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Remote Frequency Calibrations: The NIST Frequency Measurement and Analysis Service

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Introduction

The National Institute of Standards and Technology (NIST) provides its Frequency Measurement and Analysis Service (FMAS) to paying customers on a subscription basis. Subscribers to the service receive a complete frequency measurement system (FMS) that they install in their facility.* The service can measure any frequency from 1 Hz to 120 MHz in 1 Hz increments. As many as five devices can be measured and calibrated at once, even if all five have different output frequencies. The FMAS uses Global Positioning System (GPS) signals as its link back to the United States national frequency standard, the Coordinated Universal Time Scale maintained at NIST, called UTC(NIST). Since GPS can be received anywhere on the Earth's surface, the service can potentially be provided anywhere on Earth where telephone service is available. All measurements are made automatically and are traceable to the International System of units (SI) through UTC(NIST) at an uncertainty ($k = 2$) of 2×10^{-13} for an averaging time of one day.

The FMAS was designed to continuously measure and calibrate a customer's primary frequency standard, 24 h per day, 7 days per week. This continuous measurement provides the customer with confidence that their primary frequency standard is operating properly, and that its frequency uncertainty is continuously known with respect to the national frequency standard. Unlike other calibration services that only periodically complete the traceability chain, the FMAS continuously establishes traceability by measuring and reporting on the primary frequency standard's performance at all times.

NIST regularly checks each system by telephone modem to insure proper operation and to obtain the measurement data. NIST verifies the data from each system and mails each subscriber a monthly calibration report that certifies that their primary frequency standard is traceable to the SI through UTC(NIST) at a stated measurement uncertainty. If an FMS part fails, it is replaced by NIST using an overnight delivery service.

This booklet describes the FMAS in detail. It provides a physical and technical description of the service, describes its theory of operation and its measurement uncertainties, and explains how NIST provides and maintains the service for its customers.

** Throughout this document, the acronym FMAS will be used to refer to the calibration service, and the acronym FMS will be used to refer to the measurement system provided to the customers of the service.*

Acknowledgements

Special thanks are due to George Kamas, Andrew Novick, and Lisa Nelson. Kamas conceived the idea of a remote frequency calibration service, launched the service in 1984, and served as its project manager until his retirement in 1993, when he was replaced by the author. Novick has provided engineering and technical support for the service from 1998 to 2004, a role previously filled by Nelson from 1994 to 1998. Without their dedicated efforts, operation of the FMAS would not have been possible.

Chapter 1

History and Physical Description

The FMAS is a network of individual frequency measurement systems located at each of its customer's laboratories, and connected by telephone lines to the NIST laboratories in Boulder, Colorado. Each individual system includes a GPS satellite receiver and antenna, a time interval counter, and a computer that controls the measurements. The data collected from all customer sites are stored and archived at NIST, and calibration reports are sent each month to every customer. Several master units are also maintained by NIST. The master units, which comprise the same hardware and software as the customer's units, continuously compare the received GPS signals to the national frequency standard. In this way, NIST can continuously monitor the frequency uncertainty of each customer's unit, and the uncertainty of their primary frequency standard.

This chapter begins by providing a history of the FMAS. It then provides a physical description of the FMAS components and facilities.

A. History of the FMAS

The FMAS has its origins in contractual work performed by NIST (then called the National Bureau of Standards, or NBS) for the United States Air Force, specifically the Rome Air Development Center (RADC), during the period from about 1980 to 1983. The project was led by NBS engineer George Kamas. The RADC's contractual requirements called for a frequency measurement system that was versatile enough to measure a variety of different inputs, transportable enough to work at a variety of different field sites, and flexible enough to be reconfigured by the operator. In addition, it should be microprocessor controlled, so that it could run continuously without operator attention [1].

From the beginning, the plan was for each measurement system to receive its frequency reference over the air, using a radio receiver as a transfer standard. GPS was not originally considered for use with the FMS because only a few satellites had been launched, and low cost GPS receivers would not be available for several years. NBS's own 60 kHz broadcast from WWVB was briefly considered and then dismissed, due to the then high cost of a quality receiver and the fact that the single transmitter (then producing only 13 kW) failed to adequately cover the entire United States. The now defunct Omega navigation system (turned off in 1996) was also briefly considered but ruled out due to its relatively poor performance and the lack of available commercial receivers. As a result, it was decided that LORAN-C, the 100 kHz radionavigation system, was the optimal choice. The multiple, high power transmitters in the LORAN-C system covered all of the United States. In addition, the stable ground wave signals were locked to atomic oscillators maintained at the transmitter sites, and therefore served as an excellent frequency reference. Although NBS did not control the LORAN-C signals, it had been continuously monitoring the signals for years by comparing them to the national frequency standard, so their performance was well documented. The results of these LORAN-C comparisons were published monthly in the *Time and Frequency Bulletin* [2].

During the RADC effort, several different frequency measurement systems were designed by NBS. Two basic approaches were used. The first approach relied on commercial test equipment controlled over the IEEE-488 bus by a dedicated instrument controller and a commercially available LORAN-C disciplined oscillator. The total cost per system with this approach exceeded $30,000 (estimated 1984 cost). The second approach relied on low cost personal computers as the controller of custom instruments that were specifically designed for the single purpose of measuring frequency. The frequency reference was a LORAN-C navigation receiver designed for fishing boat navigation, but modified to output stable pulses from the master station of the nearest LORAN-C chain. After incurring some initial development costs, it was possible to build a system using the second approach for well under $10,000. This made it realistic for NBS to launch a measurement service on a cost recovery basis, whereas the cost of building multiple units using the first approach would have been prohibitive. Several systems were built and tested by both NBS and the RADC, and it was decided to offer these systems on a subscription or lease basis to other calibration laboratories.

This proposed frequency measurement and calibration service was based on a unique concept. Instead of the customer sending their device under test to NBS for calibration, NBS would send a measurement system to the customer. This concept, often called a remote calibration, is seldom possible or practical in other fields of metrology, but was already commonplace in the field of time and frequency, where radio broadcasts of standard frequency and time interval had existed for decades. For example, NBS/NIST radio station WWV has continuously broadcast standard frequency signals since 1923 [3]. However, this new service went beyond simply providing a signal. NBS would provide the entire measurement system and automate the calibration procedure. In addition, NBS would obtain the data over a telephone link and issue a monthly calibration report to each customer, making it perhaps the first NBS calibration service to calibrate and certify a customer's standard without actually handling the device.

During 1983, the NBS Frequency Measurement Service was announced at both the *Frequency Control Symposium* [4], and the *Precise Time and Time Interval Meeting* [5], two established meetings attended by the time and frequency community. A measurement system was shipped to the service's first customer (the Federal Aviation Administration) on January 19, 1984. The initial response to the service was favorable, and by the end of 1984, a total of 18 calibration laboratories had subscribed to the new service, and measurement systems had been delivered to each of them.

The new service was reviewed at a regional meeting of the National Conference of Standards Laboratories (NCSL) by one of its first customers in the latter part of 1984 [6]. The customer's review identified a number of problems with the first implementation of the measurement system, most related to software, reliability, and LORAN-C reception. Overall, however, the review was favorable. It noted the advantages of the FMS over the 60 kHz WWVB phase comparator that this particular customer had previously used as their frequency reference, and commented that "support from NBS is superb." NBS personnel quickly moved to correct the problem areas, and by the time a report was given about the new service at the 1985 national meeting of the NCSL [7], most problems were resolved, and a smoothly operating, reliable service was in place.

A photograph of the original FMS system is shown in Figure 1.1. The instrument controller was an early personal computer, the Apple IIe, with a 6502 microprocessor running at 1 MHz and 64 kilobytes of memory. The unit had low-resolution graphics capability that allowed it to display phase graphs of the collected data on screen and to print them on a dot-matrix printer for archival purposes. The system's operating system and all of its software resided on one single sided floppy disk with a capacity of about 124 kilobytes. A second floppy disk drive, with the same capacity, stored all of the collected data. The controller interfaced to a time-of-day clock, a 300 baud modem that was used to communicate with NBS, and a time interval counter (TIC). The custom designed TIC was controlled through a bidirectional parallel interface. It included a built-in multiplexer that allowed switching between four different incoming start/stop signals, so that different frequency sources

Figure 1.1. The original FMS (1984).

could be selected and measured simultaneously, a feature still included in current FMS units. The TIC multiplied its incoming external time base signal up to 100 MHz, and then measured time interval by simply counting zero crossings of the time base while the gate was open. Resolution was thus limited to 10 ns, the period of the time base frequency.

The original FMS contained two other instruments not under computer control. The first was the LORAN-C receiver that served as the frequency reference. The receiver was controlled by the operator through the front panel, although operation was essentially automatic after the initial installation. The receiver was connected to a 2.4 m tall fiberglass whip antenna. Since the incoming signal was at 100 kHz, signal loss was small, permitting long lengths of RG-58 antenna cables (sometimes more than 100 m) to be used as the antenna download. The receiver output Group Repetition Interval (GRI) pulses to the TIC. The GRI is the interval between LORAN-C pulse groups. Depending upon the station being tracked, the GRI ranged from 49.9 to 99.9 ms, producing an odd rate frequency ranging from about 10 Hz to about 20 Hz. The customer's primary frequency standard was divided to match this frequency using the second instrument not under computer control, a frequency divider. The divider was configured by the operator using several different switches. In addition to producing the LORAN-C GRI frequency, the divider could accept several 1, 5, or 10 MHz inputs signals and divide them to 1 Hz [8, 9]. The measurement uncertainty of the service was originally quoted as $< 1 \times 10^{-11}$ (at an averaging time of 1 day) using LORAN-C as a reference [5], and later reduced to 1×10^{-12} [9].

Throughout the 1980's, new features were added to the basic FMS design, most of them at the request of customers. The customer base continued to increase, with about half of the units located at United States military installations. The service had 40 subscribers for the first time in 1987 and briefly rose to an all-time high of 60 customers in 1991. At this time a large number of military bases began to close, resulting in the loss of more than two-thirds of the military customers. Although a number of private industry customers were added, the total number of customers dropped back into the 40 to 50 range, an area where it remains in 2004.

The second generation FMS unit (Figure 1.2) debuted in about 1990 [10]. LORAN-C was still used as the reference frequency, but a smaller, better performing receiver was used. The TIC and the frequency dividers were integrated into one box, and shortly afterwards on to a single expansion card, but the counter resolution was still limited to 10 ns. Modem speed was increased to 2400 baud. The software was ported from the Apple IIe to a PC-compatible platform and was made much more interactive and powerful, providing better graphics and data analysis features. As a result, the service's name was changed from "Frequency Measurement Service" to "Frequency Measurement and Analysis Service," so both the service and the agency now had new names (NBS had become NIST in 1988).

Throughout the 1980's, the attention of the time and frequency community had begun shifting away from LORAN-C and towards the Global Positioning System (GPS), an orbiting constellation of satellites that each carried atomic oscillators. The first experimental GPS satellite was successfully launched in 1978, GPS signals were routinely used by NBS for time and frequency comparisons by 1980 [11], and NBS had launched a GPS-based time service, called the *Global Time Service*, at about the same time the FMAS began in 1984 [4]. GPS performance was superior to that of LORAN-C, the signals were easy to receive, and the coverage area was essentially worldwide.

Figure 1.2. The second generation FMS (1990).

There were several reasons, however, that prevented the FMAS from quickly shifting away from LORAN-C and to GPS. One was that the FMAS was based on continuous measurement of the customer's frequency standard, 24 h per day, 7 days per week. Until a sufficient number of GPS satellites were launched, there would be intervals when no satellites were in view, and when no measurement data could be collected. This was the situation in the early to mid-1980's, and it was not until March 1994 that the entire constellation of 24 orbiting satellites was in place. A second reason was that early GPS receivers and antennas were much more expensive than the LORAN-C equipment being used, too expensive to use without substantially raising the subscription price of the FMAS. A third reason was that the United States Department of Defense (DoD) had classified GPS as an experimental system for military use. Consumer GPS products appeared throughout the 1980's, but GPS was not completely accepted as a frequency reference by non-military calibration laboratories until it was declared operational for civilian use. Initial Operational Capability (IOC) was formally declared by the DoD and the Department of Transportation (DoT) on December 8, 1993. Prior to IOC, GPS was considered a developmental system whose operation, including signal availability and accuracy, was subject to change at the discretion of the DoD [12].

By the time IOC for GPS was declared, work was underway on the third generation FMAS system, this one based on GPS. The first GPS unit was shipped by NIST in November 1994. While all new subscribers to the FMAS received a GPS based system, it was four years (November 1998) before the last LORAN-C system had been replaced with the new GPS units. The new GPS unit (see Figure 1.3) included many new features included a five-channel GPS receiver. A new TIC with integrated frequency dividers was developed with a resolution of < 30 ps, an improvement of more than three orders of magnitude over the previously used counter [13]. Other new features included the capability to store and record short term measurements and produce Allan deviation graphs, faster data transfer to NIST (14.4 kilobits/s), increased data storage capacity, and improved graphics [14, 15]. The measurement uncertainty (at k = 2) was reduced by a factor of two, to 5×10^{-13} for an averaging time of one day.


Figure 1.3. The third generation FMS (1994).

The fourth generation FMS system (Figure 1.4) was introduced in 2000. With minor revisions, it is still the unit being provided by the FMAS at this writing (2004). The unit's key new feature was a new time interval counter card with an integrated eight-channel GPS receiver [16]. The counter's resolution and stability were identical to the previous TIC, but it included programmable frequency dividers. The third generation system had been limited to measuring frequencies of 1, 2, 2.5, 5, and 10 MHz. The programmable frequency dividers allowed the measurement of any frequency from 1 Hz to 120 MHz that was an even multiple of 1 Hz. This allowed the calibration of frequency sources used in telecommunication systems (1.544, 2.048, 44.736 MHz, for example), as well as specialized frequencies used in other industries [17]. The eight-channel receiver produced uncertainties slightly lower than those of the earlier five-channel version, and when the GPS system deactivated its selective availability program in May 2000 [18], the measurement uncertainty was further reduced to its current specification of 2×10^{-13}. A complete technical description of this fourth generation FMS is provided in Chapter 2.

Table 1.1 summarizes the features of the four generations of frequency measurement systems provided to customers by the FMAS. Note that the monthly service fee for the service has remained the same from 1990 to 2004.

Figure 1.3. The fourth generation FMS (1994).

B. Facilities

Since the FMAS is a remote calibration service, the actual measurements take place in the customer's laboratory. However, the NIST Time and Frequency Division maintains areas designated as FMAS facilities, including a laboratory where GPS is continuously compared to UTC(NIST), a work area where new FMS units are assembled and tested, a storage room where an inventory of spare parts is maintained, and office space where billing and calibration records are maintained (Chapter 3.D). In addition, NIST maintains several FMS units in non-FMAS facilities, including units at radio stations WWV and WWVH.

The FMAS laboratory is connected by coaxial cable to the UTC(NIST) time scale, receiving both 5 MHz and 1 pulse per second (pps) signals. Inside the FMAS laboratory, the 5 MHz signal is distributed using three 5-channel low-noise distribution amplifiers. The 1 pps signal is distributed using two 5-channel low-noise distribution amplifiers. The delay in the incoming 1 pps signal has been calibrated and is known to be 375 ns with respect to UTC(NIST). Therefore, it is used as an absolute timing reference for GPS comparisons.

Three GPS antennas, with their absolute position surveyed to an uncertainty of < 1 m, are located on the rooftop above the FMAS laboratory. The incoming 1575.42 MHz GPS L1 signals are distributed within the laboratory by three antenna splitters. One is an eight-channel splitter with its own power supply, the other two are four-channel splitters powered by a DC voltage from one of the connected receivers.

Table 1.1. A feature summary of the FMS units provided by NBS/NIST.

Feature	**1st Generation**	**2nd Generation**	**3rd Generation**	**4rth Generation**
Year introduced	1984	1990	1994	2000
Reference signal	LORAN-C	LORAN-C	GPS	GPS
Measurement channels	4	4	5	5
TIC resolution	10 ns	10 ns	< 30 ps	< 30 ps
Input frequencies	1 pps 1, 5, 10 MHz	1, 2, 2.5, 5, or 10 MHz	1, 2, 2.5, 5, or 10 MHz	1 Hz to 120 MHz in 1 Hz steps
Interactive data analysis software	No	No	Yes	Yes
Data transfer to NBS/NIST (bits/s)	300	2400	14400	14400
Monthly service cost	$300	$500	$500	$500
Measurement uncertainty (1 d average)	$< 1 \times 10^{-11}$	1×10^{-12}	5×10^{-13}	2×10^{-13}

Maintaining a tightly controlled laboratory environment is not critical for the FMAS operation. The GPS receivers embedded inside the FMS are not particularly sensitive to temperature. Receiver delays can change by several nanoseconds or more (a frequency change of a few parts in 10^{14} over the course of a day) if large temperature fluctuations occur, but receiver delays will remain constant as long as the temperature remains constant [19]. Large receiver temperature fluctuations normally don't occur, since the GPS receiver is enclosed in a case that maintains a nearly constant internal temperature. Even so, the temperature of the FMAS laboratory is continuously recorded, and average temperature is held near 24° C, with peak-to-peak variations of about 2° C, representing a fairly typical calibration laboratory environment.

The FMAS work area includes a work bench with several cabinets containing tools and the hardware, cables, and miscellaneous parts needed for assembly. Standard laboratory test equipment including oscilloscopes, frequency counters, and signal generators are available in the work area and used for testing FMS units. Although functional tests are regularly performed on the test equipment, they do not need to be regularly calibrated, since the national frequency standard is used as the external time base frequency for all devices.

The storage area contains the spare parts for the FMAS, including the larger parts such as rack chassis and equipment racks. When FMS units are returned by customers, they are moved to this storage area. Parts that are determined to be in complete working order and that are still cosmetically acceptable are returned to inventory and sent to other customers. The other parts are disposed of or held in the storage area until they are picked up and removed by the NIST surplus property department.

1. Configuration of Remote FMS Units

One goal of the FMAS is to provide an identical FMS unit to each customer. This is desirable for two reasons. First, it is imperative that data are collected in the same way at all sites so that the assigned measurement uncertainties at each site are equivalent. Second, it is easier for NIST to stock replacement parts if all units use identical parts. Unfortunately, some commercially available parts of the FMS (particularly the computer parts) have very short product life cycles. For example, it is usually impossible to purchase the exact same model of printer that was purchased one year ago. For this reason, NIST attempts to procure multiple items at one time, and maintain an inventory of spare parts, although resources seldom permit “stockpiling” a large number of spares. When the inventory is depleted, an attempt is made to procure a functionally equivalent part (plug, pin, and software compatible) if the identical part is no longer available.

The FMS units are shipped to the customer already assembled. To avoid damage, they are shipped in wooden crates by the NIST shipping and receiving department. The customer is responsible for mounting the GPS antenna, connecting cables, and so on, using procedures that are clearly explained in the *Operator’s Manual* [20] provided with each unit. Table 1.2 lists the items included in each shipment of the FMS unit which is pictured in Figure 1.4.

Table 1.2. Items included in the FMS unit shipped to customers.

Item	Description
Equipment Rack	Standard 19” (48.3 cm) equipment rack with side mounted carrying handles, 12.25” (31.1 cm) of interior rack space.
Rack Mount Computer Chassis	Includes 300 W power supply, 8-slot passive backplane with Personal Computer Interface (PCI) and Industry Standard Architecture (ISA) card slots, 10” (25.4 cm) LCD color video monitor, 3.5” (8.9 cm) floppy disk drive, internal cooling fans, bulkhead connectors mounted on rear panel (5 BNC connectors for input frequencies, 1 TNC connector for GPS antenna).
Rack Mount Keyboard	Sliding shelf keyboard, standard PC layout.
Single Board Computer	Includes 486 microprocessor or equivalent running at 66 MHz or faster, 4 megabytes of RAM, ISA bus card edge connector, watchdog timer, RS-232, keyboard, speaker, and parallel printer interfaces.

Item	Description
Solid State Flash Memory Disk	16 megabyte or higher capacity with embedded ROM-DOS operating system. Measurement software is preinstalled.
Video Card	Compatible with minimum requirements of VGA standard, 640 × 480 resolution, 16 colors.
Modem	14.4 kilobit per second modem (V.32 standard), compatible with existing software.
Time Interval Counter	Custom designed counter with 8-channel multiplexer, 24-bit frequency dividers, 30 ps resolution. Accepts 1, 5, or 10 MHz external time base signal, provides RS-232 interface for GPS receiver [16].
GPS Receiver	Motorola Oncore 8-channel parallel tracking GPS receiver (mounts on time interval counter card).
GPS Antenna	Active GPS antenna with > 30 dB gain, mounting hardware, and cable. The cable is made to customer's specification. Total signal loss on cable should not exceed 20 dB for the GPS L1 carrier frequency of 1575.42 MHz. Various types of coaxial cable are used to meet this requirement.
Uninterruptible Power Supply (UPS)	500 VA supply with four AC outlets.
BNC Cables	BNC to BNC cables provided for all 5 measurement channels.
Printer and Supplies	Inkjet printer with spare ink cartridges, printer cable, and paper. Must be compatible with Hewlett-Packard Deskjet graphics modes.
Documentation	NIST Frequency Measurement and Analysis System: Operator's Manual [20].

C. Organizational Control of the FMAS

The FMAS is managed, controlled, and maintained by the Services Group of the NIST Time and Frequency Division. The Group Leader of the Services Group reports to the Division Chief of the Time and Frequency Division, who in turn reports to the Director of the NIST Physics Laboratory. The Physics Laboratory is one of the seven operational units of NIST, which is an agency of the United States Department of Commerce.

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Chapter 2

Technical Description

This chapter describes the technical operation of the FMAS, including a discussion of the theory of operation and the specific hardware and software used to implement the service.

A. Technical Description of Hardware

The FMS blends commercially available equipment with hardware and software developed at NIST. Each piece of equipment was carefully chosen and designed to meet the measurement uncertainty requirements of the most demanding calibrations performed by our customers, but also to be inexpensive enough so that NIST can continually build, test, and replace FMS units, and still stay within its budgetary constraints. This section describes the hardware specifications and the theory of operation of each component. Figure 2.1 is a block diagram of the complete system.

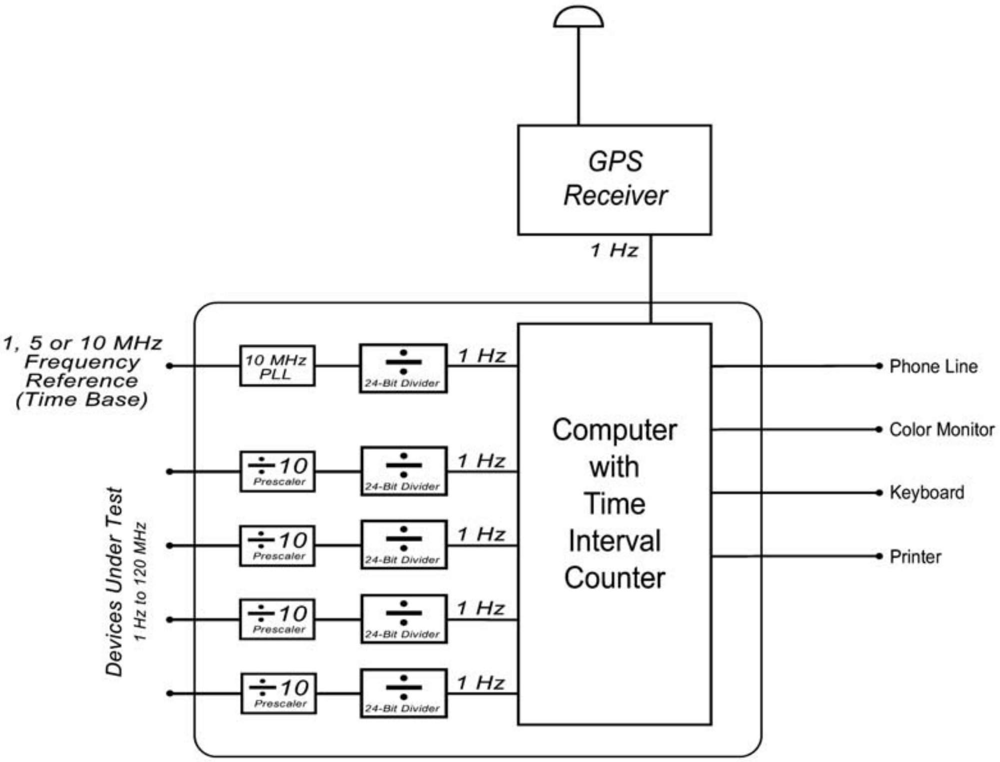


Figure 1. Block diagram of the FMS.

1. Computer System and Storage Devices

The FMS computer and measurement hardware are enclosed inside a standard 19 in (48.3 cm) rack-mount equipment chassis with a 300 W power supply. The chassis includes internal cooling fans, and was designed for industrial and instrument control applications, where the computer is never turned off. The chassis houses a 10.4 in (26.4 cm) LCD color video monitor and a 3.5 in (8.9 cm) floppy disk drive on its front panel. The rear panel includes a number of bulkhead connectors (at least five BNC connectors for input frequencies, one TNC connector for the GPS antenna). Some FMS units have unused BNC connectors that allow future enhancements to be added.

