The NIST Frequency Measurement Service

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The NIST Frequency Measurement Service (FMS) began operation in 1984 to assist users who needed to make high-level frequency calibrations traceable to NIST. Organizations can subscribe to the service by paying a monthly calibration fee to NIST. The FMS provides a complete solution to all frequency calibration problems by providing a frequency measurement system that can be instaledl in the customer's lab. The system includes all hardware, software, and documentation needed to automate the frequency measurement process. NIST provides training and phone support and validates customer data through a modem hookup. Any parts that fail are replaced using an overnight delivery service. Each lab receives a monthly report that certifies traceability to NIST.

In 1994, the service was completely redesigned to incorporate the most recent developments in the field of frequency measurement. The result is a new service that provides more features and benefits than ever before to the calibration laboratory.

Introduction

Like all calibrations, a frequency calibration is simply a comparison. The device being calibrated (usually an oscillator) is compared to some sort of standard, or reference. As a general rule, the reference should perform significantly better (usually one order of magnitude) than the oscillator. The reference must also be traceable, meaning that it should be kept in agreement with the national standards maintained by NIST.

Frequency calibrations differ from other types of calibrations in at least two important respects. First, in other fields of measurement, units are often shipped to another site for calibration. This creates problems with oscillators. If an oscillator is calibrated and then turned off, the calibration may be invalid when the oscillator is turned back on. Plus, the vibrations and temperature changes during shipment can also affect the results. For these reasons, laboratories that are serious about frequency calibrations make the calibrations on-site. Second, the reference used for most calibrations is a physical object that has to be moved from the site of one calibration to the next (like a standard set of weights used for mass calibrations). For frequency calibrations, a radio signal can be used as a reference. A number of traceable radio signals can be used: WWV, WWVB, GOES, LORAN-C, and GPS, for example.[1]

The ability to use radio signals is a tremendous advantage. It means that calibrations can be made simultaneously at a number of sites as long as each site is equipped with a radio receiver. There is no need to move the reference from one place to another.

NIST recognized the uniqueness of frequency calibrations and designed the FMS so that each user's calibrations can be performed on-site using a radio signal. In 1984, an automated measurement system was designed and installed at each customer's site.[2] Since that time, NIST has enhanced and improved the measurement system. The new design takes advantage of recent developments in both measurement hardware and software. Plus, it includes many features that customers have recommended and requested over the past 10 years.

System Design

The frequency measurement systems used by the service have always been largely comprised of commercially-available hardware. This hardware is combined with hardware, software, and measurement techniques developed at NIST to create an integrated system.[3]

The new measurement system is named the Frequency Measurement and Analysis System (FMAS). The FMAS is rack-mounted and controlled by a 486 computer. Software developed at NIST controls all aspects of the measurement process. It makes measurements, stores and graphs them automatically. It even backs up the data automatically on tape every 10 days.

The FMAS makes measurements using the time interval method. It includes a time interval counter developed at NIST with a single-shot resolution of less than 40 picoseconds with no dead time.[4] Previous versions of the system used a counter with 10 nanosecond resolution. Because of this huge improvement in resolution (over 250 times), the new system is much better suited to making short term stability measurements.

The time interval counter has five start-stop inputs. This allows the FMAS to measure and calibrate up to five oscillators simultaneously. The counter includes built-in divider circuitry and can automatically accept either a 1-, 5-, or 10-MHz input on each of the five channels. This allows the FMAS to work with most commercially-available quartz and atomic oscillators.

The FMAS uses a Global Positioning System (GPS) receiver as its reference frequency, and is connected to NIST through a telephone line.

Global Positioning System (GPS)

The GPS is a radio navigation system maintained by the U.S. Department of Defense. It consists of an orbiting constellation of 24 satellites (plus in-orbit spares). Each satellite carries a group of atomic oscillators. Although GPS is primarily used as a navigation and positioning tool, it also serves as an excellent reference for time synchronization and frequency calibrations.

Previous versions of the FMAS system used LORAN-C, but GPS has several advantages. The signal is easier to receive, requires a much smaller antenna, and offers slightly better performance. GPS also provides time-of-day information to the FMAS, whereas LORAN-C lacked a time code. The time broadcast by GPS is officially referenced to the United States Naval Observatory and is also traceable to NIST.[5] The time is kept within 340 nanoseconds of Coordinated Universal Time.

