.4.3.1 NVG SPECIFIC PRE-FLIGHT REQUIREMENTS

Prior to any NVG related flight, test aircrew should don the NVGs in a proper environment and ensure that the device is properly focused and that the device performance meets the minimum requirements for safe flight. Although summarized below, the operator's manuals should be used to ensure proper NVG focus and operation prior to each flight.

10.4.3.1.1 FOCUS

Every NVG should be focused in a dark room using either a standard EyeLane or an ANV-20/20 Infinity Focus device. Due to the fact that an eyelane will not establish a proper infinity focus, the use of the eyelane during pre-flight focus adjustments will require the aircrew to re-focus the objective lenses (lenses at the front of the NVG) once a suitable object, at least 100 feet away, can be found. Adjust the NVGs one eye at a time by focusing both (where applicable) the objective and eyepiece lenses. The eyelane and ANV-20/20 both contain a resolution chart which can be used to determine how well the NVGs are focused. The focus process is completed when additional movements of the lens positions do not improve the focus enough to allow the viewing of the next smaller resolution pattern. (In the case of the ANV-20/20 the next smaller resolution pattern is actually not smaller in total area, only the lines are closer together).

10.4.3.1.2 ENSURING PROPER OPERATION

Once the NVG is correctly focused the aircrew should look for image problems. The operator's manuals define the basic areas of concern and provide diagrams to aid in the identification of which type of image problem exists. In general, there should be no areas of the image which are significantly brighter than other areas and no areas which are dimmer. There should be no bright spots, no dark spots and the images from each monocular should overlay each other closely enough that any misalignment is hard to notice.

Once the NVG specific pre-flight has been accomplished, no further adjustments should be made to the eyepiece lenses on the NVGs, except for adjusting the objective lenses to infinity focus.

10.4.3.2 HUMAN FACTORS

Testing NVGs can be more complicated than other airborne systems because the devices are mounted in front of the eyes and essentially become windows into the dark. The human eyes have a limited ability to adapt to variations in the presentation of an image as compared to a naked eye image. Vibration, jitter, resolution, image quality, and field-of-view, all affect the aircrew's ability to perform mission tasks effectively and safely. Human factors concerns such as comfort, fit, strain, and fatigue should also be assessed.

10.4.3.2.1 PURPOSE AND METHOD

Human factors parameters should be evaluated during laboratory and ground testing. The flight environment, including acceleration and airspeed effects, offers the opportunity to evaluate the human issues associated with mission use of the NVGs and cockpit lighting systems. Where applicable, flight tests should include the evaluation of the following human factors concerns:

- Comfort and fit
- Adjustment capability

- Neck strain and fatigue
- Effects of Eye movements
- Eye fatigue
- Image quality effects on NVG use /including acceleration and airspeed effects
- Capability to quickly don and remove goggles
- Depth Perception
- Field-of-View/ Field-of-Regard

10.4.3.2.2 DATA REQUIRED

Any physiological or human factors issues listed above associated with the human factors concerns listed above.

10.4.3.3 TARGET DETECTION AND IDENTIFICATION

Flight tests involving quantitative measurements of NVG resolution are complicated to design and execute. Flight tests in helicopters can be conducted against enlarged resolution boards. The tests resemble the ground ATEF tests described in 10.4.2.1 and FLIR EOTT resolution runs in chapter seven. The vast majority of NVG related flight testing centers on the broader performance parameter of target detection and identification. Target detection and identification is not only a function of NVG resolution, but of NVG gain, Signal-to-Noise ratio, image quality and non-NVG items such as windscreen transmission and ambient light level. An excellent reference to relate resolution to target detection and identification is Johnson's "Analysis of Image Forming Systems". The following paragraphs describe the process associated with measuring target detection and identification during the NVG flight evaluation.

10.4.3.3.1 PURPOSE AND METHOD

Target detection and target identification tests directly quantify the performance of a system. The target detection and identification tests associated with Night Vision Goggle systems are consistent with the definitions used in paragraph 7.4.16.1. As described in paragraph 7.4.16.1 and specific to NVG evaluations, detection range is the range at which the operator can positively discern the presence of a target while using the NVGs. This usually requires the operator to have sufficient confidence that the target is present and that a course correction can be made toward the target. Identification range is the range at which the operator can determine whether or not the target is friend or foe (i.e., the range required to be positive enough to commit a weapon). Flight tests should be conducted using known targets under known ambient lighting conditions to measure detection and identification ranges.

10.4.3.3.2 DATA REQUIRED

- Target Type, Orientation
- Target Lighting
- Ambient Light Level
- Range for Detection
- Range for Identification

- Cockpit Lighting Levels & Display Modes
- Orientation of Aircraft at Time of Detection (used to determine which transparency – canopy, HUD, quarter panel, was between the aircrew and the target)

10.4.3.3.3 DATA REDUCTION

Comparisons should be made between existing systems and the new system using the applicable detection and identification ranges for both devices. For a comparison to be valid, a ll aspects of the test, including light levels and displays modes, should be identical for both devices under test.