The single-board computer is mounted on an eight-slot passive backplane, containing both Industry Standard Architecture (ISA) and Personal Computer Interface (PCI) card slots. The passive backplane is also used to interface to the time interval counter and other peripheral cards. The computer includes a 486 microprocessor or equivalent running at 66 MHz or faster, 4 megabytes of RAM, an ISA bus card edge connector, RS-232, keyboard, speaker, and parallel printer interfaces, and a watchdog timer. Data are stored on a solid-state flash disk with a capacity of 16 megabytes or higher. On some units this flash disk is integrated with the single board computer; on other units it resides on a separate bus card. The video interface (either integrated or on a separate card) is compatible with the minimum requirements of the VGA standard, supporting 640 × 480 resolution and 16 colors. The computer communicates with NIST via ordinary phone lines, using an analog 14.4 kilobit per second modem compatible with the V.32 standard.

2. Frequency Measurement Hardware

When FMS development began in the early 1980’s, there were already a number of established methods used by calibration laboratories to measure frequency using existing test equipment, nicely summarized and described by Kamas in the 1977 and 1979 editions of the *Time and Frequency User’s Manual* [21, 22] and by others [23-25]. The time interval method, or using a time interval counter (TIC) to make phase comparisons between a standard reference signal and an unknown signal, was chosen for the FMS. The time interval method had several advantages over alternative methods: it was relatively easy to automate; with a reasonable amount of averaging it was possible to make high resolution measurements and detect very small frequency changes; and a single measurement system (with the appropriate frequency dividers) could measure a wide range of frequencies, covering everything from timing pulses to the standard frequencies distributed by laboratories.

A block diagram of a typical time interval measurement system is shown in Figure 2.2. Two signals, one from the device under test (DUT) and one from a reference, provide input to the TIC. Both signals are divided to 1 Hz. A signal from an external oscillator is provided to the TIC for use as its time base. Data collected by the TIC are output to a computer, where they are stored and analyzed. The following sections provide a more detailed look at the specific TIC, frequency dividers, and data handling process used by the FMS.

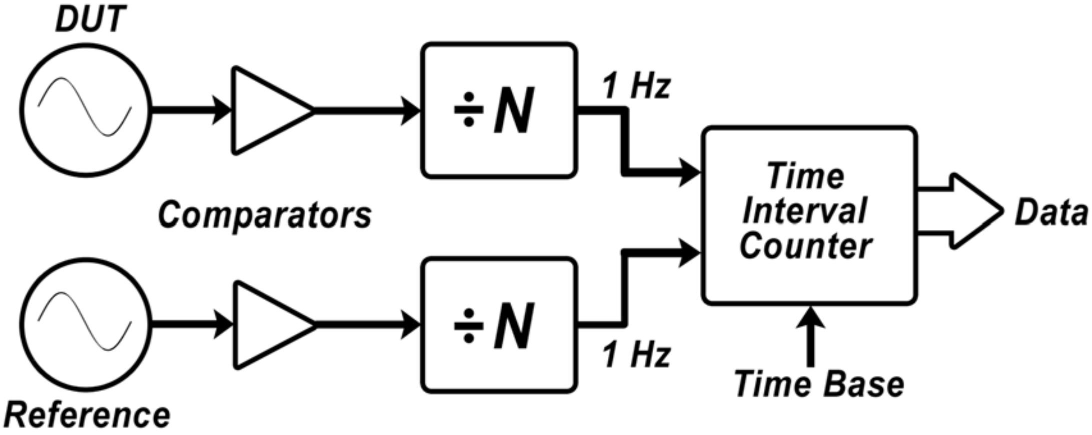


Figure 2.2. A time interval measurement system.

a) Time Interval Counter (TIC)

All TICs provide inputs for a start pulse and a stop pulse. The start pulse gates the TIC to start counting, and a stop pulse stops the counting. While the gate is open (Figure 2.3), the counter counts zero crossings from time base oscillator cycles. The resolution of the simplest TICs is equivalent to the period of a time base cycle, for example, 100 ns for a 10 MHz time base [26]. However, many TICs use interpolation schemes to divide the cycle period into smaller parts to obtain higher resolution.

The FMS TIC is able to divide the 100 ns period into about 4000 parts to allow resolution near 25 ps. This is done by using three counters inside the TIC circuitry: the main counter, the start interpolator counter, and the stop interpolator counter. The main counter provides the coarse resolution (100 ns), and the start and stop interpolator counters provide the fine resolution (< 30 ps). The main counter is a 24-bit device that counts the zero crossings of the 10 MHz time base frequency. The values read from the 16-bit start and stop counters are used to determine where the start and stop pulses are located between successive time base zero crossings. The start interpolator counter measures the time interval between the start pulse and the first zero crossing from the time base, δt_1. The stop interpolator counter measures the interval between the last zero crossing from the time base and the stop pulse, δt_2.

The interpolators consist of two integrators (A and B), a delay cell, a voltage comparator, and a 16-bit digital counter. The integrators are charged with a constant current I_{REF}. Using the start interpolator as an example, the delay cell introduces a delay equal to $\delta t_1 + T$, where $T = 100$ ns and $\delta t_1 < 100$ ns for the 10 MHz time base oscillator. This manipulation of the integrators and delay cell is done to scale, or magnify, δt_1 into a larger time interval. The digital counter, in combination with the 10 MHz time base, is used to estimate the scaled δt_1.

When the start pulse arrives, the charging current I_{REF} is sent to integrator A, and the digital counter begins counting periods of the 10 MHz time base. The charging current is sent to integrator A for the period of $\delta t_1 + T$, and then switched to integrator B. The voltage developed on integrator A, V_A is held as reference voltage for the comparator while integrator B is being charged to a voltage of V_B. When $V_B > V_A$, the comparator blocks the connection between the 10 MHz time base and the digital counter. The scaling factor for the interpolator, K, is determined as

$$K = -\frac{C_B}{C_A} + 1 \quad , \tag{1}$$

where C_A and C_B ($C_A < C_B$) are the ramping capacitances used in integrators A and B.

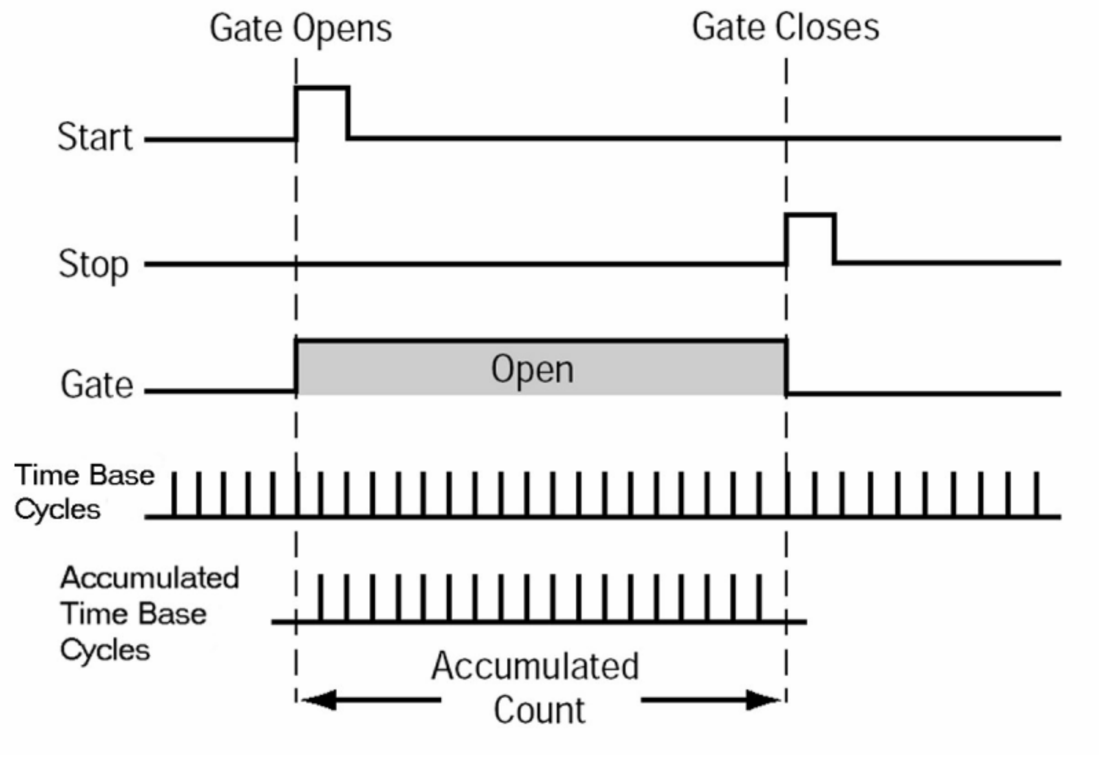


Figure 2.3. Counting time base cycles.

The reading obtained from the start interpolator counter, N_{start}, equals the number of 10 MHz pulses counted, and is linearly proportional to the time interval of δt_1. The relationship between δt_1 and N_{start} can be expressed by the linear equation

$$\delta t_1 = A \cdot N_{start} + B \quad , \tag{2}$$

where the slope A and the intercept B are determined during the interpolator calibration. During the calibration, a series of readings is taken from the start interpolator counter and maximum and minimum values ST_{max} and ST_{min} are obtained by slewing the phase of a test signal with respect to the 10 MHz time base to simulate the range of possible values for δt_1. Because the lowest possible reading from the start interpolator counter corresponds to $\delta t_1 = 0$, and the maximum possible reading corresponds to $\delta t_1 = T$, the slope and intercept of the interpolation are calculated as

$$A = \frac{T}{ST_{\max} - ST_{\min}} \, , \tag{3}$$

$$B = \frac{ST_{\min} \cdot T}{ST_{\max} - ST_{\min}} \, , \tag{4}$$

Therefore,

$$\delta t_1 = A \cdot N_{start} + B = \frac{N_{start} - ST_{\min}}{ST_{\max} - ST_{\min}} \, , \tag{5}$$

Because

$$K = -\frac{C_B}{C_A} + 1 = ST\max - ST\min \, , \tag{6}$$

the resolution of the interpolator counter is equal to T/K [13]. Using the time base and capacitance values used by the FMS TIC, where T = 100 ns, C_A = 100 pF, and C_B = 0.47 µF, the maximum possible resolution is about 21 ps

$$\frac{T}{\frac{C_B}{C_A} + 1} = \frac{100 \times 10^{-9}}{4701} = 21 \times 10^{-12} \, , \tag{7}$$

Obtaining 21 ps resolution would require the calibration software to sample N_{start} across an optimal range where the difference between the maximum value and minimum value of δt_1 would reach its theoretical limit of 4700 counts. In practice, it is not possible to sample the entire range, so the range is typically about 4000 counts. This results in TIC resolution (T / 4000 counts) of approximately 25 ps.

The stop interpolator performs a nearly identical function as the start interpolator, except that it estimates the interval of T – δt_2. Because of this, the main digital counter counts one more time base zero crossing after the arrival of the stop pulse [13].

The FMS TIC is calibrated once every 24 h using a two-part software algorithm. The first part calibrates the start and stop interpolator counters as described above. The second part of the calibration determines the differential path delay in the counter circuitry. The delay measurement is made by dividing the 10 MHz time base frequency by 256 to obtain a frequency of 39062.5 Hz and then supplying this frequency to both the start and stop inputs of the counter. The period of this frequency is 25600 ns. A series of time interval measurements are made, and the variation from the expected answer is computed. This variation indicates the counter delay, which is typically less than 1 ns. As long as this delay remains constant, it has no effect on the frequency measurement results.

During the counter calibration, five values are obtained: the maximum values of the start and stop interpolator counters (ST_{max} and SP_{max}), the minimum values of the start and stop interpolator counters (ST_{min} and SP_{min}), and the counter delay (D). During a measurement, all three counters are read and three values are obtained: the main counter reading (N_{main}), the start interpolator reading (N_{start}), and the stop interpolator counter reading (N_{stop}). Equation 8 shows how these values are combined to produce a single counter reading (TIC_R). Note that T represents the period of the time base frequency, which is a constant of 100 ns [13, 16].

$$TIC_R = N_{main}T + \frac{N_{start}T}{ST_{\max} - ST_{\min}} - \frac{N_{stop}T}{SP_{\max} - SP_{\min}} - D \quad , \qquad (8)$$

The resolution of the FMS TIC contributes measurement uncertainties of a few parts in 10^{11} over a 1 s interval, often averaging down to parts in 10^{15} after a few hours. Since these uncertainties are so low, the TIC resolution contributes no discernible uncertainty to measurements made over a 1 d interval.

The uncertainty of TIC measurements is, however, potentially limited by factors other than resolution, including count ambiguity, trigger uncertainty, or time base uncertainty [26, 27]. Like most test instruments, a TIC generally has a +1 count or –1 count ambiguity in the least significant digit of its readout, contributing a resolution uncertainty to the measurement. However, since the FMS averages multiple readings, and since the count ambiguity is nearly random, this ±1 count error normally averages down to an insignificant level.

Trigger uncertainty is a potentially more significant problem. It occurs when the TIC does not trigger at the expected voltage level on the input signal. Trigger uncertainty can be caused by incorrectly set trigger levels, or by input signals that are noisy, too large, or too small. Figure 2.4 illustrates that while triggering is desired on point *a*, noisy signals can cause triggering on points *b* or *c* [26]. If clean input signals are provided by the customer, the FMS TIC eliminates most of the triggering problem with pulse shaping circuitry that converts the incoming signals on both sides of the counter to a nearly identical shape and amplitude. There are no user adjustable trigger levels, although the TIC software is preconfigured to expect either a sinusoidal or a square wave signal. It is still possible for the customer to introduce errors, however, by over driving or under driving the TIC. In order for the automated trigger level setting to function properly, the incoming signals must have a peak-to-peak amplitude in the 200 mV to 3.5 V range at 50 W [20], and attenuators or amplifiers are sometimes needed to meet this requirement.

Time base uncertainty is not an issue because the FMS uses the customer's best available frequency standard as its external time base source. The FMS TIC uses a phase locked loop (PLL) circuit that locks a low cost 10 MHz crystal oscillator to either a 1, 5, or 10 MHz signal

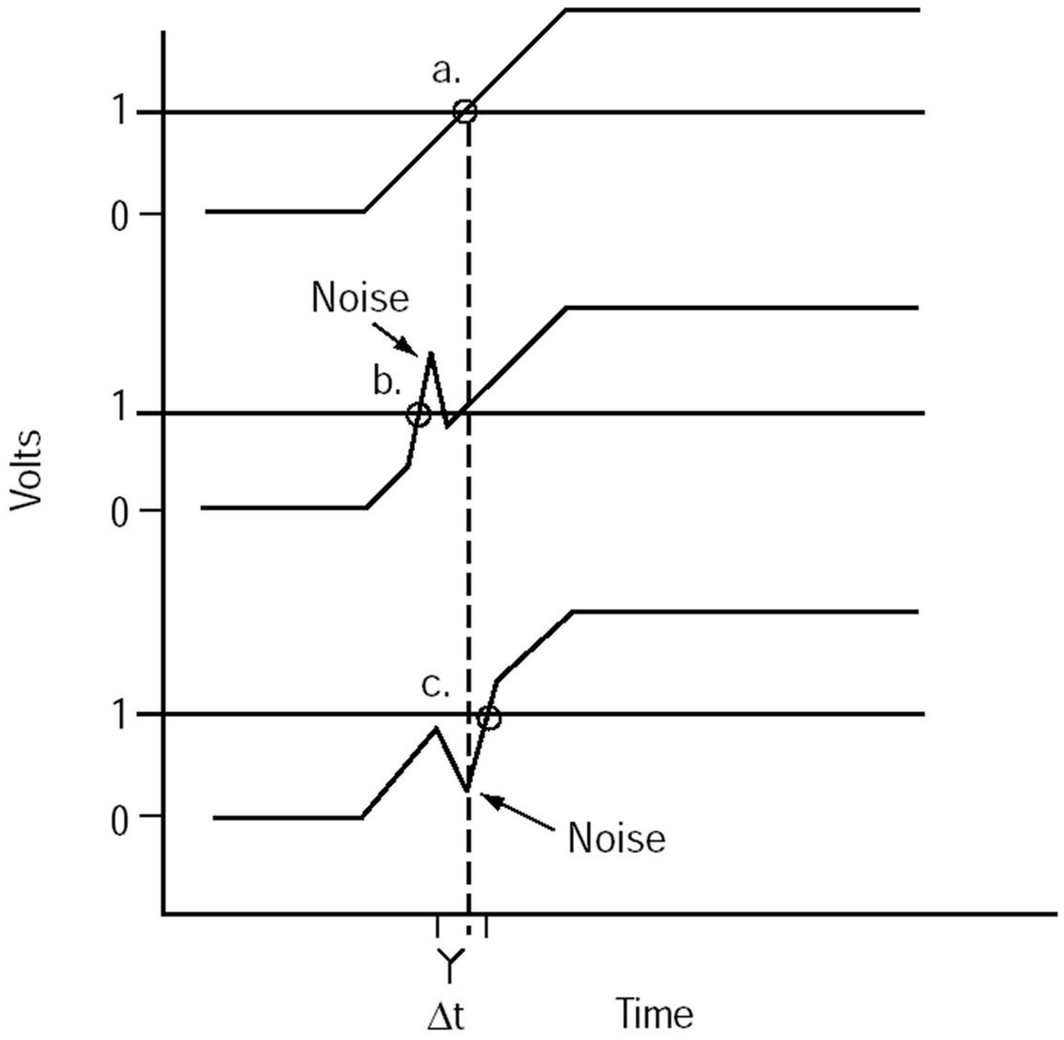


Figure 2.4. TIC trigger uncertainty due to noise.

from the customer's primary frequency standard. Typically, the customer has a stable frequency standard, with a frequency stability at 1 s no worse than 1×10^{-10}, and often one or two orders of magnitude better. When 1 Hz pulses are used to start and stop the counter, the average time interval measured is 0.5 s, therefore the time base uncertainty is 0.5 s / $10^{10} = 5 \times 10^{-11}$ s, or 50 ps, which is roughly equivalent to the uncertainty contributed by the TIC's ±1 count ambiguity, and which will be negligible after it is averaged over multiple readings. It should be noted, however, that the frequency offset of the time base oscillator does introduce an uncertainty in the absolute accuracy of each individual time interval reading (TIC_R). However, since frequency is measured by looking at the difference between time interval readings ($TIC_{R2} - TIC_{R1}$) over the measurement period, this uncertainty cancels out and becomes insignificant, since the time base contributes a nearly equal amount of uncertainty to each TIC reading.

b) Frequency Dividers

If standard oscillator frequencies such as 5 or 10 MHz are to be measured using a TIC, they first must be divided down to a lower frequency (Figure 2.2). There are least two reasons why frequency division is necessary. The first reason is that there is a limit to how fast the TIC can process and store measurements, sometimes called its sampling rate. The sample rate is limited by several factors including dead time, display time, data transfer time, and data processing time. Dead time refers to the delay that elapses between the completion of one reading (the arrival of a stop pulse) and the beginning of the next reading (the acceptance of the next start pulse). If the frequency of the input signals is too high, some information will be lost as a result of dead time [26]. For example, a TIC with a dead time specification of 200 ns would miss 50 % of the zero crossing if 10 MHz signals were connected to the start and stop inputs, since new zero crossings would arrive every 100 ns. In the case of the FMS TIC, the actual sampling rate is limited by the time interval interpolation scheme described earlier. If we make the assumption that the start and stop interpolator counters have the same scaling factor, then $ST_{max} = SP_{max}$. Because it takes an interval of $ST_{max} \times T$ to complete an interpolation, the maximum sampling rate, SR_{max} would equal

$$SR_{\max} = \frac{1}{ST_{\max} \cdot T} , \tag{9}$$

Using a value of 4700 for ST_{max}, the maximum sample rate is approximately 2128 Hz, and 2 kHz has been specified as the highest allowable input frequency that the TIC can sample without dead time [13].

The second reason for dividing down to a low frequency is to reduce the number of counter overflows and underflows. The maximum time interval recorded by the TIC is equal to the period of the stop frequency. Using once again the 10 MHz example, the maximum time interval recorded would be 100 ns. This would mean that each time the DUT had an accumulated phase change greater than 100 ns, the TIC reading would either overflow (go from 100 back to 0), or underflow (go from 0 back to 100). In order to estimate the frequency offset, the software controlling the counter would have to keep track and correct for all the overflows and underflows. This could be a difficult task with some low performance oscillators; for example a DUT with a frequency offset of 1×10^{-6} would force, on average, 10 overflows or underflows every second. It also should be noted that the TIC can produce erroneous readings if the interval between the arrival of the start and stop pulses is too small. The FMS counter can measure a minimum interval of about 2 ns (the approximate delay in 40 cm of coaxial cable). If frequent overflows and underflows are allowed, a situation is likely to be reached where the interval between the two input signals is too small to measure, forcing the TIC into producing an erroneous reading.

Like the system shown in Figure 2.2, most TIC systems used for frequency measurements divide the incoming signals to 1 Hz. However, a higher common frequency can be used. For example, the second and third generation FMS units described in Chapter 1 divided the incoming signals by 1000, stopping all counts with a 10 kHz reference signal obtained from the time base. This scheme was convenient, because it used nonprogrammable circuits embedded in the counter that did not require any software configuration. However, the maximum TIC reading was limited to 100 µs, the period of 10 kHz, so the software had to account for frequent overflows and underflows when measuring some DUTs. Also, the system could only measure frequencies whose period divided by 1000 equaled an even multiple of 100 µs, limiting the allowable inputs to 1, 2, 2.5, 5, and 10 MHz.

The current FMS unit (Figure 2.1) includes programmable frequency dividers. The dividers are circuits that simply count and block $n - 1$ cycles of the incoming frequency, where n is the nominal frequency in hertz. For example, to divide 1 kHz to 1 Hz, 999 cycles of the incoming frequency are counted and blocked and every 1000th cycle is allowed to pass through. The FMS dividers use 24-bit counters, meaning that they can count frequencies as high as 2^{24} Hz, or 16.777 MHz. All incoming signals pass through a divide by 10 prescaler before reaching the divider circuit. If the incoming frequency is known to be 15 MHz or higher (configured by the customer in software), this prescaler is turned on; otherwise it is disabled. The signal then passes through to the 24-bit divider, where it is reduced to 1 Hz. If the incoming signal is specified by the customer as 1 Hz, the 24-bit divider is disabled in software. This allows non-sinusoidal timing pulses to be measured.

In theory, the FMS can measure incoming signals as high as 167.77 MHz (Figure 2.5), since the combination of the prescaler and 24-bit divider could reduce this frequency to 1 Hz. However, due to potential problems of noise and crosstalk between adjacent counter channels (and no current customer demand for the measurement of frequencies in the 120 to 167.77 MHz range), the upper range of the FMS has been specified as 120 MHz.

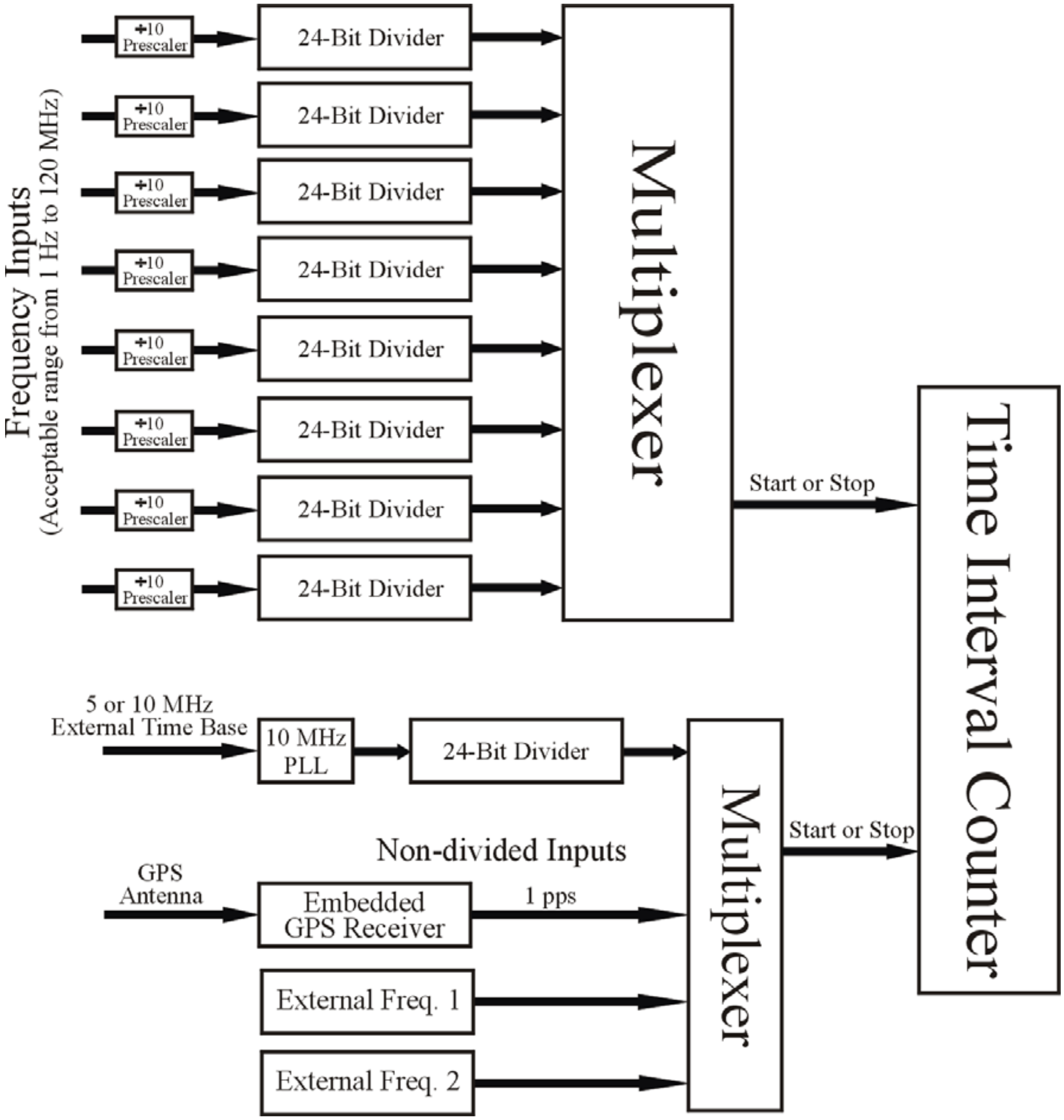


Figure 2.5. Block diagram of the FMS TIC.

c) Multiplexer

Since the inception of the service, all FMS units have included multiplexer circuitry that allows the selection of different signals as the input to the time interval counter. The multiplexer is activated each time a new measurement channel is selected, and the channels are then read in sequence from the lowest number channel to the highest. This allows multiple frequency sources to be measured at the same time, a key feature in reducing the workload for calibration laboratories.