Perhaps the biggest advantage of GPS over LORAN-C is its coverage area. LORAN-C is a ground-based system and users must typically be within 1600 kilometers (1000 miles) of a transmitter site to receive the signal. In many parts of the world, LORAN-C is not usable. For example, no transmitters are located in the Southern Hemisphere. GPS covers about 99.6% of the earth's surface, excluding only the Poles. This means that the FMAS could be used nearly anywhere on earth.

The GPS receiver used by the FMAS is rack-mounted and uses a small, conical antenna that must be mounted in a location with a clear view of the sky. The receiver is connected to the computer through an RS-232 interface. The FMAS software takes the receiver through the signal acquisition process and makes sure that the signal is usable for calibrations. The software also displays a GPS status screen, which shows signal strength and quality, and information about the satellites being tracked. The computer clock is synchronized to GPS, so that the data recorded by the system is time-stamped correctly.

When the FMAS is first installed at a customer site, it takes about 20 minutes for the GPS receiver to acquire the signal. During this time, the receiver searches the sky for satellites and computes its own geographic location. The location data is stored, and the process does not have to be repeated unless the system is moved. If the receiver is turned off, it normally acquires the signal in less than one minute when turned back on.

Once the signal is acquired, the receiver synchronizes two frequency outputs, 1 kHz and 1 Hz, to GPS. As shown in Figure 1, the 1 kHz output is used as the reference frequency. The 1 Hz output is available for applications requiring an on-time pulse.

Calibration and Characterization

In the field of frequency measurement, the terms calibration and characterization are used to refer to an oscillator. Calibration is the process of measuring an oscillator to ensure that it meets or exceeds its specified requirement for accuracy. For example, an oscillator may be required to produce a frequency accurate to one part per billion (1.00E-09) per day. Once we know that it meets or exceeds that level of accuracy, the oscillator has been successfully calibrated. In some cases, an adjustment to the oscillator must be made before the calibration is successful. If the oscillator is broken for example, and unable to meet the accuracy requirement, it is sent out for repair or removed from service.

Characterization is more involved than calibration and less likely to be required by a laboratory. It involves measuring both the accuracy and stability of an oscillator, and being able to state both characteristics in a quantitative way. For example, if we can say that an oscillator is accurate to 1.32E-08 and has a stability of 1.34E-12 at 1000 seconds, the oscillator has been *characterized* for that interval. The exact tests required to complete an oscillator characterization must be determined by the laboratory.

The FMAS was designed to make it easy to both calibrate and characterize oscillators. How easy? In the case of a calibration, you simply need to plug from one to five oscillators into the system and type in the name of each oscillator from the keyboard. You'll see a screen similar to the one shown in Figure 2. This screen displays a bar graph that shows the accuracy of each oscillator connected to the FMAS.

By looking at the graph, you can quickly tell if the oscillator meets its calibration requirement. The numbers above the bar show the oscillator's performance over the past 24 hours. If a bar extends to the number 9, it represents a relative frequency of 1.00E-09. The longer the bar, the better the performance of the oscillator. If

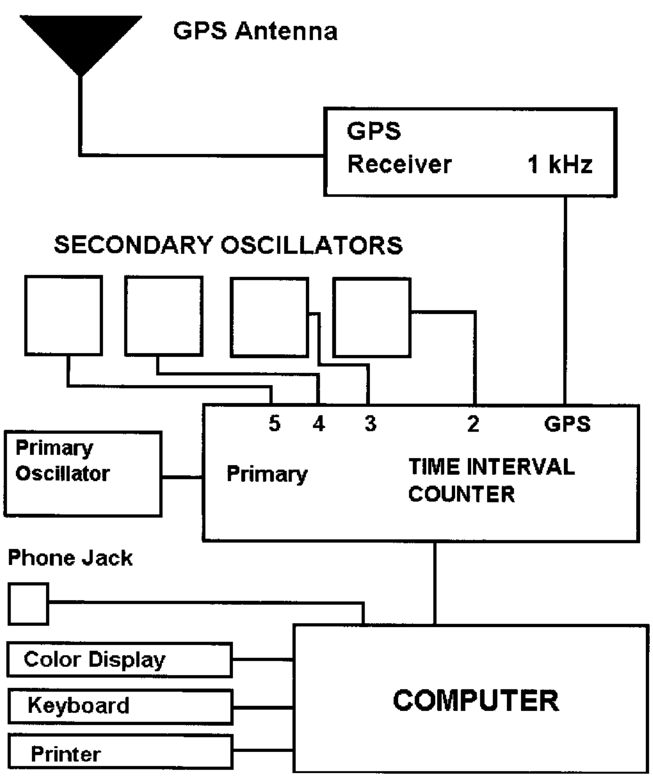

Figure 1. Block diagram of the NIST Frequency Measurement and Analysis System.

the bar extends all the way to the right, the relative frequency of the oscillator is 1.00E-13 or better.

