The Inter-American Metrology System (SIM) Common-View GPS Comparison Network

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Abstract — The Inter-American Metrology System (SIM) consists of national metrology institutes in 34 member nations located throughout North, Central, and South America, and the Caribbean region. Currently, at least ten SIM laboratories pursue time and frequency metrology, and are responsible for maintaining the national time and frequency standards for their respective countries. To benefit these laboratories and advance metrology in the SIM region, we have developed a measurement network to continuously intercompare these standards and to make the data readily accessible to all SIM members. This network utilizes the multi-channel common-view GPS technique and the near real-time exchange of data via the Internet. This paper discusses the challenges of implementing the SIM comparison network, and provides a technical description of the measurement system supplied to participating laboratories. It describes the method used to calibrate the SIM measurement systems, and describes how the measurement results are processed and reported to the laboratories. It presents data collected from comparisons between the national frequency and time standards located in Canada, Mexico, and the United States. It validates these data by comparing them to data collected from previously established time links. It concludes with a discussion of the measurement uncertainties.

I. INTRODUCTION

The *Sistema Interamericano de Metrologia* (SIM), or Inter-American Metrology System, is one of the world's five major regional metrology organizations (RMOs) recognized by the *Bureau International des Poids et Mesures* (BIPM). SIM is comprised of the national metrology institutes (NMIs) located in all 34 member nations of the Organization of American States (OAS). Although SIM is divided into five sub-regions (Fig. 1), its goal is to create a unified measurement system that extends to the entire SIM region, ensuring the uniformity of measurements, and strengthening traceability throughout North, Central, and South America back to the SI. To help reach this goal, SIM sponsors working groups in ten different metrological fields, including time and frequency [1].

Figure 1. The SIM region and sub-regions.

Developing a time and frequency comparison network for the SIM region is challenging, not only because the region is so large, but also because the available resources and the quality of the standards varies significantly from

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nation to nation. The 34 member nations range in size from very small to very large, and this is reflected in the size of their NMIs. Many of the NMIs are small, developing laboratories that are currently staffed by just a few individuals. They typically pursue perhaps one or two areas of metrology to support local industry. In contrast, others are relatively large organizations that routinely participate in international metrology comparisons, including some that maintain national standards of time and frequency and contribute to the BIPM's derivation of Coordinated Universal Time (UTC). As of June 2005, nine SIM nations are members of the BIPM's Metre Convention, and four SIM nations are associates of the General Conference on Weights and Measures (CGPM) [2]. Of these 13 countries, at least ten currently maintain some type of time and frequency standard, and seven maintain atomic oscillators and contribute to UTC (Table I). A number of other SIM nations are planning to become members of the Metre Convention and to obtain time and frequency standards, so the number of time and frequency laboratories is likely to increase in future years.

TABLE I. SIM NATIONS BELONGING TO THE METRE CONVENTION.

Country	Member or Associate?	Maintains Time and Frequency Standards?	Contributes to UTC?
Argentina	Member	Yes	Yes
Brazil	Member	Yes	Yes
Canada	Member	Yes	Yes
Chile	Member	Yes	Yes
Costa Rica	Associate	Yes	No
Dominican Republic	Member	Unknown	No
Ecuador	Associate	Yes	No
Jamaica	Associate	Yes	No
Mexico	Member	Yes	Yes
Panama	Associate	Yes	Yes
United States	Member	Yes	Yes
Uruguay	Member	Unknown	No
Venezuela	Member	Yes	No

To help advance the state of metrology in the SIM region, we have developed a common-view GPS network capable of automating continuous, near real-time comparisons between the national time and frequency standards located at SIM NMIs. To meet the needs of all participating laboratories, the network was designed to be low in cost and easy to operate, but to still provide measurement uncertainties low enough to characterize the best national standards in the SIM region.

The idea of a SIM time and frequency network was first proposed in May 2003, and the network began operation in the NORAMET (North American Metrology Cooperation) region in June 2005, continuously comparing the national time scales of the *Centro Nacional de Metrologia* (CENAM) in Queretaro, Mexico, the National Research Council (NRC) in Ottawa, Canada, and the National Institute of Standards and Technology (NIST) in Boulder,

Colorado, in the United States. It is expected to soon be extended to include NMIs in Central and South America.