The current FMS TIC actually has two multiplexers. One allows the selecting between any of eight frequency inputs as shown in Figure 2.5, but only five inputs are activated in the current software. Each of these eight inputs includes a 24-bit programmable divider, and can be any frequency from 1 Hz to 120 MHz. The other multiplexer allows selection between four inputs: a 1 pps output from the GPS receiver, 1 pps obtained by dividing the time base PLL, or two external 1 pps signals (only one of these is selectable with the current software).

Gold-plated SMA connectors are used for the eight frequency inputs and the time base input, as shown in the photo in Figure 2.6. Molex connectors are used for the two external 1 pps signals. The 1 pps output from the GPS receiver is directly obtained from a 10-pin connector on the receiver itself.

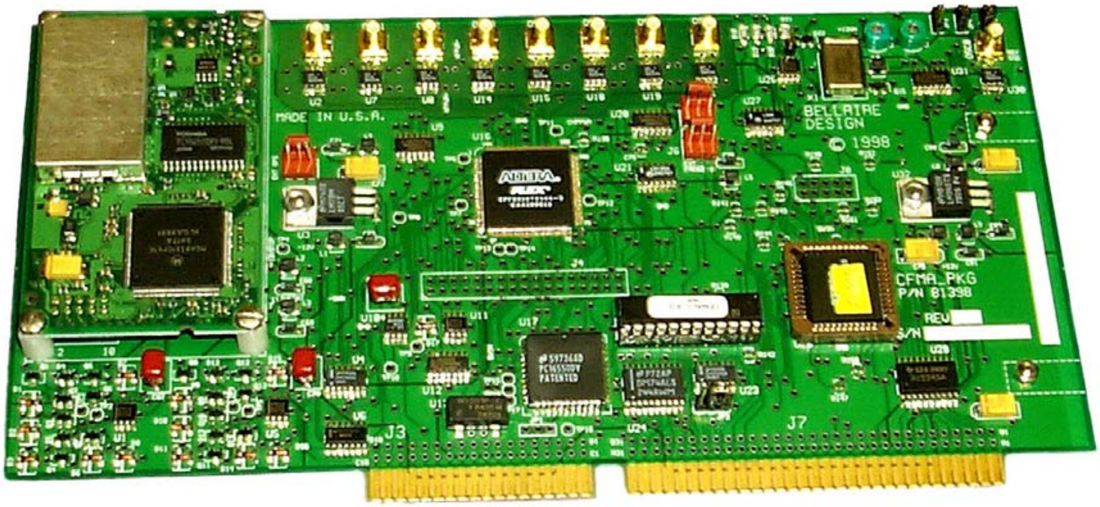


Figure 2.6. Photograph of the FMS TIC.

d) Advantages and Limitations of Time Interval Method

The time interval method employed by the FMS is very versatile, and has many advantages, including low cost, simple design, and excellent performance when measuring long term frequency accuracy or stability. The method has a much lower noise floor than the GPS reference frequency, and normally contributes no discernible uncertainty to calibrations lasting for 1 h or longer. This is evidenced by the fact that the Bureau International des Poids et Mesures (BIPM) produces its computation of the UTC time scale using data collected with TICs. In addition, the wide bandwidth of the time interval method allows the FMS to measure devices with frequency offsets ranging from 1×10^{-5} to less than 1×10^{-13} over a 1 d period, a range of approximately eight orders of magnitude. For a 10 MHz DUT, this means that the FMS can report frequency offsets as large as 100 Hz, or smaller than 1 µHz, allowing calibration of just about any type of instrument that a calibration laboratory is likely to encounter.

The main disadvantage of the time interval method is that it lacks the resolution to accurately measure frequency or to estimate short term stability at averaging times of less than about 100 s. Calibration laboratories that need to measure the short term stability of oscillators generally use a system where the signal from the device under test is converted to a lower frequency by use of a heterodyne technique that mixes, rather than divides, the signal [28, 29]. The heterodyne technique increases the measurement resolution (often by a factor of 100 or more) and decreases the measurement noise. However, several things are lost with the heterodyne technique, such as the ability to measure 1 pps timing signals or other low frequency pulses, the ability to measure a wide range of frequencies, or in some cases, the ability to measure devices that have a large frequency offset from their nominal value.

3. GPS Receiver

The FMS uses the Motorola Oncore UT+ GPS receiver with firmware version 3.2. Motorola Oncore receivers have been used by numerous laboratories for time and frequency metrology applications [30 – 33]. The small receiver (50.8 × 82.6 × 16.3 mm) mounts directly on the TIC card [16], which provides the 5 V DC needed to power the device. The TIC card also supplies the necessary line drivers needed to convert the receiver’s built-in TTL serial interface to a conventional RS-232 interface that communicates with the computer at 9600 bits/s.

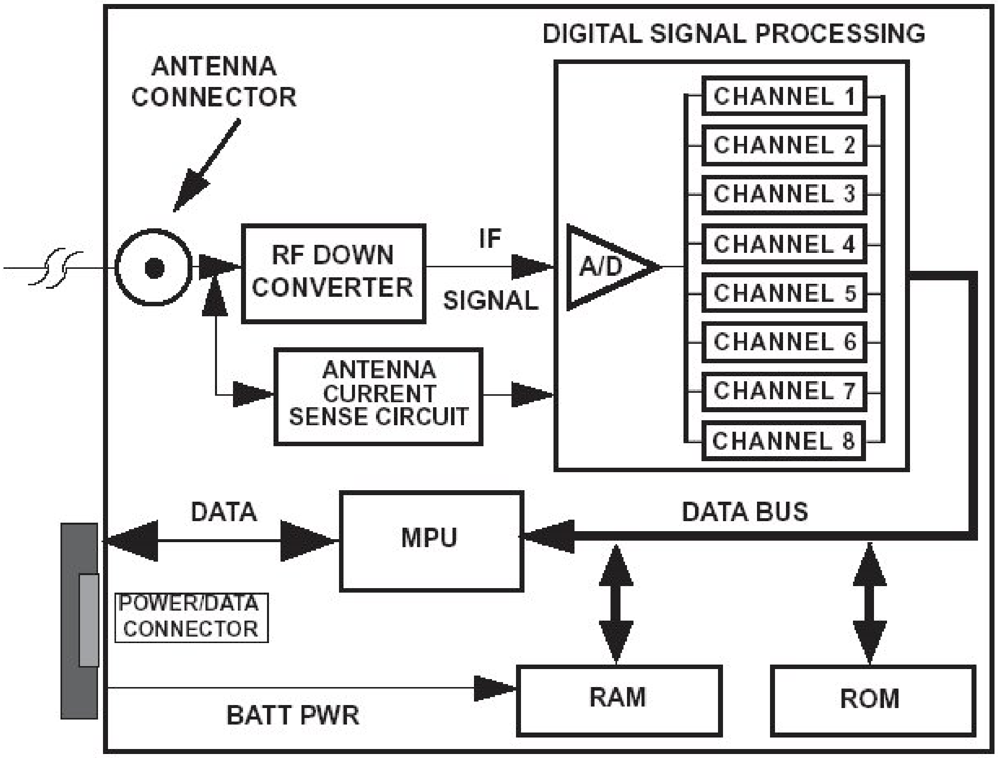


Figure 2.7. GPS receiver block diagram.

The GPS receiver searches for, acquires, and tracks satellites on eight parallel channels using the L1 carrier frequency (1575.42 MHz) and the coarse acquisition (C/A) code with a 1.023 MHz chip rate. The receiver has an onboard MC68331 microprocessor unit (MPU), so that all processing related to satellite tracking is done by the receiver itself and not by the FMS computer system. A block diagram of the receiver is shown in Figure 2.7 [34].

Although the primary purpose of GPS is to serve as a positioning and radionavigation system, the entire system relies on precise timing. The satellite ranges used to calculate position are derived from travel time measurements of the GPS signals transmitted from each satellite to the GPS receiver. After the receiver position (x, y, z) is solved for, the solution is stored in RAM. Then, given the travel time of the signals (observed) and the exact time when the signal left the satellite (given), time from the atomic clocks (either cesium or rubidium) onboard the satellites can be transferred to the receiver clock. The basic measurement made by the GPS receiver reveals the difference between the satellite clock and the receiver clock. This measurement, when multiplied by the speed of light, produces not the true geometric range but rather the pseudorange, with deviations introduced by the lack of time synchronization between the satellite clock and the receiver clock, by delays introduced by the ionosphere and troposphere, and by multipath and receiver noise. The equation for the pseudorange observable is

$$p = \rho + c \times (dt - dT) + d_{ion} + d_{trop} + r_n \,, \tag{10}$$

where p is the pseudorange, c is the speed of light, ρ is the geometric range to the satellite, dt and dT are the time offsets of the satellite and receiver clocks with respect to GPS time, d_{ion} is the delay through the ionosphere, d_{trop} is the delay through the troposphere, and r_n represents the effects of receiver and antenna noise, including multipath. An estimate of d_{ion} is obtained from the GPS broadcast. The GPS receiver discussed here uses a digitally compensated crystal oscillator (DCXO) as its local clock oscillator. The DCXO is inexpensive and not particularly stable, causing the $dt - dT$ term to change very rapidly. Therefore, the pseudorange measurement must be made every second in order to preserve GPS accuracy. If the receiver loses lock, even for 1 s, the measurements recorded by the FMS are discarded.

The receiver exploits the coherency between the L1 carrier and the C/A code by using very narrow band (0.005 Hz) code tracking. The pseudorange data collected by the narrow band code tracking function are used to compute the satellite time for each satellite in view. The receiver compensates for propagation delay and applies satellite clock corrections received from the broadcast to produce a local time estimate for each satellite. Then it averages up to eight independent satellite time measurements and computes a single local time estimate, which represents the composite timing solution from all satellites in view. This average time estimate is then used to position the 1 pps signal to coincide with the rising edge of the next second. Although the reception of only one satellite signal is required to produce a timing solution, tracking multiple satellites reduces the amount of measurement noise. Assuming that the noise is white, the noise figure can be roughly estimated as $1/(\sqrt{S})$, where S is the number of satellites being tracked.

The receiver outputs a 1 pps timing signal with a 200 ms pulse width (20 % duty cycle) and a 20 to 30 ns rise time from 0 to 5 V. The rising edge of the pulse is the on-time marker. The 1 pps is set relative to an internal asynchronous 1 kHz clock derived from the DCXO. The receiver counts the 1 kHz clocks, and uses each successive 1000 clock cycles to define the time when the measurement epoch is to take place. The measurement epoch is the point in time when the receiver captures the pseudorange and pseudorange rate measurements for the computation of position, velocity, and time. Each measurement epoch is about 1 s later than the previous epoch, with the difference from 1 s resulting from the DCXO's intentionally introduced frequency offset (which exceeds 1×10^{-5}) and its inherent frequency instability ($\pm 2 \times 10^{-6}$) [35].

The DCXO runs at a nominal frequency of 19.096 MHz. The output signal from this oscillator is divided by two to produce a 9.548 MHz signal, and the cycle synchronized most closely to the satellite broadcasts is used as the receiver's 1 pps output within the selected 1 ms epoch. The period of this clock frequency is approximately 104 ns, so the 1 pps signal has a ± 52 ns ambiguity. Therefore, if the phase of the physical 1 pps signal produced by the receiver is plotted it looks like a "sawtooth." The receiver returns a data message every second containing a "negative sawtooth" correction with a range of ± 52 ns and 1 ns resolution. This correction is always given for the upcoming 1 pps pulse, and is applied by the FMS software. Note that the correction is applied only in software; the physical 1 pps output is not corrected. Thus, if the 1 pps signal is distributed by the FMAS customer, the ± 52 ns ambiguity will still be present.

The receiver makes an additional correction to the 1 pps output to convert GPS time to UTC. The GPS satellites themselves use the GPS time scale as their timing reference. GPS time differs from UTC by the integer number of leap seconds that have occurred since the origination of the GPS time scale (January 6, 1980); this value is equal to 13 s as of March 2004. It also differs by a small number of nanoseconds (nearly always < 25 ns) that continuously changes. The integer-second difference is needed to correct the time-of-day solution, since this information is used to time stamp data collected by the FMS. This small number of nanoseconds represents the difference between the GPS time scale on-time marker (OTM) and an estimation of the OTM for the UTC time scale maintained by the United States Naval Observatory, called UTC(USNO). The current difference between the UTC(USNO) estimate and GPS time is broadcast from the satellites, and this correction is applied to the 1 pps signal. Therefore, the received 1 pps signal represents an estimation of UTC(USNO). The relative frequency offset between the UTC(USNO) estimate and UTC(NIST) is very small, typically a few parts in 10^{15} or less when measured over a one month interval.

It is also possible to apply a software correction for receiver and antenna delays, and to calibrate the receiver for use as a time reference. Corrections can be applied to the 1 pps signal with a resolution of 1 ns. This is not normally done with FMS units, since the quantities being measured and reported are time interval and frequency, and not absolute time synchronization to UTC. The receiver and antenna delays are ignored, and their small variations are factored into to the overall measurement uncertainty (see Chapter 5).

a) GPS Antenna

The GPS antenna provided with the FMS was designed specifically for time and frequency applications. The antenna was designed for outdoor installation, and must be mounted on a rooftop location with a clear view of the sky in all directions. The antenna has a polycarbonate outer casing, and is cone shaped, with a height of about 163 mm and a diameter of 90 mm. It has a relatively narrow bandwidth of ± 10 MHz around the 1575.42 MHz L1 carrier frequency which helps reduce interference. The receiver provides power (5 V dc at less than 27 mA) to the antenna through the antenna cable.

In GPS positioning applications, the antenna is usually located very close to the receiver (sometimes directly attached as in the case of GPS handheld receivers), so low-gain antennas are generally used. However, the FMS is usually installed in calibration laboratories where the antenna normally resides on a rooftop outside the laboratory, and the length of the antenna cable generally ranges from at least 10 m to 100 m or longer. Since the incoming 1575.42 MHz signal is not down converted at the antenna, but rather inside the receiver (Figure 2.7), a relatively high-gain antenna is needed to drive long cable runs. The FMS antenna has a gain exceeding 30 dB, with 38 dB being typical for satellites at an elevation angle of 90º. For the receiver, the optimal gain of the antenna, cabling, and any in-line amplifiers and splitters is 10 to 33 dB. Therefore, to be safe, no more than about 20 dB of loss can be tolerated in the antenna cable.

Prior to shipment of the FMS, the customer is asked for the approximate length of antenna cable needed. In some cases, standard length cables are supplied to the customer; in other cases (particularly for long cable runs), custom length cables are constructed. As a general rule, RG-58 coaxial cable is used for short cable runs, and larger diameter, more rigid cables are used for long runs. In a few instances where the cable run has exceeded 100 m, in-line signal amplifiers have been supplied to FMS customers. Table 2.1 shows the signal loss of various cable types at the L1 carrier frequency. If the loss is too large for the receiver to work properly, the number in the table is shaded. Note that the loss figures are estimates; various manufacturers' brands can have higher or lower loss figures.

Table 2.1. Antenna cable signal loss at the L1 carrier frequency as a function of cable type and length.

Cable Type Length	RG-58 (dB loss)	RG-8 (dB loss)	RG-213 (dB loss)	LMR-400 (dB loss)
10	6.4	3.3	3.6	1.7
25	16.0	8.1	9.0	4.3
50	32.0	16.3	18.0	8.6
100	64.0	32.6	35.9	17.3
150	96.0	48.9	53.9	25.9

4. Printer

An inkjet printer with a parallel interface is used to print daily phase graphs from each of the five measurement channels currently in use. During normal operation, the printer is left on at all times and the phase graphs are produced automatically. The printer can also be used to print out data tables or statistics compiled from the data if the customer desires [20]. Replacement ink cartridges are provided by NIST.

5. Uninterruptible Power Supply (UPS)

A small 500 VA uninterruptible power supply (UPS) with four AC outlets is provided with every FMS unit. The UPS is intended to keep the FMS running through short power outages, not to exceed about 15 min. The FMAS customer is responsible for providing backup power for all of the frequency sources being tested, and in some cases, the FMS itself is placed on the laboratory's backup power, and the supplied UPS is not needed.

6. Equipment Rack

A standard 19 in (48.3 cm) equipment rack with side mounted carrying handles is provided as the outer housing of the FMS. The rack has 12.25 in (31.1 cm) of interior rack space. The top, bottom, and side panels are constructed of 0.05 in (1.27 mm) thick aluminum. The printer is generally placed on top of the equipment rack. In addition to housing the hardware, the equipment rack provides some additional RF shielding for the measurement components.

B. Technical Description of FMS Software

The FMS software consists of the operating system, the remote software deployed at customer sites, and the host software which resides at the NIST Boulder Laboratories and is used exclusively by NIST personnel.

1. Operating System

The operating system is ROM-DOS 6.22 published by Datalight, Inc. ROM-DOS is similar to and compatible with the MS-DOS and PC-DOS operating systems formerly published by Microsoft and IBM, respectively. ROM-DOS is an embedded operating system that resides in flash memory on an ISA bus card. An individual ROM-DOS license is purchased by NIST for every FMS unit produced.

2. Remote FMS Software used at Customer Sites

An identical set of software programs is preinstalled by NIST on every FMS unit. The use of this software from the customer's perspective is described in the *NIST Frequency Measurement and Analysis System: Operator's Manual* [20]. This section provides a technical description of how the software works.

The software was written in the BASIC programming language, with the exception of a few routines written in assembly language. Most routines were written to run in graphics mode, with a 640 × 480 screen resolution using 16 colors. All applications (data and executable code) reside in the standard DOS memory space of 640 kilobytes.

a) GPS Software

When an FMS unit is first installed at a customer's site, or whenever it is restarted, a software program named *GPS2000* is executed. This software performs the site survey on the GPS antenna, configures the GPS receiver, and tests its integrity. When these tasks are completed, it loads the main measurement module, called *FM2000*.

Receiver Cold Start - *GPS2000* can perform a cold start or warm start of the receiver. A cold start is used when an FMS unit is first installed at a customer's site, and no information exists about the antenna position. To initiate a cold start, *GPS2000* is run with the */COLD* parameter. This parameter is included in the batch file shipped with the system, but deleted by NIST after the initial installation. The cold start performs the following functions:

- Initializes all of the receiver parameters to their default values and erases any existing almanac and ephemeris data.
- Sends time and date information from the computer clock to the GPS receiver clock to give the receiver a rough estimate of the current time.
- Configures the receiver to output data messages to the computer via the RS-232 port once per second.
- Sets the mask angle so that the receiver only tracks satellites with an elevation angle of 15º or higher.

At this point, the receiver begins searching the sky for a satellite. Once a satellite is found, the navigation message is downloaded, and the almanac and ephemeris data contained in the message are stored on disk. The GPS navigation message is transmitted at a data rate of 50 Hz and contains 25 frames. Each frame consists of 1500 bits and takes 30 s to transmit and receive. The entire message contains 37500 bits, takes 750 s to transmit and receive, and is continually repeated, so a new message begins every 12.5 min. Each frame has five subframes. Subframes four and five contain the data that are stored on disk; subframe four contains the almanac data for satellites with psuedo random noise (PRN) numbers from 25 through 32, and subframe five contains almanac data for satellites with PRN numbers from 1 through 24. The stored data occupy 1124 bytes of disk space, and consists of 34 unique formatted messages (each 33 bytes long) that correspond to the subframe and page number of the navigation message [36]. Once the signal from a single satellite has been parsed, the almanac data enable the receiver to search for other satellites. Since the navigation message repeats every 12.5 min, the process of downloading an almanac file typically takes from 12.5 to 25 min after the sky search is completed.

Other information in the navigation message is used by the receiver as part of the time and frequency solution, and is briefly summarized here. The first two words in every subframe, called the telemetry word (TLM) and the handover word (HOW), provide synchronization signals for the receiver clock. Bits 20 to 22 of the HOW contain the subframe ID code.

Subframe 1 contains the GPS week number, six bits that describe the health of the satellite, an estimate of the signal dispersion due to the ionosphere, and the coefficients of a polynomial that estimates the difference between the satellite clock and GPS time. The polynomial coefficients give the predicted time offset, frequency offset, and frequency aging of the satellite clock with respect to an origin time that is also part of the message.

Subframes 2 and 3 contain the ephemeris parameters, which are used by the receiver to compute the satellite position. As with the time parameters in Subframe 1, this computation is made with respect to a transmitted origin time. The ephemeris for each satellite is described using six Keplerian elements. The first three Keplerian elements define the shape of the orbit. They are the length of the semi-major axis of the ellipse, a, the eccentricity, e, and the time, τ, at which the satellite crosses the perigee, which is the point on the orbit nearest the Earth (the semi-major axis crosses the ellipse at perigee). The second three Keplerian elements define the orientation of the orbit in space with respect to the Earth-centered, Earth-fixed (ECEF) coordinate system in which the x–y plane is the equatorial plane of the Earth and the z-axis is perpendicular to this plane. These three parameters are the orbit inclination angle, i, the longitude (or right ascension) of the ascending node, Ω, and the angle between the ascending node and the direction of perigee measured in the orbital plane, ω [37].

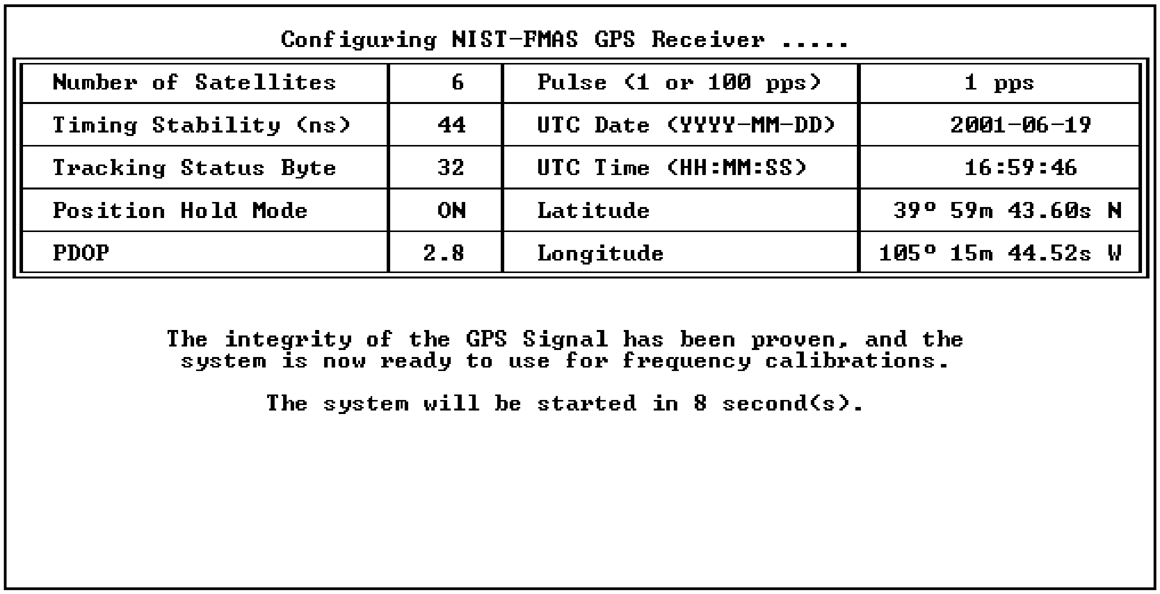
Subframes 4 and 5 contain the previously described almanac data that are stored to disk. The almanac provides a set of reduced precision ephemeris information for all satellites in the constellation, not just for the satellite whose navigation message is currently being received. Subframe 4 also includes parameters that relate GPS time to UTC(USNO), normally a difference of < 25 ns, and provides information regarding previous and future scheduled leap seconds. The leap seconds are added to UTC but not to GPS time, so that the difference between the two time scales changes by 1 s whenever a leap second occurs (Chapter 2.A.3). Once a valid UTC time-of-day message has been obtained from the GPS receiver, the date and time of the computer clock are synchronized to GPS.

