REVIEW ARTICLE

The Reach and Impact of the Remote Frequency and Time Calibration Services at NIST

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Abstract: The National Institute of Standards and Technology (NIST) has provided remote frequency and time calibration services to customers for more than three decades. These services continuously compare a customer's primary frequency and/or time standard to the coordinated universal time scale kept at NIST, known as UTC(NIST), which is the national standard for frequency and time in the United States. The remote calibration services differ from traditional calibration services in at least two important ways. The first difference is that the customer does not send the device under test to NIST. Instead, NIST sends equipment to the customer that automates the measurements and returns the results via a network connection. The second difference is that the calibration never stops. New measurement results are recorded 24 hours per day, 7 days a week. This allows customers to continuously establish traceability to the International System (SI) units via UTC(NIST) without disturbing or moving their standard. This paper discusses the reach and impact of the NIST remote frequency and time calibration services by describing how they work, their calibration and measurement capabilities, their quality system, and the requirements of the customers that they serve.

1. Introduction and Overview

Although they are now classified as calibration services, the services that comprise the remote frequency and time calibration program at NIST have their roots in the measurement assurance program (MAP) that was formally announced by NIST's predecessor, the National Bureau of Standards (NBS), in the early 1980s. A MAP was defined as a "quality assurance program for a measurement process that quantifies the total uncertainty of the measurements with respect to national or other designated standards and demonstrates that the total uncertainty is small enough to meet the user's requirements." A MAP differed from a calibration service because it focused on "the quality of the measurements being made in the participating laboratory rather than on the properties of participants instruments or standards." Participation in a MAP was potentially a way to calibrate "the entire laboratory" [1].

Before implementing the MAP program, the NBS time and frequency division had little experience performing remote calibrations for customers. The division did have, however, many years of experience in frequency and time research, in distributing frequency and time reference signals, and in participating in national and international comparisons. Once the division was aware of the requirements of potential customers, it combined the experience gained from past research, distribution, and comparison efforts to develop new services. In fact, each of the remote frequency and time calibration services currently offered by NIST can be traced to technology that was originally developed for other projects or experiments, and that was then refined until it was reliable and "user friendly" enough to make it available to customers. The goal was to make the services accessible to any customer with a frequency or time measurement requirement, regardless of where they were located or their level of metrology experience.

To illustrate this, note that the Frequency Measurement and Analysis Service (FMAS), which debuted in 1984, has its origins in work performed to develop frequency measurement systems for the United States Air Force from about 1980–1983 [2]. The Time Measurement and Analysis Service (TMAS), which debuted in 2006 [3], is based on technology first developed at NIST in 2005 to support real-time, international time comparisons for SIM (Sistema Interamericano de Metrologia or Interamerican Metrology System in English), the regional metrology organization (RMO) that supports North, Central, and South America [4]. The

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DOI:10.1080/19315775.2019.1605862

Service Name	Frequency Measurement and Analysis Service (FMAS)	Time Measurement and Analysis Service (TMAS)	NIST Disciplined Clock Service (NISTDC)		Time Code Output Service	Time Code Monitoring Service
NIST ID Number	76100C	76101C	76102C, Rubidium	76103C, Cesium	76104C	76105C
Year Introduced	1984	2006	2010		2017	2017
Other Services Required	None	None	76101C, customer must supply cesium clock for 76103C		76101C, either 76102C or 76103C	76101C, either 76102C or 76103C
Signals Measured	All frequencies from 1 Hz to 120 MHz	1 Hz	1 Hz		NA	The time codes contained in the NTP packets
Measurement Channels	5	1	1		2 outputs, NTP/PTP	12
Time Uncertainty ($k = 2$)	NA	12 ns (typical)	10 ns (typical)		NA	< 10 µs, but usually larger due to network asymmetry
Frequency Uncertainty ($k = 2$)	2×10^{-13} at 1 day	5×10^{-14} at 1 day	5×10^{-15} at 1 day		NA	NA
Interval between comparison graphs	24 hours	10 minutes	10 minutes		NA	10 minutes
Calibration Report Interval	Monthly	Monthly	Monthly		NA	NA, results available via Internet

Table 1. The NIST remote frequency and time calibration services.