Each bar is color coded, and a different color is used for each of the five channels. Often all you need to do is periodically look at the length of the bar to see if things are working properly. For example, you may need to distribute a 5 MHz signal throughout an entire facility, and maintain this signal at an accuracy of 1.00E-09 or better. If the bar extends past the number 9, you'll know that the distributed signal meets its requirements.

Of course, you may need more detail than that provided by the measurement screen. For this reason, the FMAS automatically prints a graph of each oscillator's performance every 24 hours. Since one to five oscillators can be measured, from one to five graphs are printed each day. The graphs show oscillator phase shift versus time of day. These graphs can also be printed at any time by simply pressing a key on the keyboard. The plots are printed on regular 8.5 x 11 inch paper. A sample graph is shown in Figure 3.

The graph in Figure 3 shows that the oscillator has a relative frequency (RF)of -2.33E-11. Rather than simply stating that the oscillator exceeds its calibration requirement, it specifically tells us how far the oscillator is off in frequency relative to a reference frequency. The reference frequency should be at least one order of magnitude (10 times) more accurate than the oscillator being calibrated. In this case, the oscillator being calibrated is a rubidium and the reference frequency is a cesium. The relative frequency number states the accuracy of the rubidium relative to the cesium. This is the precise kind of information needed for an oscillator characterization.

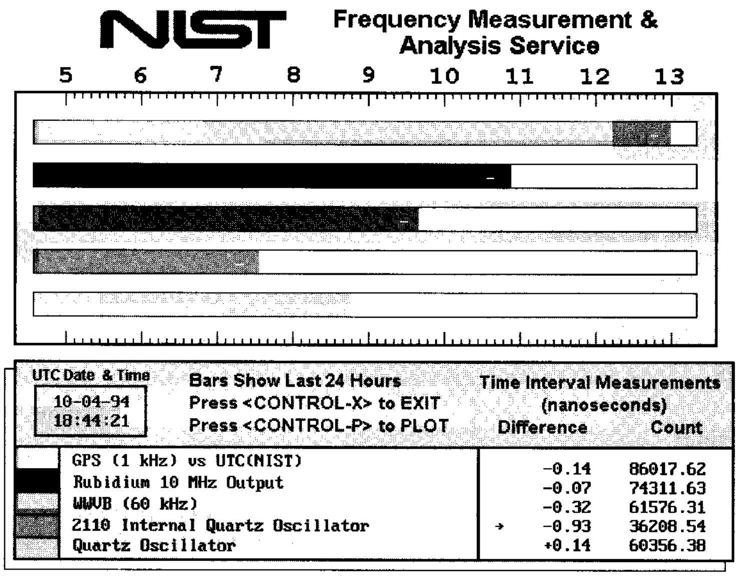

Figure 2. The NIST FMAS measurement screen.

All data recorded by the FMAS is automatically saved and can be retrieved by the user at any time. Users aren't limited to producing 24-hour graphs like the one in Figure 3. The FMAS can graph oscillator performance for intervals ranging from 2 seconds to 3000 hours (about 4 months).

Accuracy and Stability

Calibration measures whether an oscillator meets or exceeds its accuracy requirement. Since the FMAS serves as a calibration tool, its primary function is to measure accuracy. Accuracy is defined as the degree of conformity of a measured or calculated value to its definition. In other words, it tells us how accurately an oscillator produces its *nameplate frequency*. The nameplate frequency is the frequency labeled on the oscillator output. For example, an oscillator output labeled 5 MHz should produce a 5-MHz frequency. The relative frequency value tells us how close the actual frequency is to 5 MHz.

The FMAS uses relative frequency values to report accuracy. Relative frequency is dimensionless, meaning that it does not refer to a specific averaging period, or a specific unit of measurement. For example, if we say that an oscillator has a relative frequency of

1.00E-09, it means that the oscillator's frequency is off by 1 part in 10^9, or 1 part in 1 billion parts. This holds true if the nameplate frequency is 1 MHz, 5 MHz, 10 MHz, etc. The relative frequency is independent of the nameplate frequency.

