

Introduction of Precision Measurement of Nano-Dimensional Scales Using Laser Interferometer

By Winncy Du

(Mentor: Mr. Bert Haugen)

Fellowship Sponsor: Lockheed Martin Space Systems Company, Sunnyvale)

Introduction

This ETP proposal aims at enhancing existing curriculum content in the department of Mechanical & Aerospace Engineering at San Jose State University, through conveying the knowledge and research findings obtained in the 2005 IISME Summer Fellowship Program at Lockheed Martin. Specifically, the fellow plans to introduce students in her Mechatronics¹ class how to set up, adjust, analyze, and use a nano-scale precision measurement system that hasn't been available in most Universities' laboratories yet.

The key components used in the nano-level measurement system mentioned in this proposal -- laser head, interferometer, remote receiver, data acquisition board, and the computer -- are excellent examples of studying physics, mathematics, electronics, mechanics, and computer. Their synergistic integration provides a "vivid" textbook for studying the subjects of Mechatronics engineering.

Summary of the Fellow's work at LM

The fellow works in the TSA (Trombone Servomechanism Assembly) group, supervised by Mr. Bert Haugen, in Building 149 at Lockheed Martin Space Systems in Sunnyvale from July 22 to Sept. 16 (a total of 8 weeks). The main tasks include (1) set up a one-dimensional (single-axis), high precision, laser interferometer measurement system, (2) perform optical alignment, (3) conduct a sequence of tests to investigate the system's performance under various environmental conditions, and finally (4) make suggestions on how to maximize the system's performance on measuring nano-scale motion and achieve 5 nm resolution. The detailed system setup and approaches used are discussed in the later sections of this proposal along with the detailed educational plan.

Brief Description of Mechatronics Course Taught by the Fellow

ME106/EE106 *Fundamentals of Mechatronics* course, offered each semester, is a required course in Mechanical & Aerospace Engineering Department and cross-listed in Electrical Engineering Department. More than 120 engineering students from different disciplines take this course each year, including Mechanical-, Aerospace-, Electrical-, Computer-Engineering majors, and even Technology majors. One of the important contents in this course is to teach students how to use various instruments and sensors to measure typical physical quantities, such as position, velocity, temperature, force, or

¹ *Mechatronics* is the combination of "**Mechanical + Electronics**". This is relatively new area that teaches students how to integrate mechanical systems with electronic or electrical components (for control), as well as computer programming. Many modern devices, such as a washing machine, a refrigerator, and a microwave, are examples of Mechatronics products.

motion. In the normal laboratory environment, the resolution of the position measurement is about 1×10^{-3} m (or 1 mm). Not much environmental factors need to be considered when conducting a measurement. At a nano-scale measurement, however, the resolution of the measurement system is down to 1×10^{-9} m (or 1 nm) and everything could affect the measurement results significantly. The students have to pay close attention to the environmental conditions when conducting nano-scale measurements. Unfortunately, no such subjects are covered in the current course and laboratory experiments.

Learning Objectives

Upon the implementation of this ETP, the students will be able to

- (1) describe a typical setup of a Nano-dimensional measurement system using laser interferometer, including a sensor (photodetector) and a data acquisition system,
- (2) explain the characteristics and functions of each major component in the system,
- (3) illustrate how to install and align the optics to achieve the best measuring results,
- (4) perform the experimental/measurement data analyses through a computer,
- (5) know how to compensate the fluctuation of temperature, humidity, pressure, as well as mechanical and electrical noise during measurement,
- (6) understand the difference between the normal-scale measurement system and a nano-scale measurement system.

Educational Plan and Contents

In order to achieve the above six learning objectives, the following educational plan and contents are proposed.

1. Introduce the main components of a Laser Interferometer system

When the size of an object shrinks to the nano scale, a commonly-used ruler or meter no longer works. The physicist Albert A. Michelson (1852-1931) conceived an optical method and designed an interferometer to measure the length that can achieve a resolution of a fraction of a light's wavelength, e.g., 10^{-8} m [1]. This becomes the major means to measure micro- and nano-scale position or movement. Many companies, such as Agilent Technologies, Zygo, provide laser interferometers for this purpose.

In a laser interferometer the laser beam is split into two beams by a beam splitter. One of the beams is directed to a mirror located at a certain distance to provide a reference in measurements. The other beam reaches a mirror or reflector fixed on the moving object. This beam, being reflected, recombines and optically interferes with the reference beam (or beams). The superimposed light sensed by a photodetector has increased (constructive interference) and decreased (destructive interference) illumination phases, which are correlated with the measuring displacement of the object. Figure 1 shows the main components of a typical single-axis precision measurement system [2] that tracks the CD writer's motion.