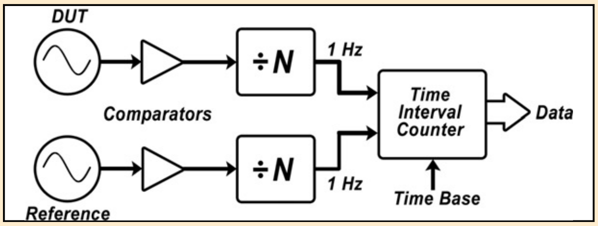

Figure 1. Time interval measurement system with frequency dividers.

common-view disciplined clock services [5] that first appeared as optional add-ons to the TMAS in 2010, were an outgrowth of experiments conducted with the United States Coast Guard beginning in 2008 [6]. Finally, the time code output and time code monitoring options for the TMAS have their roots in development work first done at NIST to support international comparisons of Internet time servers in the SIM region in 2014 [7].

NIST's approach to a MAP for remote frequency and time calibrations has always been based on a consistent philosophy and mode of operation. Every customer receives an automated measurement system that runs continuously with very little attention. This has several benefits. First, automation and standardized equipment means that every customer performs their measurements the exact same way. Second, the measurements never stop, continuing 24 hours per day, 7 days per week. Third, the customer's standard is never sent outside their laboratory, making it always available for use. Fourth, because the measurements are automated, labor costs are reduced. Finally, and perhaps most importantly, NIST staff monitor and fully support the measurements. They are available to answer questions and provide technical support, to help customers best utilize the measurement system within the framework of their laboratory, and to educate customers about time and frequency metrology. This results in services with more "value added" than traditional calibration services, which typically just deliver a certificate or report.

Table 1 lists each remote frequency and time calibration service and summarizes its measurement capabilities. Section 2 provides a technical description of how the services work. The customers and industries reached by the services and their metrological requirements are discussed in Section 3. The NIST quality system that supports the services is discussed in Section 4. Customer accreditation is discussed in Section 5, and Section 6 provides a summary.

2. Technical Description

The foundation for the remote calibration services is built upon a few fundamental time and frequency metrology techniques; including time interval measurements, common-view observations of Global Positioning System (GPS) satellite signals, control techniques that discipline a local clock so that its frequency and time agrees with a remote reference, and comparisons of received time codes to a reference clock. This section briefly describes each technique and how it applies to the services.

The FMAS (NIST Service Number 76100C) and TMAS (76101C) measurement systems include a time interval counter (TIC) and implement the time interval measurement technique. Figure 1 shows a simplified configuration where a device under test (DUT) is compared to a local reference. In both the FMAS and TMAS systems, the DUT signal is a 1 Hz output from the customer's primary standard and the local reference signal is the 1 Hz output of a GPS timing receiver. The external time base is provided by either a 5 MHz or 10 MHz signal from the customer's primary standard. Figure 1 shows frequency dividers in the path between the signal sources and the TIC, but in the case of the TMAS no frequency division is necessary. The FMAS does, however, require frequency division, a feature that allows it to measure any frequency from 1 Hz to 120 MHz, but that precludes it from measuring the DUT's time offset from NIST. The FMAS divides each signal to 1 Hz before it reaches the TIC; and includes a multiplexer so that up to five signals can be read in sequence. Because time interval is the reciprocal of frequency, the time interval data collected by either the FMAS or TMAS can easily be converted to frequency data [2].

The common-view GPS measurement technique is an essential part of the remote calibration services. The technique was first demonstrated at NBS in 1980 [8] and remains a primary method used by national metrology institutes for sending data to the BIPM (Bureau International des Poids et Mesures (BIPM) in French or International Bureau of Weights and Measures in English) for the calculation of Coordinated Universal Time (UTC) [9]. Two clocks residing at different locations cannot be directly compared, but common-view allows them to be indirectly compared if a common signal that serves as a transfer standard can be received at both clock sites. Signals from the GPS satellites provide this transfer standard.