II. DESCRIPTION OF MEASUREMENT SYSTEM

The SIM network is based on common-view observations of the coarse acquisition (C/A) codes transmitted by the GPS satellites. This technique was first used for remote comparisons of clocks and oscillators shortly after the first GPS satellite was launched [3]. Since then, it has become a primary comparison technique for the derivation of UTC [4]. Common-view GPS is also used by NMIs to support remote calibration services that link to other metrology laboratories [5, 6, 7] or to industrial time users [8].

The measurement system supplied to SIM laboratories consists of an industrial rack-mount computer running Windows 2000, a LCD monitor, and a keyboard with an integrated trackball (Fig. 2). A time interval counter with single shot resolution near 30 ps and an 8-channel GPS timing receiver are contained on a standard PC bus card [9]. The back panel of the unit contains a BNC connector that accepts either a 5 or 10 MHz reference signal as the counter's external time base, a BNC connector that accepts a 1 pulse per second (pps) signal from the local UTC time scale, and a TNC connector that connects to the GPS antenna cable. An Ethernet interface is used to connect the system to the network, and laboratories are required to provide an always-on Internet connection with a dedicated IP address. The system transmits measurement data using the file transfer protocol (FTP), and TCP port 21 must be left open if the system is installed behind a firewall.

Figure 2. The SIM common-view GPS measurement system.

A. GPS Receiver and Antenna

The SIM measurement system uses an 8-channel GPS timing receiver identical to those included in other common-view systems used for international comparisons [6, 10], and thus the performance of the SIM system is similar to those models. Although the GPS receiver is not ovenized, the temperature stability inside the rack-mount enclosure is reasonably good. The receiver temperature is normally only 1 or 2° C higher than the laboratory temperature, and the receiver's temperature range is roughly equivalent to the laboratory's temperature range. As a result, receiver delay changes due to temperature [11] are not considered to be a significant problem if the laboratory temperature is well maintained.

The GPS antenna and antenna cable are calibrated prior to shipment (Section III). The antenna is typical of those supplied by GPS disciplined oscillator manufacturers. It is cone shaped, and has a polycarbonate outer casing 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 and a gain that exceeds 30 dB, with 38 dB being typical for satellites at an elevation angle of 90º. The antenna cable (LMR-400) is supplied in a length specified by the SIM laboratory. The receiver provides 5 V dc to the antenna through the antenna cable.

B. GPS Data Collection

Unlike receivers that contribute data to the derivation of UTC, the SIM unit does not require a BIPM tracking schedule [12]. Instead, it works without any schedule, simply collecting and storing data from up to eight visible satellites. The time interval between the GPS pulse and the local UTC time scale is measured every second. Using satellite information provided by the receiver, a time offset reading is then produced for each individual satellite, and data are averaged for 10 min and stored (1 min averages are also stored, so conversion to the 13 min BIPM track format is possible). The file format contains a header with the current system settings, and GPS data in the form of a 32 × 144 matrix. The 32 columns represent the 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 min segments in 1 d. At the completion of each 10 min segment, the data are immediately sent via FTP to a web server, where the common-view data reduction (Section IV) is performed on-the-fly when requested by a user.

If a SIM receiver were able to observe eight satellites at all times during the day, it could collect up to 11 520 min of data (144 segments × 10 min tracks × 8 satellites), with no dead time or gaps between measurements. This exceeds the maximum amount of data that can be collected by receivers that use the BIPM single-channel tracking schedule (624 min) by a factor of about 18, and is about 23 % more data than the maximum amount collectable (9 360 min) by BIPM compatible multi-channel receivers.