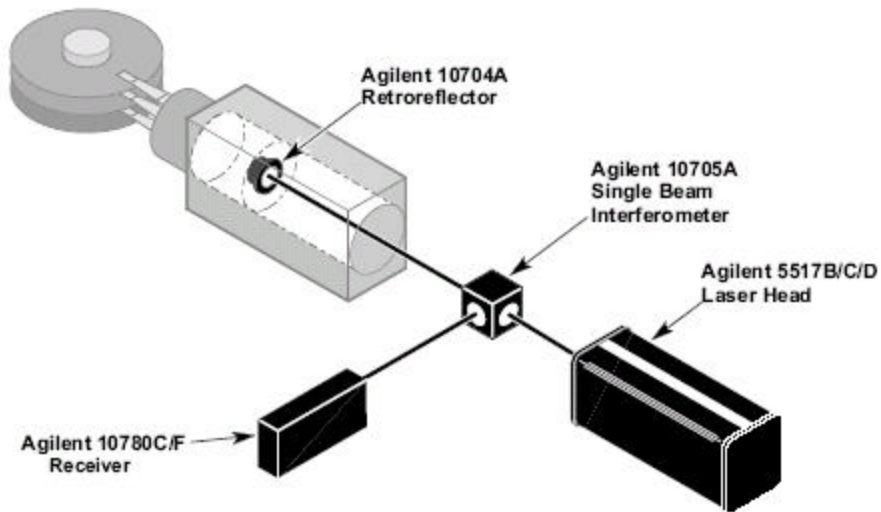


Figure 1 A typical single-axis laser interferometer system [2]

The system mainly consists of a Laser head, an interferometer, a receiver (photodetector), and a retroreflector (fixed to the CD driver).

2. Characteristics and functions of each component

Laser Head: The laser head is necessary because it provides the source of light required by the system. Different from normal lights, the laser head generates a stable, uniform, coherent, collimated light beams consisting of two orthogonally polarized frequency components for the precision measurement as shown in Figure 2. The detail description of using two-frequency laser beam at the interferometer and how they improve the measurement can be found in “Principles of Operation” in Chapter 14, Agilent Manual.

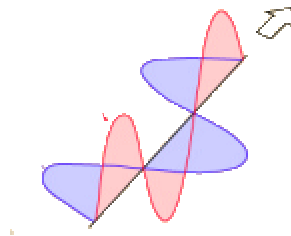


Figure 2 Two orthogonally polarized frequency components in the laser beam

Interferometer Interferometer is an optical measurement device that splits and directs a single laser beam into two paths: one goes to a reference mirror (fixed), the other to a measurement (moving) mirror. Through analyzing the returned light patterns reflected by

the two mirrors, the position of the moving target can be measured. Figure 3 shows a single-axis interferometer.

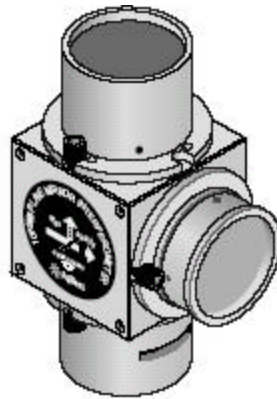


Figure 3 Agilent 10706B high stability plane mirror interferometer [3]

Receiver The receiver is used to receive the returned/reflected laser beams from the two mirrors. It is actually a photosensor coming with an electronic circuit to provide clear light patterns or high quality measurement signals, so that a computer can do further data analysis (Figure 4).

