

Proposed System for Assuring Time and Frequency Coordination Among SIM Member Nations

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Abstract

We propose a new system that would allow all participating Inter-American Metrology System (SIM) nations to continuously compare their time and frequency standards and establish traceability chains with known uncertainties across the entire SIM region. The proposed system allows all participating SIM nations to compare their measurements to all other SIM nations using the all-in-view common-view Global Positioning System (GPS) satellite measurement technique. All collected measurement data would be uploaded hourly to an Internet server where it is automatically processed and graphed. All collected data would be made available to all participants, and measurement results can be viewed using a standard Web browser from any Internet connection. The measurement uncertainty for absolute time offset relative to Coordinated Universal Time (UTC) is expected to be less than 50 ns. The measurement uncertainty for frequency (2σ) is expected to be approximately 1.5×10^{-13} at an averaging time of one day.

Introduction

The Inter-American Metrology System (SIM) resulted from a broad agreement among national metrology organizations from all 34 member nations of the Organization of American States (OAS). Created to promote international, particularly Inter-American, and regional cooperation in metrology, SIM is committed to the implementation of a global measurement system within the Americas in which all users can have confidence.

To create this global measurement system, the SIM laboratories must intercompare their primary standards, so that the uncertainties of these primary standards are known with respect to those of the other laboratories. Once this is accomplished, two major benefits will result. First, the SIM laboratory can safely use their primary standard as a national measurement reference within their country. Citizens within the country can then use this reference to establish a measurement chain that ultimately traces to the International System (SI) of units. Second, each member nation can recognize measurements made in other member nations. This mutual recognition of measurements saves time and money by reducing the number of required measurements. It also helps to stimulate trade among the member nations, and potentially between SIM members and members of other regional metrology organizations (RMOs).

While the task of building a global measurement system among SIM members has some obvious obstacles, it is certainly feasible in the field of time and frequency due to two enabling technologies: the Global Positioning System (GPS) satellite constellation and the Internet. Signals from GPS satellites provide essentially worldwide coverage. They can easily be received in all SIM member countries, serving as a transfer standard for interlaboratory comparisons. The Internet allows rapid exchange of the collected data between the member nations.

This paper proposes a system for assuring coordination of time and frequency between SIM member nations that is based upon GPS and Internet technologies. This system should be capable of creating a global measurement system amongst SIM nations by comparing the Coordinated Universal Time (UTC) time scales maintained at all SIM laboratories to each other. The beauty of the proposed system is that no single laboratory acts as the hub for the comparisons. The comparisons are truly bilateral, the system doesn't favor any one laboratory or nation, and time broadcast by GPS drops out when the measurement results are processed. Another advantage is that the hardware cost is expected to be low, approximately \$5000 (USD) per laboratory. The following sections describe the measurement technique, the measurement system itself, and the anticipated measurement uncertainties.

Common-View GPS Measurements

Common-view GPS measurements began at NIST shortly after the first GPS satellite was launched in 1978 [1], and calibration services based on this technique have existed for years at NIST and other national metrology institutes [2]. The common-view technique also plays a central role in the international calculation of UTC performed by the Bureau International des Poids et Mesures (BIPM) [3]. The technique is based on the concept that two laboratories can measure the time difference between their clocks by each comparing their local clock to the same reference at the same time. The laboratories record and exchange their measurements, and the difference between the measurements is the difference between the times kept by the two clocks.

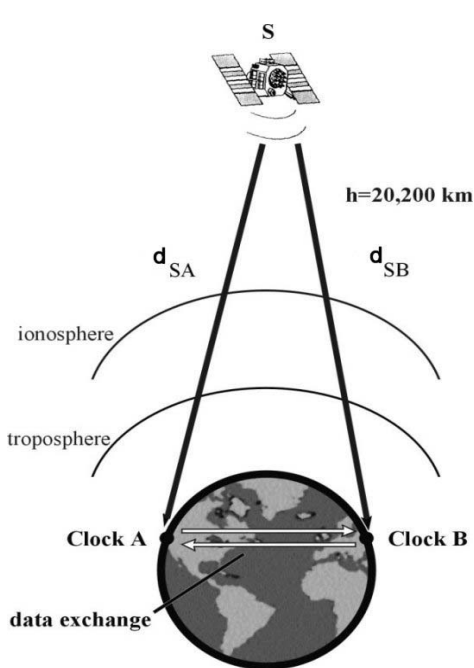


Figure 1. Common-View GPS.