During the period when the navigation message is being downloaded, the software stays in a continuous loop where a number of receiver parameters are monitored through the RS-232 interface. The loop is not exited until all of these parameters have acceptable values. During this time, the GPS antenna is surveyed by averaging position fixes. The allowable positioning uncertainty of the antenna survey needed to meet the frequency uncertainty specifications of the FMS are fairly modest, 10 m for the 2D position (longitude and latitude), and 20 m for the 3D position (altitude). Table 2.2 summarizes the receiver parameters that are monitored during the acquisition process.

Once the site survey is completed, the receiver is placed in position hold mode using the values obtained for latitude, longitude, and altitude. From this point forward, no further position fixes are computed unless the antenna is resurveyed (a new survey is not normally necessary unless the antenna is moved or if data collected by the FMS reveals a position error). The receiver’s 1 pps signal is turned on. The position data are stored for future use in a binary disk file in milliarcsecond format, and occupy only 12 bytes of disk space. The *GPS2000* software counts down for 10 s (display shown in Figure 2.8) and then loads the *FM2000* software.

Table 2.2. Parameters monitored by the FMS during GPS signal acquisition.

Receiver parameter	Acceptable value
Almanac	Almanac stored in RAM is complete and integrity has been verified.
Receiver status errors	None
Position dilution of position (PDOP)	<= 3
Satellites being tracked	>= 4
Time solution (this is a coarse estimate computed by the receiver and is not determined by actual measurement)	< 80 ns
3D position fix	Completed and integrity verified



Configuring NIST-FMAS GPS Receiver .....

Number of Satellites	6	Pulse (1 or 100 pps)	1 pps
Timing Stability (ns)	44	UTC Date (YYYY-MM-DD)	2001-06-19
Tracking Status Byte	32	UTC Time (HH:MM:SS)	16:59:46
Position Hold Mode	ON	Latitude	39° 59m 43.60s N
PDOP	2.8	Longitude	105° 15m 44.52s W

The integrity of the GPS Signal has been proven, and the system is now ready to use for frequency calibrations.

The system will be started in 8 second(s).

Figure 2.8. The GPS receiver configuration screen.

Receiver Warm Start – As previously mentioned, *GPS2000* can perform either a cold start or warm start of the receiver. A warm start is performed whenever the FMS unit is powered on or rebooted after the initial installation. In this case, it is not necessary to download a new almanac or resurvey the antenna, since the almanac and position data can be read from disk and sent to the receiver via the RS-232 port. However, the receiver parameters listed in Table 2.2

are still checked to verify receiver integrity, a process that normally takes a few minutes or less. Once this integrity check is completed, the *GPS2000* software counts down for 10 s (display shown in Figure 2.8) and then loads the *FM2000* software.

b) Initialization of Measurement Software

Each time the FMS is restarted, the *FM2000* software will automatically begin making measurements without any operator attention, provided that information about the frequency sources being measured has been previously entered. Three pieces of information are necessary [20, pp. 10-12]:

- The name of the device being tested.
- The nominal frequency of the device being tested (entered in units of hertz).
- The reference for the measurement (either GPS or the customer's primary standard).

Each time the *FM2000* software starts, normal software housekeeping is performed (arrays are dimensioned; subroutines and variables are defined, etc.). Then the measurement process is ready to begin. The first step is to read several data files, including a file name named CHANNELS that contains the three pieces of information described above. When the data files have been read and processed, the following message is displayed on screen:

Finished Reading Configuration Data

Communications are established with the GPS receiver, and the computer's time-of-day clock is synchronized to GPS, a process that will be repeated every 10 min while the system is running. When the time-of-day synchronization is complete, this message appears:

Finished Synchronization of System Clock to GPS

From this point forward, the FMS continually reads and writes data to and from the TIC previously described in Chapter 2.A.2.a. The TIC occupies 32 bytes of the computer's I/O addressing space. These bytes are designated as registers R0 to R31. R0 is at the base address of the counter. The base address may be set to either 200h or 300h using an on-board jumper. R1 is equal to the base address + 1, R2 is equal to the base address + 2, and so on.

Table 2.3 provides a listing of the registers so that the measurement software can be adequately described. Note that eight measurement channels actually exist on the TIC, but only five are used by the FMS. The TIC's functions can be programmed using the control registers (R0 through R5, and R16 through R23). Registers R28 through R31 are used to program the counter's field programmable gate array using a RBF (raw binary file). This file is uploaded to the counter before any other functions are usable. Registers R6, R7, R15, and R24 to R27 are not used.

Table 2.3. TIC control registers.

Register	Read	Write
R0	Control register 0	Control register 0
R1	Read waveform type (channels 0 to 7)	Set waveform type (channels 0 to 7)
R2	Count done and signal present	Enable count done interrupt
R3	Select dividers to set (channels 0 to 7)	Select dividers to set (channels 0 to 7)
R4	Control register 4	Control register 4
R5	Read time base frequency and start and stop Input	Set time base frequency and start and stop input
R6	Not used	Not used
R7	Not used	Not used
R8	Start counter readout (bits 0-7)	Divide value for start input (bits 0-7)
R9	Start counter readout (bits 8-15)	Divide value for start input (bits 8-15)
R10	Stop counter readout (bits 0-7)	Divide value for start input (bits 16-23)
R11	Stop counter readout (bits 8-15)	Divide value for stop input (bits 0-7)
R12	Main counter readout (bits 0-7)	Divide value for stop input (bits 8-15)
R13	Main counter readout (bits 8-15)	Divide value for stop input (bits 16-23)
R14	Main counter readout (bits 16-23)	Not used
R15	Not used	Not used
R16	Run dividers (channels 0 to 7)	Run dividers (channels 0 to 7)
R17	Load dividers (channels 0 to 7)	Load dividers (channels 0 to 7)
R18	Reset start input (channels 0 to 7)	Reset start input (channels 0 to 7)
R19	Read prescalers (channels 0 to 3)	Set prescalers (channels 0 to 3)
R20	Read prescalers (channels 4 to 7)	Set prescalers (channels 4 to 7)
R21	Clear prescalers (channels 0 to 7)	Clear prescalers (channels 0 to 7)
R22	Select channel (0 to 7)	Select channel (0 to 7)
R23	Bypass dividers (Channels 0 to 7)	Bypass dividers (Channels 0 to 7)
R24	Not used	Not used
R25	Not used	Not used
R26	Not used	Not used
R27	Not used	Not used
R28	Data transfer register 7 to 0	Data transfer register
R29	Bit mover status	Start JTAG mode
R30	Byte shift register 0-7	Start transfer
R31	Bit count/move state	Device clear

The TIC is prepared for measurements by first setting the time base frequency and then setting the frequency dividers. The time base frequency (1, 5, or 10 MHz) is set by writing to R5. This allows the counter's 10 MHz time base PLL to lock to the signal from the customer's primary frequency standard. Once this is accomplished, the 10 MHz PLL is divided to 1 pps using a series of writes to R11, R12, and R13 (the 24-bit divider occupies three 8-bit registers). This 1 pps signal from the customer's primary frequency standard is always compared to GPS on channel one of the FMS.

The nominal frequencies of the devices connected to FMS channel numbers two through five (if present) are also divided to 1 pps. Prior to setting the dividers, three steps must be performed. The first step is to select the waveform type for each of these channels by writing to R1. If the nominal frequency is 100 kHz or higher, it is assumed that the waveform is sinusoidal. If not, it is assumed that the waveform consists of TTL pulses. The second step is to determine if the nominal frequency is 1 Hz. If so, the divider on that channel is bypassed by writing to R23. The third step is to determine if the nominal frequency exceeds 15 MHz. If so, the divide by 10 prescaler for that channel is turned on by writing to R20. Now that all signal housekeeping has been performed, the divider is set by first selecting the appropriate divider for each channel with a write to R3, and then sending the 24-bit divide ratio to R8, R9, and R10. The divide values are loaded by writing to R17, and the divide counters are started by writing to R16. The following message is then displayed on screen:

Finished Setting Frequency Dividers

The next step is to calibrate the TIC, a process generically described in Chapter 2.A.2.a. The TIC is placed in calibrate mode by writing to R0. A write to R5 puts the 39062.5 Hz calibrate frequency on both the start and stop inputs to the TIC. Then the gate level is set by charging and discharging capacitors on the counter board with a series of writes to R0. A series of iterative loops are used to repeatedly arm and read the TIC at a number of different signal levels so that the start and stop interpolators can be calibrated. The counter is armed by writing to R0, and a "count done" condition is indicated by reading from R2. Once a "count done" occurs, the 24-bit main counter is read from R12, R13, and R14. The 16-bit start interpolator counter is read from R8 and R9, and the 16-bit stop interpolator counter is read from R10 and R11. When the TIC calibration is finished, the following message is displayed on screen:

Finished Calibration of Time Interval Counter

If the FMS was taking measurements the last time it was restarted, it will now automatically begin taking measurements again. If not, the user can start the measurement process by selecting MEASURE from the menu [20, p. 15].

c) Sequence of Time Interval Measurements

Measurements are made sequentially from each of the five channels with devices connected. The measurements run nearly continuously unless the FMS is stopped (either by the operator or by a power outage). Measurements stop only for a short time once every 24 h; normally at

1600 UTC (the customer can change this time). During this stoppage, the collected data are graphed and printed, and the TIC is recalibrated. The collected data are stored every hour, and the computer clock is resynchronized to GPS every 10 min. Table 2.4 shows a simplified measurement sequence that repeats every N s, where N is the number of channels in use.

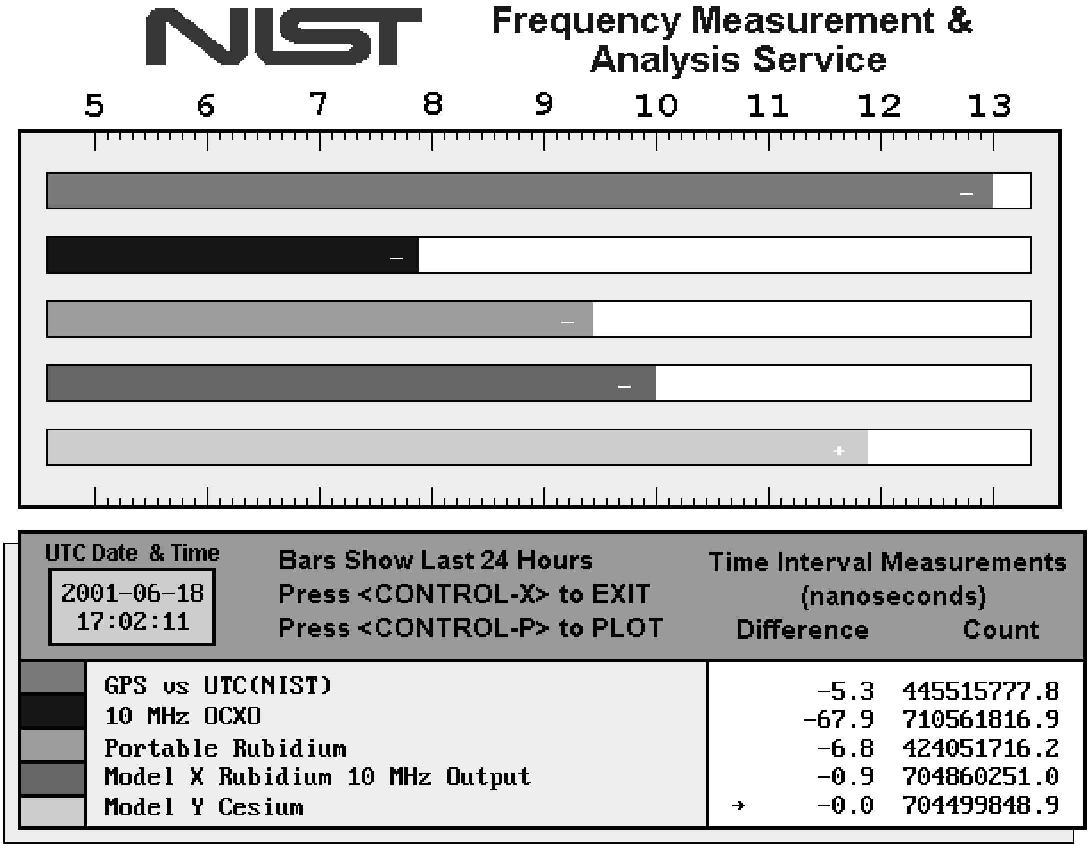
Table 2.4. Time Interval Measurement Sequence.

Step	**Action**	**Description**
1	Read each measurement channel once.	Each measurement channel is read once. Prior to each measurement, the start and stop inputs to the TIC are selected by configuring the multiplexer by writing to R5. The multiplexer used for channels two through five is always selected as the start input. A write to R22 selects which channel on the multiplexer is passed through to the TIC. The TIC is then armed and read after the "count done" flag goes high on R2.
2	Store each counter reading.	The readings are stored in the array named *lastcount*. If no reading was available (TIC timeout condition), a value of 9999 is stored in the array.
3	Check to see whether GPS receiver is locked.	Check GPS receiver status message. If receiver is unlocked, record date and time information in the file named *coast.dat*.
4	Check keyboard input.	See if user has entered a keystroke to stop the measurements (Ctrl-X), or to force the collected data to be graphed (Ctrl-P). Branch out of loop if either condition exists.
5	Print time on screen.	Print current time of computer clock on screen (ambiguous to a few tenths of a second).
6	Check time.	If it is the top of the hour (00 minutes, 00 seconds), the data collected during the past hour need to be saved to disk. If the scheduled plot time has occurred, the data need to be graphed and the TIC recalibrated. Branch out of loop if either condition exists.
7	Get "sawtooth" correction (2.3) from GPS receiver via RS-232.	The "sawtooth" correction has a range of ± 52 ns and is applied to the next measurement made using GPS as a reference.

Table 2.4., continued.

Step	Action	Description
8	Read all measurement channels again.	The reading from the current channel is stored in the count array. If no reading was available (TIC timeout condition), a value of 9999 is stored in the array. Reset divider on selected measurement channel by writing to R16 if the TIC is approaching an overflow or underflow condition.
9	Print reading from current channel on screen.	Print the reading in the "Count" column on the FMS screen (Figure 2.9), rounded to a resolution of 100 ps. If the reading is believed to be valid, print in white numerals. If the reading is invalid and is to be discarded, for example if GPS is the reference and the receiver is unlocked, print in red numerals. If no signal is available on either the start or stop channel, print NO SIGNAL.
10	Take the difference of the last two counter readings made from the same channel.	First, ensure that the last two readings are valid (no timeout conditions, divider resets, GPS unlocked, etc). Then, take the difference between the two readings, and print in the "Difference" column on the FMS display with 100 ps resolution. If the time difference between the last two readings exceeds 100 µs, print a string of asterisks in red in place of the value. This means that the frequency offset is unusually large (larger than 2×10^{-5} even if all five channels are connected), and that the data will be discarded, since something is probably wrong with the DUT.
11	Add valid differences to the accumulated phase difference for the channel.	Valid differences for each channel are added to the array named total, which has five elements, one for each channel. This array stores the accumulated phase difference for each channel, which is saved each hour. After the data are stored (see step 6), all five elements of the total array are reinitialized to 0 and the process repeats starting with step 1.
12	Copy values in count array to *lastcount* array.	Once the current count is processed, it becomes the last count. Thus, the stored difference values represent $n_2 - n_1$, $n_3 - n_2$, $n_4 - n_3$, and so on.
13	Repeat process	Return to step 3 and repeat process until the top of the hour.

While the FMS is taking data, a screen similar to Figure 2.9 is displayed. The top part of the measurement screen is a bar graph that provides the customer with a quick indication of how each oscillator is performing. The bars represent channels one through five (from top to bottom). The bars are color coded, with their colors corresponding to the boxes next to the channel names shown near the bottom of the measurement screen.



UTC Date & Time
2001-06-18
17:02:11

Bars Show Last 24 Hours
Press <CONTROL-X> to EXIT
Press <CONTROL-P> to PLOT

Time Interval Measurements (nanoseconds)

	Difference	Count
GPS vs UTC(NIST)	-5.3	445515777.8
10 MHz OCXO	-67.9	710561816.9
Portable Rubidium	-6.8	424051716.2
Model X Rubidium 10 MHz Output	-0.9	704860251.0
Model Y Cesium	→ -0.0	704499848.9

Figure 2.9. The FMS display.

When the FMS is first started, the bars extend only to the number "5" on the far left side of the screen. After the system has been running for between 1 and 2 hours, the bars will extend further (assuming that the oscillator's performance is better than 1×10^{-5}) and show the estimated frequency offset of each oscillator. The numbers at the top of the screen (ranging from 5 to 13) denote frequency offset values ranging from 1×10^{-5} to 1×10^{-13}. The longer the bar, the smaller the frequency offset of the device under test. Each bar also contains either a plus sign "+" or a minus sign "–". A plus sign means that the oscillator frequency is higher than nominal; a minus sign means the oscillator frequency is lower than nominal.

When the FMS has run for less than 24 h, the frequency offset estimate is based on all of the available data; for example, 12 h of data if the FMS has run for 12 h. However, when the FMS has collected data for more than 24 h, only the most recent 24 h of data are used to estimate the frequency offset. A new data point is stored to disk every hour. When this occurs, a new frequency offset estimate is calculated and the length of the bars might change.

The screen area below the bar graph (see Figure 2.9) contains information about the most recent time interval readings, expressed in nanoseconds. The small red box contains the current date and the current time (UTC). The "Difference" column shows the difference between the last two counter readings for a given channel. The "Count" column shows the most recent counter reading for each channel. The FMS reads each counter channel in numerical order. The arrow points to the channel currently being read [20].

d) Estimation of Frequency Offset

The FMS reports the frequency offset of each device under test, or the difference between the measured frequency and its nominal, or nameplate value. A frequency offset estimate is reported every day for each measurement channel that is in use. Another frequency offset estimate for the customer's primary oscillator is made for the entire month, and reported on the monthly calibration reports. The measurement uncertainty value shown on the calibration reports refers to the uncertainty of the monthly frequency offset estimate. The standard equation for estimating frequency offset is

$$f_{off} = \frac{f_{meas} - f_{nom}}{f_{nom}} , \qquad (11)$$

where f_{off} is the dimensionless frequency offset, f_{meas} is the actual frequency in hertz reported by the measurement, and f_{nom} is the nominal frequency in hertz that the device would ideally produce. Note that in practice f_{meas} has an associated measurement uncertainty, but f_{nom} is always an ideal value with no uncertainty. This equation is often simplified in the literature as

$$f_{off} = \frac{\Delta f}{f} , \qquad (12)$$

where f_{off} is the dimensionless frequency offset, Δf is the difference between the measured and nominal frequency in hertz, and f is the nominal frequency in hertz. This is perhaps easiest to illustrate with a frequency counter. For example, if a 10 MHz oscillator (10^7 Hz) produced a frequency counter reading that was high by 1 Hz, the equation becomes

$$f_{off} = \frac{1}{10^7} = 1 \times 10^{-7} \qquad (13)$$

Note that since the nominal frequency was included in both the numerator and denominator in Eq. 11, the value for f_{off} is now dimensionless, and not in units of hertz.

As previously discussed, the FMS measures time interval, but produces frequency information. This is possible since the relationship between frequency and time interval is known. Dimensionally, frequency is the reciprocal of time interval. A mathematical definition of frequency is

$$f = \frac{1}{T} \quad , \tag{14}$$

where T is the period of the signal in seconds, and f is the frequency in hertz. This can also be expressed as

$$f = T^{-1} \quad . \tag{15}$$

If we perform mathematical differentiation on the frequency expression with respect to time and substitute in the result, we can show that the average fractional difference in frequency is equivalent to the average fractional difference in time, or that $\Delta f/f$ is equivalent to $-\Delta t/T$

$$\Delta f = -T^{-2}\Delta t = -\frac{\Delta t}{T^2} = -\frac{\Delta t}{T} f \quad , \tag{16}$$

therefore,

$$f_{off} = \frac{\Delta f}{f} = -\frac{\Delta t}{T} \quad , \tag{17}$$

where Δt is the difference between two time interval measurements (such as the one described by Eq. 8), and T is the elapsed time between the two measurements. To keep the sign correct, note that the first reading must be subtracted from the second, therefore

$$f_{off} = \frac{TIC_2 - TIC_1}{T} = -\frac{\Delta t}{T} \quad . \tag{18}$$

To illustrate this, consider a simple example where an initial reading is made from a TIC and a second reading is made 1 s later, with the value increasing by 100 ns. This produces the same value for f_{off} previously shown in Eq. 13

$$f_{off} = \frac{100}{10^9} = 1 \times 10^{-7} \tag{19}$$

A frequency estimation of frequency offset can be made by recording a single TIC reading, waiting for a specified length of time, one hour for example, and then recording a second TIC reading. If the two readings are substituted into Eq. 18, the result is an estimate of the average frequency offset for the one hour interval. Of course, knowledge of how the frequency performed during the one hour interval has been lost. It is possible that the frequency was very noisy and unstable and thus deviated by large amounts during the hour, but coincidentally the two time interval readings were very close to the same value. For this reason, the FMS collects data throughout the interval. One data point is stored each hour by summing phase differences collected throughout the hour (Table 2.4). These one-hour phase accumulations are stored by the FMS using the file format pictured in Figure 2.10. This file is appended to every hour, and a new file is started every month.

```
Cesium 1 vs GPS
Not Used
Rubidium 1
Rubidium 2
Cesium 2
52852.000     -0.00256   8888.00000      2.11985      0.16894      0.01159
52852.042      0.00836   8888.00000      2.12173      0.17673      0.01141
52852.083      0.00827   8888.00000      2.10792      0.18175      0.00117
52852.125     -0.00504   8888.00000      2.09820      0.17746      0.00092
52852.167     -0.00143   8888.00000      2.09068      0.17019      0.00411
52852.208     -0.00365   8888.00000      2.08916      0.17076      0.00800
52852.250      0.01039   8888.00000      2.08408      0.16152      0.00409
52852.292     -0.01364   8888.00000      2.08591      0.15282      0.00089
52852.333     -0.01128   8888.00000      2.08197      0.15751      0.00358
52852.375      0.01394   8888.00000      2.08085      0.15117      0.00287
52852.417     -0.00531   8888.00000      2.08104      0.15520      0.00300
52852.458     -0.00754   8888.00000      2.07624      0.14917      0.00259
52852.500      0.01645   8888.00000      2.07451      0.15213      0.00236
52852.542     -0.01189   8888.00000      2.06955      0.15074      0.00363
52852.583      0.01042   8888.00000      2.07619      0.15165      0.00249
52852.625      0.00374   8888.00000      2.07261      0.14912      0.00899
52852.667     -0.00215   8888.00000      2.07330      0.15631      0.00393
52852.708     -0.03227   8888.00000      2.07839      0.15835      0.00627
52852.750      0.01137   8888.00000      2.10058      0.16400      0.00368
52852.792     -0.01093   8888.00000      2.10818      0.17305      0.01005
52852.833      0.01953   8888.00000      2.11426      0.17597      0.00591
52852.875     -0.02473   8888.00000      2.12401      0.16804      0.00477
52852.917     -0.00231   8888.00000      2.12180      0.16970      0.01072
52852.958      0.00409   8888.00000      2.10731      0.16868      0.00442
52853.000     -0.07642   8888.00000      2.09216      0.17042      0.00855
```

Figure 2.10. FMS phase data file.

The file header contains the channel names for each measurement channel in use, followed by six data columns. The leftmost column contains the time stamp for the data (*x* values), depicted as the Modified Julian Date (MJD) plus the fractional part of the UTC day when the 1 h sample was completed. For example, 53057.500 indicates that this row of measurements was taken on MJD 53057 in the 1 h interval from 1100 to 1200 UTC. The other five columns

(y values) contain the accumulated phase differences taken from the five measurement channels during the 1 h interval. The units for these data are microseconds, but since five digits are carried to the right of the decimal, the resolution is 10 ps. If a channel is unused, a value of 8888.00000 is stored.

To estimate frequency offset for a given measurement channel, the FMS software loads the phase data file, and creates a new two-dimensional array (x, y). The x values are the time stamps for each data point; the y values are generated by starting with an initial data point or "anchor value" of 500 000 µs, and then algebraically adding each phase difference y_i to the previous data point. A least squares line is then fit to the new array, and the slope of the least squares line is substituted for Δt in Eq. 18. The slope and y-intercept for the least squares lines are calculated as

$$\hat{\beta}_1 = \frac{SS_{xy}}{SS_{xx}} \tag{20}$$

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \quad , \tag{21}$$

where

$$SS_{xy} = \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y}) = \sum_{i=1}^{n} x_i y_i - \frac{(\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n} \tag{22}$$

$$SS_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2 = \sum_{i=1}^{n} x_i^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n} \quad , \tag{23}$$

where n is the number of data points used in the estimate.

