Calibration of Time Base Oscillators

Jim Bechtold/Editor

Counting and Clocks

Counting intervals has been going on since man's beginning. Early time measurements involved counting the number of days in terms of sunrises, sunsets, or moons. Later, the day was divided into smaller increments by using an hourglass, candles, sundial, etc. With the discovery of the pendulum, clocks were born. The accuracy of early clocks was around 1 part in 10^3.

As more accurate clocks were produced, new uses of time measurement were explored. As new uses were discovered, the need for even more accurate clocks became apparent.

Atomic Accuracy

Current state-of-the-art atomic frequency standards has attained an accuracy of 1 part in 10^{13} in the laboratory. The specified accuracy in commercially available atomic clocks has reach ±1 part in 10^{12}. This unprecedented commerical accuracy is equivalent to a gain or loss of 1 second in a minimum of 400,000 years.

Definition of a Second

Frequency standards and clocks have no fundamental differences — they are based upon dual aspects of the same phenomenon. The basic unit of time, the second, is defined as "the duration of 9,192,631,770 periods of transition within the cesium atom." Frequency is determined by counting the number of cycles over the period of a second. Therefore, the definition of a clock can be expressed as a device that counts the number of seconds occurring from an arbitrary starting time.

From this definition it appears that a clock needs three basic parts. First, a source of events to be counted. This source can be labeled a frequency standard, frequency source, or time interval standard. Second, a means of accumulating these events or oscillations. Third, a means of displaying the accumulation of time. Figure 1 shows a simple clock block diagram, including a method of presetting the arbitrary starting time and obtaining an electrical time reading from the clock (time-code-generator).

Errors in Accuracy

Accuracy in a timekeeping system is dependent on six major problem areas.

- Maintenance of accurate frequency
- Accurate time transfer
- Determination of radio propagation path delays
- Maximization of the frequency cali-bration interval
- Determination of the effects of noise in frequency generating equipment
- Determination of the effects of changing environmental conditions

This Article

Prior to analyzing the effects and impact of the above sources of error, it is necessary to determine the level of accuracy required and the tolerances essential for the individual application. Once the essential tolerances have been established, the sources of error can be analyzed to determine if they have an impact on system operation. If they do, in fact, affect the system operation, then appropriate steps can be taken to reduce that impact. This article will describe the frequency calibration interval with suggestions on how to measure your time base and the effects of how changing environmental conditions affect time-base accuracy.

Types of Time Base Oscillator

There are five basic types of time base oscillators:

- XO – Room temperature crystal oscillator (sometimes referred to as RTXO)
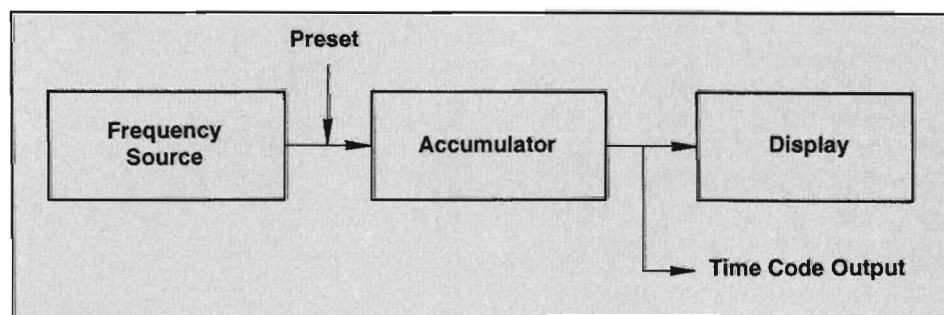- TCXO – Temperature compensated crystal oscillator

Figure 1. Basic Clock

- OvenXO – Oven controlled crystal oscillator
- Rubidium
- Cesium

Each type of time base has its own characteristics. The room temperature model would be used in a portable counter. Usually, the better the time base, the longer it takes to verify it; the poorer the time base, the harder it is to adjust. Some time-base specifications would be impractical to completely verify, so operator judgment is required to identify which parameters have to be checked, when to adjust the time base, and when to predict final performance based upon rate of change of measured performance.

Time Base Aging

The physical properties of the quartz crystal exhibit a gradual change with time resulting in a gradual cumulative frequency drift called "aging." See Figure 2. The aging rate is dependent on the inherent quality of the crystals used, and goes on all the time. Aging is often specified in terms of frequency changes-per-month since temperature and other effects would mask the small amount of aging for a shorter time period. Aging for air crystals is given in frequency changes-per-month as it is not practical to accurately and correctly measure over any shorter averaging period. For a good RTXO, the aging rate is typically of the order of 3 parts per 10^7 per month. For a high quality oven-controlled oscillator, the aging rate is typically 1.5 parts per 10^8 per month.

