The SIM Network: Improved Time Coordination for North, Central, and South America

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ABSTRACT

The *Sistema Interamericano de Metrologia* (SIM) consists of national metrology institutes (NMIs) located in the 34 member nations of the Organization of American States (OAS), which extends throughout North, Central, and South America, and the Caribbean region. SIM is one of the world's five major regional metrology organizations (RMOs) recognized by the *Bureau International des Poids et Mesures* (BIPM). Currently about half of the 34 member NMIs maintain time and frequency laboratories. In order for these NMIs to establish metrological traceability and to determine the uncertainty of their measurements, it is important for each of them to participate in international comparisons. SIM has developed a time and frequency comparison network, the SIM TF network, to reinforce or establish the international comparison capabilities of its NMIs.

The SIM TF network was developed to advance the state of metrology in the SIM region and to allow as many laboratories as possible to participate in international time coordination. It provides continuous, near real-time comparisons between the national time and frequency standards located throughout the SIM region, by utilizing the technology of both the Internet and the Global Positioning System (GPS). The SIM measurement systems are paid for either by the Organization of American States (OAS), which is the parent organization of SIM, or by the NMIs themselves.

As of early 2008, ten SIM NMIs are participating in the SIM network, and six additional NMIs are expected to be added to the network as soon as resources become available. This paper provides an overview of SIM and a technical description of the network. It also discusses the network's measurement uncertainties and presents results obtained from ongoing interlaboratory comparisons.

INTRODUCTION

As is the case with the other regional metrology organizations or RMOs, the goal of SIM is to ensure the uniformity of measurements throughout a large section of the world, strengthening traceability back to the International System of units (SI). RMOs realize this goal by performing several tasks. They review the quality systems of NMIs, and their calibration and measurement capabilities (CMCs). In addition, a well functioning RMO will help organize regional comparisons, and help the NMIs of small and developing nations to maintain standards at the level of accuracy needed to support their economy.

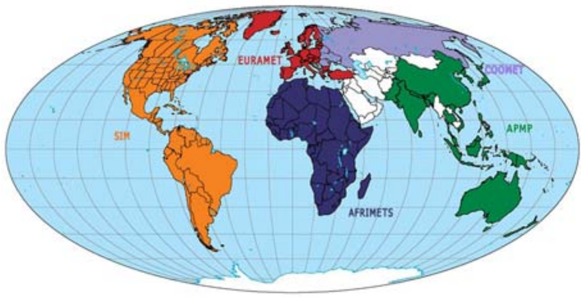

Figure 1. The world's regional metrology organizations as of July 2007 (SIM region is in orange).

Even amongst RMOs (Figure 1), SIM is particularly large. The SIM region encompasses some 27 % of the world's land mass, and about 14 % of its population (an estimated 920 million people as of 2007). The northern part of SIM resides in the largest market in the world, the region covered by the North American Free Trade Agreement (NAFTA). Within the SIM region, however, there is a large variation in both the population of the nations and in the strength of the economies. About two-thirds of the people in the SIM region (approximately 600 million people) reside in the United States, Brazil, and Mexico. In contrast, 12 SIM nations, mostly islands in the Caribbean region, have populations of less than one million. As of 2006, the per capita gross domestic product of the United States and Canada exceeded \$35,000 USD, whereas it was less than \$5,000 USD in 14 of the 34 SIM nations. This disparity in population and money directly translates into the amount of resources that are made available for metrology. For example, about 40 full-time professionals are employed in the area of time and frequency metrology at the National Institute of Standards and Technology (NIST) in the United

States, but many SIM laboratories are fortunate if they have one person, even part-time, who is free to focus on time and frequency measurements.

In spite of their varying levels of resources and the different obstacles that they face, all SIM NMIs share the same task; they must establish measurement traceability to the SI. The ability to make traceable measurements is critical to an NMI, without it they are of little use to industry in their country. International trade requires traceability in order for the measurements made in one country to be accepted and trusted in another country. As a general rule, an NMI cannot establish traceability unless it participates in international comparisons. In the time and frequency community, this usually means that an NMI must participate in the BIPM key comparisons. However, not all SIM NMIs have signed the BIPM Mutual Recognition Agreement (MRA), and some currently lack the resources, training, experience, and contacts that are required to participate in the BIPM key comparisons. To meet the needs of all SIM NMIs, and to establish a new spirit of cooperation throughout the Americas, the SIM time and frequency comparison network was developed.

