# Selecting a Primary Frequency Standard for a Calibration Laboratory

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Calibration laboratories can choose from a variety of frequency standards, including quartz oscillators, atomic oscillators, and oscillators disciplined to agree with reference signals from the Global Positioning System (GPS) satellites or other sources. The frequency calibration and measurement capability of a laboratory is largely determined by the type of primary frequency standard* that is chosen. This paper presents an overview of the various types of commercially available frequency standards. It discusses their specifications, and the pros and cons of owning and operating each type of standard. It also presents long-term performance data from a number of calibration laboratory frequency standards that are monitored by the National Institute of Standards and Technology (NIST) through its remote calibration services.

## 1. Introduction

Laboratories that perform frequency calibrations need a continuously running frequency standard. This standard, usually called the primary or "house" standard, is the reference for all of the frequency calibrations performed by the lab. Signals from the primary frequency standard are typically distributed to the areas where engineers and technicians perform their work. For example, a typical setup involves connecting the 10 MHz sine wave output from the primary frequency standard to a distribution amplifier, so that the incoming signal can be split into multiple output signals. The output signals are distributed throughout the facility, and used as the external time base for test instruments such as frequency counters, oscilloscopes, and signal generators. This allows technicians working on the bench to always have access to the traceable frequency produced by the primary standard.

Calibration laboratories (cal labs) have many types of commercially available devices to choose from when selecting a primary frequency standard (Section 2). The choice of a frequency standard is an important one, particularly for laboratories that seek accreditation, because it determines the level of calibration and measurement capability that the laboratory can claim. Some standards also require more time and effort to operate than others (for example, they might require periodic adjustment and/or occasional maintenance), so both the day-to-day operation of the lab and the cost of labor can be influenced by the choice of the primary frequency standard.

## 2. Types of Calibration Laboratory Frequency Standards

Quartz, rubidium, and cesium oscillators are the three main types of frequency standards [1, 2, 3] used by cal labs. Quartz oscillators (Section 2.1) are the least expensive choice; rubidium oscillators (Section 2.2) and cesium oscillators (Section 2.3) are atomic devices that cost more but require less adjustment and perform much better over long periods. All three types of oscillators are available as bench top or rack mounted instruments and require no special knowledge to turn on and operate. In recent years, however, a fourth type of frequency standard has become very common in cal labs. These devices, known as Global Positioning System disciplined oscillators (GPSDOs), are quartz or rubidium oscillators whose frequency is controlled by signals broadcast from the GPS satellites (Section 2.4).

Table 1 summarizes the performance of the four types of frequency standards typically utilized by cal labs. The specifications listed in the table were obtained from manufacturer's datasheets (at least several commercially available standards were reviewed in each category), and from the results of measurements performed by NIST.

There are other types of oscillators used as frequency standards, most notably the hydrogen maser. However, hydrogen masers are normally too expensive to be used outside of research laboratories or national metrology institutes such as NIST, and are rarely found in cal labs. Disciplined oscillators steered to radio signals other than GPS serve as primary standards in some cal labs, although they are less common than they once were. These are briefly discussed in Section 2.5.

### 2.1 Quartz Oscillators

Laboratory quality quartz oscillators are available in rack mount or bench top configurations. The frequency accuracy of quartz oscillators is sensitive to changes in temperature, so the most stable devices enclose the quartz crystal in a temperature controlled oven. These devices, known as oven controlled quartz oscillators (OCXOs) often have excellent short term stability and low phase noise characteristics (Table 1). [3] Their simple design makes them very reliable, and some OCXOs have run continuously