Aging rate specifies maximum frequency change with time. Any oscillator can be much better than specified but will never be worse than the indicated rate unless it is malfunctioning. You may have noticed that HP has two kinds of specifications — some oscillators are specified as having a daily aging rate, such as $<3 \times 10^{-9}$/day, while others are specified as having a monthly aging rate, such as $<3 \times 10^{-7}$/month. HP oscillators with a daily aging rate specification use ovens that sufficiently buffer the oscillator from the environment.

To determine crystal aging rate, one has to check the oscillator once a day when room temperature is at a constant value, plot these points for approximately a
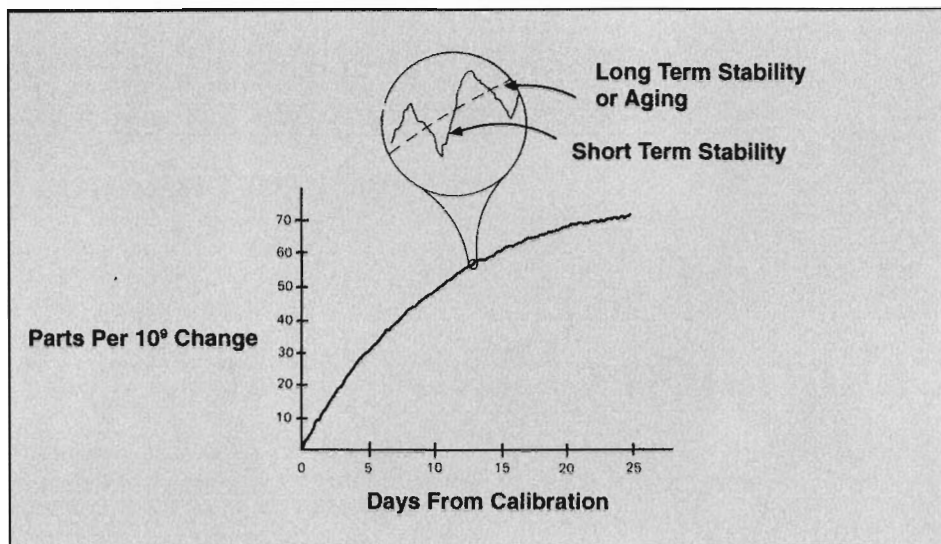

Figure 2. Effect of Aging on Frequency Stability

month, then draw a line through the points. The slope of the line is the aging rate of the crystal. By doing this you have created an "historical aging rate" of your unit. This is an important concept and each instrument should have its own history record. Table 1 summarizes the oscillator characteristics described, utilizing typical specifications of well-designed oscillators.

Time Base Warm Up

Under typical operating conditions, that is, when the instrument's power cord is left connected to the power source, there is no warm up because the time base is kept "warm" or in a "standby" mode. However, if the unit has been disconnected from the power source for 24 hours or more, the instrument should technically be warmed up for up to 30 days for it to meet guaranteed specifications. This may not be practical. Our experience has shown that approximately 85 percent of new units and 95 percent of older units will be within specifications after three days

of warm up. Of course, this is due to the aging process slowing down over time. A typical problem you may encounter with some of the older units is that the time base has aged to a point where the mechanical adjustment can no longer compensate the frequency drift because the mechanical adjusting device has reached the physical limit of its travel. On other older units, drift may be almost non-existent.

The Question

Do you have to calibrate an oven time base even though the manual for the instrument being calibrated does not have a performance test for it? The answer is YES. The oven time base needs to have a drift test performed. The decision to remove offset depends upon the needs of the customer and the type of time base being calibrated. Calibration should always be checked after repair, after being shipped (shock can cause an offset of 1 part in 10^8, and you don't know in which direction), or periodically to ensure that measurements

Table 1. Typical specifications of the five types of oscillators.

Time Base Type	Typical Aging	Typical Shift for 5 C°	Allowable Offset	Typical Warmup	Allan Variance (T=1 sec.)
XO	3×10^{-7} per month	5×10^{-6}	60 Hz	30 minutes	1×10^{-9}
TCXO	1×10^{-7} per month	1×10^{-6}	13 Hz	3 hours	1×10^{-10}
OvenXO	5×10^{-10} per day	5×10^{-10}	150 mHz	3 days	5×10^{-12}
Rubidium	1×10^{-11} per month	5×10^{-12}	400 µHz	4 hours	7×10^{-12}
Cesium	None (Primary Std.)	3×10^{-12}	6µHz	45 minutes (21.5 nsec/hour)	1×10^{-11}

made with these devices are within specifications ACCORDING TO THE USE OF THE INSTRUMENT. This is an important concept. Many users expect an oven time base to have a written specification to tell them exactly when the cumulative offset caused by aging has crossed some specification bound. These oscillators are just not specified in this manner. The use of the time base and the measurement needs of the user dictate how the time base is to be calibrated and supported.