Figure 2 is a diagram of a common-view comparison between the customer's standard and the UTC(NIST) time scale. The customer and NIST simultaneously compare their standards to signals from GPS satellites and then exchange the measurement results via the Internet. When the two measurements are subtracted from each other, the effects of GPS are removed. What remains is an estimate of the difference between the customer's standard and UTC(NIST). If the customer is located within about 5000 km of Boulder, Colorado, typically four or more of the same satellites are visible at the same time at both customer's location and at NIST. In this case, the "classic" common-view method is implemented, and the measurements involving the same satellites are aligned and subtracted from each other to obtain the time difference. At distances greater than about 5000 km, there may be periods when few or none of the same satellites are receivable at both sites. In this case the "all-in-view" method is implemented by combining data from all of the satellites received at each site, and then subtracting the composite averages from each other to obtain the time difference. This method

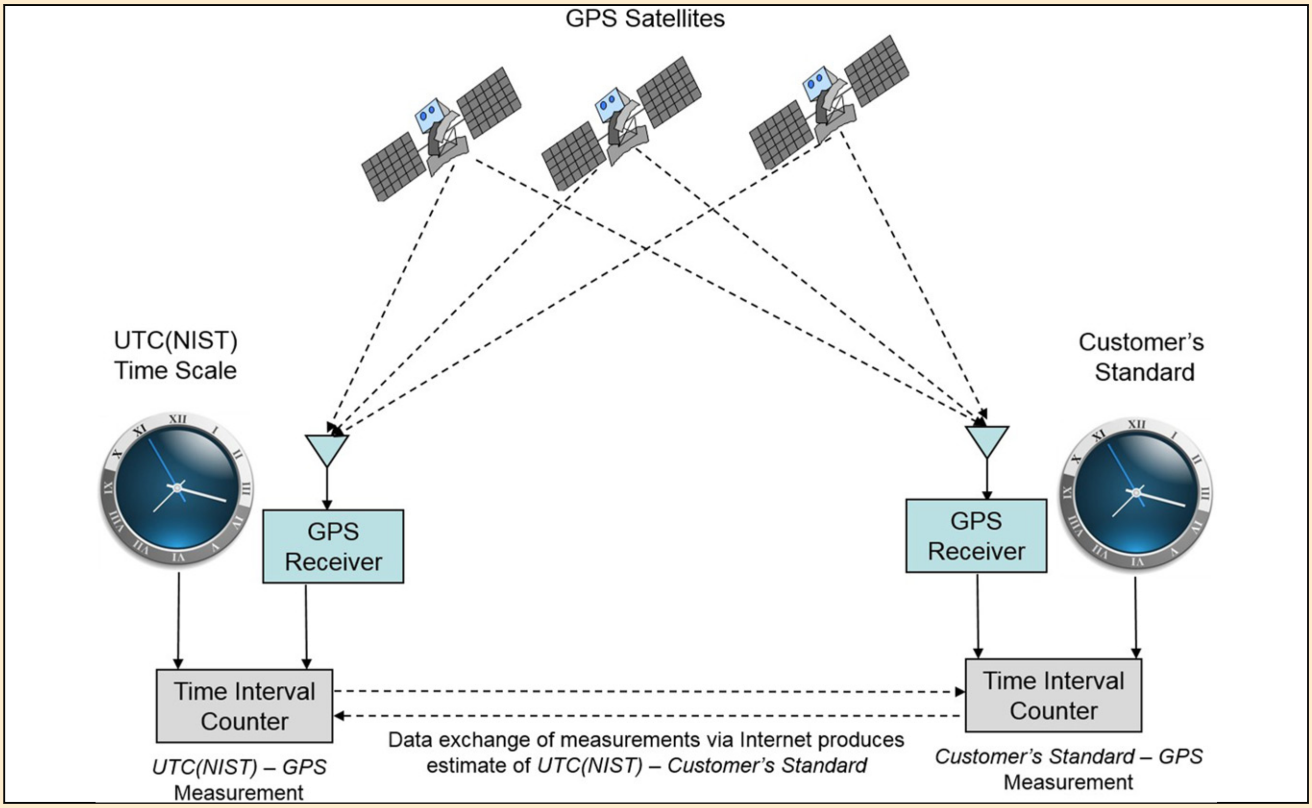

Figure 2. A common-view GPS comparison between a customer and NIST.

allows the FMAS and TMAS services to be deployed anywhere on Earth and still maintain the measurement uncertainties listed in Table 1.