III. SYSTEM CALIBRATION

Each measurement system is calibrated at the NIST Boulder laboratories prior to being shipped to the participating SIM laboratory. The calibration is done using a short baseline (~6 m) common-view comparison with UTC(NIST) as a common-clock (Fig. 3). The system under test (SUT) is calibrated using the same antenna and cable that will be sent to the participating laboratory. During the test, the SUT uses previously surveyed antenna coordinates with an estimated uncertainty of 20 cm. The calibration lasts for 10 d, and results in an average delay number, D_{Rx}, that is entered into the unit and stored prior to shipment. When the unit is installed at the participating laboratory, the reference delay, or D_{REF}, is measured and entered into the system. The reference delay represents the delay from the local UTC time scale to the end of the cable that connects to the SIM system.
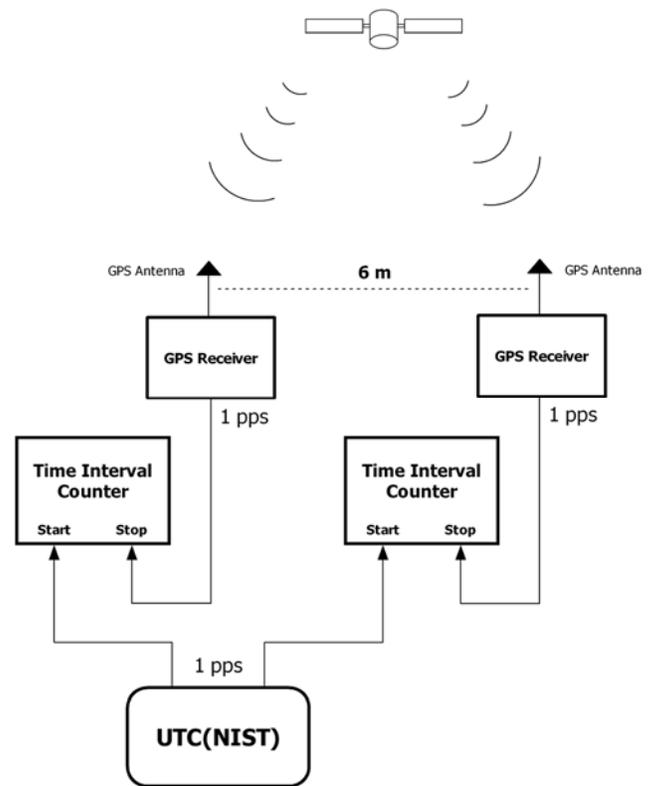

Figure 3. A common-view, common-clock delay calibration.

The time stability, $\sigma_x(\tau)$ [13], of the common-clock calibrations is typically near 0.2 ns at $\tau = 1$ d, agreeing well with other published results using similar receivers [6, 14]. Fig. 4 shows results for the NRC receiver delay calibration. The peak-to-peak variation of the 10 min averages equaled 7.2 ns, the average delay $D_{Rx} = 70$ ns, and the time deviation, $\sigma_x(\tau) = 0.17$ ns at $\tau = 1$ d. However, several potential problems with common-view, common-clock calibrations can introduce systematic errors. For example, if a short baseline common-clock test was continued for a year, it is likely that the resulting estimate of D_{Rx} would

vary by several nanoseconds depending upon which 10 d segment was chosen for analysis. This is partially because environmental factors can cause receiver and cable delays to vary over time. Furthermore, delay calibrations made in the multipath environment of NIST will likely be in error by some amount when the receiver is sent to a different multipath environment [15]. For these reasons, we assign an estimated uncertainty of 5 ns to our delay calibrations (Section VI).
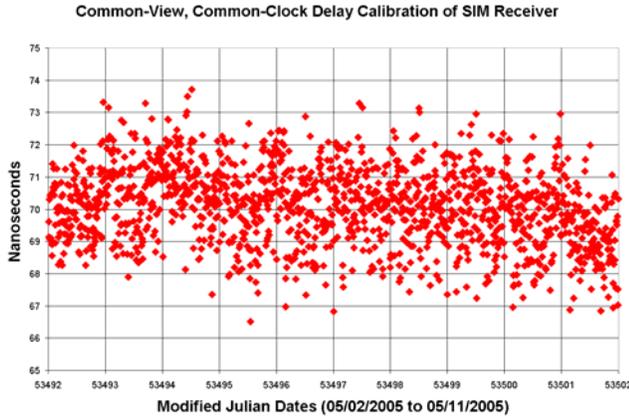

Figure 4. Data from common-clock calibration of the receiver delay.