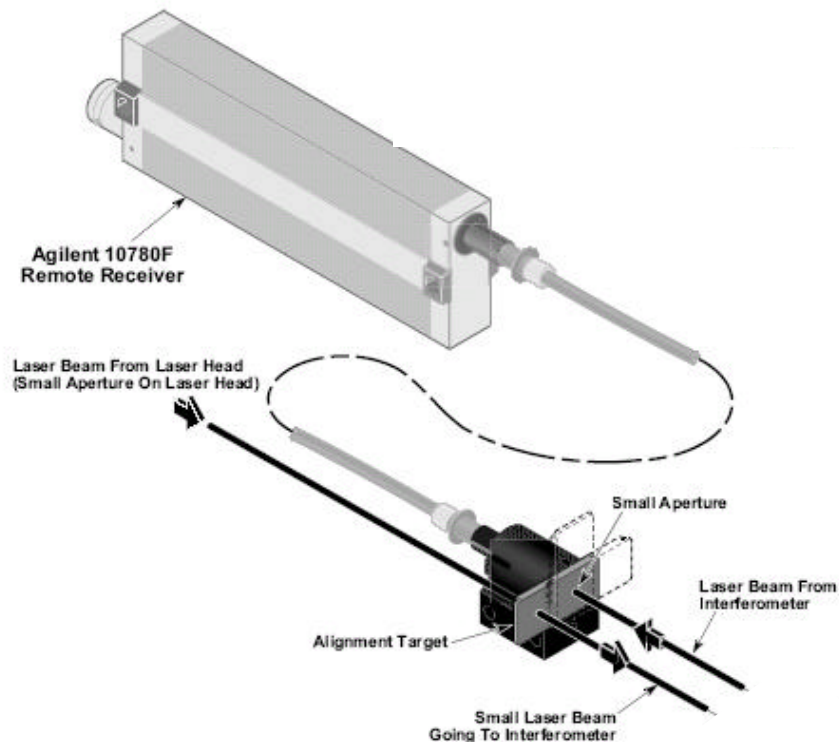


Figure 4 Agilent 10780C remote receiver [4]

3. System installation and alignment

To achieve an accurate measurement, correctly installation and proper alignment are very important. Poorly installed system and optical misalignment often results in incorrect measurement or loss of the signals. Correct alignment minimizes cosine error and the thermal drift coefficient of the interferometer, and maximizes signal strength at the receiver. Necessary techniques, such as grounding, shielding, alignment guides, will also be introduced to students.

The alignment procedures are:

- (1) Place the target to its point furthest from the laser head. Align the laser beam perpendicular to the measurement mirror by autoreflection.
- (2) Position the Agilent 10706B interferometer in the beam path between the laser head and the measurement mirror.
- (3) Place the interferometer alignment target (a circular plate with two small apertures) on the laser (input) side of the interferometer and place the alignment aid (a circular plate with one small aperture) on the outside side of the interferometer in the correct orientation (the hole allows transmission of the primary measurement beam). Select the small aperture on the front turret of the laser head.
- (4) Move the interferometer until the beam passes 1) through the center of one hole on the alignment target², 2) through the hole on the alignment aid, and 3) strikes the measurement mirror.
- (5) Pitch and yaw the laser beam until the beam reflected from the measurement mirror returns upon itself, through the interferometer and back to the small aperture of the laser head.
- (6) Remove the alignment target and select the large aperture of the laser head. Center the output beams on the receiver aperture by moving the receiver.
- (7) Connect a fast-responding voltmeter to the receiver test point. Pitch and yaw the laser beam until a signal is received. This is indicated by the voltmeter suddenly jumping to a value greater than 0.25 volt. This adjustment is critical in order to achieve the desired result.
- (8) Pitch and yaw the laser beam to achieve maximum voltmeter reading. Carefully readjust the interferometer until the voltage reading suddenly drops back to about 0.3 volt³.
- (9) Remove the alignment aid from the interferometer. Switch to the small aperture on the laser head. Block the measurement beam by placing something between the interferometer and the measurement mirror.
- (10) Place the wavelength tracker and align it to the beam splitter.

² Translucent tape over the apertures will help to observe when the beam is centered.

³ The alignment should be adjusted such that the voltage reading from the receiver test point occurs just below the sudden jump up in voltage. If the alignment is fixed to sustain this peaked voltage, system operation will be degraded.

- (11) Insert the interferometer alignment aid between the beam splitter and the high stability adapter. This allows the reference beam to be autoreflected from the high stability adapter back toward the small aperture of the laser head.
- (12) Observe the reflection of the reference beam back at the laser head. Pitch and yaw the interferometer until this reflection is returned back into the small aperture of the laser head.
- (13) Fasten the interferometer securely to preserve the pitch and yaw adjustments. Remove the interferometer alignment aid from between the beam splitter and the high stability adapter. Remove the beam block from between the interferometer and measurement mirror.
- (14) The reference and measurement beams must be centered on the receiver aperture⁴. Move the receiver side-to-side to center the beams on the receiver aperture.
- (15) Place the alignment aid back on the output side of the interferometer and switch to the large aperture on the laser head. Connect a fast-responding voltmeter to the receiver test point. Monitor the voltage reading along the complete travel of the stage. The voltage should not jump up to the previously peaked voltage.

4. Effects of environmental conditions

In precision measurement, environmental conditions such as temperature, humidity, pressure, and mechanical and electrical noises, significantly affect the measurement accuracy. A comparison of measurement results from different environmental conditions but same setup will be shown to students, including

- with and without using the wavelength tracker
- change of beam distance
- change of temperature
- vibration/floating of the optical table
- acoustic vibration
- with and without fans on
- calibration method
- isolation of the electronics devices
- plastic sheet shielding the work area (from thermal and acoustic) or tube (preclude any external aerodynamics or thermal)

In particular, the signal quality (noise level) and its effect on the measurement results and readings will be presented to students.