The TMAS produces the *UTC(NIST) - Customer's Standard* time difference estimate every 10 minutes (Figure 2), and the NIST disciplined clock (NISTDC) service converts these measurements to frequency corrections. These corrections are digitally applied to the customer's standard to keep it locked to UTC(NIST), as shown in Figure 3. The standard can be either a rubidium clock supplied by NIST (76102C) or a cesium clock supplied by the customer (76103C). The frequency and time uncertainty of the 76102C and 76103C services are equivalent, but the disciplined cesium clock service (76103C) provides much better "holdover" accuracy if the GPS signals are temporarily unavailable. For example, if the GPS signals cannot be received, the 76102C service can maintain time within 1 μs of UTC(NIST) for about 48 to 72 hours, whereas the 76103C service can maintain time within 1 μs for one year or more.

Some NIST customers, especially those in the financial sector, require the highly accurate time they receive from NIST to be distributed to computers within their organization or network, so that transactions and files can be accurately time stamped. These customers utilize the NISTDC, which typically keeps time within 10 ns of the UTC(NIST) time scale, as the reference for the Time Code Output service (76104C). This service can distribute time codes to the customer's server or client computers via either the Network Time Protocol (NTP) or Precision Time Protocol (PTP).

Another typical requirement of financial sector customers is checking the accuracy of their time servers. This helps them ensure that their time codes were correct not only when transmitted, but also when received. The Time Code Monitoring service (76105C) can check the accuracy of as many as 12 of the customer's servers by requesting NTP packets and comparing their contents to the time kept by the NISTDC. The uncertainty of this measurement is limited by network asymmetry, but this problem is largely eliminated by locating the NISTDC as close as possible to the servers being monitored, typically placing it on the same local area network in the same data center. This typically can reduce the uncertainty to near 10 μs.

The TMAS and each of its optional services can be delivered to customers who install a single rack-mounted instrument (Figure 4) at their facility. The instrument includes the GPS receiver and time interval counter required by the TMAS, the rubidium oscillator required by the NISTDC, the NTP/PTP server required by the Time Code Output service, and a hardware clock required by the Time Code Monitoring service.

3. Customer Locations, Industries Reached, and Customer Requirements

Because GPS signals are available globally, a common-view link to NIST can be established anywhere on Earth. At this writing (September 2018), NIST provides services to more than 50 remote calibration sites, as shown on the map in Figure 5.

