Automation of NIST Frequency Calibrations at Remote Sites

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Abstract

NIST has performed remote frequency calibrations since 1984 through the NIST Frequency Measurement and Analysis Service (FMAS). Customers who require traceability to the NIST frequency standard can subscribe to the FMAS by paying a monthly calibration fee to NIST.

The calibrations made at the customer's site are automated by a frequency measurement system that NIST supplies to each customer. NIST provides training and phone support for the measurement system, and obtains and validates each customer's data through a modem hookup. Each customer receives a monthly calibration report that documents traceability to NIST.

This paper provides a brief introduction to frequency calibrations, describes the measurement system delivered to the customer's site and what it does, and explains how NIST operates the service and reports calibration results. It also details some future enhancements to the service that are now under development.

1. Introduction

Like all calibrations, a frequency calibration is simply a comparison. The device under test (usually a quartz, rubidium, or cesium oscillator) is compared to a reference frequency. The reference frequency must be traceable, meaning that its uncertainty relative to national and international standards should be continually measured and reported. As a general rule, the reference should also perform significantly better (usually one order of magnitude) than the device under test.

It is recommended that frequency calibrations be performed on-site. In other fields of metrology, it is common for the device under test to be shipped to another laboratory for calibration. In other cases, the reference (for example, a standard set of weights used for mass calibrations) is moved from site to site as a transfer standard. Neither practice lends itself well to frequency calibrations. If an oscillator is calibrated and then turned off, the calibration is probably invalid when the oscillator is turned back on. In addition, the vibrations and temperature changes encountered during shipment can change the results. Thus, it is preferable for oscillators to be calibrated on site.

Fortunately, the reference used for a frequency calibration can be distributed by radio and received simultaneously at a number of sites if each site is equipped with a radio receiver. The receiver itself becomes a transfer standard that provides a comparison link to national and international standards. The signal received by the transfer standard can be either controlled or monitored by a national metrology institute (NMI) in order to achieve traceability.

Several types of time and frequency signals are transmitted in different parts of the radio spectrum. NMIs often operate high frequency and low frequency radio stations (like NIST radio stations WWV/WWVH and WWVB). [1] NIST and other NMIs monitor and compare signals from radionavigation systems like LORAN-C and the Global Positioning System (GPS), so that these signals also become traceable references.

Radio signals make it possible and practical to automate remote calibrations. They eliminate the need to physically move either the device under test or the reference to another location. NIST recognized the uniqueness of frequency calibrations and designed the FMAS so that the customer's calibrations are automated on site with a measurement system that receives the reference it needs by radio. NIST delivers the measurement system to the customer, rather than have the customer deliver the devices to be tested to NIST. The original FMAS (1984-1994) used a LORAN-C receiver as a reference [2] In 1994, the service was redesigned using a GPS receiver. [3]

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2. Current Measurement System Configuration

The measurement system delivered to FMAS customers is housed in a metal rack (approximately 712 x 529 x 546 mm). It contains a measurement computer, a rack-mounted video monitor and keyboard, a printer, a modem, a time interval counter, and a GPS receiver. A GPS antenna must be mounted on a rooftop location free from obstructions, and the system must be connected to a dedicated telephone line. Software developed at NIST controls and automates all aspects of the measurement. It makes measurements and stores and graphs them automatically. Data is stored on a non-volatile, solid state storage device. A block diagram of the system is shown in Figure 1. Over 40 of these systems are located in metrology laboratories throughout the United States and in several other countries.