To visualize how the common-view technique works, imagine two people living at opposite ends of town who want to compare the time on the grandfather clocks in their living rooms. This would be an easy problem to solve if they could get the clocks together in the same place and compare them side by side. However, moving the clocks is not possible. Therefore, each person agrees to write down the time displayed by their clock when the fire whistle (located midway between them) blows in their town, an event that happens each day around noon. They then call or email each other and exchange the time readings. If the first clock read 12:01:35 and the second clock read 12:01:47, then simple subtraction tells them that the second clock was 12 seconds ahead of the first clock when the fire whistle blew. Whether the fire whistle blew exactly at noon or not is unimportant. It only matters that it was heard at the same time at both locations. If so, the measurement reveals the difference between the two clocks, and the comparison is successful.

Instead of a fire whistle, common-view GPS comparisons (Figure 1) employ a satellite (S) and two receivers (A and B). The satellite transmits a time signal that is simultaneously received by both receivers. Both receivers compare the received signal to their local clock and record the data. Receiver A receives the signal over the path d_{SA} and compares the reference to its local clock (S - Clock A). Receiver B receives the signal over the path d_{SB} and records (S - Clock B). The two receivers then exchange and difference the data. Delays that are common to both paths d_{SA} and d_{SB} cancel out, but delays that aren't common to both paths contribute uncertainty to the measurement. The result of the measurement is (Clock A - Clock B) with an error term of $(d_{SA} - d_{SB})$. This error term can be estimated and applied as a correction to the measurement.

The $d_{SA} - d_{SB}$ term includes not only delays from the satellite to the receiving antennas, but also delays that take place after the signal is received. Therefore, a key to a successful measurement is to have equal delays at each site. This means that the common-view systems should be calibrated so that their relative delays are as close to zero as possible.

At this writing (April 2003), five SIM member nations (Argentina, Brazil, Canada, Mexico, and the United States) perform common-view GPS measurements and periodically submit their results to the BIPM as a contribution to the international UTC time scale. These measurements are done with receivers designed to accept the BIPM tracking schedule that records satellite tracks containing 13 minutes of data. The maximum number of tracks recorded is 48 for single-channel receivers, and about 450 for multi-channel receivers [4]. The results of these measurements are published in the BIPM Circular-T [5].

The all-in-view common-view technique proposed here is similar to, but not the same as, the method used by the BIPM. The key difference is that it does not use a tracking schedule. Instead, it collects as much data as possible from as many satellites as possible (limited in some instances by the eight-satellite capacity of the receiver). As many as eight common-view comparisons like the one illustrated in Figure 1 occur simultaneously each second. Every satellite is compared to the local clock for the entire period when it is above an elevation angle of 10° . The all-in-view method collects about 10 000 minutes of data per day (about 400 minutes of data from at least 24 or more operational satellites). This is about twice the amount of data collected with the BIPM multi-channel format, or about 20 times the amount of data collected with the single-channel format. More data generally results in lower measurement uncertainties, and will reduce the number of coverage gaps in the continuous comparisons between SIM laboratories.

Even if this proposed system is implemented, the SIM laboratories that contribute data to the BIPM should continue to do so, since they complete the traceability chain between SIM, the international UTC time scale, and the SI. Historically it has not been possible or practical for many SIM nations to send data to the BIPM. However, as long as some SIM members contribute data to the BIPM, all participants in the common-view network proposed here can show traceability to the SI at a known level of uncertainty.