On the other hand, crystal oscillator (clock) accuracy is seldom of consequence in practical time interval measurements. Most electronic counters have a quartz oscillator with an accuracy of 1 part in 10^6 (1 part per million) or better. As a result, the effect of oscillator stability does not affect a time interval measurement unless the display has 5 or 6 valid digits of information. While it is possible to measure long intervals with high resolution, most practical measurements today are the rise time of fast signals, propagation time through high-speed logic, or on narrow pulses. Resolving a 5 μsec interval to 1 nanosecond entails only 4 digits of information – i.e., 5000 nanoseconds – so an oscillator as poor as 1 part in a million introduces only 1/200th as much error as $\pm$1 count for this measurement. For shorter intervals the oscillator error is proportionally less.

Time interval averaging increases the number of valid digits, but here again usually not to the extent that crystal accuracy is important. Short-term stability may become important when doing time-interval averaging on narrow pulses. The short-term stability specification is statistical in nature so is worse for short averaging times. Consider for example a short-term accuracy specification of 1×10^{-9} for a 1 second averaging time. This would be 1×10^{-3} for a 1 μsec averaging time (5 nanoseconds for the example above) and would be greater for an oscillator with poorer short-term stability.

Aging rate is generally of consequence only in an application where the counter is used to make phase or time measurements to compare high precision frequency standards. In this application a counter is used to measure the time variations between once-per-second time ticks from the two different frequency standards. Each time-interval measurement may be as long as 1 second (1×10^6 μsec) on frequencies that are stable 5 parts in 10^{12} or better, so a stable crystal oscillator is needed.

Accuracy and Stability

Accuracy may be defined as the closeness of a measurement to the true value as fixed by a universally accepted standard. The measure of accuracy, however, is in terms of its complementary notion, that is, deviation from true value, or limit of error, so that high accuracy has a low deviation and low accuracy a high deviation. The plots shown in Figure 3 show successive measurements for four cases. The readings in case 2 are more spread out. This could be due to noise or the operator's inability to consistently read an analog dial. The readings in case 3 are stable but offset from actual value. The important thing is that this offset is a systematic error that can be removed by calibration. The random errors of case 4 cannot be calibrated out.

Frequency Calibration Interval

In theory, a time system based upon a quartz oscillator or a rubidium standard of known drift rate can be kept within prescribed limits of error with infrequent adjustments through a systematic approach.

With this systematic approach, the oscillator and clock are preset to offsets that will keep the time system operating within a selected accuracy for a long time despite the oscillator's drift. This drift (aging rate) must be known (measured) and must be nearly constant, so that a plot of the frequency over the adjustment interval (periods between calibration) can be approximated by a straight line.

What this means in simple terms is that the time base is adjustable, and if its drift rate is known, it can be set so that the drift remains within specifications for a longer period of time, therefore extending the interval between calibrations.

Suggested Method of Calibration

There are two excellent HP products to help an operator make these measurements quickly and accurately, and obtain a permanent record (or history) when connected to a printer. They are the HP 5372 Frequency and Time Interval Analyzer and the HP 53310A Modulation Domain Analyzer.

HP 5372A
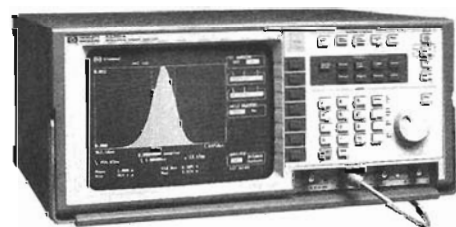
HP 53310A

The HP 53310A, often called a "frequency scope" allows the user to visually see the relationship between successive data points, with no dead time between measurements and with no appreciable delay. This allows the user
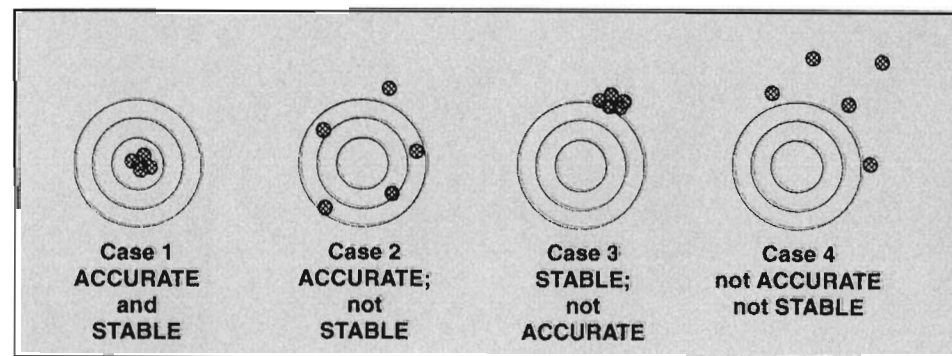