To estimate the "goodness of fit" of the least squares line to the phase data, the linear correlation coefficient, r, is calculated. The possible values for r range for -1 to $+1$, with $r = 1$ or $r = -1$ indicating that there is a nearly perfect linear relationship between the x and y values, that all data points lie on the least squares line, and that the frequency offset estimate is very accurate. The linear correlation coefficient is calculated as

$$r = \frac{SS_{xy}}{\sqrt{SS_{xx} SS_{yy}}} \quad . \tag{24}$$

The least squares line is drawn on all graphs produced on channel one of the FMS. If $r = 1$ or $r = -1$, the least squares line is nearly identical to the recorded phase data, and will overlap the data on the graph. This is nearly always the case when the measurement ran for 24 h or longer and f_{off} is $> 1 \times 10^{-12}$. Values for f_{off} and r are printed on all graphs produced by the FMS. A channel one example that includes the least squares line is provided in Figure 2.11. Note that the frequency offset estimate on this graph is very small, -4.46×10^{-14}, and that $r = -0.59$. These results show that the uncertainty of the frequency offset estimate is limited by GPS noise, but that the trend contributed by the frequency offset is still clearly visible.

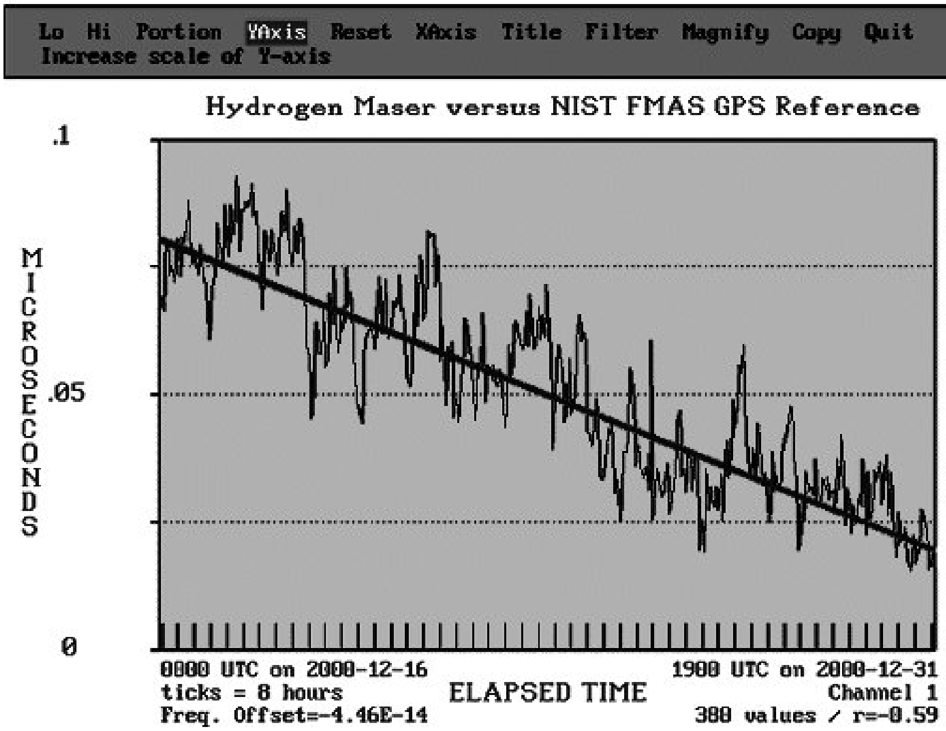


Figure 2.11. Sample FMS phase graph.

e) Graphing and Data Analysis Software

The FMS software produces phase graphs from all five channels every 24 h, unless this feature has been turned off by the customer. In addition, the customer can graph up to 3600 h (150 d) of data on demand, since all data recorded by the FMS are stored on a solid-state disk and can be retrieved at any time.

The phase graphs use the standard Cartesian x/y format. The x-coordinate is elapsed time-of-day, measured in hours. This is the quantity T shown earlier in Eq. 10. The tick marks on the x-axis are automatically scaled in intervals ranging from 1 h to 24 h, depending upon the amount of data being plotted as shown in Table 2.5.

Table 2.5. Tick intervals for x-axis used by FMS phase graphs.

Length of data run (h)	x-axis tick interval (h)
1 to 24	1
25 to 96	2
97 to 192	4
193 to 384	8
385 to 576	16
> 576	24

The change in phase, DF, is plotted as the *y*-coordinate. However, since phase is expressed in units of time (microseconds), this is actually the change in time, or the Δt quantity described earlier. The maximum and minimum values of the y_i data series are found, and the range ($y_{max} - y_{min}$) is calculated. The tick marks on the *y*-axis are then scaled using the "1-2-5-10" scaling sequence sometimes used by oscilloscopes and other test instruments. For example, a range of 3 µs would result in a *y*-axis scale of 5 µs, since the range is > 2 µs but < 5 µs. The minimum *y*-axis scale is 1 ns.

The data are normalized to 0 by subtracting the midpoint of the data from every value in the data set, making the midpoint 0. The midpoint is calculated as

$$y_{mid} = \frac{(y_{\max} - y_{\min})}{2} + y_{\min} , \tag{25}$$

where y_{mid} is the midpoint and y_{max} and y_{min} are the maximum and minimum values in the y_i data series, respectively. After the data are normalized, *x*-axis intercepts the *y*-axis at 0, and the data are scaled ± 0 as shown in Figure 2.12. The normalization of the data makes the phase graphs easier to interpret, and also make senses because no absolute time information is contained in the y_i series, therefore labeling the *y*-axis with unnormalized numbers would serve no purpose. Although the time interval readings are made at a 1 Hz rate, the alignment of the 1 pps signal is arbitrary for nearly all FMS measurements, because it is obtained by dividing a higher frequency signal. If the frequency dividers are stopped and restarted, a different cycle of the frequency passes through the divider and the 1 pps is realigned. Therefore, it is the change in phase and not the absolute phase difference that is being measured, and Δt is always relative to an arbitrary starting point, and not to an absolute time reference.

The phase graphs can be customized with a variety of editing and analysis features [20]. It is possible for the customer to "zoom-in" or "zoom-out" on a particular data segment by decreasing or increasing the scale of either the *x* or *y*-axes. It is also possible to remove outliers, one data point at a time, by deleting either y_{max} or y_{min} from the phase graph. The FMS software also includes a "Filter" function, which was designed to remove all of the outliers and phase steps from a phase graph with a single keystroke. This feature works utilizing a simple “3-sigma, 2-pass” filter. First, the mean and standard deviation (σ) of the y_i data series are computed; then data points that fall more than 3σ from the mean are removed and the process is repeated. To avoid removing valid data, the software will not attempt to filter data sets where the range is < 1 μs, where the number of values in the data series is less than 9, where the computed frequency offset is $< 1 \times 10^{-12}$, or where the absolute value of r exceeds 0.99.

Data points deleted from the phase graph are not deleted from the disk, and customers can restore the phase graph to its original status whenever they wish. The *FM2000* software also allows the customer to view the data set and its associated statistics in tabular form.

f) Frequency Stability Analysis Software

The *FM2000* software contains a module that allows customers to collect phase data from any of the five measurement channels for up to 1 h (3600 s). The data are collected at a 1 Hz rate and not averaged, so that the customer can examine, graph, and store raw phase data. This feature is useful for several applications. It can be used to identify potential noise sources, such as periodic steps or outliers that might be present in the frequency produced by a defective

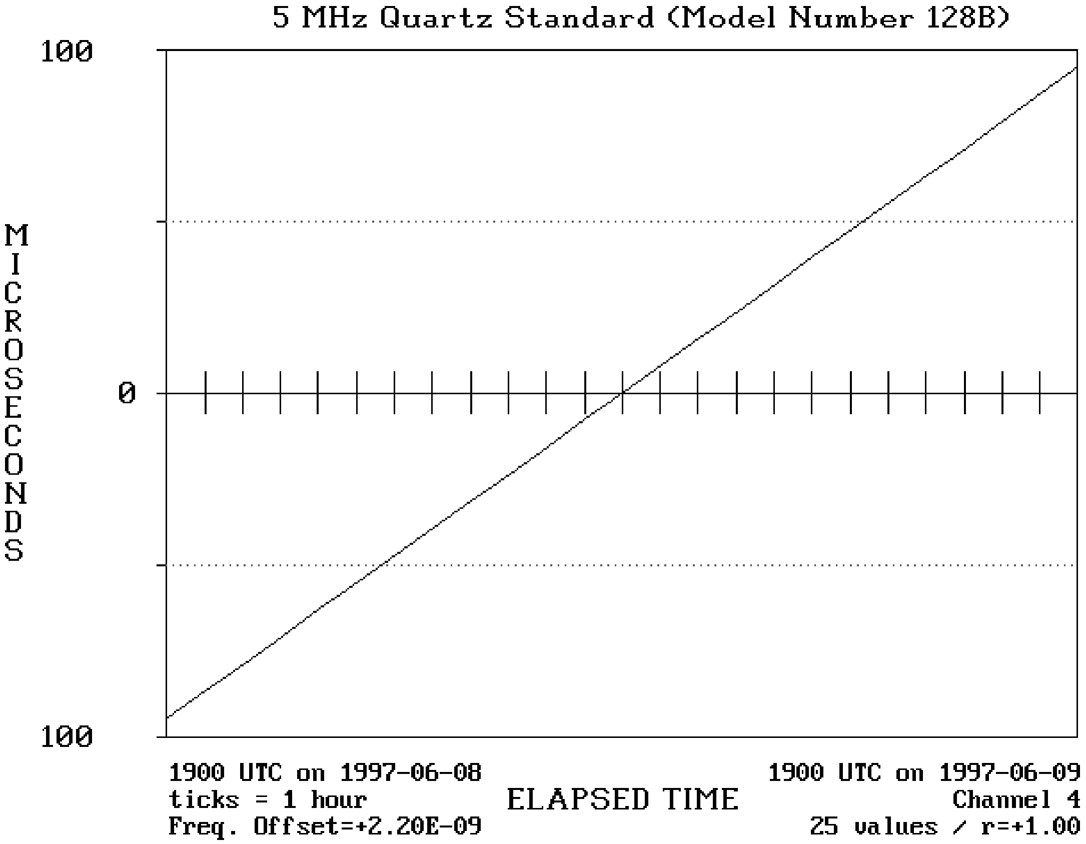


Figure 2.12. FMS phase graph with data normalized to 0.

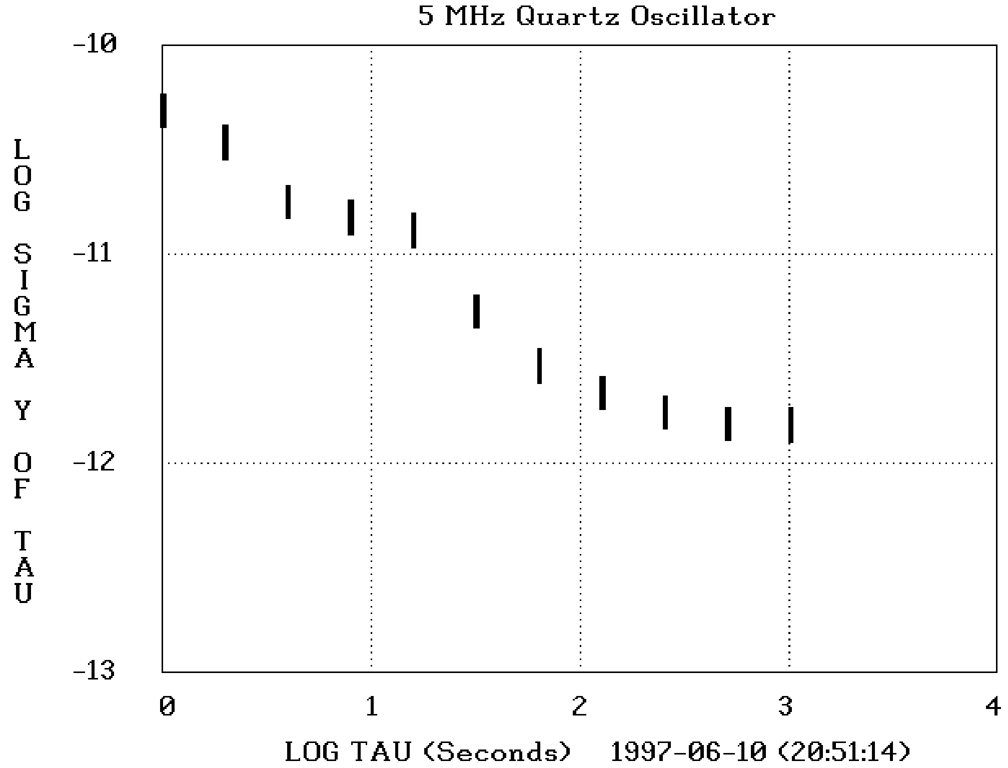


Figure 2.13. FMS Allan deviation graph.

device. It can be used to graph the “warm-up” curve of an oscillator that has just been turned on. It is also useful for a quick calibration or adjustment of oscillators with a frequency offset larger than about 1 × 10^{-10}, where a 24 h measurement might not be practical or necessary.

Customers can also graph the Allan deviation of the collected phase data. The Allan deviation, $\sigma_y(t)$, is a standardized statistic used to estimate frequency stability [38]. Because the FMS makes time measurements to compute frequency, it estimates the Allan deviation with the equation for time series data using overlapping samples

$$\sigma_y(\tau) = \sqrt{\frac{1}{2(N-2m)\tau^2} \sum_{i=1}^{N-2m} \left[x_{i+2m} - 2x_{i+m} + x_i\right]^2} , \qquad (26)$$

where x_i is a set of phase measurements in time units that consists of individual measurements, x_1, x_2, x_3, and so on; N is the number of original time residual measurements spaced by τ_0 (1 s); m is the number of original frequency measurements of sample time τ_0 ($m = N - 1$); and $t = m\tau_0$. The FMS uses the octave method of computing $\sigma_y(t)$, where every τ value is twice the length of the previous τ. Figure 2.13 shows an Allan deviation graph created with the FMS.

These graphs use a "log-log" format, with the *y*-axis scale indicating the dimensionless frequency stability, and the *x*-axis scale indicating the averaging time τ in logarithmic format (log τ 3 = 10^3 s = 1000 s).

The FMS was designed to measure the long term accuracy and stability of frequency sources, and should not be considered as an alternative to measurement systems designed specifically to measure the short term stability of oscillators. When measuring devices that contain an oven-controlled quartz oscillator (OCXO) at $\tau \leq 100$ s, there is a good possibility that the FMS noise floor, limited by the TIC, will be higher than the DUT noise floor. In these instances, the Allan deviation reveals only the FMS stability, and not the DUT stability. It also should be noted that many quartz and rubidium oscillators reach their noise floor at a τ of < 100 s, so by the time that FMS noise has averaged down to a sufficient level, information about the short-term stability of these devices has been lost. As mentioned earlier, laboratories that need to measure the short term stability of oscillators should use a system based on a heterodyne technique that mixes, rather than divides, the signal [28, 29]. However, at τ values > 100 s the FMS should produce essentially the same Allan deviation results as a heterodyne type system.

Customers can also produce graphs of the daily frequency offset of their primary frequency standard (Figure 2.14). On these graphs, the *x*-axis scale indicates the day of month (one month of data is contained on each graph), and the *y*-axis scale indicates the dimensionless frequency offset. A straight line of markers indicates that the oscillator is stable and able to

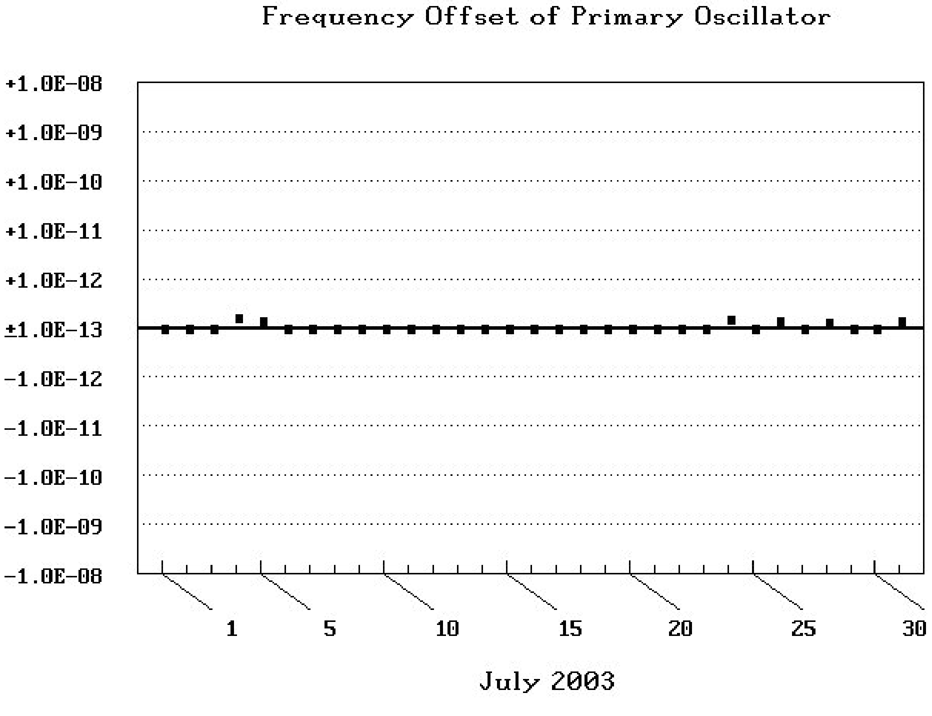


Figure 2.14. FMS frequency history graph (one month).

produce nearly the same frequency day after day. In Figure 2.14, UTC(NIST) is being compared to GPS, and the daily frequency offset estimate seldom exceeds 1×10^{-13}. A similar graph is provided to the customer on the monthly calibration report (Chapter 3.G).

g) Diagnostic Software

Diagnostic routines are included in the *FM2000* software that allow the customer or NIST (via modem) to view the current status of GPS satellite reception. The GPS status screen includes information about all satellites currently being tracked; including their PRN number, elevation angle above the horizon, health indicator, time offset in nanoseconds relative to the receiver's composite timing solution, and signal strength. The signal strength information is particularly important, since it can be used to identify and troubleshoot reception problems. Signal strength is reported as carrier to noise power density ratio (C/No), or the ratio of the power level of a signal carrier to the noise power in a 1 Hz bandwidth. In order for the FMS to meet its specifications, the C/No value should be in the 40 to 50 dB-Hz range, with 51 the maximum value that can be reported by the receiver. Values of less than about 38 indicate that the receiver is close to losing lock.

Additional diagnostic software allows the user to force a calibration of the TIC, a process generically described in Chapter 2.A.2.a. The forced TIC calibration displays the calibration results in tabular form. These results are not displayed during the automatic calibration that takes place every 24 h, but it might be necessary to look at them in some instances.

3. Host Software Used at NIST

Two customer software applications written at NIST are used to process the measurement data downloaded from each customer's site (Chapter 3.A.2). The first application, called *FMSFILER*, accepts as input the raw frequency data files (Chapter 3.E.2) downloaded from every customer, and then outputs processed data files (Chapter 3.E.3) that contain an uncertainty statement generated using the technique described in Chapter 5.C. *FMSFILER* assigns a status code to every calibration. A calibration is defined as a measurement made over a 24 h interval, so during the average month, each customer records about 30 calibrations. This status code is either a 0, which means that the calibration is valid, or a 9, which means that the value reported was either out of tolerance, unrealistic, incomplete, or missing, or that the FMS was being operated improperly. The report preparer at NIST then uses *FMSFILER* to review all calibration results with status codes of 9. If the calibration is considered by NIST personnel to be valid, the status code is changed from 9 to 0. If not, the status code is changed to a value ranging from 1 to 6, and a comment is added to annotate the situation. The allowable status codes are described in the section on calibration reports (Chapter 3.G). During a typical month, about 97 % of all calibrations are automatically marked with a status code of 0, and only about 3 % require additional review by the NIST staff. Of the approximately 3 % that require additional review, over half are changed to a status code of 0 (marked valid) after the NIST review is completed.

The second application, called *TREPORT*, accepts the processed data files (Chapter 3.E.3) and prints out a three-page calibration report for every customer. While most of the processing has already been done by *FMSFILER*, a graph of the daily frequency values is generated by *TREPORT*. The format of the monthly calibration reports is described in detail in Chapter 3.G.

Chapter 3

Operational Procedures

This chapter discusses the hardware and software maintenance required by the FMAS. It also discusses failure modes, record keeping, security issues, and how calibration reports are created and sent.

A. Hardware Maintenance

This section describes how the FMS hardware is maintained and checked both before and after its shipment to the customer.

1. Verification of the FMS prior to shipment

Each FMS unit is completely tested prior to shipment to the customer's site. Since the unit has just been assembled, all parts need to be full tested to confirm that they are fully functional and meet the FMS specifications. All FMS systems are "burned-in" for a long period of time, usually several weeks or more, before shipment to the customer.

The performance of each FMS unit is verified in one of two ways. The first way involves using the same frequency source, usually UTC(NIST) since it is readily available in the FMAS laboratory, as the start and stop input to all five measurement channels. This represents a "self-test" of the measurement system. Since the same input is being compared to itself, in theory, the frequency offset should be 0, but in practice, some noise is always produced by the measurement system. When a self-test is performed, this measurement system noise is examined to see whether it is within acceptable limits (typically low parts in 10^{15} or high parts in 10^{16} after one day of averaging). Units are not shipped until the amount of self-test noise is deemed acceptable.

The second type of test involves measuring a signal with a known frequency offset [39]. This signal is generated by locking a direct digital synthesizer (DDS) to UTC(NIST) and producing a 10 MHz signal offset by 1 mHz. This signal then has a known frequency offset of 1×10^{-13} relative to UTC(NIST), so the FMS should return that value when measuring the signal over an interval of a few hours or longer. An example of this measurement is shown in Figure 3.1. Note that since UTC(NIST) distributes a 5 MHz standard frequency, a low-noise frequency doubler is used to produce the 10 MHz DDS time base input.

The same type of test can be used to validate GPS performance on channel one of the FMS (Figure 3.2). However, if a 1×10^{-13} offset is used, it will take more than 1 day of averaging (usually about one week) to get a "clean", accurate measurement of the frequency since the peak-to-peak GPS variations (one-hour averages) have a typical daily amplitude near 20 ns, and this offset represents a daily phase change of just 8.64 ns [39].

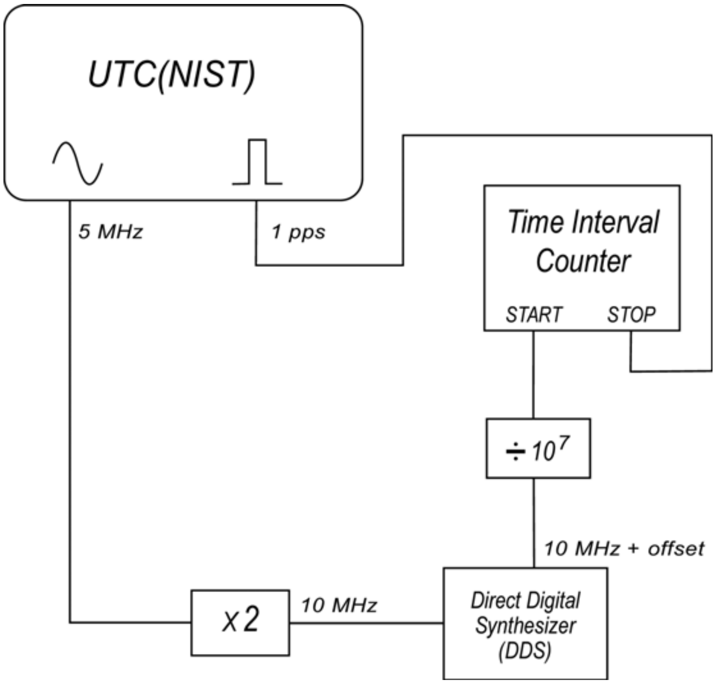


Figure 3.1. Verifying an oscillator to oscillator comparison with a known frequency offset.

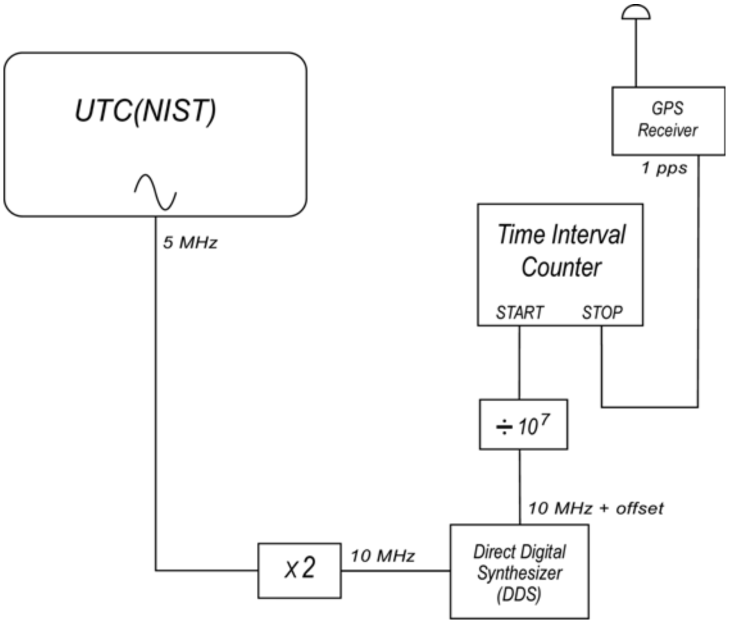


Figure 3.2. Verifying a GPS to oscillator comparison using a known frequency offset.