5. Methods of experimental/measurement data analysis

The data from the remote sensor, the laser electronics board, and the wavelength tracker will be fed to Agilent 10887B Axis Board (equipped with a data acquisition system) and recorded in a computer. The principle of the data acquisition system, signal conditioning, and several signal (data) processing algorithms will be introduced to students, including:

- (1) Sampling theory, analog to digital (A/D) converter, sampling and hold circuit.

⁴ Use translucent tape over the receiver aperture to observe the beams.

- (2) Low pass filters to attenuate data noise, Amplifiers.
- (3) Data normalization & calibration; stochastic, time, and frequency domain data analyses.

6. *Recognize the difference between measurement systems for nominal-, micro- and nano-scale*

Measurement systems for different purpose or scales have different environmental requirements. Students should have an ability to distinguish these systems and their typical setups and configurations. Several real-world measurement systems for difference scale measurements will be demonstrated to students, including the nominal-dimension measurement, micro-scale measurement, and nano-scale measurement. Pictures, such as one shown in Figure 5, related to the micro-scale and nano-scale measurement systems will be shown to students.

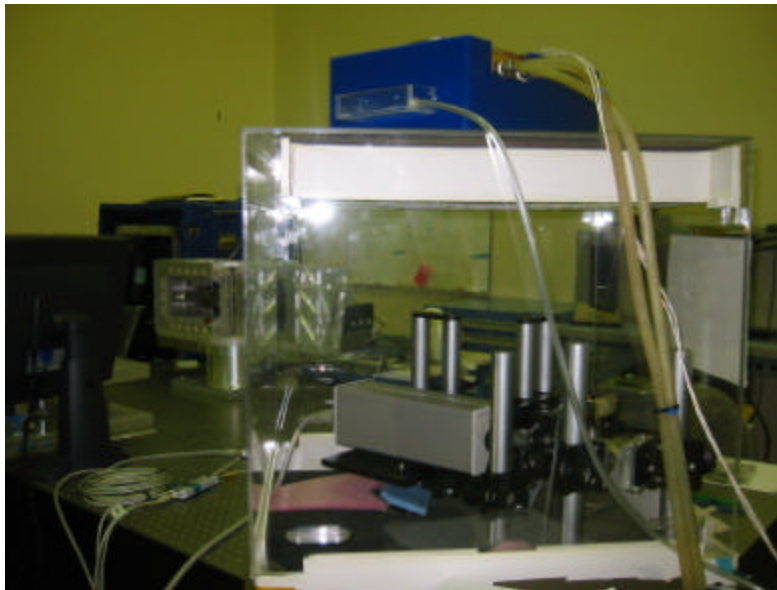


Figure 5 A single-axis Laser interferometer measurement system set up by the fellow

Assessment Methods

The students' learning effectiveness through this ETP, will be evaluated through the forms of exams, student interview, and survey. The results will be reported to IISME for future reference. The samples of the exam, the interview and survey questions are shown as follows.

Samples of Exam Questions:

- 1. Use the concept of interference to explain how the interferometer works.
- 2. Is light the only type of wave that can undergo interference?
- 3. If someone places a sample of very hot water near one of the beam paths, halfway between the beam splitter and the end mirror, what will happen on the readings.

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4. If you move the interferometer's adjustable mirror by the slightest amount, the pattern of fringes changes, and eventually it goes away. Why is the instrument so sensitive to the position of the mirror?
5. Do some quick research (perhaps on the Internet) and see if you can find some ways that interferometers are used in the 'real world'.

Samples of Interview and Survey Questions:

1. Do you think the provided materials give you enough information on laser interferometers?
2. How do these materials help you extend your knowledge on measurement systems?
3. If enough components and materials are provided, do you think you can set up a measurement system and implement a nano-scale measurement?
4. Do you like to share your knowledge on nano-scale measurement to other students?

Acknowledgement

The fellow thanks IISME for providing this unique and wonderful opportunity to bridge industry research work to university educational programs. The fellow also thanks Mr. Bert Haugen for his offering this challenging work and his full support for this work.

Reference

- [1] Richard S. Figliola and Donald E. Beasley, "Theory and Design for Mechanical Measurements", 1991 by John Wiley & Sons, Inc. pp. 423-426.
- [2] Agilent User's Manual, Chapter 3, page 30.
- [3] Agilent User's Manual, Chapter 7D, page 3.
- [4] Agilent User's Manual, Chapter 8, page 11.

	<i>Bert Haugen</i>	<i>9/19/05</i>
Signature	Bert Haugen (Mentor) Lockheed Martin Space Systems (Sunnyvale)	Date