DESIGN GOALS

The concept of a SIM time and frequency comparison network was first discussed at NIST in 2003. The plans for the network were formalized in a meeting held in Ottawa, Canada in July 2004 between representatives of the three North American NMIs: the Centro Nacional de Metrología (CENAM) of Mexico, the National Research Council (NRC) of Canada, and NIST of the United States. The design goals for the network were:

- To establish cooperation and communication throughout the SIM region by building a network that allowed even the smallest labs to compare their standards to the rest of the world.
- To choose equipment that was low cost and easy to install, operate, and use, because SIM NMIs typically have limited resources and small staffs.
- To make measurements with uncertainties small enough to characterize the best standards in the SIM region. This meant that the measurement uncertainties had to be as small, or nearly as small, as those of the BIPM key comparisons.
- To report measurement results in near real-time, without the processing delays of the BIPM key comparisons.
- To build a democratic network that did not favor any single laboratory or nation, and to allow all members to view the results of all comparisons.

After the design goals were established, the development of the network quickly proceeded. SIM measurement systems were delivered by NIST to CENAM and NRC in the spring of 2005, and the first comparisons began in May 2005 [1, 2].

TECHNICAL DESCRIPTION

The SIM network is based on common-view observations of the coarse acquisition (C/A) codes transmitted by the GPS satellites on the L1 carrier frequency of 1575.42 MHz. This technique was first used to compare remote clocks and oscillators shortly after the first GPS satellite was launched [3], and remains the most common comparison technique used for the derivation of Coordinated Universal Time, or UTC [4].

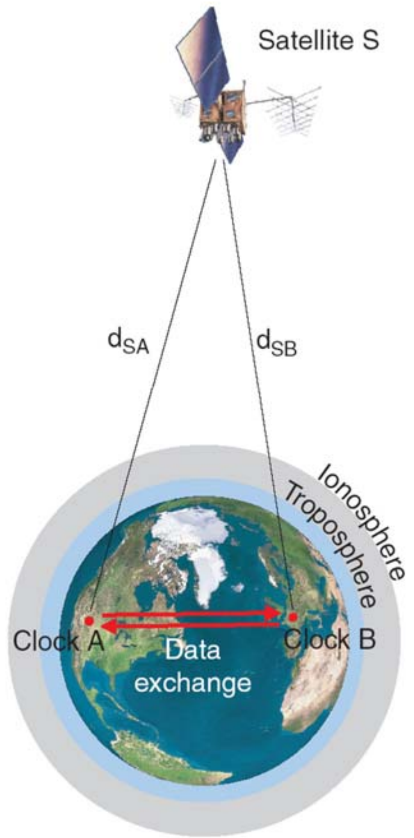

Figure 2. Common-view GPS Measurements.

Common-view GPS comparisons use one or more GPS satellites as the common-view reference (Figure 2). The objective is to use GPS as a transfer standard so that time standards located at remote locations can be compared. The common-view method involves a GPS satellite (*S*), and two receiving sites (*A* and *B*), each containing a GPS receiver, a time interval counter, and a local time standard. The satellite transmits a time signal that is nearly simultaneously received at *A* and *B*, and a measurement is made every second at both *A* and *B* that compares the received GPS signal to the local time standard. Thus, the measurement at site *A* compares the GPS signal received over the path d_{SA} to the local clock, *S - Clock A*. Site *B* receives GPS over the path d_{SB} and measures *S - Clock B*. The two receivers then exchange data and take the difference among them. Delays that are common to both paths d_{SA} and d_{SB} cancel out, but delays that are not common to both paths contribute uncertainty to the measurement. The result of the measurement is (*Clock A* - *Clock B*) with an error term of $d_{SA} - d_{SB}$. Thus, the basic equation (Eq. 1) for common-view GPS measurements is

$$(Clock_A - GPS) - (Clock_B - GPS) =$$

$$Clock_A - Clock_B + (d_{SA} - d_{SB}). \qquad (1)$$

After the components that make up the systematic $d_{SA} - d_{SB}$ error term are measured or estimated, they are either applied as a correction to the measurement or are accounted for in the uncertainty analysis. The systematic $d_{SA} - d_{SB}$ error 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 well understood and characterized delays at each site that are obtained through calibration. All SIM systems are calibrated at NIST prior to shipment to the host NMI. Each calibration lasts for 10 days and is performed using the common-clock method [1, 2].