Requirements for SIM Participants

To participate in the proposed network, a SIM laboratory must have the following items:

- A 1 pulse per second (pps) signal from their national standard. If the laboratory is interested in time comparisons, this 1 pps signal must be on-time with respect to the local UTC time scale. If the pulse is not on-time, frequency comparisons with the other

participants are still possible. If the laboratory maintains a UTC time scale with multiple oscillators, the 1 pps signal should originate from the composite average of the time scale. However, if the local version of UTC originates from one oscillator (true in many cases), the single oscillator can be used. A cesium oscillator is preferred, but a rubidium oscillator or GPS disciplined oscillator (GPSDO) is sufficient.

- A stable 1, 5, or 10 MHz signal for use as the external time base to the measurement system. If possible, this signal should originate from the same source as the 1 pps signal.
- The ability to mount the supplied GPS antenna within 75 m of the measurement system, and to route the supplied cable from the antenna to the system.
- For best results, the ability to perform a site survey of the GPS antenna supplied with the system to within a few meters or less for latitude, longitude, and altitude (the system can automatically perform a quick site survey with an uncertainty of about 20 meters).
- An always-on Internet connection with a dedicated IP address. This is required for automatic operation and for near real-time data reduction, but laboratories can upload data from a dial-up Internet connection or via email if necessary.

Description of Measurement System

The measurement system sent to the customer's site includes a time interval counter (TIC) with an integrated GPS receiver [6]. The TIC and an eight-channel GPS receiver are both contained on a single circuit board designed for use in a standard personal computer. The TIC has a single shot resolution of < 30 ps, and a 2σ stability of < 100 ps at an averaging time of one day. The TIC requires an external time base oscillator supplying 5 or 10 MHz. The system at each SIM laboratory compares the 1 pps output from the local version of UTC to the 1 pps output of the GPS receiver, and collects and stores one reading per second (Figure 2).

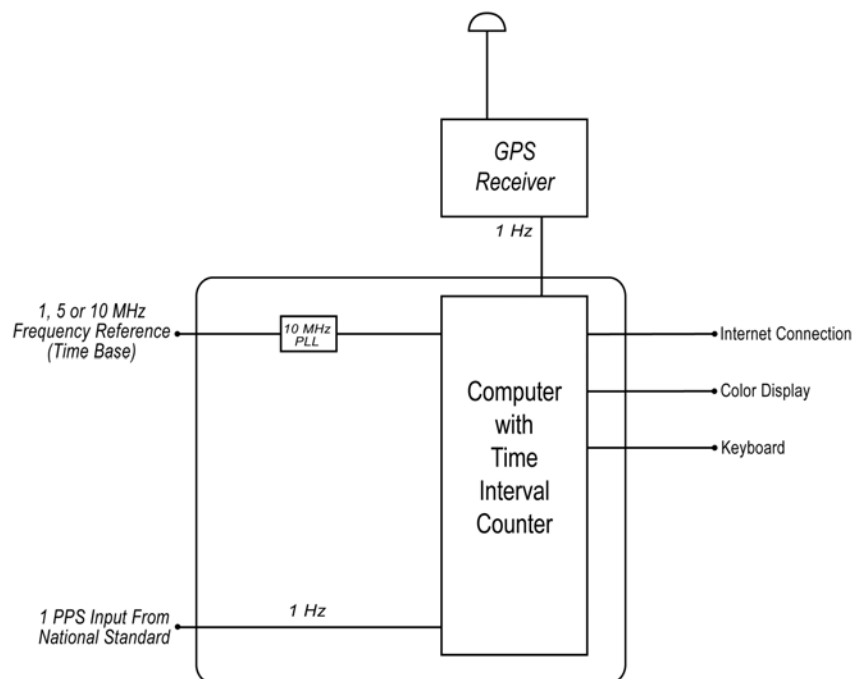


Figure 2. Block Diagram of Proposed Measurement System.