| Case 1 ACCURATE and STABLE | Case 2 ACCURATE; not STABLE | Case 3 STABLE; not ACCURATE | Case 4 not ACCURATE not STABLE |

Figure 3. Accuracy

to "zero-in" a measurement quickly without the time-consuming and frustrating back-and-forth "clockwise-a-litle;" "counter-clockwise-a-bit;" "clockwise again," etc.

The HP 5372A allows you to measure phase shift continuously over a period of up to 18 hours and provides built-in Allan variance calculations.

Each unit has marker readouts that allow the operator to express frequency differences in the conventional "parts-in-the-10-to-the-nth" notation with a minimum probability of mathematical or procedural error.

One thing cannot be over-stressed; the limiting factor for almost all time bases is your ability to keep the temperature constant for the duration of the test. This is why the ability to make measurements and adjustments quickly is so important.

Once you have created a historical rate of drift (aging) for your particular instrument, you can calibrate it to an offset to take advantage of the known drift. For example, if you know that the time base drifts from low to high at a certain rate, you can calibrate your unit at the low end of its specification so that it will drift from low through center and be at the high end of its specification at a prescribed point in time.

Recalibration Charts for Quartz Oscillators and Rubidium Standards

Figures 3a and 3b are useful for estimating the length in days of the recalibration cycle for an oscillator with a known drift rate, which will keep the time system based on that oscillator within prescribed error limits. A recalibration cycle is the time, in days, that can be allowed to pass between calibration adjustments. A shorter cycle (more frequency adjustments) is needed to keep a system accurate to ±100 μs (total time excursion equals 200 μs), rather than to 1 ms.

To use the charts, select the slant line marked for the aging, or drift rate — parts-per-day for quartz oscillators and parts-per-month for rubidium standards — of the oscillator. Note the intersection of this line with the horizontal line corresponding to the permitted error excursion. This intersection, referred down to the horizontal axis, gives the recalibration cycle.