| Oscillator Type | Quartz (OCXO) | Rubidium | Cesium Beam | GPSDO |
|---|---|---|---|---|
| Typical Frequency Accuracy (1 day average) | $1 \times 10^{-7}$ to $1 \times 10^{-10}$ | $5 \times 10^{-9}$ to $5 \times 10^{-12}$ | $1 \times 10^{-12}$ to $5 \times 10^{-14}$ | $1 \times 10^{-12}$ to $5 \times 10^{-14}$ |
| Stability at 1 second | $1 \times 10^{-11}$ to $1 \times 10^{-13}$ | $5 \times 10^{-11}$ to $5 \times 10^{-12}$ | $5 \times 10^{-11}$ to $5 \times 10^{-12}$ | $1 \times 10^{-10}$ to $1 \times 10^{-12}$ |
| Stability at 1 day | $1 \times 10^{-10}$ | $5 \times 10^{-12}$ | $8 \times 10^{-14}$ to $2 \times 10^{-14}$ | $8 \times 10^{-13}$ to $5 \times 10^{-14}$ |
| Aging/year | $5 \times 10^{-7}$ to $5 \times 10^{-9}$ | $< 1 \times 10^{-10}$ to $5 \times 10^{-10}$ | None, by definition. However the frequency does shift slowly, typically by parts in $10^{-17}$ per day. | None, the output is a steered frequency that is corrected for aging and drift |
| Phase Noise (dbc/Hz, 10 Hz from carrier) | -125 to -140 | -90 to -130 | -130 to -136 | -90 to -140 |
| Life Expectancy | Indefinite | > 15 years | 5 to 20 years<br>10 years is typical | > 15 years |
| Maintains an acceptable TUR when calibrating quartz oscillators found in test equipment | No | Yes | Yes | Yes |
| Produces an on-time pulse without being synchronized to another source | No | No | No | Yes |
| Produce frequency accurate to within $\pm 1 \times 10^{-11}$ for 24 hours or longer | No | Yes, with periodic adjustment | Yes | Yes |
| Cost | $1,000 to $5,000 | $2,000 to $10,000 | $30,000 to $55,000 | $3,000 to $15,000 |

Table 1. Typical performance characteristics of calibration laboratory primary frequency standards.

for decades without failing. However, their accuracy can change rapidly due to frequency drift and/or aging, and a cal lab will have to adjust an OCXO on a regular basis in order to maintain average frequency to better than $1\times 10^{-9}$.

This is illustrated in Figure 1, which shows seven years of monthly average frequency values for an OCXO that was continuously measured with the Frequency Measurement and Analysis Service (FMAS), a remote frequency calibration service operated by NIST. [4] During most of this period, the customer adjusted the OCXO frequency to compensate for aging when the frequency offset exceeded about $2\times10^{-9}$. However, there was one period where the frequency offset nearly reached $1\times 10^{-8}$ and remained there for almost two years. There were also a few occasions when the power to the OXCO was interrupted and the frequency shifted to a different offset value when the power was restored.

Quartz oscillators meet the needs of countless applications, but as Figure 1 suggests, the large variations in their frequency over the long term make them a poor choice as a cal lab's primary frequency standard. Their shortcomings are amplified when you consider that the device under test (DUT) for most frequency calibrations will be a quartz time base oscillator inside a test instrument such as a signal generator or frequency counter. [5] This means that if a quartz primary standard is chosen, the cal lab will be forced to calibrate quartz DUTs with a reference that could have similar performance, making it impossible in some cases for the lab to maintain an acceptable test uncertainty ratio (TUR) between the reference and the DUT. For this reason alone, even the smallest cal labs should avoid the use of a quartz primary standard, and opt instead for an atomic standard or a GPSDO. This requires spending more money initially, but will enhance the measurement capability of the lab, and save both time and money in the long run.

**2.2 Rubidium Oscillators**

Rubidium oscillators are the least expensive atomic frequency standards. They usually cost about 1/10 as much as a cesium oscillator, but their typical accuracy is normally about 1000 times worse than a cesium if they are never adjusted. For example, a $3,500 rubidium might typically be accurate to a few parts in $10^{10}$ after its initial warm up