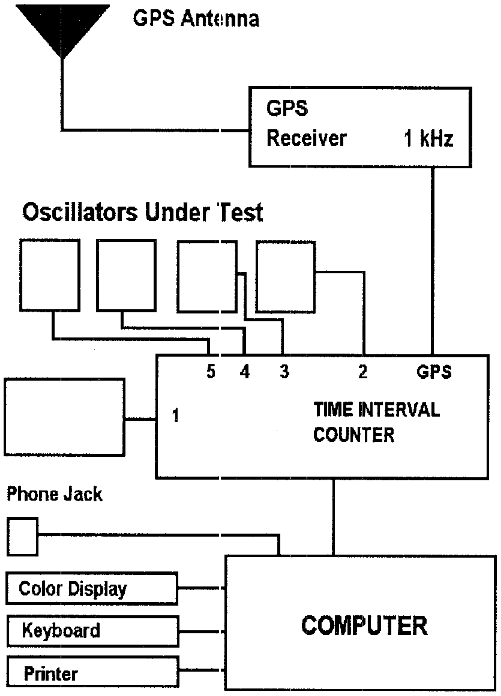

Figure 1 – Diagram of FMAS Measurement System

The FMAS makes measurements using the time interval method, with a time interval counter designed specifically for frequency calibrations. The counter's single-shot resolution is < 40 ps and it can sample at a rate of up to 2 kHz with no dead time. [4] The counter includes a multiplexer that allows switching between 5 input frequencies. This allows the FMAS to measure and calibrate up to 5 devices simultaneously. The counter includes built-in divider circuitry and can automatically accept a 1, 2, 2.5, 5, or 10 MHz input on each of the 5 channels. This allows the FMAS to directly accept the output of most quartz and atomic frequency standards.

The GPS receiver provides a 1 kHz frequency reference directly to the counter. The receiver can track multiple satellites using the L1 carrier frequency of 1575.42 MHz. The receiver is an OEM module that has been embedded into the FMAS design; it is mounted on a custom printed-circuit card that connects directly to the computer's bus and is controlled entirely by software. Software controls the GPS signal acquisition when the system is first turned on and checks the integrity of the received signal while calibrations are in progress. The software also synchronizes the computer's time-of-day clock to GPS every 10 min to insure that the collected data are accurately time stamped.

The GPS antenna is a quadrifiler helix housed in a small plastic cone about 80 mm in diameter. The antenna contains a low noise amplifier that provides about 37 dB of gain and is powered by the receiver through the antenna cable. The amplifier provides sufficient gain to drive about 20 m of standard coaxial cable (RG-58). Cable runs of over 100 m are possible by using a combination of lower-loss cable and inline amplifiers. If the antenna is properly installed, GPS reception should be extremely reliable, and unlike ground-based systems, reception is possible anywhere on Earth.

3. Operation of the Measurement System

The FMAS calibrates oscillators by making a phase comparison between the device under test and the reference using the time interval method. To reduce the uncertainty and increase the confidence of the measurements, data are averaged for 1 h and a calibration is completed every 24 h. The time interval counter serves as a phase comparison device that measures the phase rate of change between the device under test and the reference. The system software records the time interval measurements and performs the required calculations necessary to show the frequency offset of each device. [5] The time interval counter used by the FMAS is stable to ~100 ps/day and therefore contributes an uncertainty of just 1×10^{-15} to the calibrations.

The FMAS compares the customer's primary frequency standard to GPS on channel 1 and compares other frequency standards to the customer's primary standard on channels 2-5. The measurement uncertainty of the customer's primary standard relative to NIST is limited to 5×10^{-13}, mainly due to the fluctuations of the GPS broadcast. For national security reasons, the United States Department of Defense (USDOD) intentionally degrades the accuracy of GPS through its Selective Availability (SA) program, which adds noise to the signal. Although averaging reduces the effects of SA, it remains the largest contributor to the measurement uncertainty of the FMAS. Table 1 lists the measurement specifications of the FMAS.

Once the system is started, measurements run unattended, 24 hours per day, 7 days per week. While measurements are in progress, the system displays a bar graph that shows the frequency offset of each device over the past 24 h, with a scale ranging from parts in 10^5 to parts in 10^{13}. A different colored bar is used for each of the 5 devices under test. Laboratory personnel can quickly look at the bar graph to check the status of their frequency standards. For example, a calibration laboratory may be required to distribute a 5 MHz signal throughout an entire facility, and to maintain the frequency of this signal to within 1×10^{-10}. A quick glance at the measurement display will indicate whether the distributed signal meets the requirement.

The measurement system can produce its results in both tabular and graphical format. Some data are produced automatically. The FMAS automatically prints a graph of each oscillator's performance every 24 h at a time selected by the customer. Since 1 to 5 oscillators can be measured, from 1 to 5 graphs are printed each day. Other data can be retrieved on demand. Since all data recorded by the FMAS are stored, they can be retrieved at any time. The FMAS can produce stability graphs (using the Allan deviation) for intervals ranging from 1 to 1000 s. It can produce phase comparison graphs showing the device's frequency offset for intervals ranging from 2 to 3600 h (about 5 months). A sample phase comparison graph is shown in Figure 2.