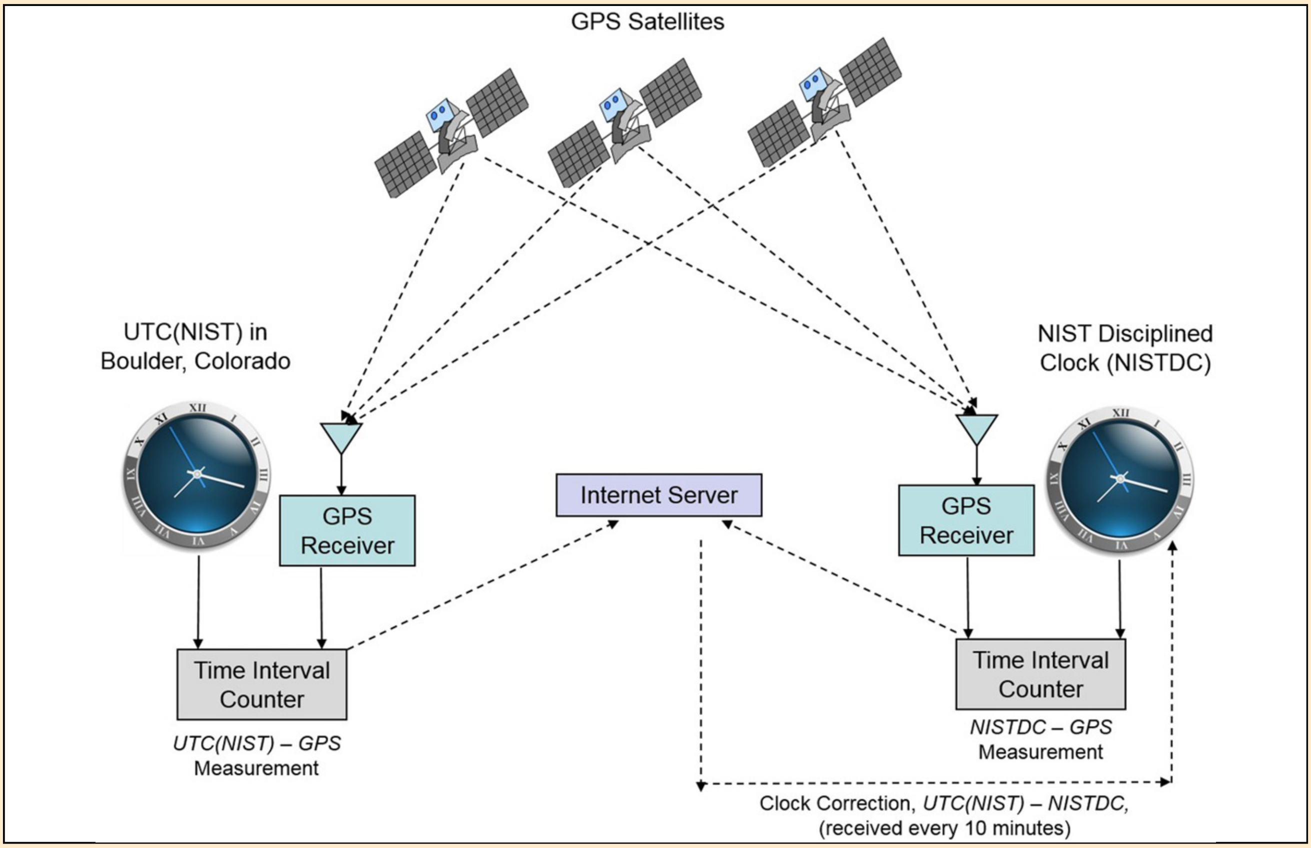

Figure 3. A common-view GPS comparison resulting in a NIST disciplined clock.

Figure 4. The TMAS measurement system that NIST supplies to customers.

The red clocks on the map represent FMAS customers, the blue clocks represent TMAS customers, and the green clocks represent TMAS/NISTDC customers. The customers are located in 23 states and 7 sites outside of the United States.

The services reach and impact a wide variety of industrial sectors (Figure 6). The largest customer group consists of in-house calibration laboratories who use the NIST reference to calibrate their primary standard, and then in turn use their primary standard as the reference for calibrations of other equipment. Industries whose in-house calibration laboratories rely on the NIST services include U.S. defense contractors (13%), aerospace (9%), and nuclear energy (2%), in addition to U.S. military installations (13%). Collectively, these in-house calibration laboratories represent 37% of the customer base. The largest industrial sector represented in the customer base consists of manufacturers of electronic test and measurement equipment and instrumentation (26%), which includes manufacturers of frequency and time standards, such as atomic oscillators and GPS disciplined oscillators. These customers require NIST validation of their measurements to ensure that the products they design, manufacture, and sell can meet their desired specifications for frequency and/or time. Private calibration laboratories that sell calibrations to customers outside of their own organizations, and nonmilitary U.S. government laboratories each contribute 8% to the NIST customer total. The customers described in this paragraph are primarily interested in frequency measurements, although many also maintain an accurate time standard.