Example 1.
A time system is to be maintained to within 10 ms based on a quartz oscillator with a positive aging rate at $5 \times 10^{-10}/$ day. Use Figure 3a to estimate the length of the recalibration cycle by locating the slant line marked $5 \times 10^{-10}/$ day and note its intersection with the horizontal line corresponding to a total time excursion of 20 ms (±10 ms). The answer read from the chart is 60 days. Note that to use Figure 3a, aging rate must be expressed in parts-per-day and permitted time excusion in milliseconds.
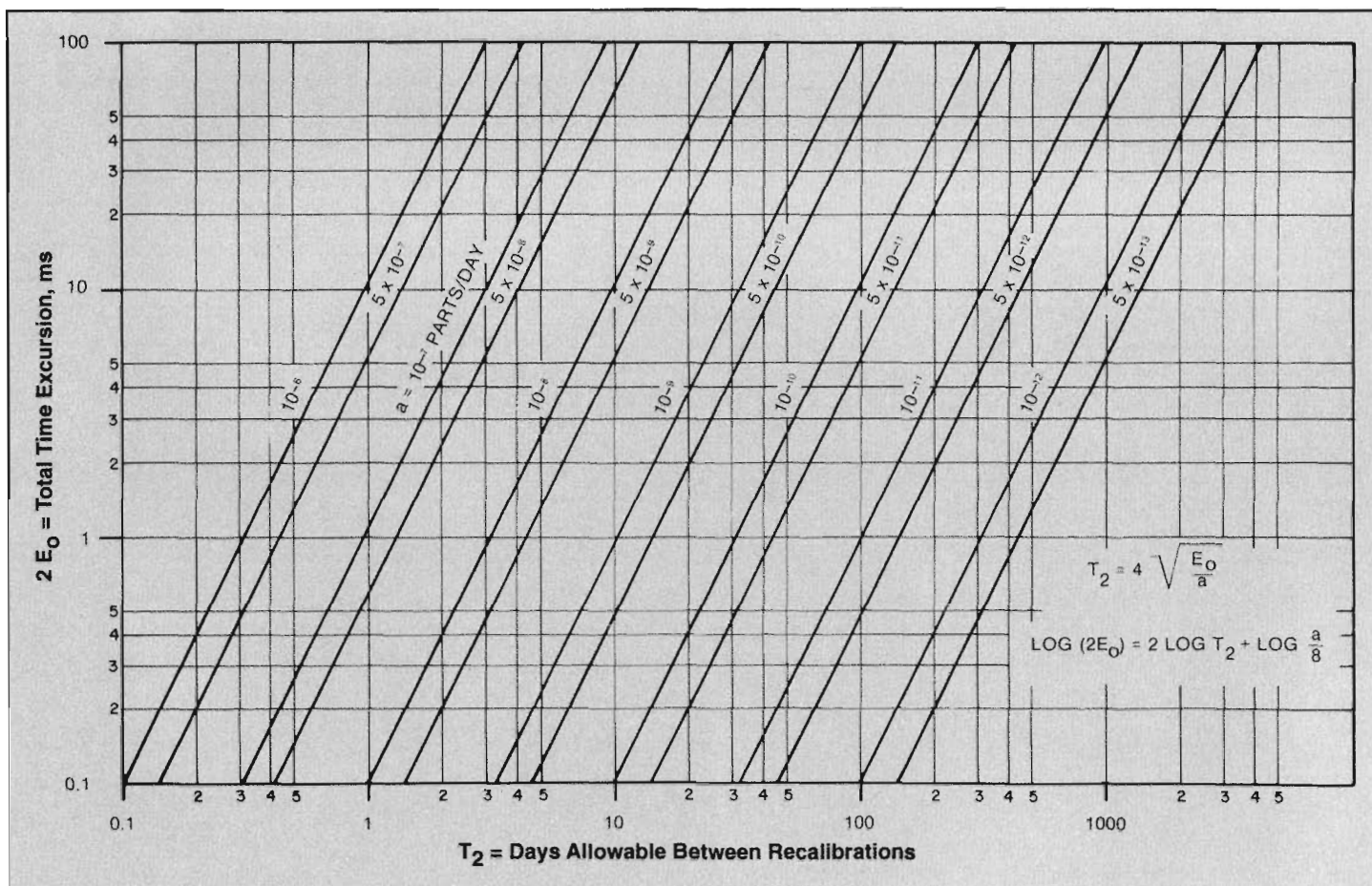
Example 2.
A rubidium-based time system is to be

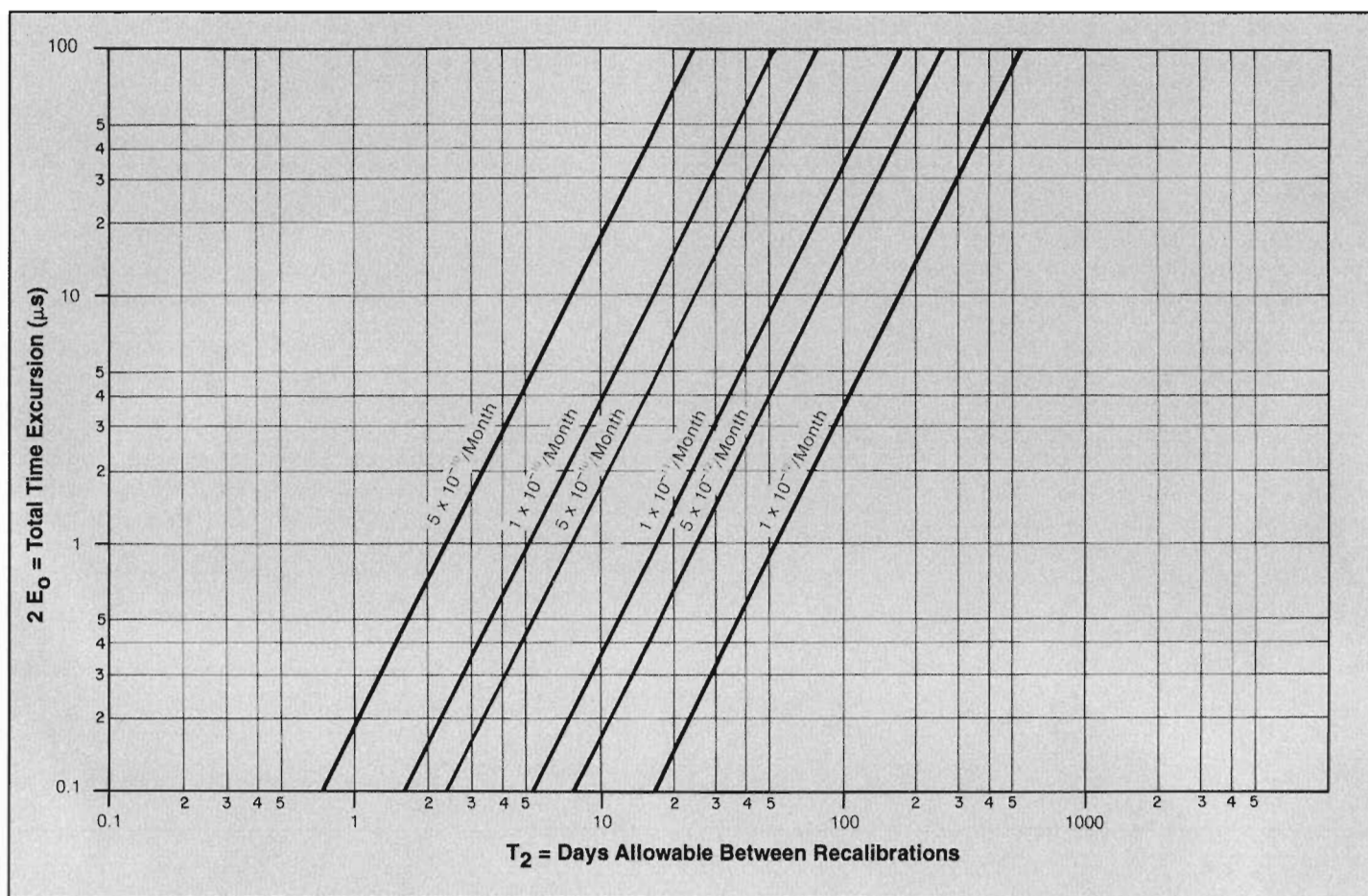Figure 3a. Recalibration Chart for Quartz Oscillators.