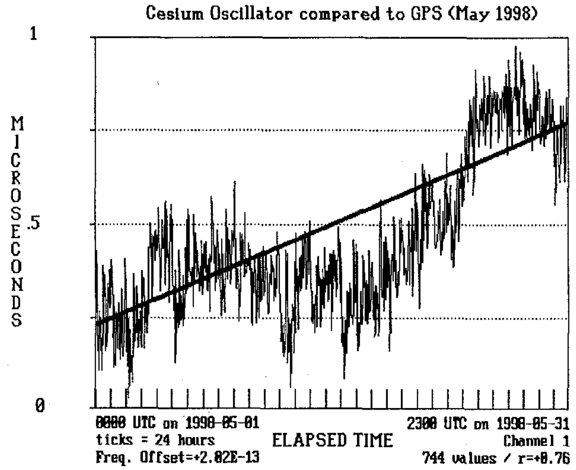

Figure 2 – Sample Phase Comparison Graph

NIST is responsible for the maintenance of the measurement system hardware. All problems are diagnosed remotely using the modem connection and through telephone consultation with the customer. The remote communications software included with the FMAS allows NIST personnel complete access to the system. If necessary, NIST can perform maintenance on the measurement computer, like recovering a damaged file or installing an update to the measurement software. If any part of the FMAS fails, a new part is sent (usually overnight), with installation instructions.

Table 1 – FMAS Measurement System Specifications

Number of measurement channels	5
Input frequencies accepted by system	1, 2, 2.5, 5, and 10 MHz
Data capacity (single graph)	3600 h
Averaging period (long term measurements)	1 h
Averaging period (short term measurements)	1 s
Single shot counter resolution	< 40 ps
Measurement uncertainty w/GPS at 24 h	5×10^{-13}
System stability (Allan deviation) at 1000 s	$< 1 \times 10^{-13}$

4. Reporting of Calibration Results

NIST personnel retrieve data from each customer through a modem connection, analyze the data at the NIST laboratories, and then prepare and send a monthly calibration report to the customer. The report is compliant with section 13 of ISO Guide 25 and ANSI/NCSL Z-540. [6,7] The report lists the customer name and the manufacturer and model number of the device under test, and displays the calibration data in both tabular and graphical form. It also provides a statement of measurement uncertainty.

NIST assigns a status code to each daily calibration. The possible status codes are listed in Table 2. If a status code other than 0 is assigned, the report contains a brief comment that explains the problem. NIST personnel investigate all calibration problems and take action to prevent them from occurring again. NIST can identify GPS broadcast errors through GPS status reports made available by the USDOD and through its own continuous monitoring of the GPS constellation made available on the Internet. [8]

Each report is signed by two authorized signatories at NIST (the report preparer and a supervisor).

5. Future Enhancements to the FMAS

NIST is currently redesigning the FMAS with four goals in mind: making the system more versatile, making the system easier to use, reducing the measurement uncertainty, and using the Internet as a data transfer and remote control mechanism.

Table 2 – Status Codes Used on FMAS Calibration Reports

Status Code	Description
0	*Valid Calibration* – NIST has determined that all components of the measurement system were working properly during the calibration, and that the device under test was within tolerance.
1	*No Data* – No data were recorded. The measurement system was either turned off or malfunctioning.
2	*GPS Reception Error* – A problem with GPS reception had a negative impact on the calibration.
3	*GPS Broadcast Error* - Information broadcast from a GPS satellite had a negative impact on the calibration.
4	*Measurement System Error* – NIST has determined that the measurement system was malfunctioning due to a hardware or software error.
5	*Device Under Test Error* – The device under test was out of tolerance during the calibration.
6	*Device Under Test Change* – The device under test was replaced by another device during the 24 h calibration.

To improve the system's versatility, we recently completed the design of a new time interval counter board with an embedded GPS receiver. The resolution and stability of the new counter is at least equivalent to our previous counter, but more importantly, it adds several new features that will make future systems more versatile. The new system will allow up to 9 devices to be connected at once, or four more than the previous version. The new system will also accept *any* input frequency from 1 Hz to 100 MHz. This was accomplished by adding a 24 bit programmable frequency divider to every input (input frequencies higher than 16 MHz are prescaled before passing through the divider). Whereas the previous system could only calibrate devices with standard frequency outputs of 1, 2, 2.5, 5, or 10 MHz, the new system will be able to calibrate oscillators that produce any frequency up to and including 100 MHz. This allows the calibration of frequency sources used in telecommunication systems (1.544, 2.048, and 44.736 MHz, for example), as well as specialized frequencies used in other industries. Measurements will be made at either a 1 Hz or 100 Hz rate.