The financial sector currently represents 21% of the customer base, a percentage that is likely to increase in the future. Financial market customers generally have little interest in frequency measurements. Their main concern is obtaining accurate time from UTC(NIST) for their computers, which time stamp files and transactions. The importance of this sector in economic terms is difficult to overstate, and

Figure 5. Locations of NIST remote frequency and time calibration customers (red clocks indicate FMAS, blue clocks indicate TMAS, green clocks indicate TMAS/NISTDC).

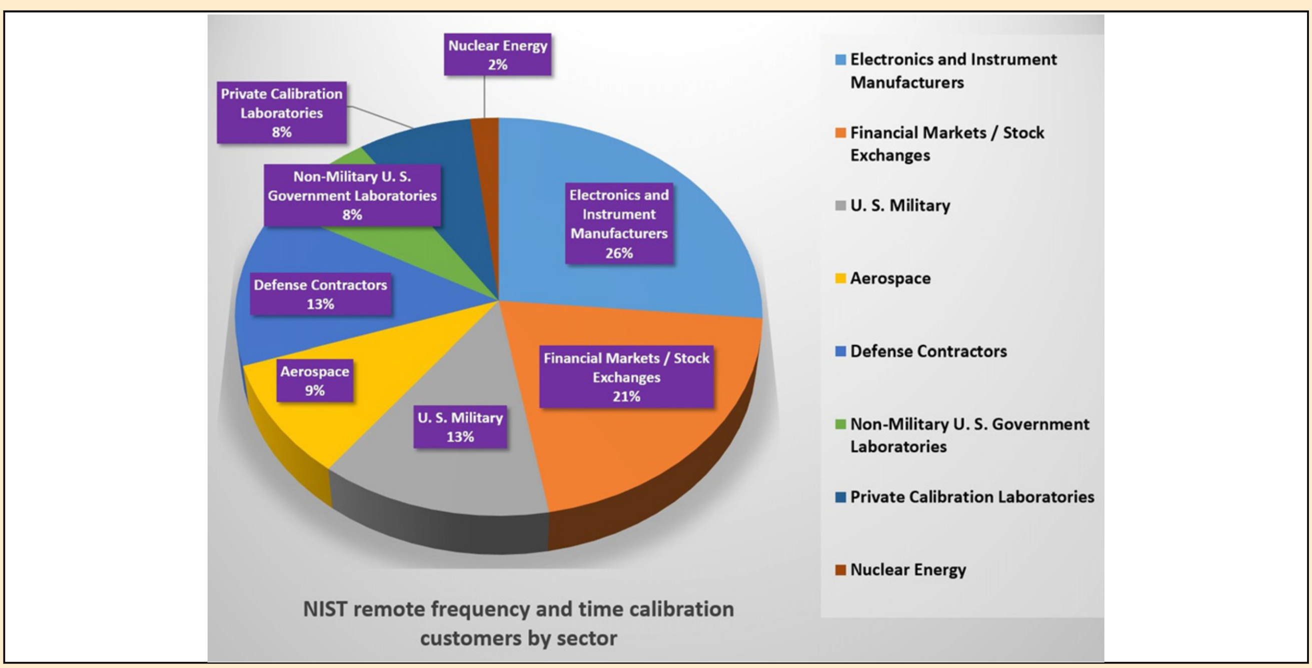

Figure 6. Percentages of NIST remote frequency and time calibration customers by sector.

thus continuing to meet the needs of these customers is a priority for the remote calibration program.

The customers consider the measurement assurance they receive from NIST to be an essential part of their daily operation. In other words, they require the capabilities of the NIST services, and NIST must ensure that these capabilities always meet or exceed the customer's requirements. The requirements vary from sector to sector. For example, a frequency measurement uncertainty requirement of a few parts in 10^{13} over a 1-day interval is currently small enough to meet the needs of most equipment manufacturers and of both in-house and private calibration laboratories. This requirement is met by both the FMAS and TMAS (Table 1). Industrial requirements for time measurement uncertainty are generally limited to ~1 μs, with the most stringent customer requirements currently about 0.1 μs (100 ns), which is also easily exceeded by the TMAS and NISTDC services. Financial market timing requirements have uncertainty requirements that are typically 1000× larger, but that can be difficult to meet because they apply not only to the electrical pulses used for synchronization, but also to the digital time codes that must be transferred to computer systems. The most stringent financial requirement in place at this writing (September 2018) is 100 μs time accuracy (with respect to UTC) for clocks involved in high-frequency trading in Europe [10]. This requirement is currently being met and exceeded by the TMAS and its optional services [11]. Although customer requirements are currently being met, enhancing the services to meet future requirements has been, and remains, a continuous challenge.