In addition to having the measurement integrity verified, each FMS unit must pass a series of other tests prior to shipment. A checklist of these tests is prepared for each unit and stored at NIST for diagnostic and information purposes. The other items on the checklist are summarized in Table 3.1.

Table 3.1. Items checked and logged prior to each FMS shipment.

Description of item	**Information logged**
Computer	MPU type, clock speed, amount of RAM, flash disk capacity, I/O port addresses and IRQ settings, software installation verified, cooling fans tested, floppy drive tested, modem tested by calling unit, results from a standardized speed test used to verify performance.
GPS receiver	Model number and firmware revision number. Fully tested, including its ability to provide power to the GPS antenna.
GPS antenna	Type of antenna, type of antenna cable, and length of antenna cable.
Time Interval Counter	Serial number and results of counter calibration. All channels and dividers are tested, and peak-to-peak values recorded in nanoseconds for counter self test on channels 2 through 5.
Printer	Tested by printing graphs from all five channels in succession.
Keyboard	Keys tested, rack mounting hardware tested so that it moves in and out smoothly.
Signal connectors	Tested for continuity and for proper labeling.
Video monitor, printer, and UPS	Tested for functionality. Serial numbers and NIST property numbers (when applicable) are recorded.
Accessories	A list of accessories packed with the system.

2. Verification of the FMS after shipment

After the FMS is installed by the customer and is successfully taking measurements, it is called by NIST personnel at least twice each month (at the beginning of each month and at mid-month) to verify correct operation. Systems that need more attention are called more often. If a phone connection cannot be established, NIST assumes that something is wrong (either with the FMS or the phone line) and the customer is immediately contacted.

During a remote system check, NIST personnel can view the identical measurement screen seen by the customer. In most cases, the measurements are stopped briefly, and data are downloaded for inclusion in the monthly calibration reports. If necessary, diagnostic software can be run to make sure that all FMS components are working properly. On rare occasions, new software is installed, or a new survey of the GPS antenna is initiated. A log sheet is filled out during every system check. Table 3.2 lists the information logged by NIST during each remote system check.

Table 3.2. Information logged at NIST during each remote check of an FMS unit.

Item logged or downloaded	Description
Frequency offset	The frequency offset of the customer's primary standard during the last 24 h is logged. If this value looks unusual, steps are taken to determine the cause of the anomaly.
Date of last system restart	This date is recorded to see if the system has been restarted lately. Under normal conditions, the system does not need to be restarted. Frequent restarts might mean that there are frequent power outages in the laboratory, or that the system is malfunctioning or being used improperly.
Dates and times when the GPS receiver was unlocked	Whenever the GPS receiver is unlocked (an extremely rare event for most customers), the date and time are recorded and logged.
Manufacturer and model number of primary frequency standard	Normally, this information does not change, or if it does, the change is usually reported in advance by the customer. However, it needs to be checked for reporting purposes.
Miscellaneous information	Anything unusual seen during the system check (including difficulties in connecting by phone) is recorded and logged.

B. Software Maintenance

The software maintenance is simplified by the fact that all remote FMS units contain identical software, although the software might be configured slightly differently from unit to unit to allow for minor hardware differences. Also, since the software runs 24 hours per day under a variety of conditions at customer sites, any errors are easily recognized. When software "bugs" are found, or new features are added, new software is uploaded and installed over the modem link. If the change impacts the customer in any way, NIST will contact the customer and inform them of the change. This contact is normally done with a written notice sent by mail.

Multiple documented copies of the master source code are kept at NIST, along with associated documentation for compilers, programmable hardware, and other items that influence the software architecture of the FMS.

C. Customer Maintenance

With a few small exceptions, the FMS requires no customer maintenance. The customer is responsible for ensuring that the GPS antenna is still mounted properly on the roof, that there is paper in the printer (if daily phase graphs are desired), that the backup power for their frequency sources is functioning, and that the telephone line connected to the FMS is still functioning properly. However, since NIST inspects each system by modem regularly, they can alert the customer to most potential problems. Most of the time, the customer can assume that everything is fine unless they "have heard from NIST."

When parts fail, they are immediately replaced using an overnight delivery service. Since NIST personnel do not travel to the customer's sites, the installation of the new part is normally performed by the customer. Most installations are very simple to perform. However, if the customer is not comfortable with the installation or if NIST cannot determine which part has failed, NIST sends a completely new FMS to the customer, and the data collected by the old unit are transferred to the new unit.

D. Failure Modes

FMAS failures can be divided into three groups: hardware failures, software failures, and GPS signal failures. Each type of failure is discussed in this section.

1. Hardware Failures

The FMS hardware is very reliable, but most problems regarding the FMS are related to hardware failures. NIST quickly works to correct FMS hardware problems (Chapter 3.C), and any hardware failures that impact the measurements are annotated on the calibration report. Table 3.3 summarizes the various types of hardware failures experienced in the past by FMS customers. The various failures are listed in descending order or occurrence, with the failures most likely to occur listed at the top of the table.

Table 3.3. Hardware failures experienced by FMS units at customer sites.

Part name	**Symptom/Cause**	**Critical to measurements?**	**Action taken by NIST**
Video monitor	No measurement display at customer's site. CRT monitors often fail after being left on for several years or more. The LCD monitors being used now have a longer life expectancy.	No, the measurements continue without a display.	Replacement part sent.
Printer	No printouts, poor quality printouts, or paper jamming. This is usually due to a mechanical failure in the printer.	No, the measurements continue without a printer.	Replacment part sent.
Telephone line	NIST cannot connect via modem due to a non-working telephone line.	No, the measurements continue.	The customer is responsible for getting the telephone line repaired.
Computer "freezes"	Computer display is frozen, measurements stop. This can be due to a general computer failure, but is sometimes due to overloading the time interval counter, operating the unit in a high RF environment, or using poor quality signal cables.	Yes, the measurements stop.	The computer is reset, if problems continue it is replaced. If TIC is being overdriven, attenuators are installed on input signals.
Computer power supply	FMS will not power up. Power supplies eventually fail, although the mean time between failure (MTBF) is typically 50 000 to 100 000 h (roughly five to ten years).	Yes, measurements stop.	Replacement part sent.
GPS receiver/ antenna	No data on channel one. Antenna and cable failures are more common than receiver failures since those components are located outdoors, but occasional damage to receivers occurs due to electrical storms.	Yes, traceability to NIST is lost, but measurements on channels two through five continue.	Replacement part sent. A lightning arrestor is installed on antenna if electrical storms are a problem in the area.
UPS	FMS will not power up, or is being rebooted intermittently. A bad UPS unit can cause numerous problems.	Yes, measurements stop or are constantly interrupted.	Replacement part sent.

Table 3.3, continued.

Part name	Symptom/Cause	Critical to measurements?	Action taken by NIST
Modem	Will not answer telephone calls from NIST. Most problems can be solved by rebooting. Modem failures are rare, but the modem circuits can sometimes be damaged by a power surge over the telephone line.	No, measurements continue without modem.	Replacement part sent. Sometimes surge protection is applied to the phone line.
Disk Drive	Data cannot be stored or are corrupted, FMS normally (but not always) stops. Since a solid state disk is used, drive failures are rare.	Yes, measurements stop or data are lost.	Replacement part sent. Data from old drive are transferred to new drive, if possible.
Distribution amplifier or cables from primary standard	Weak or intermittent signal causes the time base PLL on the FMS to miss a zero crossing, resulting in phase steps in data that are an even multiple of 100 ns.	Yes, measurements are contaminated by unwanted noise.	NIST assists customer in finding the source of the problem.

2. Software Failures

When software failures occur, the software is fixed, and new software is uploaded and installed over the modem link (3.B). If these failures adversely impacted the measurements, or caused FMS downtime, these failures are annotated on the next calibration report.

3. GPS Signal Failures

A signal failure occurs if the FMS cannot receive the GPS signal. The most common reason for this is a hardware failure concerning the GPS receiver or antenna (Table 3.3). However, in some cases, GPS reception is weak or intermittent due to local interference, or in very rare instances, the GPS satellites actually transmit bad data.

If local interference is the problem, NIST works with the customer to solve it. Often, this requires relocating the antenna. One case of interference involved an antenna located in the line-of-sight of a radar testing range at a U.S. military facility. Another case involved a GPS antenna located too close to another GPS antenna that was equipped with a preamplifier. The second GPS antenna had a crack in the coaxial antenna cable and was essentially rebroadcasting the L1 signal from about 1 m away, blocking GPS reception entirely. Most problems are caused by placing the antenna in an area where a clear sky view is not available in all directions, resulting in signals from satellites in parts of the sky being blocked. Most interference problems are solved shortly after the FMS is installed at the customer’s site.

If a single GPS satellite is broadcasting bad data, there is a good chance that it will not be noticeable to the FMAS customer. The FMS GPS receiver drops bad satellites from the time and frequency solution if they are marked as unhealthy by the GPS status message. It also drops satellites from the solution if their clock signals substantially disagree with the data being received from the other satellites, a feature known as TRAIM (Time Receiver Autonomous Integrity Monitoring) [34]. However, for a short time, bad data might be processed by the FMS. For example, a satellite clock might go bad minutes or hours before GPS master control updates the status message. Or, the TRAIM feature might be tricked by a situation where most or all of the satellites are broadcasting bad data. In these extremely rare instances, NIST personnel will discover a problem in the GPS data received at more than one customer site, since the same signals will be simultaneously received at multiple laboratories. To verify that the GPS broadcast was bad, NIST personnel consult several sources, including the NANU (Notice Advisory to Navstar Users) messages published by the United States Coast Guard. These messages inform users of any changes or unusual events that impact the GPS constellation [40]. Information from the NANUs is used to annotate the situation on the customer's calibration report.

E. Record Keeping

The FMAS records are described below. They include customer information files, raw measurement data files, and processed measurement data files.

1. Customer Information Files

There are three database files that contain customer information, as listed below. This information is stored on a single computer at NIST, and backed up both to removable media and to an internal network location (the combined file size is less than 1 megabyte). All files are accessed using software developed at NIST. The file format is dBase.

- **Main File** – This file contains the customer's name, address, phone number, and information about their primary frequency standard (manufacturer and model number). It also contains a list of all NIST property that is on-site at the customer's location. Information from this file is automatically extracted and copied into the processed measurement files (see below).

- **Billing File** – This contains the billing address for each customer, the customer purchase orders, and the expiration dates. The software automatically generates the information necessary to bill the customer.

- **Parts Inventory File** – This file contains the spare parts inventory stored at NIST, including the property number of each item. If a customer needs to send a part back to NIST, that information is also recorded here.

2. Raw Measurement Data Files

Since the FMS is a remote calibration service, all measurements are made and stored at the customer's location on local media. The measurement data are downloaded, stored, and backed up at NIST, but a copy remains on the customer's system. Therefore, if those data are lost at NIST, it is usually possible to download them again. The raw data consist of two files (both are ASCII text files):

- **Phase Data File -** This file is appended to every hour, and a new file is created monthly. It contains the time and date stamps for the measurements, the names of the devices being measured, and the phase measurements made from up to five oscillators (Figure 2.10). The average monthly file size is about 60 kilobytes. If 50 FMS systems are in operation, this means about 3 megabytes of phase data are stored each month.

- **Frequency Data File -** This file is appended to daily, and a new file is created monthly. It stores the estimated frequency offset of the customer's primary oscillator, and other data that indicate the confidence level of the measurement. The average monthly file size is about 1 kilobyte. The file name is MMMYY.##, where MMM is a three character prefix for the current month, YY is the two digit year code, and ## is the customer number.

3. Processed Measurement Data Files

These files are also ASCII text files. They are generated from the raw frequency data files by the *FMSFILER* software developed at NIST (Chapter 2.B.3). The processed file includes the customer's name and address; a description of the device under test, the daily frequency offset values, a statement of measurement uncertainty, and comments entered by NIST personnel that explain out of tolerance conditions. The processed files are run through the *TREPORT* software application developed at NIST (Chapter 2.B.3) that generates the actual calibration reports mailed to customers. The file name is MMMYYUNC.##, where MMM is a three character prefix for the current month, YY is the two digit year code, "UNC" is a tag that denotes the file contains an uncertainty statement, and ## is the customer number. Copies of the calibration report are not stored, but any calibration report can be regenerated almost instantly from the processed file.

The processed files are backed up periodically at NIST on removable media, and also copied to the NIST internal network for further redundancy. If the processed files are lost, they could be regenerated at NIST from the raw files, but the process might be fairly labor intensive (it typically takes 8 to 12 h per month to generate the processed files for all FMS customers). However, once a calibration report is sent, it should not be necessary to access the processed files again, unless a customer asks for a calibration report to be resent (an event that happens only several times each year).

F. Security Issues

Security is not a large concern with the FMS units located at customer sites, and no security violations have ever occurred. It is important to note that the units are not networked in any way with other computers in the facility. Instead, they are simply connected to ordinary analog telephone lines and accept only incoming phone calls; their software does not allow them to make a call.

Each FMS comes with remote communications software preinstalled. When a call is received from NIST, a series of commands allows NIST personnel to download the data. It is conceivable that an outside caller using identical remote communications software could call the system, somehow learn and enter the commands, and download, change, or delete the software or the calibration data. However, the chance of this happening is extremely small, because the FMS phone numbers and command structure are unpublished and kept in a secure area at NIST. Even if someone were able to “log-on” to an FMS, there is relatively little damage they could do. They could not use the FMS to obtain entry into another computer, since the FMS is not on a network. Downloaded data consist of columns and rows of numbers that contain no sensitive information and would likely mean nothing to a potential intruder. Deleted data or software could easily be restored since backup copies are kept at NIST, and NIST personnel would be able to tell whether the data had been tampered with.

G. Calibration Reports

All FMAS customers receive a monthly calibration report by mail. These reports are nearly always mailed before the 7th day of the month following the month when the calibrations were performed. For example, the February report is nearly always mailed before March 7th.

A sample calibration report is shown in Figure 3.3. The report is three pages long, and the content contained on each page is summarized in the following sections.

- **Page 1**

This page contains a header with the NIST service identification number (76100S) as listed in the *NIST Calibration Services User’s Guide* [41], and the address of the NIST Time and Frequency Division.

The top portion of page 1 contains some general information about each customer including: the customer’s address, the main point of contact, and the manufacturer, model number, and type of the customer’s primary frequency standard (called the device under test). The rest of page 1 contains a brief description of the calibration method, and some general information about the FMAS. This text will change slightly from time to time as changes are made to the service.

The bottom of page 1 contains a footer (also found on pages 2 and 3) that lists the issue date of the report, the report number, the NIST service identification number [41], and the page number. The report number is a six-digit number that uniquely identifies the report. The format for the report number is ##YYMM, where ## is the customer number, YY is a two-digit year code, and MM is the number of the month.

- **Page 2**

This page contains a table that lists the daily frequency offset values for the customer’s primary frequency standard. Each frequency offset value is the result of a 24 h calibration (Chapter 2.B.2.d). The table also lists the correlation coefficient r as a measure of confidence for each calibration, and a status code for each calibration. The status codes are explained in Table 3.4.

Table 3.4. Calibration report status codes.

Code	Description
0	*Valid Calibration* - NIST has determined that all components of the FMS worked properly during the calibration and that the calibration results are valid. This usually means that the result was within a k = 2 coverage area with respect to the average frequency. However, in some cases a valid calibration falls outside of the k = 2 range.
1	*No Data* - No data were recorded. The measurement system was either turned off or malfunctioning or no DUT signal was present.
2	*GPS Reception Error* - NIST has determined that the customer had a problem with GPS reception during the calibration. The cause could be either due to a malfunctioning receiver, antenna, or cable, or due to a source of interference.
3	*GPS Broadcast Error* - NIST has determined that a GPS satellite was broadcasting invalid data that adversely influenced the calibration. Note that this situation rarely occurs.
4	*Measurement System Error* - NIST has determined that the FMS had failed or was malfunctioning due to a hardware or software failure.
5	*DUT error* – The customer's primary frequency standard was out of normal tolerance during the calibration.
6	*DUT change* – The customer has replaced their primary frequency standard with another device.

If a status code other than 0 is assigned, it is accompanied by a brief comment that explains the situation. If a status code of 0 is assigned it means that the calibration is considered valid, and no further comment is necessary.

- **Page 3**

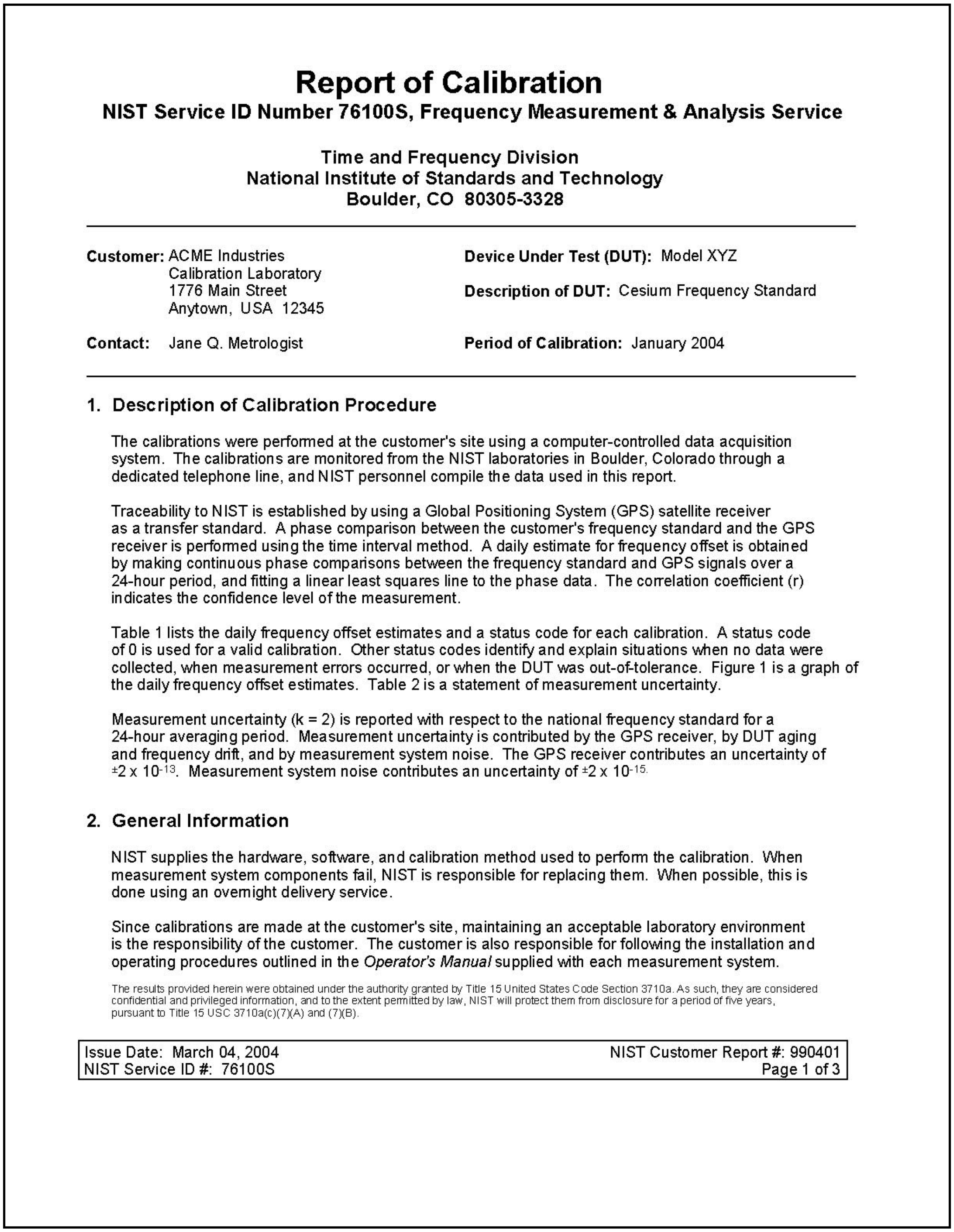
This page contains a graph showing the daily frequency offset values for the customer's primary frequency standard. The *x*-axis shows the days of the month, with each tic mark representing 1 d. The *y*-axis shows the frequency offset, with the middle of the y-axis representing a frequency offset of 1×10^{-12} or less. The plot accommodates oscillators that are high in frequency (the top half of the plot), or low in frequency (the bottom half). Frequency offsets larger than $\pm 1 \times 10^{-8}$ are off the scale and plotted along the top or bottom line of the graph.

An uncertainty statement, consisting of a table of values (see Chapter 5.C for computational details), is below the frequency graph. These values are described in Table 3.5.

Table 3.5. Items listed on FMAS uncertainty statement.

Item	Description
Days when data were recorded	The number of days in the month when a calibration of the customer's primary frequency standard was performed. In most cases, this equals the number of days in the month since the calibrations are continuous.
Days within tolerance (k = 2)	The number of days when the customer's primary frequency standard was within two standard deviations of its average frequency.
Mean Frequency Offset (MFO)	The mean (or average) frequency offset for the customer's primary frequency standard for the specified month.
Uncertainty (U), (k = 2)	The measurement uncertainty assigned to the calibration of the customer's primary frequency standard. This number will seldom be smaller than $\pm 2 \times 10^{-13}$, since it is limited by the GPS propagation noise that is still present after 1 d of averaging.
$\mathbf{FO_{lower} = MFO - U}$	The lower band performance limit of the customer's primary frequency standard during the month. There is a 95.4 % probability that the frequency offset remained above this value and below FO_{upper} throughout the entire month.
$\mathbf{FO_{upper} = MFO + U}$	The upper band performance limit of the customer's primary frequency standard during the month. There is a 95.4 % probability that the frequency offset remained below this value and above FO_{lower} throughout the entire month.

The bottom of page 3 contains logos for the United States Department of Commerce and NIST, and signatures and telephone numbers from the preparer of the calibration report and the manager of time and frequency services at NIST. The customer is invited to contact these individuals if they have questions about the report.



Report of Calibration

NIST Service ID Number 76100S, Frequency Measurement & Analysis Service

Time and Frequency Division
National Institute of Standards and Technology
Boulder, CO 80305-3328

Customer: ACME Industries
Calibration Laboratory
1776 Main Street
Anytown, USA 12345

Contact: Jane Q. Metrologist

Device Under Test (DUT): Model XYZ

Description of DUT: Cesium Frequency Standard

Period of Calibration: January 2004

1. Description of Calibration Procedure

The calibrations were performed at the customer's site using a computer-controlled data acquisition system. The calibrations are monitored from the NIST laboratories in Boulder, Colorado through a dedicated telephone line, and NIST personnel compile the data used in this report.

Traceability to NIST is established by using a Global Positioning System (GPS) satellite receiver as a transfer standard. A phase comparison between the customer's frequency standard and the GPS receiver is performed using the time interval method. A daily estimate for frequency offset is obtained by making continuous phase comparisons between the frequency standard and GPS signals over a 24-hour period, and fitting a linear least squares line to the phase data. The correlation coefficient (r) indicates the confidence level of the measurement.

Table 1 lists the daily frequency offset estimates and a status code for each calibration. A status code of 0 is used for a valid calibration. Other status codes identify and explain situations when no data were collected, when measurement errors occurred, or when the DUT was out-of-tolerance. Figure 1 is a graph of the daily frequency offset estimates. Table 2 is a statement of measurement uncertainty.

Measurement uncertainty ($k = 2$) is reported with respect to the national frequency standard for a 24-hour averaging period. Measurement uncertainty is contributed by the GPS receiver, by DUT aging and frequency drift, and by measurement system noise. The GPS receiver contributes an uncertainty of $\pm 2 \times 10^{-13}$. Measurement system noise contributes an uncertainty of $\pm 2 \times 10^{-15.}$

2. General Information

NIST supplies the hardware, software, and calibration method used to perform the calibration. When measurement system components fail, NIST is responsible for replacing them. When possible, this is done using an overnight delivery service.

Since calibrations are made at the customer's site, maintaining an acceptable laboratory environment is the responsibility of the customer. The customer is also responsible for following the installation and operating procedures outlined in the *Operator's Manual* supplied with each measurement system.

The results provided herein were obtained under the authority granted by Title 15 United States Code Section 3710a. As such, they are considered confidential and privileged information, and to the extent permitted by law, NIST will protect them from disclosure for a period of five years, pursuant to Title 15 USC 3710a(c)(7)(A) and (7)(B).

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Figure 3.3.a. FMAS calibration report (page 1).