The control software measures the time interval between the GPS pulse and the local clock every second. It uses information supplied by the receiver to produce a time offset reading for each individual satellite, and stores 10 minute averages for each satellite. The data from a complete day is stored in a daily file as a 32 column \times 144 row matrix. The 32 columns represent the maximum possible number of GPS satellites, with each satellite's data stored in the column whose number equals its pseudo random noise (PRN) code. The 144 rows represent the number of 10-minute segments in 1 day. The collected data is uploaded to an Internet server via the file transfer protocol (FTP). The frequency of this upload can be varied, but if an "always on" Internet connection is available, we propose uploading at least once per hour to obtain near real-time measurement results.

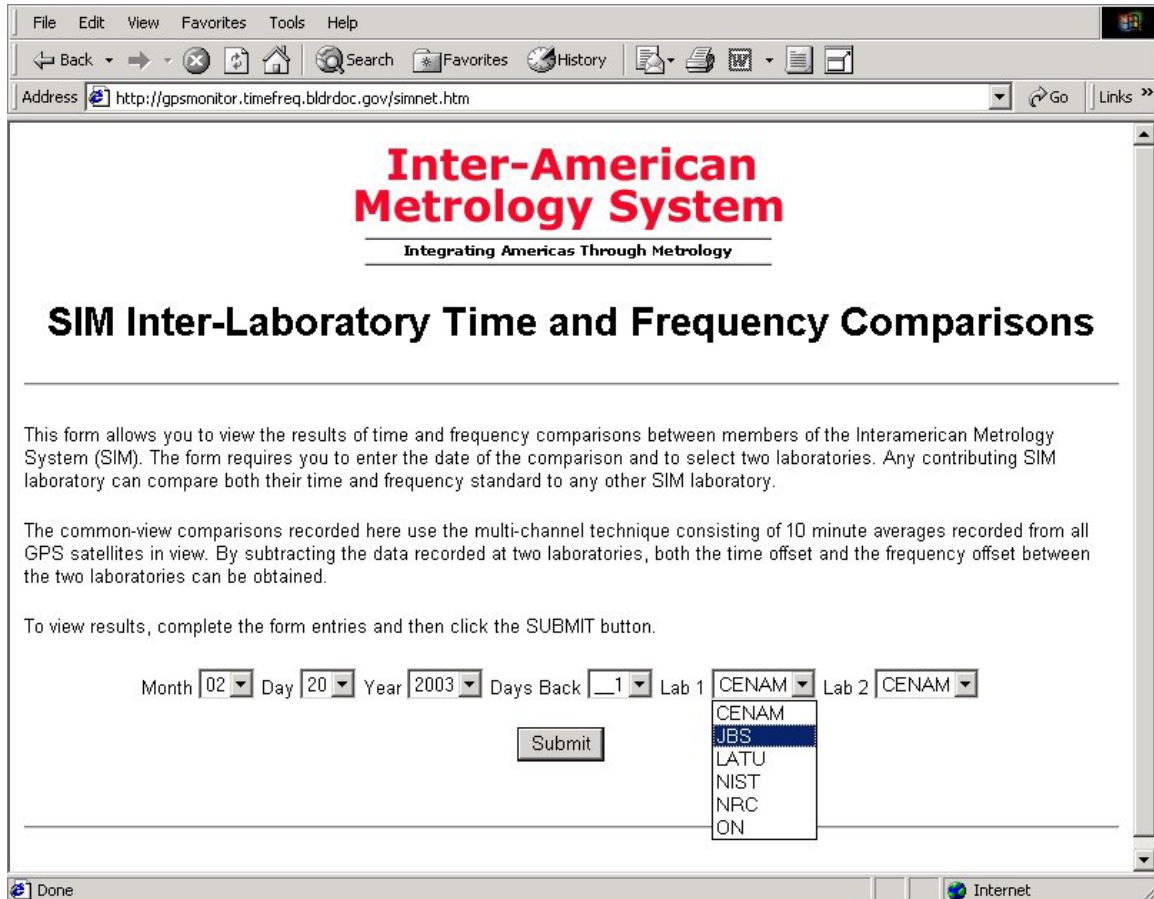


Figure 3. Prototype web form for selecting laboratories for comparison.