We can compute the actual frequency output of an oscillator if we know the nameplate frequency and the relative frequency. To illustrate this, Figure 3 is a graph of an oscillator with a nameplate frequency of 5 MHz that has a relative frequency of -2.33E-11. What is the actual output frequency of the oscillator? To find out, first multiply the nameplate frequency by the relative frequency:

$$(5 \times 10^6)(-2.33 \times 10^{-11})$$
$$= -11.65 \times 10^{-5}$$
$$= -0.0001165 \text{ Hz}$$

This is the frequency offset in Hertz. Therefore, the actual frequency is:

4,999,999.9998835 Hz

In addition to accuracy, the FMAS can also measure the stability of an oscillator. Stability is a description of the frequency change of an oscillator that occurs over time. A more proper term for these changes is probably instability, but the term stability is more widely used. Short-term stability usually refers to changes over intervals less than 100 seconds. Long-term stability can refer to measurement intervals greater than 100 seconds, but usually refers to periods longer than 1 day.

A statistical test used to measure stability is the Allan Variance (AVAR), also called the two-sample or pair variance.[6] AVAR graphs look different than the graphs used to measure accuracy. They don't show the rate at which the oscillator is drifting or how close the oscillator is to the correct frequency. Instead, they show the stability of the oscillator output with the drift removed. To illustrate this difference, Figures 4 and 5 both use data from the same 5-minute measurement period. Figure 4 shows the accuracy of the oscillator, and Figure 5 shows its stability.

AVAR plots use a logarithmic scale. The values along the x-axis (called *tau* values) represent the length of the averaging period in seconds. Each division represents an averaging period 10 times longer than the previous division. For example, a tau value of 2 represents an averaging period of 100 seconds (10^2). A tau value of 3 represents an averaging period of 1000 seconds (10^3).

The values along the y-axis represent the result of the measurement. A value of -10 means that the oscillator has a stability of 1.00E-10. This value should not be confused with the accuracy (relative frequency). For example, an oscillator off in frequency by 1.00E-08 may reach a stability of 1.00E-12 in 1000 seconds. This means that even though the oscillator is producing a frequency off by 1.00E-08, it is doing so at a very stable rate.

A typical AVAR plot (Figure 5) shows the stability values improving as the measurement period increases in length. This will

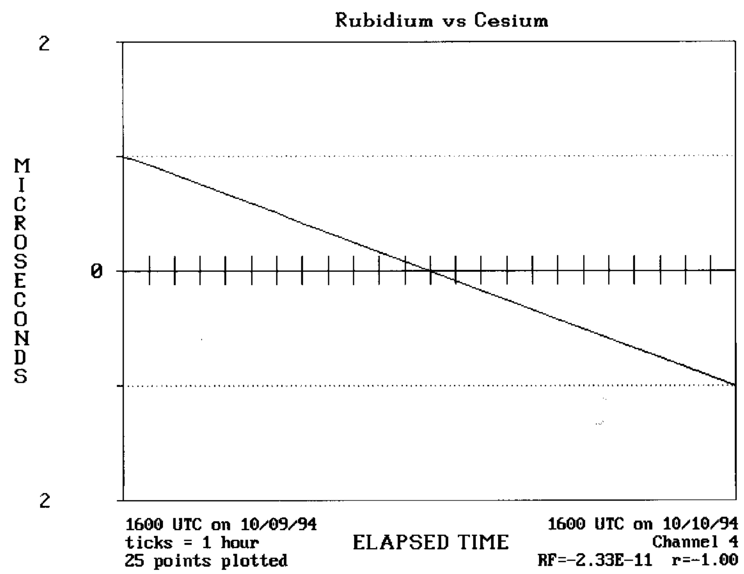

Figure 3. A sample graph produced by the NIST Frequency Measuring and Analysis System.