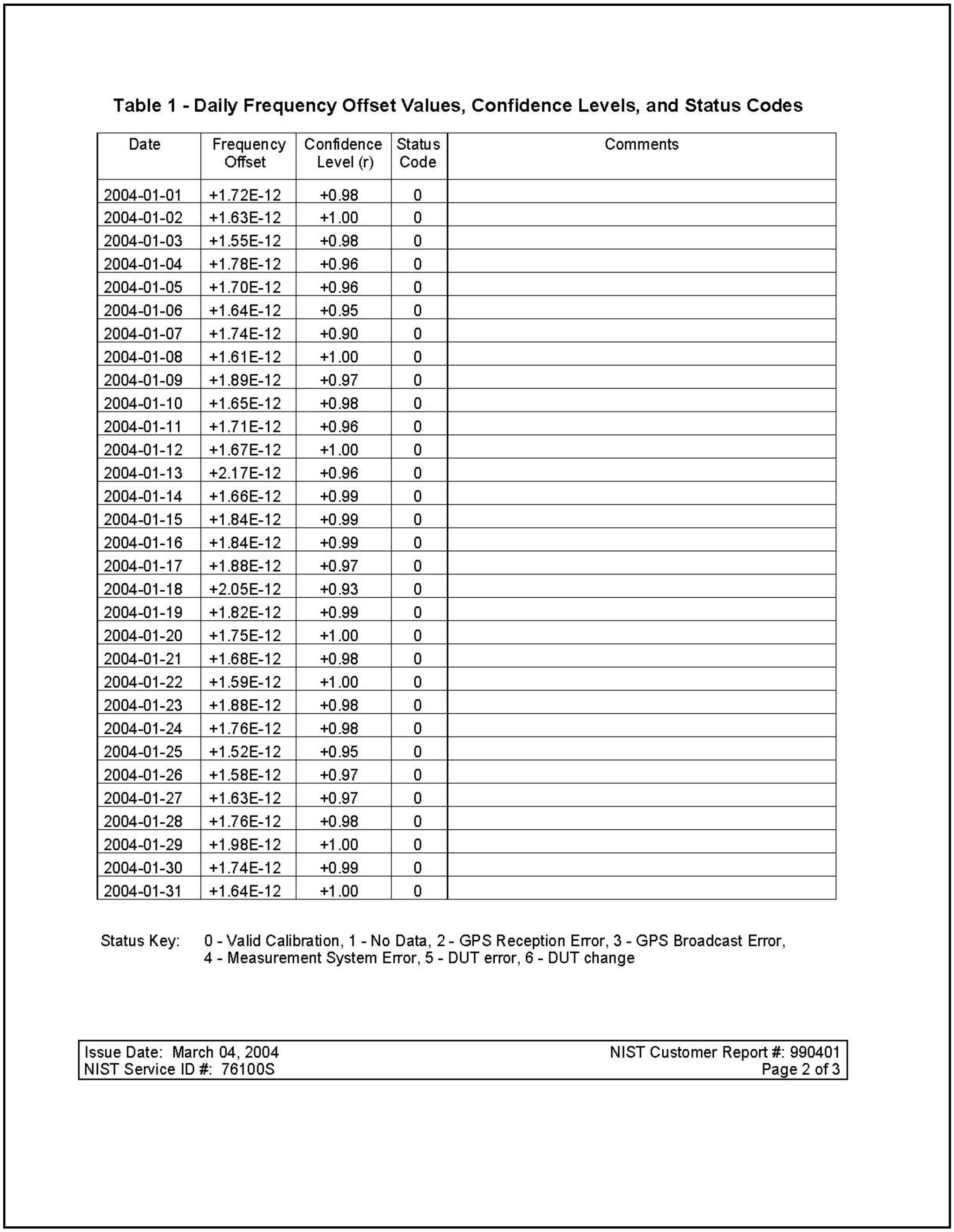

Table 1 - Daily Frequency Offset Values, Confidence Levels, and Status Codes

Date	Frequency Offset	Confidence Level (r)	Status Code	Comments
2004-01-01	+1.72E-12	+0.98	0	
2004-01-02	+1.63E-12	+1.00	0	
2004-01-03	+1.55E-12	+0.98	0	
2004-01-04	+1.78E-12	+0.96	0	
2004-01-05	+1.70E-12	+0.96	0	
2004-01-06	+1.64E-12	+0.95	0	
2004-01-07	+1.74E-12	+0.90	0	
2004-01-08	+1.61E-12	+1.00	0	
2004-01-09	+1.89E-12	+0.97	0	
2004-01-10	+1.65E-12	+0.98	0	
2004-01-11	+1.71E-12	+0.96	0	
2004-01-12	+1.67E-12	+1.00	0	
2004-01-13	+2.17E-12	+0.96	0	
2004-01-14	+1.66E-12	+0.99	0	
2004-01-15	+1.84E-12	+0.99	0	
2004-01-16	+1.84E-12	+0.99	0	
2004-01-17	+1.88E-12	+0.97	0	
2004-01-18	+2.05E-12	+0.93	0	
2004-01-19	+1.82E-12	+0.99	0	
2004-01-20	+1.75E-12	+1.00	0	
2004-01-21	+1.68E-12	+0.98	0	
2004-01-22	+1.59E-12	+1.00	0	
2004-01-23	+1.88E-12	+0.98	0	
2004-01-24	+1.76E-12	+0.98	0	
2004-01-25	+1.52E-12	+0.95	0	
2004-01-26	+1.58E-12	+0.97	0	
2004-01-27	+1.63E-12	+0.97	0	
2004-01-28	+1.76E-12	+0.98	0	
2004-01-29	+1.98E-12	+1.00	0	
2004-01-30	+1.74E-12	+0.99	0	
2004-01-31	+1.64E-12	+1.00	0	

Status Key: 0 - Valid Calibration, 1 - No Data, 2 - GPS Reception Error, 3 - GPS Broadcast Error,
4 - Measurement System Error, 5 - DUT error, 6 - DUT change

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Figure 3.3.b. FMAS calibration report (page 2).

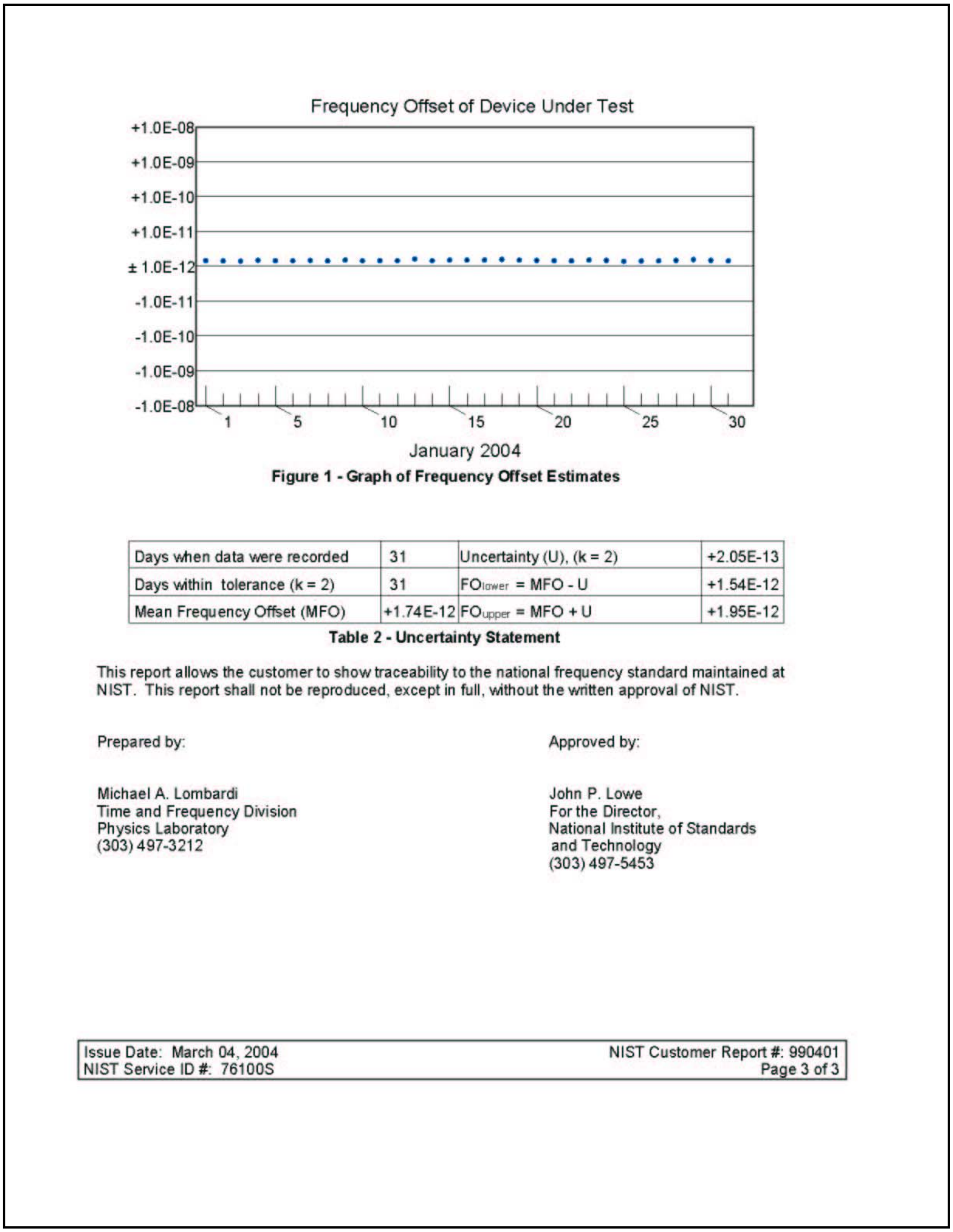

Figure 1 - Graph of Frequency Offset Estimates

Days when data were recorded	31	Uncertainty (U), (k = 2)	+2.05E-13
Days within tolerance (k = 2)	31	FO_{lower} = MFO - U	+1.54E-12
Mean Frequency Offset (MFO)	+1.74E-12	FO_{upper} = MFO + U	+1.95E-12

Table 2 - Uncertainty Statement

This report allows the customer to show traceability to the national frequency standard maintained at NIST. This report shall not be reproduced, except in full, without the written approval of NIST.

Prepared by:

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Figure 3.3.c. FMAS calibration report (page 3).

The FMAS calibration report contains the necessary elements listed in Section 5.10 ("Reporting the Results") of *ISO/IEC Standard 17025* [42]. Table 3.6 lists the ISO/IEC 17025 reporting requirements and where they are included on the FMAS calibration report.

Table 3.6. ISO Standard 17025 requirements for reporting of calibration results.

ISO/IEC 17025 section	Description	FMAS report page number
5.10.2.a	Title	1
5.10.2.b	Name and address of issuing laboratory, and location where calibrations were carried out	1
5.10.2.c	Unique identification of the calibration certificate on every page	1, 2, 3
5.10.2.d	Name and address of client	1
5.10.2.e	Identification of method	1
5.10.2.f	Description of item being calibrated	1
5.10.2.g	Date of performance of the calibration	1, 2, 3
5.10.2.h	Sampling plan or procedures	NA
5.10.2.i	Calibration results	2, 3
5.10.2.j	Names, functions, and signatures of persons authorizing the calibration certificate	3
5.10.2.k	Statement that results relate only to items being calibrated	NA
5.10.2.Note 1	Page numbers and total number of pages	1, 2, 3
5.10.2.Note 2	Statement specifying that certificate should not be reproduced without consent of issuing laboratory	3
5.10.4.1.a	Environmental conditions that have an influence on measurement results	1
5.10.4.1.b	Measurement uncertainty statement	3
5.10.4.1.c	Evidence that the measurements are traceable	1, 3
5.10.4.2	Statement of compliance	NA
5.10.4.3	Results before and after calibration instrument repair, when applicable	2
5.10.4.4	No recommendation on calibration interval shall be given	NA

Table 3.6, continued..

5.10.5	Opinions and interpretations shall be documented	2
5.10.6	Results obtained from subcontractors must be identified	NA
5.10.7	Electronic transmission of results	NA
5.10.8	Format of Certificate accommodates each type of calibration carried out	1, 2, 3
5.10.8.Note 1	Layout designed for ease of assimilation by reader	1, 2, 3
5.10.8.Note 2	Headings should be standardized	1, 2, 3
5.10.9	Amendments to certificates shall meet all requirements of ISO/IEC 17025	NA

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Chapter 4

Customers

This section describes the number and location of FMAS customers, the type of customers, the potential capacity of the service, and the ways that NIST interacts with and supports the customers.

A. Number and Location of Customers

From 1987 to 2004, the number of FMAS customers has fluctuated between about 35 and 60. The 60 customer peak was reached in 1990, prior to the closure of a number of United States Navy calibration laboratories. Figure 4.1 shows the approximate location of FMAS customers in the United States as of March 2004. A few customers are located outside the United States (not shown in the figure), since the use of GPS signals allows the FMS to be operated anywhere in the world. Historically, about 70 % of the FMAS customers operate cesium

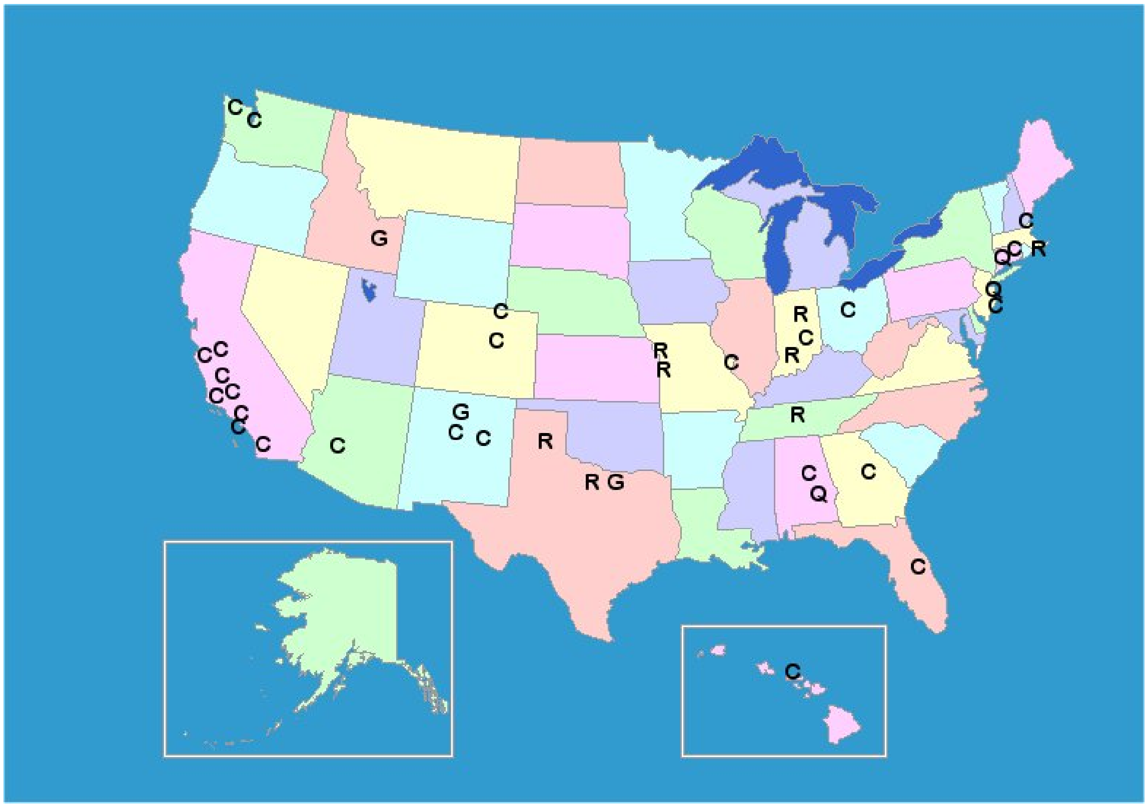

Figure 4.1. Approximate locations of FMAS customers in the United States.

oscillators as their primary frequency standard, denoted by the letter "C" in Figure 4.1. The letter "R" denotes that a rubidium oscillator is used as the primary standard, "G" represents the use of a GPS disciplined oscillator, and "Q" represents the use of a quartz oscillator.

NIST is always ready to accept new FMAS customers. Most customers subscribe for multiple years, and customer turnover is low, but reaching potential new customers is not particularly easy. How many potential FMAS customers are there in the United States? Answering this question requires identifying the needs of an FMAS customer. It is probably safe to assume that any customer or potential customer of the FMAS is required (for legal, contractual, practical, or policy reasons) to maintain a continuously running, traceable frequency source with a known uncertainty that they can use as a reference for calibrations or other measurements. Their known uncertainty requirement is probably never larger than about 1×10^{-9} and often smaller than 1×10^{-10} since customers with lesser requirements probably cannot justify the subscription costs. In addition, the FMAS customer is probably required to provide documentation that these requirements are being met; a requirement satisfied by the monthly calibration certificate issued by NIST. Based on these assumptions, the number of potential FMAS customers in the United States, including those who already subscribe, can be roughly estimated as somewhere between 200 and 250 laboratories. To support this estimate, the *NCSL International Directory of Standards Labs*, an on-line database [43], lists 998 United States standards laboratories, including 457 with time and frequency capabilities as of March 2004. However, it is believed that roughly half of these laboratories require uncertainties too large to justify the cost or use of the FMAS. For example, some perform only simple calibrations of timing devices, such as stopwatches, and/or simple frequency calibrations of tuning forks used by law enforcement officers. Other listed laboratories are not potential FMAS customers since they provide only consulting services related to time and frequency metrology, and do not maintain an actual standard.

B. How the FMAS is Used by its Customers

Most FMAS customers are calibration and testing laboratories, located at either government or commercial facilities. These laboratories use the FMS to continuously monitor and measure their primary frequency standard and to establish documented measurement traceability back to the SI. This primary frequency source is then distributed throughout a laboratory or facility and used as a reference for other measurements. For example, a laboratory might send the output of its 10 MHz standard through a multi-channel distribution amplifier, so that signals can be distributed to the workbench of every engineer or technician involved in tests or measurements. The 10 MHz signal can then be used as the traceable time base or external trigger source for test equipment such as frequency counters, signal generators, and oscilloscopes. At the same time the 10 MHz signal is being used as the working reference standard for other measurements, it is being continually measured and monitored by the FMS, and its performance is reported upon by NIST.

Since it has a total of five channels, the FMS can also be used by the customer to measure and calibrate four other devices without interrupting the continuous calibration of their primary frequency standard. For example, the FMAS customer might be a commercial calibration laboratory that routinely calibrates a large number of frequency counters. When a frequency counter is sent to the lab for calibration, its time base can be measured on the FMS, and the collected data can be used by the NIST customer to create a calibration report for **their** customer. It's fairly typical for a device to spend just one or two days connected to an FMS channel, and then be returned to service after its frequency uncertainty has been measured and documented.

To support their calibration workload, many laboratories specify a frequency uncertainty requirement for their primary standard. This generally ranges from 1×10^{-9} to 1×10^{-12}. A number near 1×10^{-11} should meet nearly all workload calibration requirements [44] and is a fairly typical requirement for a high quality laboratory. This is because the 1×10^{-11} requirement exceeds the manufacturer's specification by about a factor of 10 for nearly all of the items they are likely to be asked to calibrate, thus establishing a desirable test uncertainty ratio of 10:1. Therefore, the FMS uncertainty of 2×10^{-13} (Chapter 5) should exceed the present needs of nearly all calibration labs, both for distributing frequency and for calibrating other devices.

The FMAS can also be a very useful tool for customers seeking laboratory accreditation in frequency calibrations, since it provides a documented and controlled method for performing traceable calibrations. The two major accreditation bodies in the United States are the American Association for Laboratory Accreditation (A2LA) and the National Voluntary Laboratory Accreditation Program (NVLAP). At this writing (March 2004), six FMAS customers have received accreditation for frequency calibrations from NVLAP and three from A2LA. The *NVLAP Calibration Laboratories Technical Guide for Time and Frequency Measurements* [45] notes that:

> *"The FMAS can benefit NVLAP customers seeking accreditation in the frequency calibration field. In some cases, it can eliminate or reduce the need for proficiency testing (and its associated fees) in the frequency calibration area."* [45, p.15]

In addition to calibration and testing laboratories, the FMAS is also used by telecommunication companies, manufacturers of time and frequency related equipment, and others who need a convenient, traceable way to measure frequency. One of the most interesting applications involved using the FMS to measure the performance of a time and frequency distribution system (including cesium and rubidium oscillators) on board a United States Naval ship in a high magnetic field environment [46].

C. Customer Interaction and Technical Support

The majority of FMAS technical support is still handled by telephone, although an increasing amount is now handled through email. Customers are encouraged to call NIST whenever they have a question or problem related to the service, or any other concern related to time and frequency metrology. Most problems are given immediate attention and quickly resolved, and very few customer complaints regarding the quality of technical support have been received during the 20 year span (1984 to 2004) that the service has been operational. NIST also interacts with customers through its web page and through its seminars, as described below.

1. Web Page

The FMAS web page on the NIST Time and Frequency Division web site is primarily used to inform new customers about the service. However, the page also is useful to current customers. It contains current pricing and financial information about the service that can be used by purchasing departments that are renewing or extending the service agreement. It also contains an electronic copy of the *NIST Frequency and Measurement and Analysis System: Operator's Manual* [20], and other technical articles that serve as useful reference material for FMAS customers. The page can be found at **http://tf.nist.gov/service/fms.htm**

2. Seminars

FMAS customers are entitled to attend a free training seminar. Although the FMS does not really require any training to install and use (experience has shown that it is a task easily handled by any calibration laboratory technician), these seminars are useful for explaining the concepts behind the service, and serve as an introductory course in time and frequency metrology. These seminars typically last for two days. In the past, many of these seminars were scheduled on an ad hoc basis at the NIST laboratories in Boulder, Colorado, and this option is still utilized when necessary. From 1999 to 2004, they have been held each January immediately prior to the *Measurement Science Conference* (MSC) in California. Future seminars are expected to be held at MSC, and/or at the National Conference of Standards Laboratories International (NCSLI) headquarters training facility in Boulder, Colorado. A portable equipment rack containing various time and frequency related instrumentation, including a FMS unit, has been constructed for use as a teaching tool in these seminars.

FMAS customers who require or desire more advanced time and frequency training are encouraged to attend the annual *NIST Time and Frequency Metrology Seminar*. This seminar is a comprehensive four-day course that explores the course material in more detail than the introductory courses. It has been held each summer at the NIST Boulder Laboratories since 1976, typically attracting forty or more students (a registration fee is charged to FMAS customers who attend this seminar).

Chapter 5

Measurement Uncertainties

This chapter discusses the measurement uncertainty of the FMS unit, the uncertainties of measurements made with and without GPS, and how the service establishes traceability to the SI through UTC(NIST).

The FMS uncertainties are reported in a manner that utilizes elements of the ISO and NIST guides [47, 48]. In general terms, frequency uncertainty is usually expressed in terms of accuracy and stability. Accuracy is a Type B uncertainty that quantifies the offset from an ideal value, such as the frequency offset quantity previously discussed. Stability is a Type A uncertainty that indicates how well a device produces the same frequency offset over a given period. Stability estimates are calculated from a set of frequency offset measurements and show frequency fluctuations with respect to an average frequency offset. The offset values are obtained by sampling or averaging over the stated time interval tau (t). Standard deviation (σ) can be used to measure frequency stability for white noise processes, but a common "non-classical" statistic used to estimate frequency stability is the previously described Allan deviation, $\sigma_y(\tau)$ [38].

The FMAS defines a calibration as a 1 d (24 h) measurement. Therefore, measurement uncertainty is specified at an averaging time of 1 d. This is done for both practical and technical reasons. For example, 1 d is a long enough period to calibrate nearly anything that a lab will be asked to calibrate, but not too long to be considered impractical. Longer measurement runs and more averaging would obviously result in lower measurement uncertainties, but the uncertainties are already low enough to meet the customer's requirements. Measurement uncertainty is contributed by GPS (Chapter 5.A) and by the FMS itself (Chapter 5.B). A 1 d calibration is generally sufficient to reduce the $k = 2$ noise floor of both GPS (2×10^{-13}) and the FMS (2×10^{-15}) below the noise floor of the DUT, resulting in a clean measurement of the DUT with an uncertainty that is not inflated by either reference or measurement system noise, and that meets or exceeds the laboratory's requirements.

A. Uncertainties of Measurements made with GPS

When estimating the measurement uncertainty of GPS with respect to UTC(NIST), it should first be noted that both time scales are steered to agree with the international UTC time scale maintained by the Bureau International des Poids et Mesures (BIPM). As a result, the GPS signals and UTC(NIST) are essentially phase locked to each other with a very long time constant used for the steering. Over long time periods, the Type B uncertainty contributed by the frequency offset is insignificant, $< 1 \times 10^{-15}$, and for practical purposes it can be regarded as 0. Figure 5.1 illustrates this by showing a GPS to UTC(NIST) comparison for the entire year of 2003. The graph shows many short term frequency fluctuations, but the frequency offset for the entire year, estimated using the slope of a linear least squares line, is -1.7×10^{-16}.