All graphing, reduction, and analysis of data is performed by web-based applications hosted on the Internet server that can be accessed by all SIM participants. Prototype web software has been developed as a common gateway interface (CGI) application written using both a compiled BASIC scripting language, and a Java graphics library. The two laboratories being compared are selected from a simple form (Figure 3). The web software can load up to 200 days of 10-minute averages (28800 data points) from two common-view receivers, align the data sets, perform the A minus B subtraction, graph the results and calculate both the time deviation $\sigma_x(\tau)$ and Allan deviation $\sigma_y(\tau)$ of the data set (Figure 4). In addition, both sides of the common-view track

recorded from any individual GPS satellite can be viewed, and tabular data can be copied from the web page and pasted into a spreadsheet or other software application for further analysis.

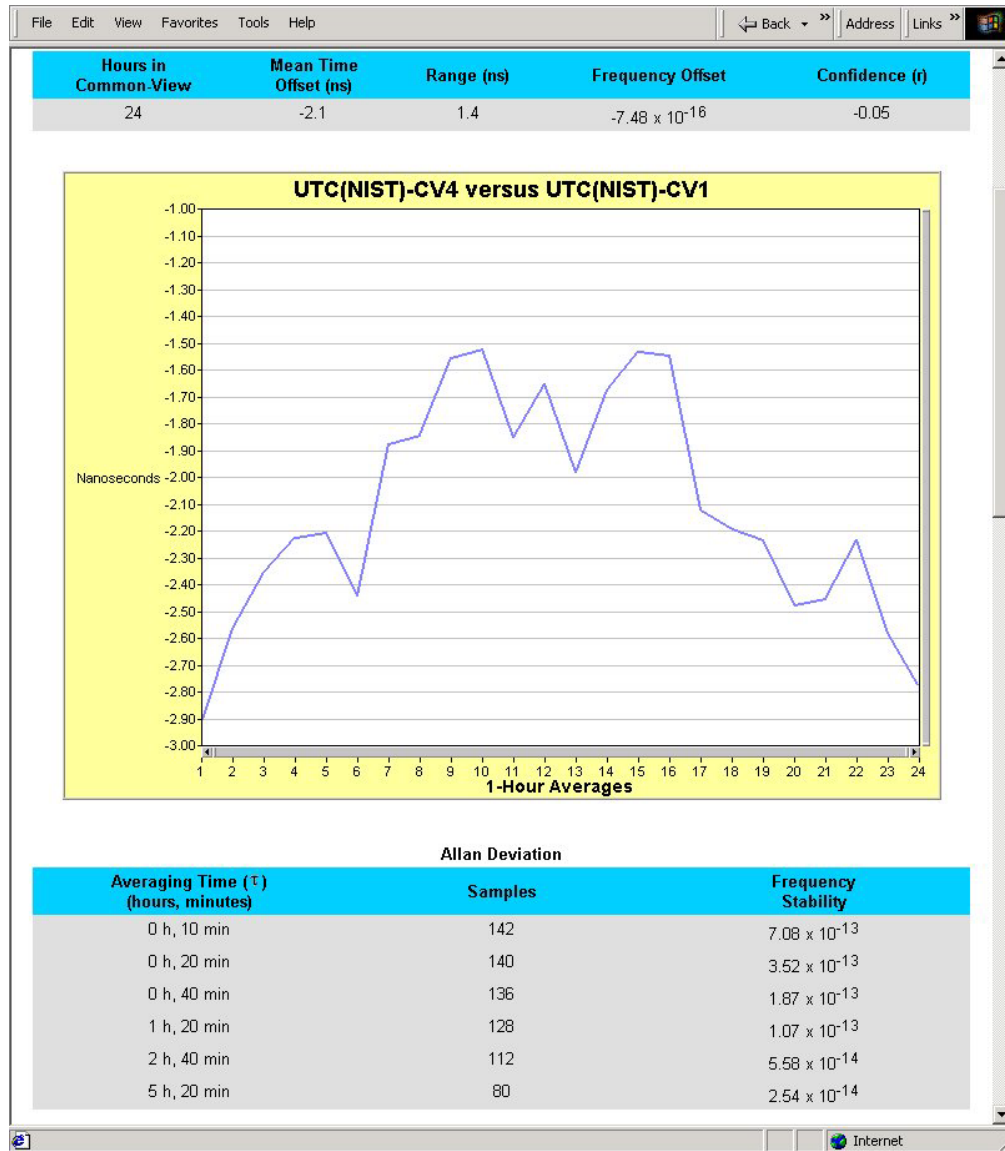


Figure 4. Sample time difference plot and statistics displayed in web browser.

Calibration of Unit Prior to Shipment

Each system would be shipped to the customer’s site with a calibrated GPS antenna and cable included. The system would have a delay constant already entered into the software known as D_{RX} , that refers to the total receiver delay, including the delay in the receiver itself, in the antenna, and in the antenna cable. The value for D_{RX} would be obtained by doing a comparison with a master receiver installed at the NIST laboratories in Boulder, Colorado, and reducing the relative delays between the test system and the master system to as close to zero as possible. During the calibration, the test system is connected to an antenna whose 2D and 3D coordinates are known to within about 1 meter. The antenna and cable used during the calibration in Boulder are shipped with the system.

A second delay number would be entered into the software after the system arrives at the SIM laboratory. This number, known as the clock delay, D_{clock} , is the cable delay between the reference clock and the measurement system. It can be estimated (normally to within a few nanoseconds) by using the published delay constants for the type of cable used, or measured (normally with an uncertainty of about one nanosecond) using a time interval counter.

Estimated Measurement Uncertainties