To improve the system's ease of use, we are adding a more graphically oriented user interface. We might eliminate both the keyboard and mouse by using a touch screen. We also intend to increase the system's data capacity.

To reduce the measurement uncertainty, future versions of the FMAS may use the multi-channel common-view technique to directly compare the customer's frequency standard to the NIST standard. Currently, the FMAS uses GPS in the *one-way* mode. The receiver simply uses the signal from whatever satellites are currently in view and produces frequency using a composite average of these satellites. Due to SA, the uncertainty of this method is limited to about 5×10^{-13} when averaged for 1 day. The multi-channel common-view technique will require the FMAS to make measurements from individual satellites and to store these measurements in a format identical to a master system located at NIST. When NIST processes the customer's data, it will align data where both NIST and the customer were receiving a signal from the same satellite at the same time. The effects of SA are removed by subtracting the customer's data from the NIST data, and what remains is the offset between the customer's frequency standard and the NIST standard. [9] Since as many as 8 satellites can be tracked at once, customers in the United States should be able to obtain continuous, 24 hours common view data with NIST, and the overall measurement uncertainty of the FMAS should improve by a factor of nearly 10, to parts in 10^{14}.

The biggest constraint in using the common-view method is that it requires a real time data exchange between NIST and the customer in order for the calibration results to be immediately known. It is possible to use the Internet for this real time data exchange, although Internet connections are not currently available to all customers. Even if Internet data transfer is not available, the common-view corrections can be applied to the monthly calibration report generated by NIST and sent to each customer.

Use of the Internet (rather than the phone system) as a remote control mechanism is also a useful feature of the new design. It is possible to turn each measurement system into a Web server (accessible only to authorized users) and to even design the system to use a complete Web based interface. The advantages and disadvantages of these approaches are still being weighed, but some type of Internet connectivity will undoubtedly be added.

6. Customer Benefits

The FMAS standardizes the way that a laboratory performs frequency calibrations. All customers record data in the same way using identical calibration procedures. Customers do not need to develop their own calibration system or establish a traceability chain back to national and international standards. Instead, NIST oversees the entire measurement process remotely. The measurements and uncertainty analysis become the responsibility of NIST and require little or no attention from the user. Since the calibration burden is passed from the customer to NIST, the labor savings often easily exceed the service costs.

The FMAS can also benefit customers who seek compliance with International Organization for Standardization (ISO) requirements or who pursue laboratory accreditation. The FMAS is compliant with ISO Guide 25 and the United States equivalent, the ANSI/NCSL Z540-1. [6,7] It can therefore assist laboratories seeking accreditation through organizations such as the National Voluntary Laboratory Accreditation Program (NVLAP) operated by NIST. NVLAP assesses the technical competence of calibration labs and grants accreditation to those who qualify. [10]

NVLAP can accredit laboratories in 8 different fields of calibration. Each field is divided into more specific areas called parameters. For example, frequency calibration is a parameter in the time and frequency field. Since FMAS customers are using a traceable, documented calibration method with quantified uncertainties; they can obtain NVLAP accreditation for frequency calibration if they choose to do so.

7. Summary

Using radio receivers as transfer standards makes remote frequency calibrations both possible and practical. NIST has performed remote frequency calibrations since 1984 through its Frequency Measurement and Analysis Service (FMAS). Each FMAS customer receives a frequency measurement system that resides in their laboratory and automates the calibrations. Data from the system are transferred to NIST through a telephone modem, and monthly calibration reports are sent. The current version of the FMAS has a measurement uncertainty of 5×10^{-13} and can simultaneously calibrate up to 5 devices using GPS signals in one-way mode as a reference. A new measurement system now under development will calibrate up to 9 devices simultaneously and will accept any input frequency from 1 Hz to 100 MHz. The new system is expected to reduce the measurement uncertainty to $< 1 \times 10^{-13}$ using GPS signals in common-view mode and to use the Internet rather than telephone lines as a data transfer mechanism. FMAS subscribers benefit from the use of a standardized calibration system that reduces labor costs and helps them obtain accreditation in the frequency calibration field.

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