Figure 3. The SIM Measurement System.

The measurement system supplied to SIM laboratories (Figure 3) records the common-view measurements and sends them to a central web server for processing. The system consists of an industrial rack-mount computer that contains a time interval counter with single shot resolution of less than 0.1 ns, and an eight-channel GPS receiver. The system accepts either a 5 or 10 MHz reference signal as the counter's external time base, and a one pulse per second (pps) signal from the local time standard. 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 via the Internet by use of the file transfer protocol (FTP). Passive mode FTP is now used for most connections to avoid problems with firewalls, and the file uploads have become very reliable.

The eight-channel GPS receiver is nearly identical to receivers used in other common-view systems that submit data to the BIPM for the derivation of UTC [5], and thus the performance of the SIM system is similar to those units. All SIM systems now use an aperture coupled slot array antenna that was designed to mitigate the reception of multipath signals (Figure 4). This "pinwheel" type antenna is smaller and lighter than a choke ring antenna, but rejects multipath signals equally as well [6, 7].

Figure 4. GPS Pinwheel Antenna.

The SIM system does not use a tracking schedule; it simply collects and stores data from up to eight visible satellites. This allows the collection of as much data as possible [1, 2], limited only by the eight-channel capacity of the receiver. The time difference between GPS and the local standard is measured every second, and both 1-minute and 10-minute averages are recorded for as many as eight satellites. The header of the SIM files contains the current system settings (including antenna coordinates and cable delays), followed by a 32 × 144 matrix containing the measurement data. The 32 column numbers match the pseudo-random noise (PRN) codes of the GPS satellites. The 144 rows represent the number of 10 minute segments in one day.

The SIM data format is incompatible with the Consultative GPS and GLONASS Time Transfer Sub-committee (CGGTTS) format used by the BIPM [8], but collects about 23 % more data than the CGGTTS multi-channel format, as shown in Table 1. Software that converts SIM data to the CGGTTS format has been developed to assist NMIs that need this capability.

Table 1. Comparison of common-view data formats.

Method	Daily Tracks	Track Length	Satellites	Daily Minutes
CGGTTS single-channel	48	13	1	624
CGGTTS multi-channel	90	13	8 typical	9360
SIM	144	10	8 max	11520

NEAR REAL-TIME REPORTING OF RESULTS

The SIM network reports results in near real-time. All systems upload data every 10 minutes to an Internet server that processes common-view data "on the fly" whenever a request is made. Requests are made with any Java-enabled web browser, and are usually processed within a fraction of a second. No special software is needed, and no training is required. The network is democratic and does not favor any laboratory or nation. All members can view the results of all comparisons, and no NMI is designated as the pivot laboratory.

The web-based software processes up to 200 days of data at once. It aligns the tracks where two laboratories simultaneously measured the same satellite, and performs the common-view data reduction. The results are graphed as either one-hour or one-day averages, and the time deviation, $\sigma_x(\tau)$, and Allan deviation, $\sigma_y(\tau)$ [9], of the entire data set are displayed. In addition, 10-minute, one-hour, or one-day averages can be viewed in tabular form and, if desired, copied into a spreadsheet or other application for further analysis.

The web site of the SIM Time and Frequency Metrology Working Group (http://tf.nist.gov/sim), includes a real-time grid (Figure 5) that shows the most recent time differences between SIM NMIs. The grid receives new data every ten minutes, and refreshes automatically every five minutes. Clicking on the time difference values on the grid displays a phase plot of the comparison for the current day. This display can be accessed by the general public.

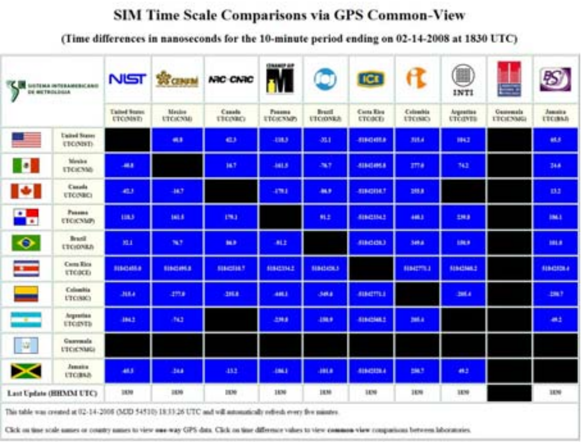

Figure 5. The SIM Real-Time Measurement Grid.