Estimating the uncertainty of the proposed measurement system involves looking at both the systematic (type B) uncertainties that influence the results of absolute time comparisons, and the statistical (type A) uncertainties that influence the results of both the time and frequency comparisons. A summary of the type B uncertainties is given in Table 1. With reasonable attention paid to the site survey, it should be possible for most participating laboratories to reduce the type B uncertainty to well under 50 ns.

Table 1. Summary of Type B uncertainties.

Contributing Factor	Description	Range
Estimate of D_{Rx}	This value is estimated prior to shipment of the unit. If the antenna and cable shipped with the system are used by the participating laboratory, the uncertainty should be less than 5 ns.	1 to 10 ns
Estimate of D_{clock}	This estimate of cable delay made by the participating laboratory should have an uncertainty of less than 5 ns, even if calculated from cable delay figures.	1 to 5 ns
Antenna Site Survey	If an automatic site survey is performed by the measurement system, the altitude estimate could be in error by 20 meters or more, resulting in worst-case time offset errors of more than 60 ns. A survey of antenna position (latitude, longitude, and altitude) to within 1 meter can reduce this uncertainty to a few nanoseconds.	2 to 70 ns
Other sources of uncertainty	This includes systematic delays introduced by connectors, errors in the time interval counter calibration, and other miscellaneous factors.	1 to 10 ns
Combined Type B Uncertainty	Obtained by using the ISO method of taking the square root of the sum of the squares.	3 to 72 ns

The type A uncertainty is limited by both the stability of the measurement system itself (for example, GPS receiver stability), and by environmental factors that are different at the two receiving sites (errors that are the same at both sites cancel out, a key advantage of the common-view method). As a general rule, the type A uncertainties become larger as the baseline between the two comparing laboratories becomes longer. For example, the proposed system applies a correction broadcast by the satellites for delays introduced by the ionosphere, but the ionospheric conditions will be different above each site, and perhaps very different over long baselines. Multipath delays caused by signals bouncing off other objects before reaching the antenna will also be different at each site and will not cancel out.