Figure 3b. Recalibration Chart for Rubidium Standards.

maintained within 10 us. The drift rate is a positive 1×10^{-11}/month. Looking at the appropriate slant line on Figure 3b corresponding to the drift rate yields a recalibration time of 101 days for an excursion of 20 μs.

Temperature Effects

A very small temperature change can drastically affect the frequency of a time base. In some cases, $1/2°C$ temperature change can cause as much drift as 2 weeks of aging. Two points are worth remembering with respect to temperature effects. First, the change of frequency with temperature is usually not a linear function; furthermore, all crystals, even though the same kind, may have very different frequency-temperature curves. Individual oscillator frequency-temperature curves must be made to determine a particular unit's actual performance. Second, the effects of temperature change can be reduced by providing a more constant ambient temperature (controlled room temperature) when better performance

is required.

Line Voltage Change

Crystal oscillator frequency is also influenced by line voltage changes (often because the instrument's power dissipation increases, which causes the temperature inside of the instrument to rise). Good circuit design, proper buffering, and good mechanical design can reduce these effects. Operators needing better performance can use a line regulator to better control line voltage fluctuations.

Summary

Each time base ages differently. You should create a history file for each of your instruments and plot its drift. Determine how the unit is going to be used. If your measurements require extreme accuracy, the time base will have to be calibrated more often. Either way, when you calibrate the time base, adjust it to the extreme end of its specification and let it drift through center to the other end of its specification,

maintaining calibration for the longest period of time.

Keep your instruments plugged into the power source to maintain constant internal temperatures, and use a line regulator to buffer line voltage changes.

Above all, think about how you are using the instrument and what is reasonable to expect from it. Do not try to use your counter to calibrate a cesium-beam frequency standard.

Acknowledgements:

I would like to thank Chris Franks at the Hewlett-Packard Santa Clara Division for his guidance with this article. For more information on the subject, I recommend the free Hewlett-Packard Application Note 52-2, *Timekeeping and Frequency Calibration*. Ask your local HP office for HP P/N 5952-7874. Comments on this article are invited and we will answer each and every one. If you have recommendations for future articles about this subject, please send them to the editor. □

Hardware Support for Test and Measurement Systems

Ken Callender/Hewlett-Packard

Introduction

Hewlett-Packard Test & Measurement Cooperative Support service for self-maintainers provides all the essential support elements you need to complement your internal hardware maintenance capabilities. With this service you will have everything you need to fully address your unique requirements. You use your trained maintenance organization for labor and rely on HP for training, replacement parts, diagnostic support tools, repair documentation, and remote backup support.

This cooperative support service is available for HP's large test & measurement systems. Examples are the HP 83000 Series Digital IC Test Systems, HP 3060 and 3070 Board Test Systems, and the HP 9470/9472 Power Mixed Signal Test Systems to name a few. More will be added to this list in the future.

Features

HP T&M Cooperative Support service for self-maintainers provides the following features for HP Test and Measurement systems designated by HP as eligible for this service.