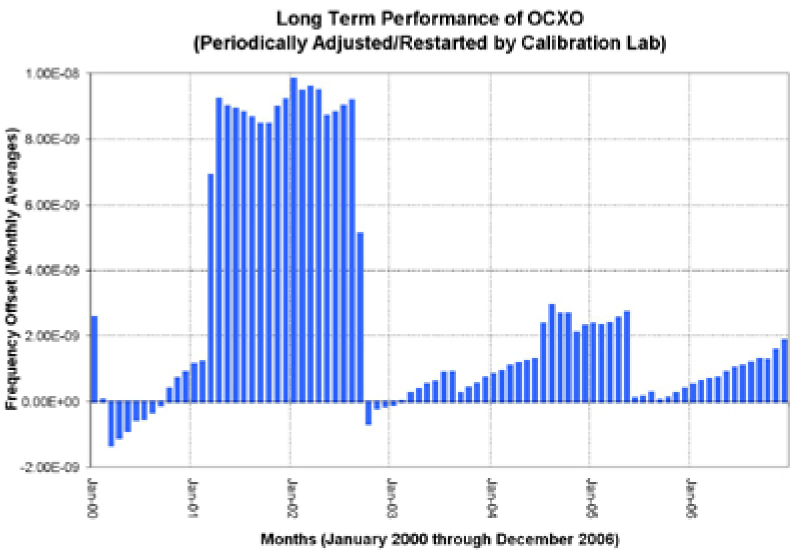


Figure 1. Seven years of monthly frequency offset values from the same OCXO.

period, whereas a $35,000 cesium will probably be accurate to within a few parts in $10^{13}$ or better. However, many cal labs adjust their rubidium standards on a regular basis, and this allows them to maintain average frequency to within a few parts in $10^{11}$ or $10^{12}$ over periods of months or years.

The adjustments are made to compensate for the aging and frequency drift that changes the rubidium frequency slowly over time. Manufacturers typically specify the aging rate of rubidiums as $< 5 \times 10^{-11}$ per month, but this specification is often conservative, as the frequency of a well behaved rubidium standard typically changes by less than $1 \times 10^{-11}$ over the course of a month. [6] Even so, the frequency change can still exceed $1 \times 10^{-10}$ if left unadjusted for a year, which could cause the TUR for calibrations to become unacceptably small, depending upon the laboratory's requirements.

Figure 2 shows long-term performance data from four rubidium standards maintained by cal labs that subscribe to the NIST FMAS. [4] The graph shows the daily frequency offset values (24 hour averages) for each device for the entire year of 2007. *Rb1* is a particularly well maintained and regularly adjusted rubidium whose frequency always remained within $5 \times 10^{-12}$. *Rb2* is the same model of oscillator as *Rb1*, but the operator's frequency adjustments were not as precise. Even so, the average daily frequency was kept within $\pm 2 \times 10^{-11}$ for the entire year. *Rb3* is less stable than *Rb2* and *Rb3*, and the operator's adjustments tended to overcompensate for the aging rate, but the average daily frequency still remained within $\pm 4 \times 10^{-11}$. And finally, *Rb4* was permitted (for the most part) to free run without adjustment over the course of the year. The operator made occasional adjustments, but they were insufficient to remove the linear trend contributed by the aging rate. The oscillator began the year high in frequency by about $2 \times 10^{-11}$, and ended the year high in frequency by about $8 \times 10^{-11}$. This level of performance still exceeds the requirements of this particular laboratory, as it would with many other cal labs.

### 2.3 Cesium Oscillators

Cesium oscillators have been available commercially since the 1950s [7], and the SI second is defined as 9,192,631,770 energy transitions of the cesium atom. Thus, cesium oscillators are true primary standards that meet all performance requirements, and are the obvious and preferred choice of frequency standard for cal labs with the most demanding requirements. However, not all labs can justify the cost of a cesium. They typically cost at least $30,000 per unit, and their beam tubes eventually run out of cesium, typically after about 10 years. [8] The cost of replacing a beam tube is often about half the purchase price of the cesium itself, so the cost of ownership is high compared to other standards.