Figure 5 shows the potential stability of the system. These data were obtained by installing a prototype system at NIST in Boulder, Colorado, and connecting the system to a 1 pps output from

the UTC(NIST) time scale and to the Internet. This system was calibrated against a NIST master receiver over a very short baseline of 37 m, and then run for 72 hours in common-view against the master receiver. The peak-to-peak variation of the one hour averages was 4.4 ns, the mean time offset was 0.6 ns (type B uncertainty), and the 2σ variation in the time offset (type A uncertainty) was 2.2 ns.

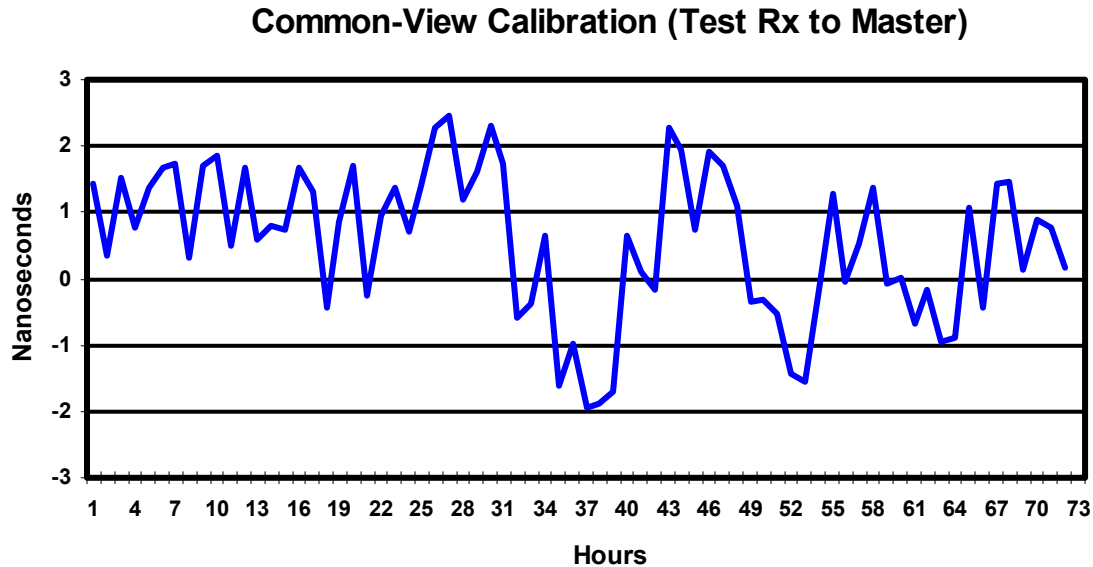


Figure 5. Graph of data collected during 72-hour receiver calibration.

Over a long baseline the number of satellites in common-view will become smaller (it is expected that there will be short periods when no satellites will be in common-view at both sites over the longest baselines), the difference between the relative delays between the two sites will become larger, and the type A uncertainty would become correspondingly larger. Table 2 shows the approximate baseline lengths of some SIM laboratory cities. Note that some baselines are quite long; the baseline between Buenos Aires, Argentina and Boulder, Colorado is more than 9500 km. Even so, we expect the 2σ type A uncertainty to be less than 15 ns across most of the baselines shown in the table. If an averaging period of one day is used, we would expect the noise introduced by the devices being compared to exceed the noise introduced by the common-view measurement technique, in nearly all cases.

Table 2. Approximate baseline lengths (kilometers) between SIM laboratory cities.

	Buenos Aires	Boulder	Kingston	Ottawa	Queretaro	Quito	Rio de Janeiro	San Jose
Buenos Aires	---	9531	6106	9000	7526	4321	2027	5596
Boulder	9531	---	3667	2481	2203	5211	9476	3935
Kingston	6106	3667	---	3042	2500	2015	5809	1192
Ottawa	9000	2481	3042	---	3564	5054	8223	4013
Queretaro	7526	2203	2500	3564	---	3310	7869	2109
Quito	4321	5211	2015	5054	3310	---	4594	1276
Rio de Janeiro	2027	9476	5809	8223	7869	4594	---	5762
San Jose	5596	3935	1192	4013	2109	1276	5762	---