- On-site start-up visit
- Semi-annual on-site reviews
- Electronic access to service notes (through HP SupportLine)
- License to use hardware diagnostics and updates*
- Remote hardware troubleshooting assistance
- Parts replenishment (03W only, excluded for 03X)*
- One customer-initiated on-site HP visit to repair hardware failure on eligible HP Test and Measurement Systems
- Direct access to technical assistance (Measurement Systems Knowledge Center)

Benefits

- Increase the availability of your test and measurement systems
- Improve the productivity of your system engineers and managers
- Maximize your organization's ability to maintain HP T&M systems
- Significantly enhance the productivity of your internal service organization
- Accurately predict your annual maintenance costs

*The optional parts replenishment is available under the 03W option electron only.

For More Information

Ask your HP office for the following documents.

Description	HP P/N
HP Cooperative Support User's Guide	5962-9778E
HP Cooperative Support Data Sheet	5962-8520E
HP Cooperative Support Terms and Conditions	5952-9777E

HP 8648A/B/C Loaner Program Eliminates Lengthy Downtimes

Henry Jeung/Hewlett-Packard

For U.S. Customers Only

Customers in the U.S. can eliminate downtime for calibration and reduce downtime for repair from a week to a day! Hewlett-Packard now offers an affordable way to quickly obtain a loaner signal generator so that you can keep operating when your present signal generator needs calibration or repair. If you cannot afford downtime for your HP 8648A/B/C Signal Generator, consider the following two options:

Shared Loaner Contract

You can purchase a three-year loaner contract. Any time your HP 8648A/B/C Signal Generator fails during the three years, a loaner instrument will be express mailed to you within hours. You keep the loaner until your instrument is repaired and returned.

You can also use the loaner once during the three years while your signal generator is being calibrated. Since calibrations are planned in advance, you can arrange to have the loaner arrive at your location before disconnecting your generator for calibration. Downtime will be limited to the time it takes you to connect the loaner in place of the instrument requiring calibration.

This three-year contract is available for $500.00 U.S. If at any time during the three years you want additional calibrations, you can have a loaner delivered for $200.00. Your instrument must be repaired and calibrated at the

Hewlett-Packard Golden Gate Customer Service Center in California. Costs of repair and calibration are not included in this contract price.
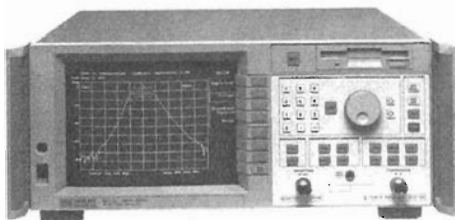
Per-incident Usage

Per-incident service can be purchased at any time you require a loaner by contacting the HP Golden Gate Customer Service Center administration group at (415) 694-2620. Once this contract is set up, you can then order a loaner for $350.00 per usage to take the place of your

New Test Software for the RF Network Analyzer

John Vallelunga/Hewlett-Packard

Introduction

Hewlett-Packard's Microwave Instruments Division has released a new version of test software for the HP 8711A RF Network Analyzer. This software is intended to replace the previous software (HP P/N 08711-10009). That version only automated four of the eight required tests, did not allow equipment substitution, and was difficult to work with. The new version has eliminated these shortcomings and has added several improvements, some of which are listed below.

Enhancements

- The program includes graphical setup connections, customized to your equipment being used. You will no longer need to refer to the manual for proper setup equipment and connections.
- Multiple equipment and mass storage configurations can be saved.
- Data storage is automatic; results can be archived and later retrieved at any time.
- Simple, immediate, one-disk operation. Although installation to a hard drive is preferred, it is not required. This is NOT an 'STE-9000' program.
- Elimination of the "special" option of the power sensor. The HP 8481D H70 is no longer required; a normal 8481D will suffice.
- Includes a quick HP-IB scan to verify equipment setups; DUT can be on a different bus from test equipment.
- Also includes several handy service utilities.
- Can be run on a PC using an HP BASIC Language Processor Card.

How to Obtain the Software

This program can be ordered as HP part number 08711-10011 through your local HP office. The price is approximately $50.00 U.S.

This new version can now be used in place of all the documented performance tests in the manual which will save a considerable amount of test time.

Other Important HP 8711A News

HP recently released firmware revision A.02.10 for the HP 8711A. This firmware now allows the use of a standard HP 8481D power sensor instead of the previously required HP 8481D Option H70. This sensor is used in ALC adjustment #104 on those instruments with a built-in attenuator (Option 1E1). Together with the above test software, the need for this special option sensor has been eliminated. However, care must now be used when performing adjustment #104. Following the procedure in the manual could result in a non-functioning ALC. For further information, order service note 8711A-05 from:

Hewlett-Packard
Bench Briefs
100 Mayfield Ave.
Mt. View, CA 94043

The new firmware is available as HP P/N 08711-60063 through your local HP office.