IV. COMMON-VIEW DATA REDUCTION

As mentioned previously, the common-view technique is a primary mechanism by which NMIs compare their time standards and contribute data to UTC [4], allowing them to establish measurement traceability to the SI. Some SIM laboratories already contribute to UTC (Table I), but most do not. The laboratories that do not contribute to UTC will benefit greatly from participation in the SIM network, because it allows them to establish measurement traceability to the SI by linking to laboratories that do contribute. UTC contributors also benefit because the SIM network processes measurement results in near real-time, allowing all participants to instantly view their time differences with respect to each other and get a much better "feel" for how their time scales are performing. This is in sharp contrast to the BIPM reporting system. Unless they privately exchange and process data, current UTC contributors only see the time difference between themselves and another SIM laboratory when the monthly *Circular-T* [16] is published, and by then the measurement results are typically 2 to 8 weeks old.

A. Web-based Analysis Software

The SIM measurement systems upload data every 10 min to an Internet server that hosts data reduction and analysis software. This software can process common-view data "on the fly" whenever a request is made from a participating laboratory. Requests are normally processed within a fraction of a second, and can be made using any Java-enabled web browser from any Internet connection, through a password protected web site. The system was designed to be democratic, and not to favor any one laboratory or nation. All SIM laboratories can view the results of comparisons between any two laboratories in the network, and no single laboratory acts as the hub. The comparisons are truly multilateral, and as with all GPS common-view comparisons, the time broadcast by the satellites drops out of the equation when the measurement results are processed.

The web-based analysis software was developed at NIST as a group of common gateway interface (CGI) applications for a Windows 2000 server. Each CGI application was written using a combination of a compiled BASIC scripting language, and a Java graphics library. The software can process up to 200 d of data (28 800 10-min segments) from two SIM laboratories. It quickly aligns the common-view tracks where both laboratories viewed the same satellite at the same time and performs the common-view subtraction for each aligned track. A time difference, *TD*, for a single 10 min track is computed as

$$TD = \frac{\sum_{i=1}^{8}(SatA_i - SatB_i)}{CV} \qquad (1)$$

where $SatA_i$ is the series of individual satellite tracks recorded at site A, $SatB_i$ is the series of tracks recorded at site B, and CV is the number of satellite tracks common to both sites.

The time difference values can be graphed as 1 h or 1 d averages, and the software computes both the time deviation, $\sigma_x(\tau)$, and Allan deviation, $\sigma_y(\tau)$ [13], of the entire data set. In addition, the one-way GPS data recorded at all participating laboratories can be viewed, and 10 min, 1 h, or 1 d data (for either one-way or common-view) can be copied from the web browser and pasted into a spreadsheet or other application for further analysis [17].

B. Common-View Baselines

As noted previously, the SIM system can collect up to 11 520 min of GPS data per day if eight satellites are always being tracked. In practice, however, eight satellites are not always visible and incomplete tracks are discarded, reducing the amount of collected data. The three systems now operating in the NORAMET region each use an elevation mask angle of 10°, and all collect roughly 10 400 min of data per day, meaning that each receiver is operating at about 90 % of its theoretical satellite capacity.

The amount of data usable for common-view reduction depends upon the length of the baseline and the geographic orientation of the two laboratories. Generally speaking, the number of satellites in common-view decreases as the length of the baseline increases. Table II illustrates this by displaying the length of the baselines in the NORAMET region, and the amount of available common-view data. For comparison purposes, the 6 m baseline used for delay calibrations at NIST is included in the table.

TABLE II.   SIM BASELINES IN THE NORAMET REGION.