The real-time reporting of results allows all participants in the network to instantly compare their time standards to each other. This benefits all SIM NMIs, including the five (CENAM, CENAMEP, NIST, NRC, and ONRJ) that currently send data to the BIPM for the computation of UTC. The UTC contributors can now view intercomparison data without waiting for the BIPM's monthly *Circular-T* [10], which includes results that are typically from two to seven weeks old at the time of publication. Another advantage is that the shortest reported averaging time (τ_0) is equal to 600 s for the SIM data, as opposed to 5 days in the case of the *Circular-T* data. This makes it easier to identify short-term fluctuations, and allows measurement problems to be solved more quickly.

CURRENT AND FUTURE MEMBERSHIP

As of February 2008, ten NMIs have SIM measurement equipment installed in their laboratories, and are members of the SIM network, which allows them to contribute data to the network. An additional six laboratories have formally expressed interest in joining the network, and will be added to the network as resources become available (Table 2).

A map of the SIM region showing the current and known future members of the network is provided in Figure 6. We anticipate that other SIM NMIs are also interested in establishing a time and frequency laboratory, and that additional requests to join the network will eventually be received.

Table 2. Current and Future SIM Network Members.

Country	NMI	Member of SIM Network	National Standard
Argentina	INTI	Yes	Cesium
Brazil	ONRJ	Yes	Time Scale
Canada	NRC	Yes	Time Scale
Chile	INN	Future	Rubidium
Colombia	SIC	Yes	Cesium
Costa Rica	ICE	Yes	Cesium
Guatemala	LNM	Yes	Rubidium
Jamaica	BSJ	Yes	Cesium
Mexico	CENAM	Yes	Time Scale
Panama	CENAMEP	Yes	Cesium
Paraguay	INTN	Future	Rubidium
Peru	INDECOPI	Future	Rubidium
St. Lucia	SLBS	Future	Rubidium
Trinidad / Tobago	TTBS	Future	Rubidium
United States	NIST	Yes	Time Scale
Uruguay	UTE	Future	Rubidium

As shown in Table 2, four SIM NMIs operate time scales comprised of an ensemble of cesium oscillators and/or hydrogen masers as their national standard. Five operate a single cesium oscillator. The remaining NMIs are expected to use rubidium oscillators, at least intially, as their national standard. We expect that many SIM NMIs will upgrade their time and frequency standards and improve their measurement capabilities as more resources become available. Some laboratories that begin with rubidium oscillators will obtain a cesium oscillator, and then eventually obtain the multiple cesiums needed to build an ensemble time scale. This progression has already begun. New cesium oscillators went online at SIC in Colombia in January 2008 and at INTI in Argentina in February 2008.

Figure 6. A SIM map showing the locations of the current (light) and future members (dark) of the network.

MEASUREMENT UNCERTAINTIES

Estimating the uncertainties of the SIM measurements involves evaluating both the Type A and Type B uncertainties as described in the ISO standard [11]. Uncertainties are combined by using the root sum of squares method, where k is the coverage factor (Eq. 2):

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

To evaluate the Type A uncertainty, we use the time deviation, $\sigma_x(\tau)$, at an averaging time of one day. The time deviation [9] is a metric calculated automatically by our web-based software that indicates the amount of time transfer noise. For most SIM baselines, $\sigma_x(\tau)$ at 1 day is typically about 1.5 ns, and can be as large as 5 ns. However, for the 2471 km baseline between NIST and NRC, $\sigma_x(\tau)$ at 1 day was less than 0.7 ns for the approximate 8-month interval shown in Figure 7.

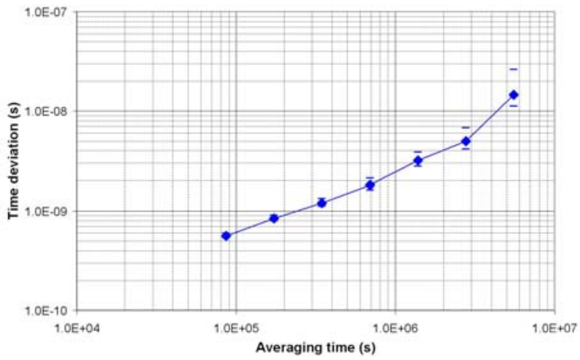

Figure 7. Time deviation of NIST-NRC link for the period from January through August, 2007.