To test the system's ability to measure frequency, a direct digital synthesizer (DDS) was locked to a 5 MHz signal from the UTC(NIST) time scale and used to generate a test signal with a known frequency offset of 1×10^{-13} with respect to UTC(NIST). This test frequency was connected to one common-view prototype system, and UTC(NIST) with no offset applied was connected to another common-view system separated by a 6.2 m baseline [7]. A comparison was made for 7 days, and the results are shown in Figure 6. Although some noise is shown on the graph, the trend contributed by the frequency offset is clearly visible (a peak-to-peak time offset of about 60 ns in 7 days). The slope of the linear least squares line fitted to this data yields the correct frequency offset of 1.00×10^{-13} .

Although results like this will not be possible over a long baseline, we expect the frequency uncertainty of the proposed system to be no worse than 1.5×10^{-13} at an averaging time of one day, based on a worst case 2σ type A uncertainty of approximately 15 ns.

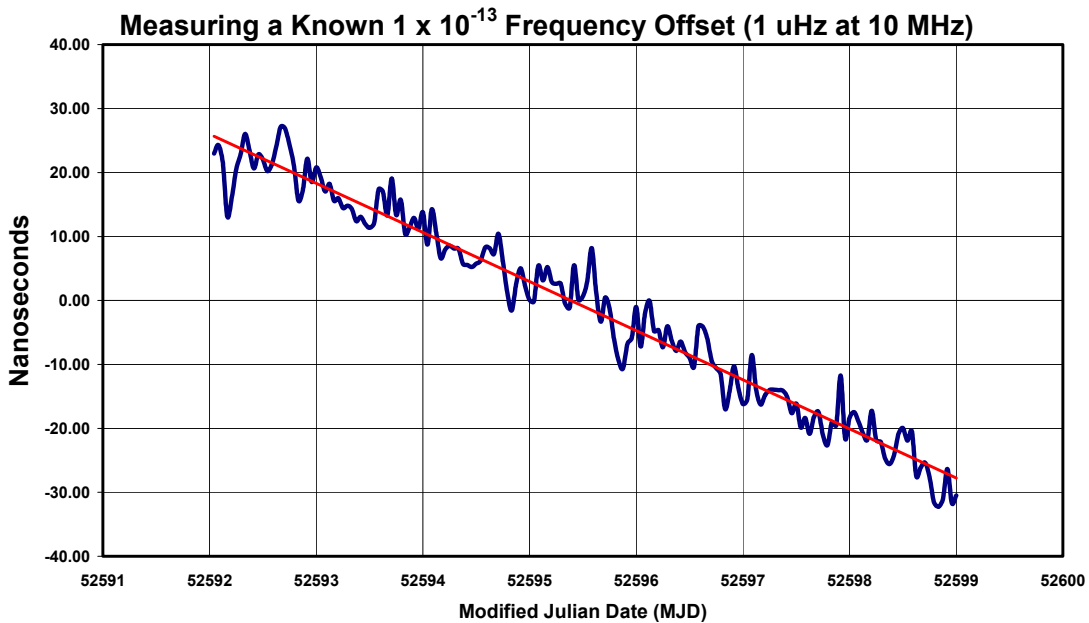


Figure 6. Measurement of a known 1×10^{-13} frequency offset.

Summary and Conclusion

We propose a system for assuring time and frequency coordination among SIM member laboratories that would be an important part of the global measurement system envisioned by SIM. The cost of this system is expected to be about \$5000 per laboratory. All collected data would be made available to all participants, and measurement results can be viewed using a standard Web browser from any Internet connection. The measurement uncertainties are expected to be low enough to meet all existing requirements of SIM member nations. The measurement uncertainty for absolute time offset relative to Coordinated Universal Time (UTC) is expected to be less than 50 ns. The measurement uncertainty for frequency (2σ) is expected to be approximately 1.5×10^{-13} at an averaging time of one day, with lower uncertainties obtainable over longer averaging times.

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* This paper is a contribution of an agency of the United States Government, and is not subject to copyright.

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