Baseline	Length	Usable data	Unused data
Calibration	6 m	10 400 min	None
CNM/NIST	2198.9 km	8 100 min	22 %
NRC/NIST	2471.3 km	8 200 min	21 %
NRC/CNM	3520.7 km	7 600 min	27 %

As expected, over the short calibration baseline, the two receivers track the same satellites, and all collected data are in common-view. However, over the longest baseline in the NORAMET region, between NRC and CENAM, only about 7600 min of common-view data are collected, meaning that about 27 % of the collected data is unused. The SIM region (Fig. 1) is very large, and some baselines will be much longer than the 3521 km NRC to CENAM baseline. For example, the baseline between Boulder, Colorado and Brazil is about 9400 km long, roughly equivalent to the distance between Boulder, Colorado and Rome, Italy. For this reason, we are considering modifying the data reduction software to support both the "pure" common-view method, where individual satellite tracks are aligned and differenced (Eq. 1), and the "all-in-view" method (Eq. 2) where the satellite tracks are not aligned. Instead, the average of the $SatA_i$ and $SatB_i$ data series recorded at both sites is calculated, and the time difference TD equals the difference between the two composite averages:

$$TD = \overline{SatA_i} - \overline{SatB_i} \qquad (2)$$

The "all-in-view" method would allow all collected GPS data to be usable over all baselines. The effect of this is currently unknown, but it would perhaps improve results over long baselines, and should have little effect on results obtained from the existing NORAMET baselines.

C.   Near Real-Time Common-View

Because common-view measurements require data to be exchanged and processed, the measurement results are not obtainable in real-time. However, near real-time common-view is possible if the Internet or another medium is used to rapidly exchange and process data. The idea of a near real-time common-view system for C/A code receivers is not new. It was suggested by Levine in 1999 [18] and perhaps earlier by others, and implemented several years ago for short-baseline comparisons at NIST [17, 19] and for international comparisons between NMIs in China, Japan, and Korea [20] and perhaps elsewhere. Even so, near real-time systems are still the exception rather than the rule, and the SIM network is believed to one of the first in existence. It reports measurement results that are never more than 10 min old if the Internet links are operational.

To help illustrate the appeal of near real-time common-view, Fig. 5 shows a web page that displays SIM time scale differences based on the most recent 10 min comparison. This display refreshes every 5 min, and can be used to monitor the time scales at all participating labs. By clicking on a time difference value, a user can view the common-view results between the two selected laboratories for the

current UTC day. By clicking on the name of a time scale, a user can view one-way GPS data from the selected laboratory for the current UTC day. The grid can be expanded to accommodate future members of the network. The number of unique baselines, B, equals

$$B = \frac{L^2 - L}{2} \qquad (3)$$

where L is the number of participating laboratories. Only the three NORAMET baselines are currently in use, but this number would grow to 45 unique baselines if ten SIM laboratories were to participate in the network.
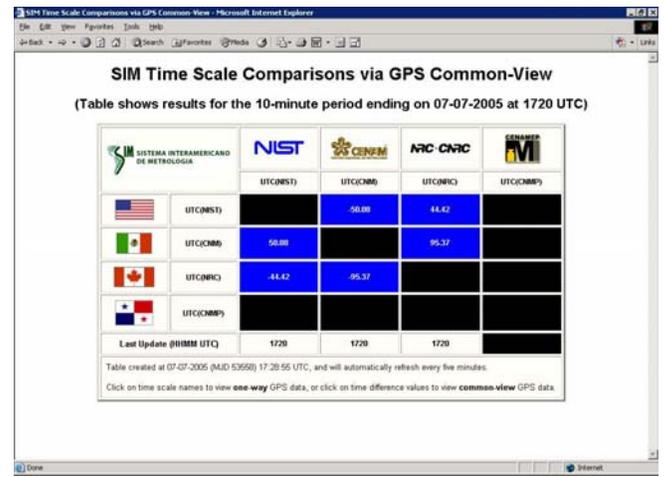

Figure 5. A near real-time display that compares SIM time scales.

V.   MEASUREMENT RESULTS

SIM measurement systems began operation at NIST in April 2005, at CENAM on 2005/05/18 (MJD 53508) and at NRC on 2005/06/03 (MJD 53524). At this writing, data have been collected for about three months (June-August 2005) from all three laboratories, and thus data from three comparisons NIST − CENAM (Fig. 6), NIST − NRC (Fig. 7), and NRC − CENAM (Fig. 8) are presented here. Each graph displays the SIM results, the results obtained from the single-channel GPS timing receivers that each laboratory currently uses to submit data to the BIPM, and the published results obtained from the *Circular-T* [16]. All data are presented as 1 d averages, but the *Circular-T* data (diamond shaped markers) are available only at 5 d intervals.