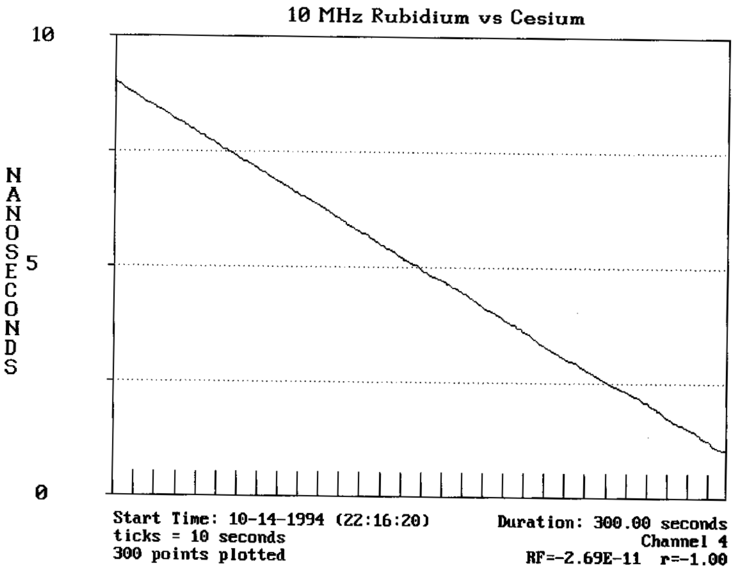

Figure 4. Accuracy plot of rubidium over 5-minute period.

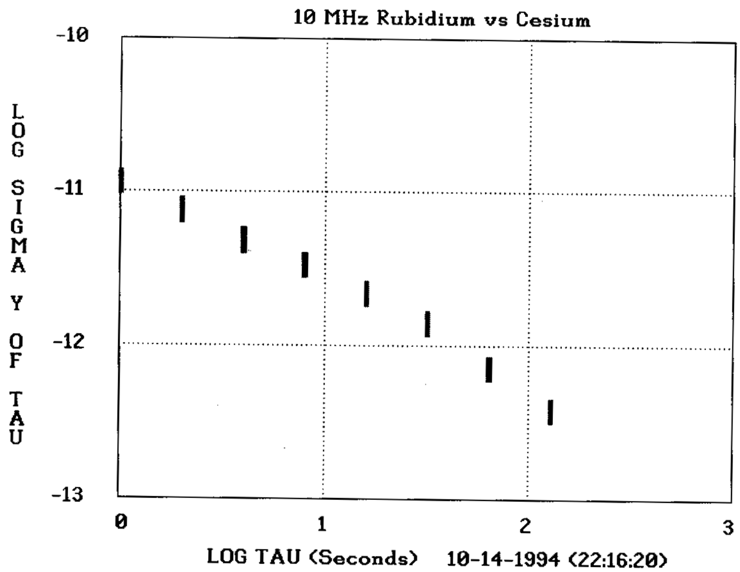

Figure 5. Stability plot (AVAR) of rubidium over 5-minute period.

continue until the oscillator reaches its noise floor, at which point the stability values will level out and then eventually start to get worse. Most oscillators reach their noise floor at a tau value of around 3. The FMAS is capable of measuring stability at a level of 1.00E-14 at a tau value of 3. This is good enough to measure nearly any oscillator.

NIST Service Support

NIST completely supports each customer of the NIST Frequency Measurement Service. If any part of the FMAS fails, it is replaced immediately (usually overnight). Plus, each FMAS is shipped with remote communications software. This allows NIST to run each system from Boulder, Colorado through the phone lines. NIST can diagnose and troubleshoot problems with the system, and view and graph the measurement data. If necessary, NIST can even perform maintenance on the computer, like optimizing the hard drive, recovering a damaged file, or installing an update to the measurement software.

NIST downloads the daily relative frequency values from each customer and sends a monthly report which certifies that their data is traceable. If the data is poor, NIST will investigate the problem and help the customer correct it. Technical support is provided by telephone Monday through Friday, during normal working hours.

Laboratory Accreditation

Over the past few years, it has become increasingly important for calibration laboratories to become accredited and for their companies to obtain ISO 9000 registration. The NIST Frequency Measurement Service conforms to the guidelines published by the National Voluntary Laboratory Accreditation Program (NVLAP), which became operational in May 1994.

The NVLAP guidelines are based on ISO Guide 25, ISO-9002, and the ANSI/NCSL Z540-1 standard. Service customers can easily obtain NVLAP accreditation for frequency calibration if they choose to do so.

References

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6 D. B. Sullivan, D. W. Allan, D. A. Howe, and F. L. Walls, editors, *Characterization of Clocks and Oscillators*, NIST Technical Note 1337, 1990.

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NIST Frequency Measurement and Analysis System Specifications

Number of Measurement Channels	5
Input Frequencies Accepted by the System	1, 5, 10 MHz
Maximum Number of Data Points per Graph	3000
Averaging Period (long term measurements)	1 hour
Averaging Period (short term measurements)	1 second
Single Shot Measurement Resolution	< 40 psec
Accuracy using GPS (24 hours)	5.00E-13
Stability (AVAR) after oscillator self-test of 1000 seconds	1.00E-14