Figure 3 shows the daily frequency offset values from a cesium frequency

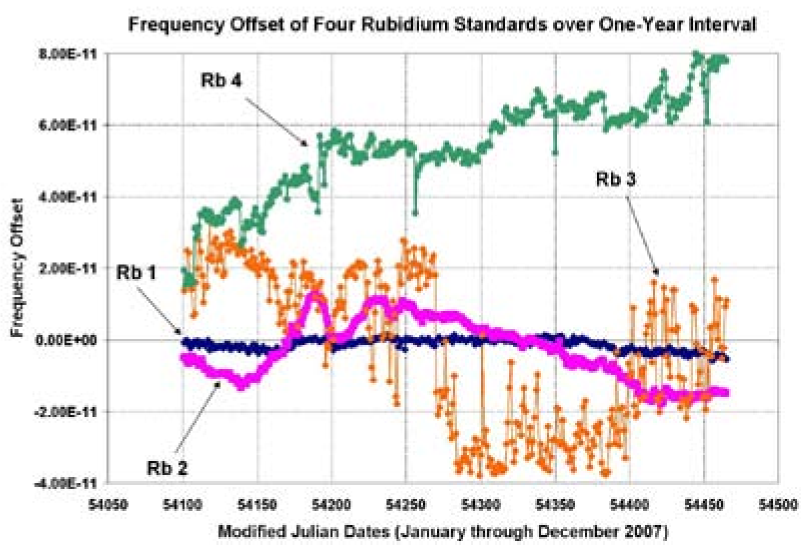


Figure 2. Long-term performance data (one year) from four rubidium frequency standards.

standard maintained by a cal lab over an eight-month interval. These measurements were made by the Time Measurement and Analysis Service (TMAS) [9], a remote calibration service operated by NIST that has lower measurement uncertainties than the FMAS. This device had been set on frequency nearly perfectly by the operator, and the average frequency offset is about $2 \times 10^{-14}$. The variation in the data is partially caused by the instability of the cesium at an averaging time of one day ($\sim 3 \times 10^{-14}$), but more so by the uncertainty of the TMAS measurements ($5 \times 10^{-14}$, $k = 2$). Not all cesium standards perform this well, but most can realize average frequency near $1 \times 10^{-13}$ if they are properly maintained and operated, and can do so for many weeks, months, or years without requiring adjustment.

Cesium oscillators are exceptional performers that directly realize the SI second, but they still must be regularly checked to make sure they are working properly. When a cesium oscillator fails, it becomes an OCXO, often with a large frequency offset of parts in $10^7$ or $10^8$. Thus, the cal lab must develop a procedure that ensures that its cesium standard is working properly. This might involve performing diagnostic tests through the front panel or a computer interface or by continuously comparing the cesium to another standard to check for any abnormal behavior.

**2.4 GPS Disciplined Oscillators**

GPSDOs use signals from the GPS satellites to steer a local oscillator, which is usually an OCXO or rubidium. Because GPS is a radio navigation system that relies on precise time and frequency for its accuracy, the performance of a GPSDO is usually excellent, particularly over the long term. A GPSDO is a self-calibrating standard that never requires adjustment, because the adjustments are made internally by the signals from the satellites. However, they do require a small outside antenna that needs to be mounted on a rooftop location near the lab, which might not be possible in some buildings. In addition, even though all GPSDOs receive signals from the same satellites, their design characteristics and performance can vary significantly. [10, 11]

The timing signals broadcast by the GPS satellites are continuously steered to agree with Coordinated Universal Time (UTC). This means that over very long averaging periods of multiple days or weeks, a GPSDO that is locked to the satellite signals will be inherently accurate and inherently stable. However, most frequency calibrations last for one day or less, so from the point of view of a cal lab, the most important specification of a GPSDO is frequency accuracy at one day. The accuracy can be no better than the stability, so a reasonably good metric to use when evaluating a GPSDO is its frequency stability after one day of averaging, as estimated with the Allan deviation (ADEV). [12]

Figure 4 shows the estimated frequency stability at one day for seven different GPSDO models that were calibrated by NIST. The ADEV estimates at one day range from about $8 \times 10^{-13}$ to about $5 \times 10^{-14}$ with a stability of $1 \times 10^{-13}$ or less, indicating a very high quality unit. GPSDOs that employ a rubidium local oscillator (dark colored bars in Figure 4) cost more and are generally (but not always) more stable than those that employ a quartz local oscillator (light colored bars).