Note that the *Circular-T* data includes measured ionospheric (MSIO) corrections obtained from measurements made near both receiving sites, while the other two data sets use the less accurate modeled ionospheric (MDIO) corrections obtained directly from the satellite broadcasts. The *Circular-T* data is obtained after post processing the raw BIPM submission data, so those two data sets are strongly correlated, and most of the differences between them are probably due to the difference between the MSIO and MDIO corrections.
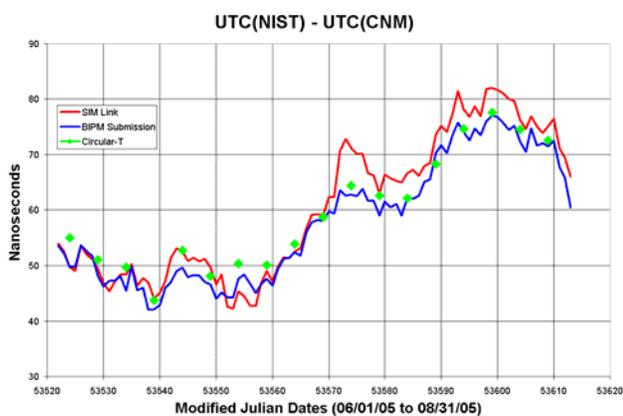
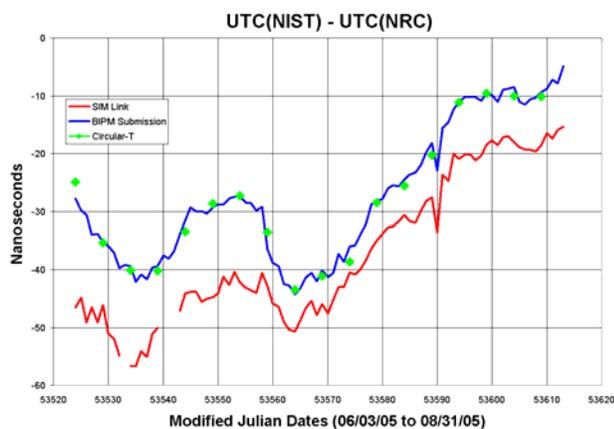Figure 6. UTC(NIST) – UTC(CNM) comparison.

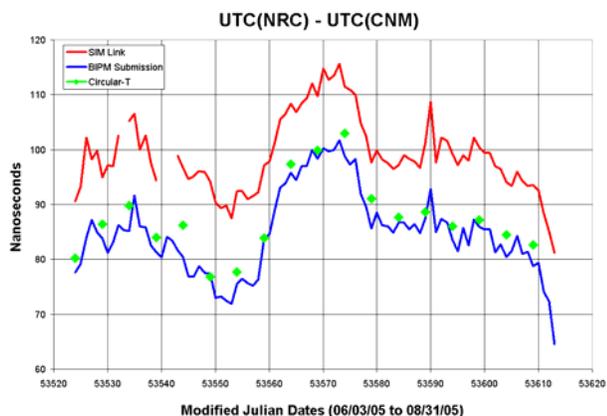Figure 7. UTC(NIST) – UTC(NRC) comparison.

Figure 8. UTC(NRC) – UTC(CNM) comparison.

The results indicate that the phase and stability of the SIM links agrees well with the BIPM submission data. In addition, the time offset between the SIM and BIPM links falls well within the coverage area of our estimated measurement uncertainties, as we shall see in Section VI.

The mean time offset between the links, and the time and frequency stability of both links are provided in Table III for the three NORAMET baselines. Note that the mean time offsets for the links involving NRC are for the period after MJD 53559, when an altitude correction was made to their BIPM receiver antenna (Fig. 7 and 8).

TABLE III. RESULTS FROM NORAMET BASELINES.