10.4.3.4 DISPLAY USABILITY

10.4.3.4.1 PURPOSE AND METHOD

There are three issues associated with display usability relative to the use of Night Vision Goggles. First is the issue of readability – can the display be used in a specific environment? Second is interference with the NVG – does the display degrade the NVG image? And third reflections - does the display cause reflections which obscure the scene or otherwise interfere with the aircrew's ability to complete a mission?

In each flight environment (including daylight and unaided night), the aircrew should evaluate whether or not the information on the display can be read when viewed directly, during day and unaided night flight, or when viewed under the NVG during NVG aided night flights. Mission representative profiles should be run during a full spectrum of lighting conditions.

NVG interference should be evaluated with the display set at a usable level for the ambient conditions. NVG interference can fall into three broad categories. The first is "de-gain" which is a reduction in scene contrast caused by a bright source in the field-of-view. When a bright source is viewed through the NVG a protective circuit, called the auto-brilliance control, limits the voltage to the image tube MCP and effectively reduces the gain. This results in a darkening of the desired scene in order to protect the image tube from damage due to the bright source.

The second form of interference between a display or light group and the NVG is veiling glare. Veiling glare is a phenomena seen when a bright source, outside of the field-of-view of the NVG, interacts with the image tubes causing undesired energy to enter the scene. This results in a brightening of the background and an overall reduction in scene contrast through the NVG. Veiling glare is often described as a green ghost effect across the entire scene.

The third form of interference between a display or light group and an NVG is the reflection of the display off one or more transparency within the cockpit. This reflection ranges from mere annoyance to serious degradation of the performance of the NVG. In the best cases the reflection is dim and is only present at certain angles. In the worst cases the reflection is bright and causes NVG de-gain and veiling glare effects similar to those experienced when viewing the display directly. Reflection effects are often worse in low light conditions and may not be a factor in high light (full moon) environments.

All cockpit controls and displays require a certain level of readability in high ambient direct sunlight and in low ambient NVIS conditions. The range of luminance, radiance and contrast required for each item in the cockpit is explained in great detail in MIL-L-85762 and should be used as a guide for evaluation. Mission representative profiles should be run during a full spectrum of lighting conditions. Systems integration with the HUD is crucial. The ability to observe all the flight, navigation and weapons parameters should not be adversely affected while using the NVGs. If a raster FLIR image is projected in the HUD, the aircrew should be able to easily switch from the NVG image to the FLIR HUD image quickly without degradation. This can be accomplished with adequate eye relief and some look around or with an auto scene reject (ASR) option, found only with Type II NVGs. The ASR feature can shut down the NVG image while the NVGs are inside the HUD FOV to allow viewing of the FLIR image through the combiners and restore the NVG image while the NVGs are outside the HUD FOV. A lighting mockup and aircraft ground test should be conducted prior to flight test to ensure acceptability for flight.

In addition to NVG related reflections (i.e., reflections that can be seen through the NVG), the flight test should also be used to evaluate standard naked eye reflections. And, like the NVG related reflections, naked eye reflections are often worse in low light than in high light. If reflections significantly affect the performance of the mission, additional filtering or glare shielding may be required.

10.4.3.4.2 DATA REQUIRED

- Display/Light under evaluation
- Ambient light level
- Pass/Fail on readability
- Type of NVG interactions if present
- Reflection location for naked eye reflections
- Qualitative assessment – transmissity of HUD
- Mission impact due to display/light readability, NVG interference or naked eye reflections

10.4.3.5 WARNINGS AND CAUTIONS

10.4.3.5.1 PURPOSE AND METHOD

By their nature, warning and caution lights must draw the attention of the aircrew. At the same time these lights can not be so incompatible as to significantly degrade the scene outside the cockpit as viewed through the NVG. MIL-L-85762A requires specific luminance and NVIS Radiance levels for warning lights so that they can be clearly seen both through the NVGs and with the naked eye when looking under/around the NVG. In addition, since the same warning lights are used during the daytime, they must be bright enough to draw the attention of the aircrew during daylight flight. Qualitative evaluations should be made of the night and day readability of the warnings and caution lights. Notes relative to any degradation in NVG performance when, the warning light is illuminated, should clearly indicate the ambient condition present during the evaluation (i.e., daylight, high-light night, low-light night…).