The use of GPSDOs as primary standard in cal labs is now common but remains controversial in some quarters. Some detractors claim that GPSDOs cannot be used to establish traceability, which is simply not true. The traceability of a GPSDO can be established in the same fashion as that of a quartz, rubidium, or cesium oscillator if the measurement uncertainty is known (see Section 3). In fact, because the time and frequency outputs of a GPSDO are steered to agree with UTC, they will have better long-term accuracy and stability than any free running oscillator, including a cesium.

A more valid concern is that some cal lab managers prefer to have a standard (such as a cesium or rubidium) whose frequency can be adjusted and controlled by cal lab personnel, rather than a GPSDO whose frequency is adjusted automatically by signals from the satellites. Another concern is that the short-term stability of some GPSDOs can be poor when compared to free running oscillators, due to the frequency or phase steps that are introduced when the local oscillator is steered to agree with the satellites. Some GPSDOs, however, are stable enough in the short-term to satisfy

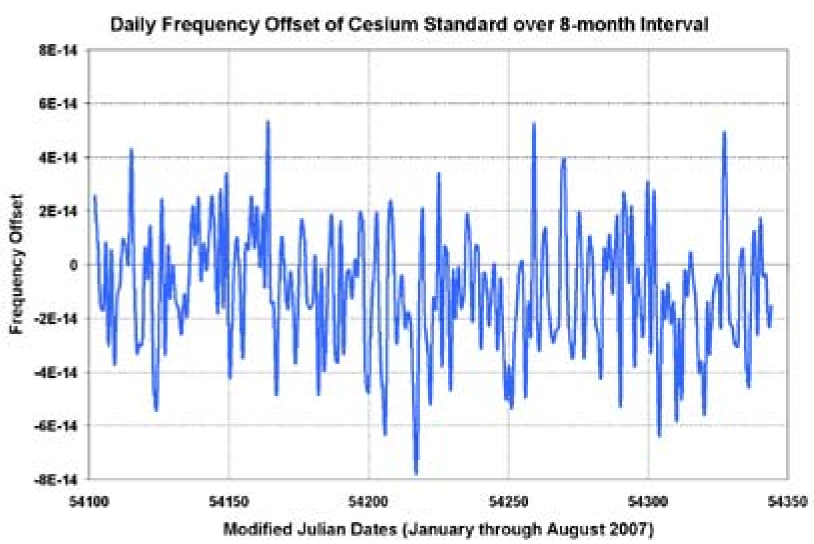


Figure 3. Performance of a cesium frequency standard over an 8-month interval.

the requirements of nearly any cal lab.

As is the case with cesium oscillators, the biggest issue concerning GPSDOs is that they tend to be trusted unequivocally, even when they have stopped working. Because they work so well without adjustment, they are often allowed to run for long periods without any attention. To guard against trusting the output of a failed device, cal labs that use a GPSDO as their primary standard must have a procedure that allows them to determine whether the device is working and properly tracking satellites. This might involve periodically checking the front panel lights and indicators to verify if the unit is locked, and/or using a computer to monitor the number of satellites being tracked, the received signal strength, the health of the local oscillator, and so on.

NIST has firsthand experience with GPS receivers failing for a myriad of reasons, including: RF interference (jamming), local oscillator failures, antennas falling off the roof during high wind conditions, antenna cables being cut by repairmen, antenna cables being gnawed through by squirrels and other animals, and even one unusual incident where a trespasser with a rifle used a GPS antenna for target practice. Needless to say, it is important to verify that a GPSDO is working properly, and to know if it has stopped working.