Baseline	Mean Time Off. between links	$\sigma_x(\tau)$ at 1 d		$\sigma_y(\tau)$ at 1 d	
		SIM	BIPM	SIM	BIPM
CNM/NIST	2.6 ns	1.2 ns	1.3 ns	2.5E-14	2.6E-14
NRC/NIST	7.6 ns	1.5 ns	1.1 ns	2.9E-14	2.3E-14
NRC/CNM	13.2 ns	2.0 ns	1.8 ns	4.0E-14	3.5E-14

VI. UNCERTAINTY ANALYSIS

Estimating the uncertainty of the SIM comparison links involves evaluating both the Type A and Type B uncertainties as described in the ISO standard [21]. Brief examples are given here for both time and frequency.

A. Time Uncertainty

We use the time deviations, $\sigma_x(\tau)$, reported in Table III to evaluate the Type A uncertainty, U_a, of the 1 d time averages. The Type B evaluation is more difficult, but we have identified seven components that can potentially introduce systematic errors as listed in Table IV.

TABLE IV. TYPE B TIME UNCERTAINTIES.

Component	Explanation	Estimated Uncertainty
Delay calibration errors	See Section III	5 ns
Ionospheric Delay Errors	SIM common-view system does not apply MSIO corrections	3 ns
Antenna Coordinates Error	Assumes that antenna position (x, y, z) is known to within 1 m	3 ns
Time interval counter	The absolute accuracy of the SIM system counter is near 2 ns	2 ns
Environmental variations	Receiver delays can change due to temperature or voltage fluctuations from power supplies, antenna cable delays can change due to temperature	2 ns
Estimate of D_{REF}	Usually done with a time interval counter and is subject to errors near 2 ns	2 ns
Resolution Uncertainty	Software limits the resolution of entered delay values to 1 ns	0.5 ns

Six of the seven components in Table IV have a uniform (rectangular) distribution, and the uncertainties we have

assigned them should be applicable to all SIM baselines. However, the 3 ns uncertainty we have assigned to antenna position assumes that the laboratory knows their antenna coordinates to within 1 m, but this is often not the case. The SIM system can survey its own antenna position, but if this option is used, the uncertainty due to antenna position will increase, quite possibly to > 15 ns, becoming by far the largest time uncertainty component. This is due to the significant errors introduced by GPS receivers when estimating vertical position. The combined Type B uncertainty, U_b, is obtained by taking the square root of the sum of the squares, since we assume that the uncertainty components are independent and not correlated, and is estimated as 7.4 ns. The combined expanded uncertainty U_c is obtained by this equation, where k is the coverage factor

$$U_c = k\sqrt{U_a^2 + U_b^2} \qquad (4)$$

If we use a coverage factor of $k = 2$ and the $\sigma_x(\tau)$ values from Table III as our U_a estimates, then U_c is nearly identical for all three baselines: 15.0 ns for the CENAM/NIST baseline, 15.1 ns for the NRC/NIST baseline, and 15.4 ns for the NRC/CENAM baseline. Both the BIPM submission and Circular-T data shown in Fig. 6, 7, and 8 falls within these coverage areas, and there appears to be considerable overlap between the two coverage areas, which validates our results. As with all uncertainty analysis, the "true" value of a measurement result is indeterminate. We can only claim that there is a high probability that it lies somewhere within the coverage area [21].

B. Frequency Uncertainty

Frequency uncertainty can be estimated by fitting a least squares linear line to the data to obtain a mean frequency offset, Y, and then using $2\sigma_y(\tau)$ as the type A uncertainty U_a ($k = 2$ coverage). Since there is no significant type B component for frequency, the combined uncertainty U_c can be regarded as equivalent to the type A uncertainty, or $< 1 \times 10^{-13}$ for all NORAMET baselines at an averaging time of 1 d. The upper and lower bounds of the coverage area are represented by $Y + U_c$ and $Y - U_c$, respectively.

VII. Summary

The SIM common-view GPS comparison network began operation at three NORAMET laboratories in June 2005, and is expected to significantly advance the state of time and frequency metrology throughout the SIM region. Measurement results are in good agreement with existing time comparison links used for BIPM submissions, but the SIM measurements have the distinct advantage of being available in near real-time. Future work will focus on increasing the number of participating laboratories, reducing the measurement uncertainties, exploring the use of the "all-in-view" method for long baselines, and perhaps the eventual creation of a UTC(SIM) time scale.

VIII. Acknowledgements

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