To evaluate the Type B uncertainty, we have identified seven components that can potentially introduce systematic errors in the mean time offset between SIM standards. The Type B uncertainties are discussed below and summarized in Table 3.

***U_B*, Calibration** - The 10-day common-clock calibrations of SIM units performed at NIST in Boulder, Colorado produce a receiver delay estimate, D_{Rx}, that is entered into the configuration file of each unit prior to shipment. These calibrations are typically stable, $\sigma_x(\tau)$, (τ = 1 day) to 0.2 ns or less, but the absolute value of D_{Rx} can vary depending upon which 10-day segment is chosen. However, the use of the pinwheel antennas [6] described earlier, along with high quality antenna cable and connectors, has improved the repeatability of the calibrations. This is illustrated in Figure 8, which shows results from a unit that was continuously calibrated at NIST over a 244-day interval spanning from January through September 2007, producing 235 overlapping 10-day segments. During this interval, the peak-to-peak variation is about 1 ns. Even so, a variety of factors can cause the calibration to have an uncertainty of as large as 4 ns when the system is operated in a different environment after shipment, with 2 ns perhaps being typical.

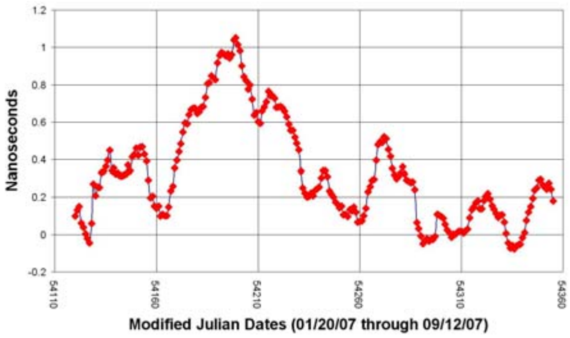

Figure 8. Time variation in 235 consecutive 10-day calibrations between SIM measurement units.

***U_B*, Coordinates –** The SIM NMIs are required to obtain coordinates for the GPS antenna prior to starting the measurements. If the antenna position can be independently surveyed, the resulting coordinates can be keyed into the system software. If not, the SIM system can survey the antenna position by averaging position fixes for 24 hours, a method that does an excellent job of determining the antenna's horizontal position (latitude and longitude), typically to within less than 20 cm. However, the self survey often does a poor job of surveying vertical position (elevation), and the vertical position error is often many times larger than the horizontal position error, as large as 10 m in extreme cases. An error in the vertical position introduces a timing uncertainty of more than 2 ns per meter. For this reason, elevation is often obtained through an independent survey.

Most SIM laboratories will be able to obtain their X, Y, Z coordinates to within 1 m, so the typical Type B uncertainty due to antenna coordinates should not exceed 3 ns. However, if the SIM software is used to determine elevation, this uncertainty could be as large as 25 ns in extreme cases, making antenna coordinate error the largest potential contributor to the combined uncertainty (Table 3).

***U_B*, Environment -** GPS receiver, antenna, and antenna cable delays can change over the course of time due to temperature and other environmental factors. The SIM GPS receiver is sensitive to temperature changes, but its performance will be stable if the laboratory temperature is controlled. The receiver temperature is not controlled, but is typically just a few degrees Celsius higher than the laboratory temperature, with a similar range. However, a sudden change in laboratory temperature can sometimes cause the receiver delay to change by several nanoseconds, usually returning to its previous delay when the temperature returns to normal. Smaller receiver delay changes can occur slowly over time for reasons that are not completely understood. These delay changes might be caused by fluctuations in power supply voltages, vibration, or humidity.

The GPS antenna and part of the cable are outdoors, and are thus subjected to large daily and annual variations in temperature (the annual temperature range in Boulder, Colorado can exceed 60 °C). Even with such a wide temperature range, the actual changes in the electrical delay of the cable are insignificant, but they can potentially cause the receiver tracking point to change and introduce phase steps in the data. The SIM system reduces this possibility by using a high quality antenna cable with a low temperature coefficient. As a general rule, changes in outside temperature are less of a problem than temperature changes inside the laboratory.