10.4.3.5.2 DATA REQUIRED

- Identification of the warning/caution light being evaluated
- Ambient condition (light level)
- Ability of the light to draw the aircrew attention through the NVG
- Ability to draw attention when looking under/around the NVG
- Interference between the light and NVG causing degradation to the normal image
- System fault detection and failures

10.4.3.6 FAULT DETECTION AND FAILURES

10.4.3.6.1 PURPOSE AND METHOD

Depending on the reliability and maintainability of the system, means to check the system's status and detect failures can be important. Evaluate in the laboratory, the reliability of the system to detect systems failures. Evaluate airborne, the capability of the fault detection system to amply inform the aircrew of system status and impending or actual system failures.

10.4.3.6.2 DATA REQUIRED

- Fault detection reliability
- Suitability of the display of faults/failures

10.4.3.7 EXTERNAL LIGHTING

10.4.3.7.1 PURPOSE AND METHOD

The location and type of external aircraft lighting can be crucial to accomplishing formation tactics. The ability of a formation of aircraft to operate as an element, while remaining undetected by the enemy is vital to successful mission completion. External lighting tests should quantify and qualify the effects of own aircraft exterior lighting and the effects of other aircraft lighting on the NVG systems under evaluation. Mission representative formation tactical profiles should be used for these evaluations with the caveat that build-up should be used wherein initial join-up and form flight are carried out at a considerable distance prior to moving to a previously established safe profile for NVG aided form flight.

10.4.3.7.2 DATA REQUIRED

- Anomalies
- Detection ranges for different lighting settings
- Ambient light level
- Effects of own aircraft exterior lighting on form flight safety
- Exterior lighting configurations and characteristics

10.4.3.8 COCKPIT PERFORMANCE IN OTHER THAN NVG RELATED FLIGHT

10.4.3.8.1 PURPOSE AND METHOD

Most NVIS compatible lights, displays and filters are used for both day and unaided night flights as well as for NVG related flights. This requires a careful evaluation of all cockpit lighting/displays in both daylight and various unaided (i.e., no NVGs) night environments. In order to evaluate the daylight readability of an instrument, flights should be conducted during daylight hours using flight profiles, which include flying towards and away from the sun, and flying in overcast conditions. Similarly unaided night evaluations should include flights towards and away from the moon as well as into overcast conditions. The principle focus should be on whether or not the displays, HUD, warning lights, and other cockpit instruments are adequately usable in the various flight environments.

10.4.3.8.2 DATA REQUIRED

- Ambient Light Level (i.e., daylight, Full moon, Overcast Starlight…)
- Data related to the readability of the displays
- Data related to display reflections off the transparencies

10.4.3.9 MISSION UTILITY

10.4.3.9.1 PURPOSE AND METHOD

The bottom line for all combat systems testing is to determine the impact of the test item on mission accomplishment. Mission representative profiles should be conducted to assess the capability to perform mission tasks with NVDs. Specific profiles should include:

- Target Engagement Capability
- Low Altitude Navigation and Terrain Avoidance Capability
- Medium Altitude Navigation Feasibility
- A/A Intercept Feasibility
- Feasibility of conducting Lights Out Takeoff, Landing and Taxiing (when applicable)
- Systems Integration during Navigation, Targeting and Weapons Employment.
- Formation Maneuvering.

10.4.3.9.2 DATA REQUIRED

Aircrew should identify and report workload ratings, and system capabilities and limitations.

10.5 ELECTROMAGNETIC COMPATIBILITY TEST

Whenever a new electronic device is introduced into the cockpit, electromagnetic compatibility testing is required prior to flight. NVGs and related cockpit lighting modifications need to be tested on the ground with systems operating (including engines and flight controls) to ensure that these devices are not sources of electromagnetic interference and to ensure that their operation is not degraded by other systems in the aircraft.

10.6 SAFETY CONCERNS

Human factors, such as eyestrain, neck fatigue and display/image imperfections, greatly affect the ability to safely operate an aircraft in demanding tactical situations. The ability to perform a safe ejection, bailout, or emergency egress is always a concern. Finally, improper lighting and displays will degrade NVG performance, sometimes imperceptibly, increasing the chances of becoming involved in a mishap. To properly address these safety concerns, sufficient laboratory and ground tests need to be conducted to mitigate the risks prior to any flight tests. And, as previously mentioned, the flight test should encompass build up from low pilot workload environments to high workload environments such as:

- High ambient lighting flight testing before low ambient lighting flight
- High altitude before low altitude
- High moon elevation and before low angle on low levels
- Single aircraft operations before section tactics
- Benign maneuvering before aggressive maneuvering
- Benign terrain before mountainous terrain.

With systems like NVGs, build-up is not only required to clear the equipment for higher risk testing, it is also required for aircrew proficiency.

In situations when an evaluation includes testing a new technology NVG and the opportunity exists, a safety aircrew should use the older, known and proven technology while the evaluation aircrew uses the new device. Finally, for aircraft that use NVGs during takeoff and landing, the aircrew should taxi the aircraft, conduct up and away flights, and conduct low approaches prior to actual takeoff and landings with the NVGs in operation.

10.7 REFERENCES

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