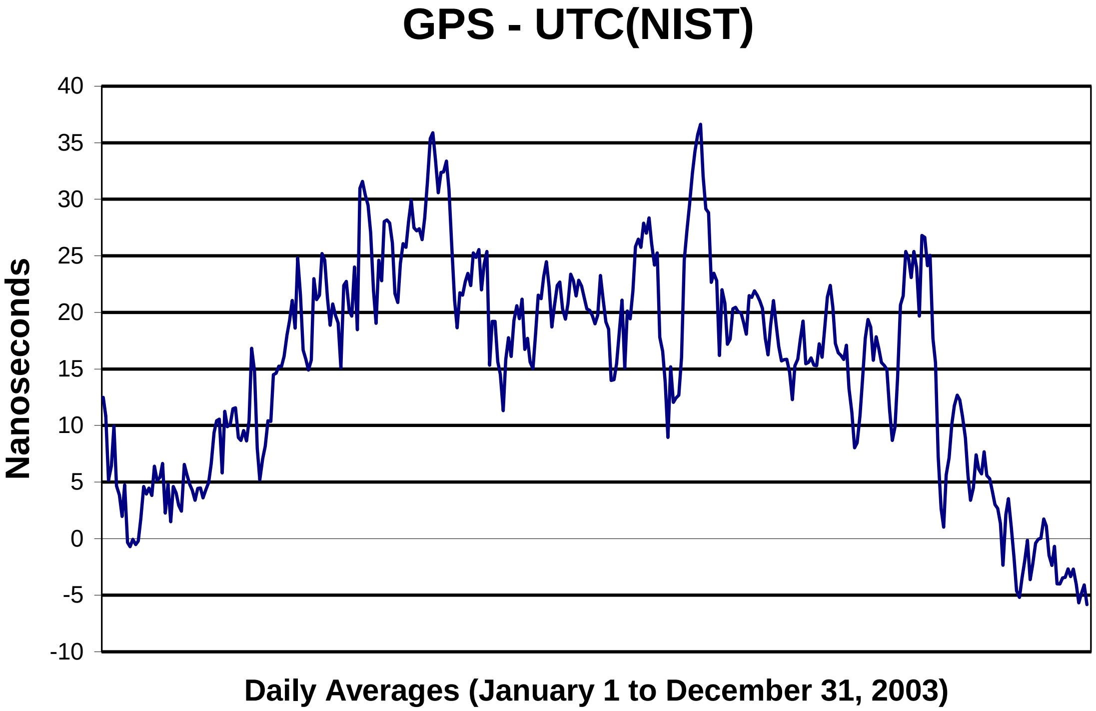

Figure 5.1. GPS versus UTC(NIST) during 2003 (1 d averages).

When looking at the GPS data in Figure 5.1, or at GPS data collected by the FMS over its 1 d calibration interval, it becomes obvious that the uncertainty in the frequency offset estimate is almost always several times larger than the average frequency offset itself. This is because GPS is always steered to be accurate relative to UTC, so continuous corrections are being made to compensate for the Type B uncertainty. Thus, the uncertainty of a GPS measurement made over a 1 d interval is essentially equivalent to the Type A uncertainty, which is limited by GPS propagation noise.

The Type A frequency uncertainty of the FMS GPS receiver was estimated with two different statistical techniques, Allan deviation and standard deviation, both involving a comparison with UTC(NIST). The test was run for one month (31 d). A data set consisting of 31 daily frequency offset estimates was created using the least squares line technique described in Chapter 2. A frequency graph of these data is shown in Figure 5.2. The average frequency offset (as indicated by the straight line) is $< 4 \times 10^{-14}$ and would continue to get smaller over a longer data run.

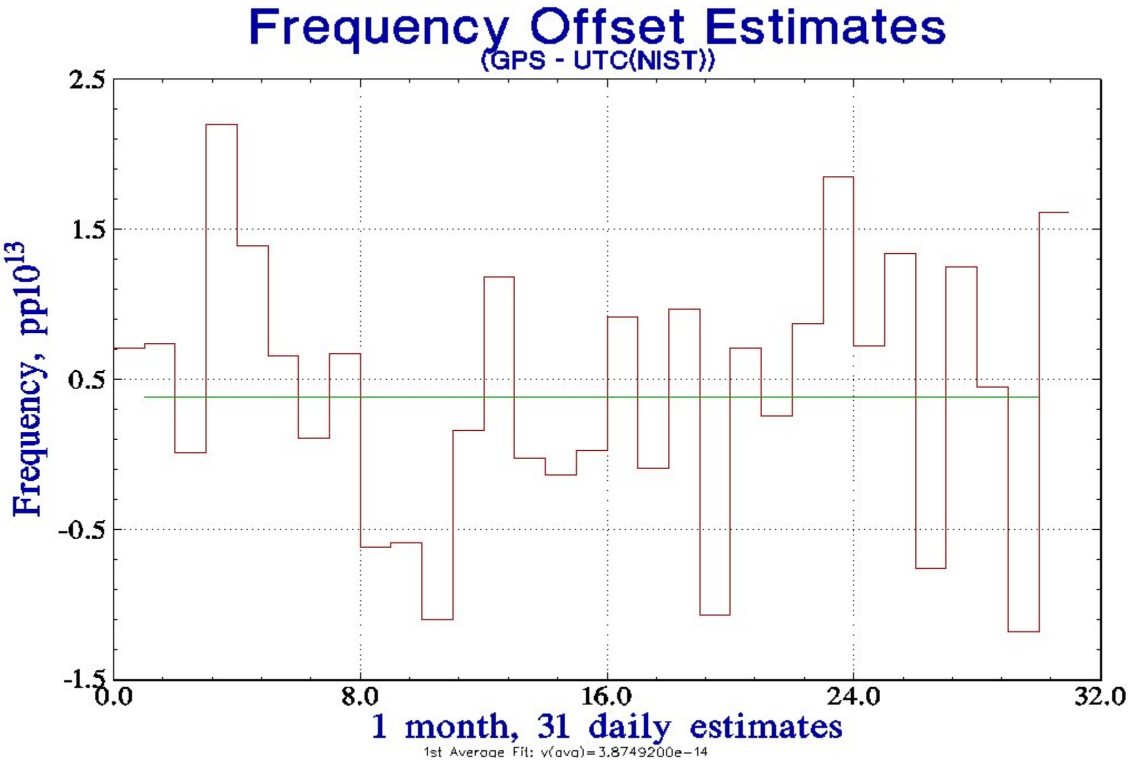

Figure 5.2. Graph of daily frequency offset estimates (GPS – UTC(NIST)).

The two statistics should produce essentially the same result if the noise processes are white, an assumption that is basically true for the dominant FMS noise source at 1 d, which is GPS propagation noise. First, the Allan deviation, $\sigma_y(\tau)$ at $\tau = 1$ d was calculated as 8.77×10^{-14}, then doubled to produce a $k = 2$ coverage area of 1.75×10^{-13}. Next, the standard deviation (σ) was calculated as 8.71×10^{-14}, then doubled to produce a $k = 2$ coverage area of 1.74×10^{-13}. These numbers are rounded up to 2×10^{-13} and used as the FMS frequency offset uncertainty estimate ($k = 2$) for a 1 d calibration using GPS as a reference. Note that these data were collected after only a coarse survey of the receiving antenna was done as described in Chapter 2.B.2.a. A better antenna survey, which is not always possible at customer sites, would result in a slightly lower frequency uncertainty.

It should be noted that the linear regression technique used to estimate the daily frequency offset "smooths" the data and makes the 1 d uncertainty estimate slightly lower than it would be if the entire raw data set were used. Figure 5.3 shows the Allan deviation graph for all of the 1 h averages collected by the FMS during the 31 d interval. This graph uses the "all tau" method, so $\sigma_y(\tau)$ is calculated for all possible τ values. Note that the first τ value is 1 h, the averaging time of the FMS. At $\tau = 24$ h, $\sigma_y(\tau)$ equals 1.31×10^{-13}, or 2.62×10^{-13} when expanded to $k = 2$, slightly higher than the "smoothed" data. Not all of the data for the month is used to estimate the Type A uncertainty because the FMS treats each 1 d period as an independent calibration, and a frequency offset estimate is reported daily. Therefore, a day with "bad" data affects only a single daily calibration. A "bad" data point can be removed if necessary so that it does not affect the uncertainty analysis for the entire month (Chapter 5.C.).

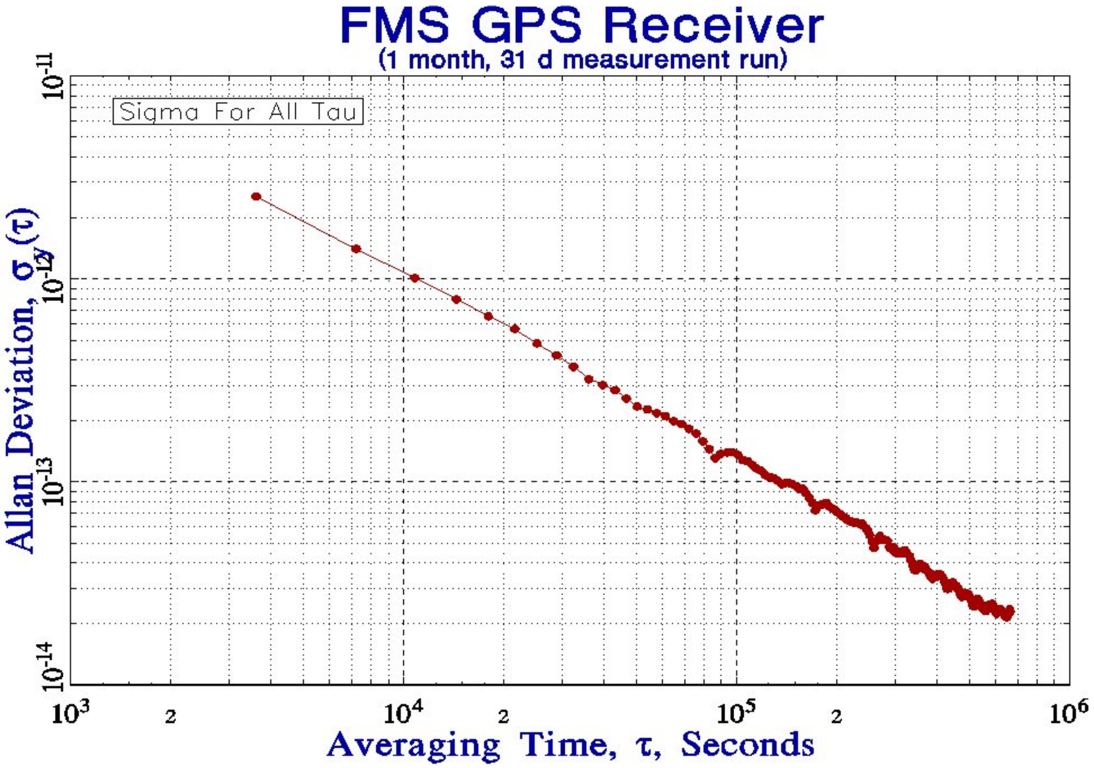

Figure 5.3. Frequency stability (Allan deviation) of FMS GPS receiver.

B. Uncertainties of Measurements made without GPS

The uncertainty of measurements made without GPS (oscillator to oscillator comparisons) is estimated as 2×10^{-15} ($k = 2$) for an averaging time of 1 d. The limiting factors for these measurements are either noise introduced by the frequency dividers or noise introduced by the time base PLL on the TIC when it is used to generate the stop pulse. This is the scenario that exists whenever a customer compares a secondary oscillator to their primary oscillator. The PLL circuit has small frequency variations over time due to temperature and voltage fluctuations in the power supply. The TIC's built-in frequency dividers are usually present in all comparisons made with the FMS, unless an incoming 1 pps test signal is compared to an external 1 pps signal, a configuration seldom used by FMAS customers. Frequency dividers always add some measurement noise or jitter to the counter readings [28], but this problem was minimized in the FMS design, where the majority of the counter's digital circuitry is included in a programmable logic device (PLD). The PLD allows measurement noise and delays to be reduced since the counter and divider circuitry is housed in a single integrated circuit [16], an advantage over using discrete components.

The TIC itself introduces significant resolution uncertainties at short averaging times, but these are indiscernible after 1 d of averaging. As previously discussed, the TICs single shot resolution is near 25 ps, which limits its ability to detect frequency changes smaller than a few parts in 10^{11} at an averaging time of 1 s. However, the TIC noise, which is typically white phase noise, averages down to a few picoseconds at about 100 s, and the noise floor is typically a few parts in 10^{16} at an averaging time of 1 d, or below the noise floor of the frequency dividers or time base PLL.

From a practical perspective, the most important characteristic of any frequency measurement system is its ability to resolve small frequency differences between two oscillators. If the noise floor of the measurement system has been accurately determined, it should be able to make a clean measurement of a frequency offset that is a factor of 10 larger than the noise floor. In the case of the FMS, its noise floor estimate of 2×10^{-15} (k = 2) suggests that it should be easily able to resolve a frequency offset of 2×10^{-14} over the standard 1 d calibration period. To test this premise, an 80 MHz direct digital synthesizer (DDS) was phase locked to UTC(NIST), and its output signal was offset in frequency by −1 μHz (-1.25×10^{-14}). This signal was then connected to channels 2 and 3 of the FMS, where it was divided to 1 pps and used as the start pulse on both channels. On channel 2, the stop pulse was obtained by locking the TIC PLL circuit to UTC(NIST), and then dividing the 10 MHz output to 1 pps. On channel 3, the stop pulse was obtained directly from UTC(NIST) using an external divider. The phase graphs from the two measurements are shown in Figures 5.4 and 5.5.

The measurement was run for 16 d (384 h). Note that the two graphs look very similar. There is some noise visible along the measurement trace, but the trend contributed by the frequency offset is obvious. At least some of the noise is due to the instability of the DDS used to generate the start pulse on both channels, and is not attributable to the FMS itself. At $\tau = 1$ d, $\sigma_y(\tau)$ is estimated as approximately 2×10^{-15} for both measurements. The test demonstrates that the FMS has a sufficiently low noise floor to easily reveal and measure a 1.25×10^{-14} frequency offset, with both techniques producing a result within 2×10^{-16} of the expected value.

C. Discussion of Uncertainty Statement on Calibration Report

The uncertainty statement on the NIST calibration report provides the frequency uncertainty of the customer's primary frequency standard, and not the measurement uncertainty of the FMS, which was discussed in sections B and C above. It reports the average frequency offset and a range of possible frequency offset values for the customer's primary frequency standard based on a k = 2 coverage area (2σ). Therefore, there is a 95.4 % probability that the frequency offset will remain within this estimated range during the month for which values are reported. The estimated range for the frequency offset values is limited by GPS noise, and can generally not be made narrower than $\pm 2 \times 10^{-13}$ with respect to the average frequency. In many cases, the range is made wider due to the frequency aging and drift of the customer's primary frequency standard, and in some cases, due to frequency adjustments made by the customer.

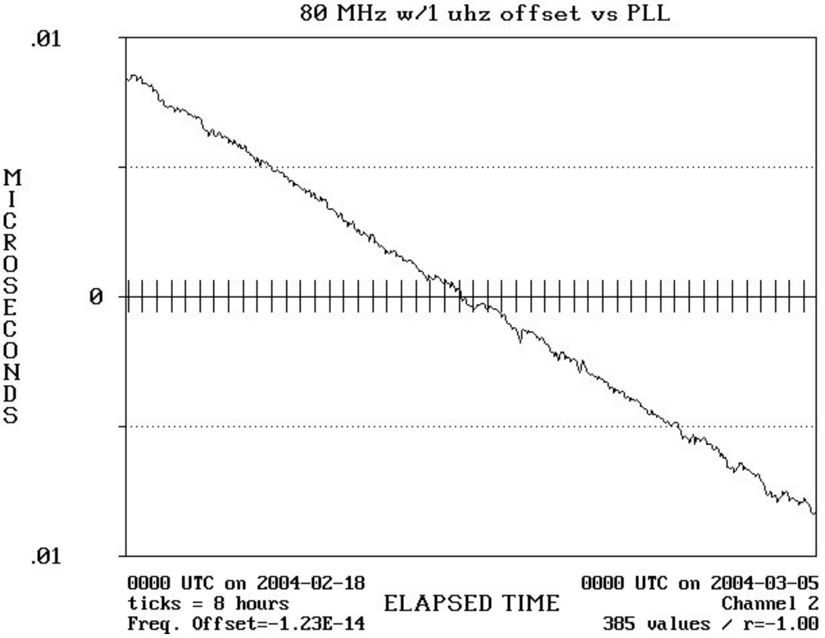

Figure 5.4. Measuring a 1.25 × 10^{-14} frequency offset with TIC PLL as stop pulse.

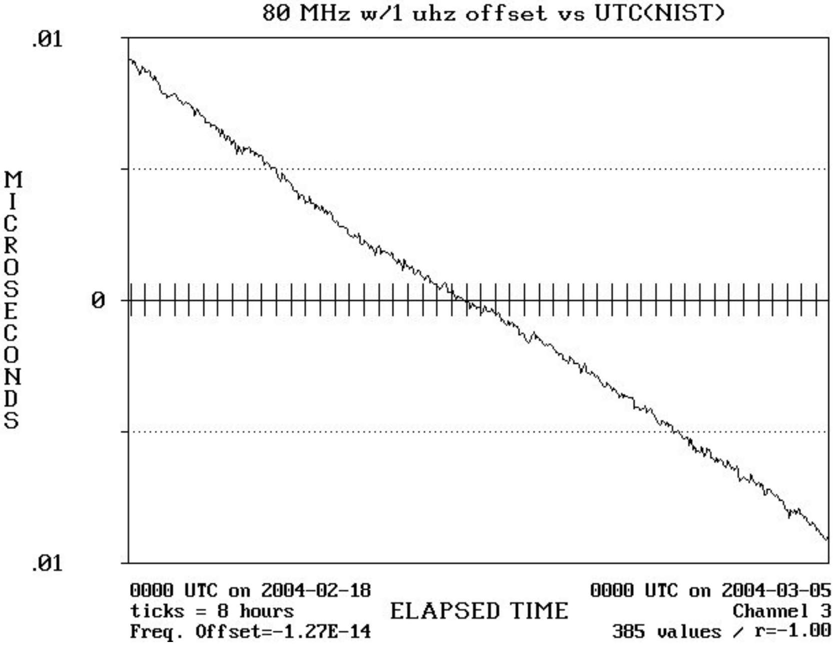

Figure 5.5. Measuring a 1.25 × 10^{-14} frequency offset with an external 1 pps stop pulse.

Table 5.1. Sample FMAS calibration report uncertainty values.

Days when data were recorded	31	Uncertainty (U), (k = 2)	+2.05E-13
Days within tolerance (k=2)	31	FO_{lower} = MFO – U	+1.54E-12
Mean Frequency Offset (MFO)	1.74E-12	FO_{upper} = MFO + U	+1.95E-12

An uncertainty statement is shown in tabular form in Table 5.1. This statement is identical to the uncertainty statement that appears on page 3 of the calibration report pictured in Figure 3.3.c, and previously described in Table 3.5.

The daily frequency offset values become the y_i data set, which contains from 28 to 31 values, depending upon the length of the current month. The mean frequency offset for the month, *MFO*, and the standard deviation are calculated by utilizing a simple "3-sigma, 2-pass" filter. The mean and standard deviation (σ) of the y_i data series are computed, data that fall more than 3σ from the mean are removed, and the process is repeated. Therefore, the *MFO* and σ are calculated from the second pass, in some cases with outliers removed. The uncertainty, *U*, is set equal to 2σ and is added to and subtracted from *MFO* to obtain the upper and lower bounds of the uncertainty range, FO_{upper} and FO_{lower}. Then, all values in the y_i data set, including those that were excluded from the original calculation of *MFO* and σ, are checked to see if they fall outside the upper and lower bounds of the uncertainty range. If so, they are marked as out of tolerance and require annotation by the person preparing the calibration report (Chapter 3.G).

In the uncertainty statement listed in Table 5.1, it was determined that the customer's primary standard was high in frequency on average by 1.74×10^{-12} during the one month interval, and that there was a 95.4 % probability that the frequency offset stayed between +1.54 and +1.95 parts in 10^{12} with respect to the nominal frequency.

D. Establishing Traceability to the SI through UTC(NIST)

One of the main benefits of the FMAS is that it simplifies a laboratory's task of establishing traceability to the SI. Calibration laboratories are generally required to establish traceability of their own measurement standards and measuring instruments to the SI by means of an unbroken chain of calibrations or comparisons linking them to relevant primary standards of the SI units of measurement. The link to SI units may be achieved by reference to national measurement standards [42]. One obvious way to establish traceability then is for a calibration laboratory to make a measurement that directly compares its primary standard to the national standard. This could be done if the laboratory sends its primary standard to its National Metrology Institute (NMI) for calibration. Even then, however, traceability would only be established at a given point in time, and would have to be periodically reestablished [49]. For example, if a house standard were calibrated by an NMI ten years ago, it would not be considered sufficient evidence to establish traceability today.

In frequency metrology, transfer standards such as GPS make it possible to continuously establish traceability by making continuous comparisons against the national standard. This is often done via common-view comparisons, which have been performed by NMIs using GPS satellites since 1980 [11], and prior to that time with signals from LORAN-C, television, WWV, and other sources. The common-view method is conceptually simple. Since it is often impossible to bring two oscillators to the same physical location to compare them, both oscillators are continually compared to signals originating from a reference transmitter, *R*. Receivers at each oscillator site (*A* and *B*) simultaneously receive the signal from *R*, compare the received signal to their oscillator, and store the measurement data. Thus, one site measures the frequency offset between *R* and oscillator *A*, the other site measures the frequency offset between *R* and oscillator *B*. The two sites then exchange their data and subtract one data set from the other. The resulting data reveals the frequency offset between oscillator *A* and oscillator *B*, since the frequency offset of *R* falls out of the equation [18]. Through the use of common-view GPS, a direct comparison to the national frequency standard can be made, meaning that the traceability chain back to the NMI contains only one link [39].

The FMAS is based on a hybrid form of the common-view technique. NIST continuously monitors the GPS satellites with several "master" FMS units identical to those used by customers and with a number of other receivers, so the GPS signals are in common-view. At NIST, the master FMS GPS receivers are being continually compared to UTC(NIST), the national frequency standard, so the frequency uncertainty of an FMS unit is well characterized. Continuous evidence that GPS uncertainties are at or below the 2×10^{-13} specification claimed by the FMAS is provided to the public in the *NIST GPS Data Archive*, which publishes daily measurement values for *GPS − UTC(NIST)* for all satellites in the constellation (http://tf.nist.gov/service/gpstrace.htm) using the same type of receiver used by the FMS. However, the FMAS is not a true common-view service because the data collected at the customer's site are not subtracted from the data collected at NIST. This has the advantage of allowing measurement results to be reported to the customer in real time because no continuous data exchange is required with NIST before results can be shown.

In the FMAS model, the traceability chain back to the NMI consists of two links. The first link is the comparison between the local device under test and GPS. The second link is the comparison between GPS and UTC(NIST) performed by NIST [39]. This same general model (Figure 5.6) for establishing traceability to the SI through an NMI can be applied to any other signal that is monitored, but not controlled by the NMI [50]. Note that in Figure 5.6 links B and C represent the two links back to the NMI, and link A represents the link from the NMI back to the SI. In a true common-view system, the unlabeled diagonal line would serve as a single link back to the NMI (replacing links B and C), but exchanging and differencing data would be required.

Subscribing to the FMAS is obviously not the only way that a laboratory can establish traceability in frequency to the SI. The use of GPS disciplined oscillators (GPSDOs) is now widely accepted as a proper way to establish traceability. However, one key component of establishing traceability involves quantifying the measurement uncertainty of each link in the traceability chain. This can be a difficult problem, because the uncertainties of all GPS measurements are receiver dependent, and different models of GPSDOs produce different results, even when operated under identical conditions [51-52]. It is also not always obvious to a laboratory whether a GPS receiver is working properly or meeting its specifications [44]. The FMAS solves these problems since the uncertainties of its GPS measurements have been well characterized and are highly repeatable. All customers use identical hardware and hardware operated in a controlled, identical fashion and the achievable uncertainties are essentially identical at all customer sites. NIST has confirmed this through many years of experience performing remote frequency calibrations at numerous geographic locations.

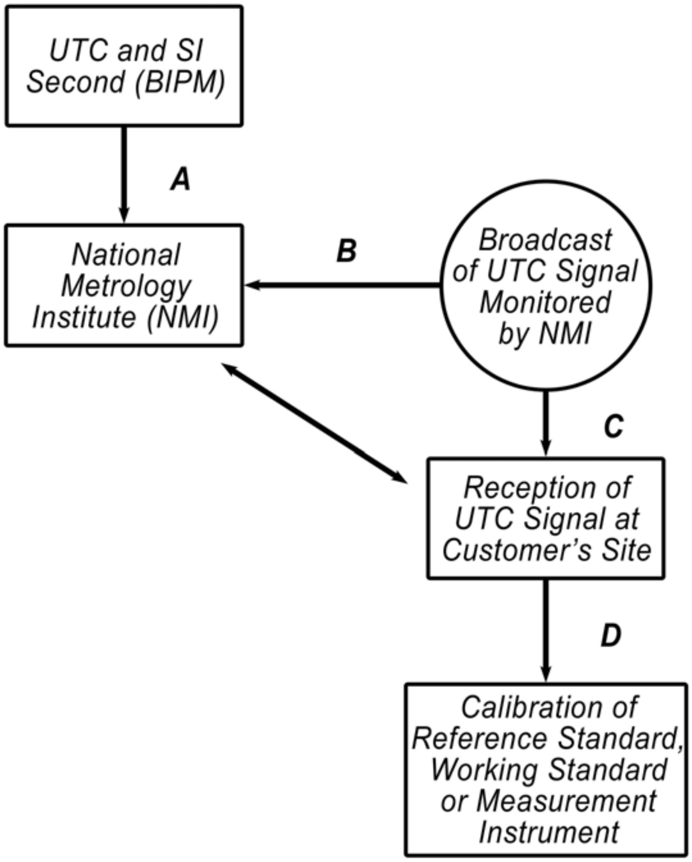

Figure 5.6.. The generic traceability model used by the FMAS.

Products or companies named in this document are cited only in the interest of providing a complete technical description of the FMS, and identification neither constitutes nor implies endorsement by NIST or by the U. S. government. Other products may be found to work as well.

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