Because of the relatively simple and inexpensive hardware used in the SIM system, some uncertainty due to the environment is inevitable, no matter how tightly the laboratory temperature is controlled. We estimate this uncertainty to be about 3 ns, perhaps reduced to about 2.5 ns in a laboratory with tight temperature control.

***U_B*, Multipath** – Uncertainty due to multipath is contributed by GPS signals that are reflected from surfaces near the antenna. These reflected signals can interfere with, or be mistaken for, the signals that follow a straight line path from the satellite. SIM NMIs have agreed to mount their antennas in an area with a clear, unobstructed view of the sky on all sides, and the antenna (Figure 4) was designed to mitigate multipath [6, 7]. Even so, some errors due to multipath are difficult to detect and avoid, and a Type B uncertainty of 2 ns is considered typical.

***U_B*, Ionosphere -** The SIM systems apply the modeled ionospheric (MDIO) corrections broadcast from the satellites to the measurements in real-time, and do not apply post-processed measured ionospheric (MSIO) corrections. This makes the measurement results nearly instantly available, with the delays limited only by the 10-minute averaging time, and a tiny amount of computer processing and Internet transfer time. However, ionospheric conditions are not identical at both sites (particularly when it is dark at one site and daylight at the other), and the use of locally generated MSIO corrections would provide better accuracy. The difference between the MDIO and MSIO corrections is a Type B uncertainty that generally increases as a function of the length of the baseline. For the 8623.5 km baseline between NIST and ONRJ, this uncertainty was estimated as 3.2 ns [12]. It will typically be about 2 ns for most SIM baselines, and less than that for comparisons between NMIs located in neighboring countries.

***U_B*, Reference Delay –** The NMI is responsible for measuring the reference delay, or D_{REF}, and entering this value into the system software. The reference delay represents the delay from the local time standard to the end of the cable that connects to the SIM system. This is typically a one-time measurement made with a time interval counter. The Type B uncertainty will typically be about 1 ns.

***U_B*, Resolution -** The SIM software limits the resolution of the entered delay values to 0.1 ns, which is roughly equivalent to the single-shot resolution of the time interval counter. This contributes an insignificant resolution uncertainty of 0.05 ns that should be the same for all laboratories.

As shown in Table 3, the measurement uncertainty of the SIM network depends upon a number of factors, including the accuracy of the antenna coordinates, the environmental and multipath conditions, and the length of the baseline between laboratories. The combined uncertainty (k = 2) is typically about 11.5 ns, and could be less than 10 ns in some instances. However, it is unlikely that all of the Type B components involved in a given comparison can be controlled at the "best case" level shown in Table 3.

Table 3. Measurement Uncertainties (nanoseconds).

Uncertainty Component	Best Case	Worst Case	Typical
U_A, $\sigma_x(\tau)$, τ = 1 d	0.7	5	1.5
U_B, Calibration	1	4	2
U_B, Coordinates	1	25	3
U_B, Environment	2.5	4	3
U_B, Multipath	1.5	5	2
U_B, Ionosphere	1	3.5	2
U_B, Ref. Delay	0.5	2	1
U_B, Resolution	0.05	0.05	0.05
U_C, k = 2	7.0	53.8	11.5

MEASUREMENT RESULTS

In its default configuration, the SIM network uses the "classic" common-view technique to reduce data. This technique aligns and differences data from the individual satellite tracks, and discards data collected from satellites that are not in common view at both sites. The basic equation is

$$TD = \frac{\sum_{i=1}^{N}(REFGPS_i(A) - REFGPS_i(B))}{CV}, \qquad (3)$$

where TD is the average time difference between the clocks at sites A and B, N is the number of satellites tracked by the multi-channel GPS receivers (for the SIM receivers, N has a maximum value of eight), $REFGPS_i(A)$ is the series of individual satellite tracks recorded at site A, $REFGPS_i(B)$ is the series of tracks recorded at site B, and CV is the number of satellite tracks common to both sites. This method is used to produce the time difference numbers in the real-time grid (Figure 5).

Figure 9 shows the results of a comparison between the ensemble time scales of CENAM and NIST across a 2199 km baseline for the eight-month period beginning June 1, 2008 and ending on January 31, 2008. The daily values from the SIM network include error bars showing the estimated uncertainty. Values from the BIPM *Circular-T* are shown at five-day intervals, and fall well within this uncertainty. Note that the two time scales never differed by more than about 45 ns. Figure 10 shows data from the same interval for a comparison between the CENAM time scale and the single cesium standard maintained by CENAMEP in Panama across a 2544 km baseline. Again, the *Circular-T* values fall within the estimated uncertainty of the SIM network.