### 2.5 Other Types of Disciplined Oscillators

A small number of manufacturers produce disciplined oscillators controlled by radio signals other than GPS (Table 2), and those devices are used as frequency standards in some cal labs. The most common reference signals used to discipline oscillators in the pre-GPS days were low frequency (LF) signals from ground based transmitters, such as LORAN and NIST radio station WWVB. [13]

Both LORAN and WWVB disciplined oscillators were once easy to find in cal labs, but are rarely found today, since nearly all of the commercially available models have been discontinued. However, the recently enhanced LORAN system (known as eLORAN) could entice manufacturers to introduce new models that could potentially rival the performance of GPSDOs. [14] CDMA-disciplined oscillators are another available option. They receive cellular telephone signals that are referenced to GPS and perform at a level nearly equivalent to a GPSDO. They work without an outdoor antenna, which helps if the laboratory is in a room that lacks access to the roof. [15]

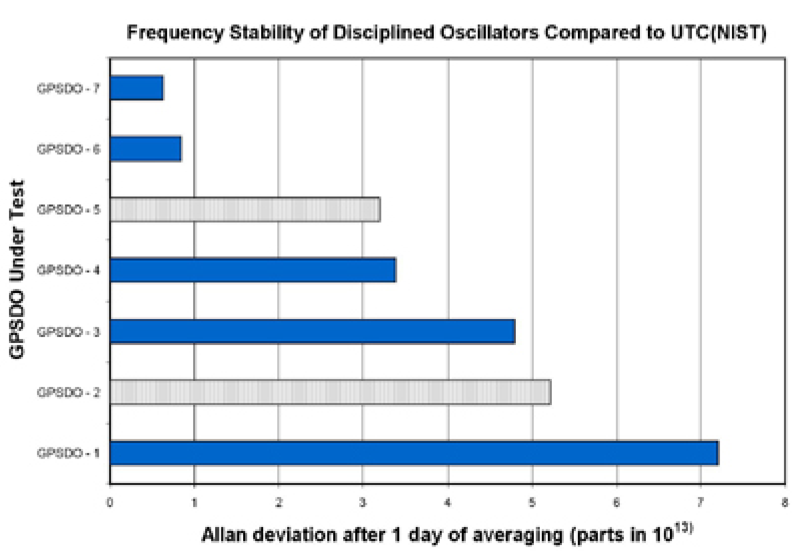


Figure 4. Frequency stability comparison of seven different GPSDOs.

## 3. Traceability and the Use of Remote Calibration Services

Cal labs are required to establish traceability of their measurement standards by means of an unbroken chain of calibrations or comparisons that traces back to the International System (SI) units of measurement. Establishing traceability requires knowing the measurement uncertainty of a standard with respect to the SI. The obvious way for a cal lab to obtain this uncertainty value is to calibrate its primary standard against the national standard. This can be done by sending the primary standard to the National Metrology Institute (NMI), which is NIST in the United States.

Even then, however, traceability would be established only at a given point in time, and would eventually have to be reestablished by another calibration. For example, if an auditor was told that a lab's primary standard was last calibrated by an NMI five years ago, they would almost certainly agree that the traceability chain was no longer valid, and would probably deny accreditation to the laboratory.

Transfer standards, such as the oscillators onboard the GPS satellites, make it possible for cal labs to continuously establish traceability. This is accomplished by using the common-view technique, which is conceptually very simple. The common-view technique does not require the cal lab's standard to be sent out for calibration. Instead, it remains at home, where it is continuously compared to radio signals originating from a reference transmitter, *R*. The national standard, located at the NMI, is simultaneously compared to R. Thus, the cal lab measures the frequency offset between *R* and their house standard, while the NMI simultaneously measures the frequency offset between *R* and the national standard.

The data from both sites are collected in the same place, and the two data sets are subtracted from each other. The resulting data reveal the frequency offset between the cal lab's primary standard and the national frequency standard, because the frequency offset of *R* falls completely out of the equation. In common-view GPS measurements, the GPS satellites serve as R. Since the satellite signals can be received anywhere on Earth, the common-view technique allows any cal lab to make a continuous comparison to the national frequency standard and to know the uncertainty of their primary frequency standard at all times.