Service Manual Omissions

Several commonly used part numbers for 75 ohm HP 8711As were inadvertently omitted from the service manual. Please add the following 75 ohm parts.

Description	HP P/N
Front panel assembly	08711-60071
Front dress label	08711-80004
Test port assy (conn and brackets)	08711-60039
J2 to RF out cable	08711-20047

Also omitted was the entire chassis (frame and interconnect board). The HP P/N is 08711-60009 for all instrument versions. □

HP 8648A/B/C Signal Generator while it is being repaired or calibrated at the HP Golden Gate Customer Service Center.

For more information about either of these programs, contact the HP Direct Marketing Services group at 1-800-835-4747, option 1. □

1994 Bench Briefs* Instrument Service Note Index

SN Type	SN No.	Abstract	HP FIRST Document ID No.
MA	6010A-09	AC input filter assembly replacement	6051
MA	6011A-10	AC input filter assembly replacement	6052
MA	6030A-17	AC input filter assembly replacement	6053
MA	6031A-19	AC input filter assembly replacement	6054
MA	8112A-02A	Replacing 24v supply fuses with jumpers improves reliability	6007
MA	8116A-03B	Replacing 24v supply fuses with jumpers improves reliability	5875
MA	8560E-04B	Firmware upgrade kit improves performance	5797
IO	8560E-09	Mod A6 power supply to be compatible with A15 assemblies	6003
MR	8560E-10	New A15 RF assy climins high displayed noise level in wide B/W	6011
MA	8561E-03B	Firmware upgrade kit improves performance	5796
MR	8561E-07	New A15 RF assy climins high displayed noise level in wide B/W	6012
MA	8563E-04B	Firmware upgrade kit improves performance	5799
MR	8563E-09	New A15 RF assy climins high displayed noise level in wide B/W	6013
MR	8564E-01	Firmware upgrade to address flatness instability	6004
MA	8564E-01A	Firmware upgrade kit improves performance	6004
MR	8564E-02	New 5V reg improves power supply loading when mass mem mod connected	6028
MR	8565E-01	Firmware upgrade to address flatness instability	6005
MA	8565E-01A	Firmware upgrade kit improves performance	6005
MR	8565E-02	New 5V reg improves power supply loading when mass mem mod connected	6029
MR	8590D-04	New PAL device eliminates instrument failures	6037
MR	8591C-01	New PAL device eliminates instrument failures	6038
MR	8591E-04	New PAL device eliminates instrument failures	6039
MR	8592D-02	New PAL device eliminates instrument failures	6040
MR	8593E-05	New PAL device eliminates instrument failures	6041
MR	8594E-05	New PAL device eliminates instrument failures	6042
MR	8595E-05	New PAL device eliminates instrument failures	6043
MR	8596E-05	New PAL device eliminates instrument failures	6044
IO	E1650A-05	Alternative test procedure for TOH and POH ports	6056
IO	E1652A-04	Alternative test procedure for TOH and POH ports	6057
MR	E2411C-01	New capacitor corrects clock PLL lock problem at upper freqencies	6008
IO	37721A-12	Instructions to retrofit virtual remote facility (Opt V01)	6017
MR	37724A-01	Power supply modification improves reliability	6018
MR	54502A-06	Mod eliminates input resistance performance test failure	6020
MR	54503A-05	Mod eliminates input resistance performance test failure	6021
MR	54504A-02	Mod eliminates input resistance performance test failure	6022
MR	54510A-01	Mod eliminates input resistance performance test failure	6023
MR	54600A-10	Mod replaces defective BNC connector	6031
MR	54600B-01	Mod replaces defective BNC connector	6032
MR	54601A-10	Mod replaces defective BNC connector	6033
MR	54601B-01	Mod replaces defective BNC connector	6034
MR	54602A-02	Mod replaces defective BNC connector	6035
MR	54602B-01	Mod replaces defective BNC connector	6036
IO	54721A-01	Instructions on changing channel or trigger input connector to Type-N	6024
MR	89430A-02	New plastic tubing prevents power supply cable short	6026
IO	89440A-06	89410A/89430A repair strategy	6049
IO	89441A-01	89410A/89431A repair strategy	6050

Service Note Types				
IO	Information Only		MA	Modification Available
MR	Modification Recommended		SA	Safety
PS	Priority Safety		SM	Interoffice Service Memo (IOSM)

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