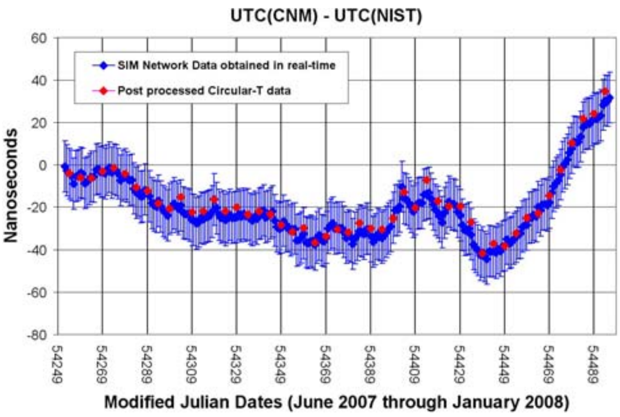

Figure 9. Eight-month comparison between the CENAM and NIST time scales.

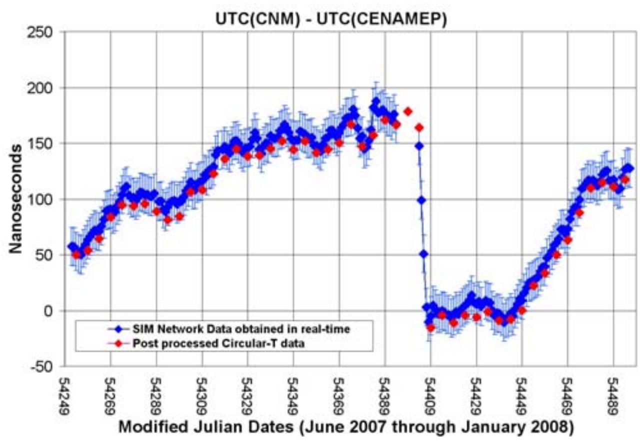

Figure 10. Eight-month comparison between the CENAM time scale and CENAMEP's cesium standard.

The "classic" common-view method does not always work across the wide geographic area covered by the SIM network, because there are intervals when no satellites are in common view at both sites. For the 8623.5 km baseline between NIST and ONRJ, for example, there are no satellites in common-view about 10 % of the time, and on average, only 1.4 satellites are simultaneously visible at both sites [12]. To allow for these situations, the SIM network can also present results using the "all-in-view" method (Eq. 4), where the satellite tracks are not aligned and no tracks are discarded **[**13**].** Instead, the average of the $REFGPS_i(A)$ and $REFGPS_i(B)$ data series recorded at both sites is calculated, and the time difference *TD* is the difference between the two averages:

$$TD = \overline{REFGPS_i(A)} - \overline{REFGPS_i(B)} \qquad (4)$$

The utility of the all-in-view method is now well established. A variation of the all-in-view technique has been used by the BIPM since September 2006 to process the GPS data used in the calculation of UTC, with the Physikalisch-Technischen Bundesanstalt (PTB) in Germany serving as the pivot laboratory for all GPS links **[**13**].** Because none of the satellites used in the comparison are required to be in common-view, the all-in-view method allows comparisons to be made between two laboratories located anywhere on Earth.

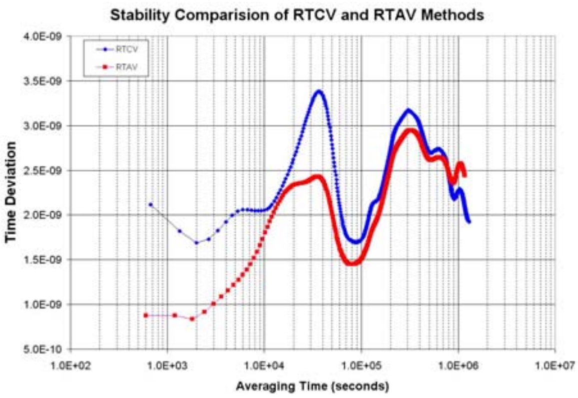

Figure 11. Time deviation graph comparing the RTCV and RTAV methods over a long baseline.