NIST offers two remote calibration services that utilize different forms of common-view GPS measurements. The Frequency Measurement and Analysis Service (FMAS) can calibrate up to five frequency standards at once with an uncertainty of $2 \times 10^{-13}$ at one day, and calibration reports are mailed to customers every month. [4] The Time Measurement and Analysis Service (TMAS) can measure a 1 Hz signal timing pulse from a single standard with an frequency uncertainty of $5 \times 10^{-14}$ at one day. In addition to this lower uncertainty, the TMAS has two other advantages: it can measure the absolute timing accuracy of a cal lab's primary standard with an uncertainty of less than 15 ns (the FMAS measures frequency only), and its customers can view their measurement results in real-time via the Internet. [9] Table 3 summarizes the features and costs of the two services.

Subscribing to the FMAS or TMAS is certainly not the only way that a laboratory can establish frequency traceability to the SI. Laboratories can send their standards out for periodic calibration, or intercompare their standards to other standards of known uncertainty. However, both the FMAS and TMAS provide a convenient, turnkey solution for the cal lab. Subscribers to remote calibration services usually save both time and money and easily achieve accreditation, because the measurement uncertainty of their primary standard is always known and the validity of the traceability chain is never in doubt.

| Signal | Carrier Frequency | Description | Frequency Accuracy (1 day of averaging) |
|---|---|---|---|
| **CDMA** | 800, 900, 1700, 1800, and 1900 MHz regions | Over 100,000 North American base stations deliver forward link signals that cover about a 50 km radius. | $5 \times 10^{-13}$ |
| **LORAN** | 100 kHz | A network of 29 ground based transmitters whose signals cover the United States and Canada. | $\sim 1 \times 10^{-13}$ |
| **WWVB** | 60 kHz | A single transmitter in Fort Collins, Colorado whose signal covers the United States during the nighttime hours. However, daytime coverage is tenuous in many areas. | $5 \times 10^{-12}$ |

Table 2. Non-GPS signals used to discipline frequency standards.

## 4. Summary and Conclusion

Cal labs can choose from many different types of commercially available frequency standards. The choice of a frequency standard is important, particularly for accredited laboratories, because it determines the level of calibration and measurement capability that the laboratory can claim. Cal labs should avoid the use of quartz oscillators as their primary standard, and should choose between the other available options (atomic oscillators or disciplined oscillators) based on the lab's metrological requirements and its available resources. Once the primary frequency standard is in place, cal lab managers must develop a procedure for determining its uncertainty, so that traceability to the SI can be continuously established.

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| Featu re | FMAS | TMAS |
|---|---|---|
| Number of Channels | 5 | 1 |
| Frequency Inputs | 1 Hz to 120 MHz | 1 Hz only |
| Time Uncertainty w/ respect to UTC(NIST), (k = 2) | Not Available | 15 ns |
| Frequency Uncertainty w/ respect to UTC(NIST), (k = 2) | $2 \times 10^{-13}$ at 1 day | $5 \times 10^{-14}$ at 1 day |
| Data connection to NIST | Telephone line | Internet |
| Reporting of Results | Daily printouts of phase plots, monthly calibration report sent via mail | Real-time reporting via Internet, updated every 10 minutes |
| Customer Service | Phone and email support, replacement parts shipped when necessary via overnight delivery service | Phone and email support, replacement parts shipped when necessary via overnight delivery service |
| Web Site | tf.nist.gov/service/fms.htm | tf.nist.gov/service/tms.htm |
| Start-up Fee | $1500 | $1500 |
| Monthly Fee | $500 | $750 |

Table 3. FMAS/TMAS comparison.

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* The term "primary standards" is often reserved for a standard whose value is accepted without reference to other standards that produce the same quantity. For example, cesium fountain standards (such as NIST-F1 in the United States) are currently recognized as true primary frequency standards because their uncertainty can be estimated by summing or combining the effects of their frequency shifts, without comparing them to other standards. However, the term "primary standards" is also commonly used to refer to the best standard available at a given laboratory or facility. It is in that sense that the term is used throughout this paper.

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