4. NIST Quality System

The remote frequency and time calibration services are supported by the NIST quality system (NIST QS). The calibration part of the NIST QS is built on the foundation of *ISO Guide 17025* [12]. Measurements uncertainty is reported to customers using methods compliant with the international standard [13], but the uncertainty analysis also incorporates metrics specific to frequency and time metrology, such as the Allan deviation and Time deviation [14].

The NIST QS documentation includes the NIST quality manual (QM-I), a quality manual for each of the technical divisions at NIST (QM-IIs), and a quality manual for each of the calibration services (QM-IIIs) [15, 16]. The time and frequency division maintains its own QM-II quality manual, and separate QM-III quality manuals for the FMAS and TMAS services. These manuals are revised whenever necessary. In addition, quality reports that document any changes or issues related to the services are required to be written every three months. These reports are sent to the NIST quality manager and distributed to other NIST managers as necessary.

Each technical division at NIST has its quality system assessed every five years. The time and frequency division was previously assessed in 2005, 2010, and 2015, with the next assessment scheduled for 2020. After all findings recorded by the assessors are addressed (findings can include either nonconformities or observations), the NIST quality manager presents the division's quality system at a SIM general assembly meeting, where it can be approved or disapproved. If approval is given, it is valid for five more years.

NIST and other national metrology institutes with quality systems approved by their RMO can apply to have their calibration and measurement capabilities (CMCs), and the services that provide them, listed in the BIPM's Key Comparison Database (KCDB) [17, 18]. Inclusion in the KCDB means that the calibration service is internationally recognized by all signatories of the CIPM (Comité International des Poids et Mesures in French or International Committee of Weights and Measures in English) mutual recognition agreement (MRA). The MRA signatories include nearly every industrial nation [19]. The FMAS and TMAS are each listed in the KCDB. This means that their measurements are internationally recognized as being traceable to the SI at their stated levels of uncertainty.

5. Customer Accreditation

Most NIST customers must have their measurement capabilities periodically assessed or audited, which is often a prerequisite for them staying in business or meeting the contractual requirements of their own customers. Many NIST customers also seek laboratory accreditation. Having access to the continuous measurements records that both the FMAS and TMAS provide benefits the customer and can make the assessment and accreditation processes go much smoother. For example, the two major accreditation bodies for U.S. calibrations laboratories are the National Voluntary Laboratory Accreditation Program (NVLAP) and the American Association for Laboratory Accreditation (A2LA). As of March 2018, five NIST customers are accredited for frequency measurements by NVLAP [20] and nine are accredited by A2LA [21] with CMCs ranging from 2.5×10^{-12} to 1.3×10^{-13}.

Customers outside of the traditional calibration world, such as those in the financial sector, also undergo periodic assessments and audits and must be able to prove that they comply with the standards of regulatory bodies. In the financial sector, these regulatory bodies include the Financial Industry Regulatory Authority (FINRA) and the ultimate authority, the U.S. Securities and Exchange Commission (SEC). The TMAS/NISTDC service, which can provide logs of time measurements results recorded every second, allows financial market customers to easily provide regulators with the metrological evidence they are seeking.

6. Summary

By providing continuous monitoring and reporting of a customer's measurements, the NIST remote frequency and time calibration services do more than traditional calibration services; they provide measurement assurance and improve the quality of all frequency and time measurements made at the customer's location. The services satisfy the requirements of customers in many sectors and industries, are supported by the NIST quality system, are internationally recognized as being traceable to the SI, and can help customers pass legal metrology assessments and achieve accreditation.

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