Figure 11 compares the Type A uncertainty of the real-time common-view (RTCV) and real-time all-in-view (RTAV) methods as employed by the SIM network over the long baseline between NIST and ONRJ. The graph shows the time deviation, $\sigma_x(\tau)$, for a 60-day measurement interval, using the "all-tau" method. The RTAV method produces lower TDEV values for all intervals from τ = ~10 min to τ = ~5 d (note that due to the missing tracks, τ_0 = 665 s for the RTCV method), and it improves upon the stability of the RTCV method by more than a factor of 2 at averaging times of less than 30 minutes. Both methods produce a distinct diurnal at τ = ~0.5 d due to the error in the MDIO correction, which is more accurate during the nighttime hours than during the daytime. It is interesting to note that the difference in stability between the RTAV and RTCV methods at intervals longer than τ = 1 d is relatively small, because clock noise begins to dominate the transfer process over longer intervals. As a general rule, the RTAV method provides noticeable improvement when compared to the RTCV method if the length of the baseline exceeds 5000 km [12]. Of course, the greatest virtue of the RTAV method is simply that it always works, even when no satellites are in common view.

SUMMARY AND CONCLUSION

The SIM time and frequency network began operation in June 2005, and ten NMIs participate as of February 2008. The network provides NMIs with a convenient way to compare their standards and to establish traceability to the SI. The SIM network produces measurement results that agree closely with results published in the BIPM's *Circular-T*, but have the distinct advantage of being available in near real-time.

SIM is not as well established in the world timekeeping arena as the European Collaboration in Measurement Standards (EURAMET) or the Asia-Pacific Metrology Programme (APMP), but participation from the Americas is clearly on the rise. It seems likely that SIM has more potential for growth in both the number and capability of timing laboratories than any other RMO. The SIM network will continue to aid in this expansion, and contribute to new advances in time and frequency metrology in North, Central, and South America.

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REFERENCES

[1] M. A. Lombardi, A. N. Novick, J. M. Lopez, J. S. Boulanger, and R. Pelletier, "The Interamerican Metrology System (SIM) Common-View GPS Comparison Network," *Proceedings of the Joint 2005 IEEE Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, August 2005, pp. 691-698.

[2] M. A. Lombardi, A. N. Novick, J. M. Lopez, J-S. Boulanger, R. Pelletier, and C. Donado, "Time Coordination Throughout the Americas via the SIM Common-View GPS Network," *Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, December 2006, pp. 427-437.

[3] D. W. Allan and M. A. Weiss, "Accurate time and frequency transfer during common-view of a GPS satellite," *Proceedings of 1980 Frequency Control Symposium*, May 1980, pp. 334-346.

[4] E. F. Arias, "The metrology of time," *Philosophical Transactions of the Royal Society A*, vol. 363, 2005, pp. 2289-2305.

[5] J. Nawrocki, J. Azoubib, and W. Lewandowski, "Multi-channel GPS time transfer and its application to the Polish atomic time scale," *Proceedings of the 1999 IEEE Frequency Control Symposium*, April 1999, pp. 190-193.

[6] W. Kunysz, "High Performance GPS Pinwheel Antenna," *Proceedings of the 2000 International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GPS 2000)*, September 2000.

[7] M. A. Lombardi and A. N. Novick, "Effects of the Rooftop Environment on GPS Time Transfer," *Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, December 2006, pp. 449-465.

[8] D. W. Allan and C. Thomas, "Technical Directives for Standardization of GPS Time Receiver Software," *Metrologia*, vol. 31**,** 1994, pp. 69-79.

[9] IEEE, "IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology - Random Instabilities," *IEEE Standard 1139-1999,* March 1999.

[10] BIPM web site (http://www.bipm.org). The site contains an archive of past *Circular-T* publications.

[11] International Organization for Standardization (ISO), "Guide to the Expression of Uncertainty in Measurement," prepared by *ISO Technical Advisory Group 4, Working Group 3,* 1995.

[12] M. A. Lombardi, V. S. Zhang, and R. de Carvalho, "Long Baseline Comparisons of the Brazilian National Time Scale to UTC(NIST) Using Near Real-Time and Post-Processed Solutions," *Proceedings of the 39th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, November 2007.

[13] G. Petit and Z. Jiang, "GPS All in View time transfer for TAI computation," *Metrologia,* vol. 45, February 2008, pp. 35-45.