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THE SIM TIME AND FREQUENCY NETWORK

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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 them to participate in international comparisons. The SIM time and frequency network was developed to allow NMIs to participate in continuous international comparisons with a minimum of effort and cost.

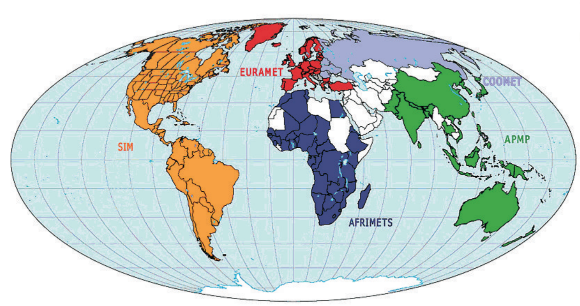
The SIM network has advanced the state of metrology in the SIM region by allowing as many laboratories as possible to participate in international time coordination. It provides continuous, near real-time comparisons between the national time and frequency standards located throughout the SIM region, by utilizing both the Internet and the Global Positioning System (GPS).

As of September 2008, 12 NMIs have been sent SIM time and frequency measurement systems. These systems have been paid for either by the OAS, which is the parent organization of SIM, or by the NMIs themselves. Nine of these laboratories are already engaged in continuous interlaboratory comparisons, with the other three expected to begin soon. Four additional NMIs have expressed interest and will 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 presents the results of interlaboratory comparisons and discusses the network's measurement uncertainties.

INTRODUCTION

SIM shares the same goals as its fellow regional metrology organizations (RMOs); it works to ensure the uniformity of measurements throughout a large section of the world by establishing traceability 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 organizes regional comparisons, and help the NMIs of small and developing nations maintain standards at the level of accuracy that is needed to support their economy.

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



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 populations of the nations and 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 other SIM nations, mostly islands in the Caribbean region, have populations of less than one million. As of 2007, the per capita gross domestic product (GDP) of the United States and Canada exceeded $38,000 USD, but ten SIM nations had GDPs of $7,000 USD or less. This disparity in population and money directly translates into the relative amounts 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 those of 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 favored no single laboratory or nation, and to allow all members to view the results of all comparisons.

Once 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].

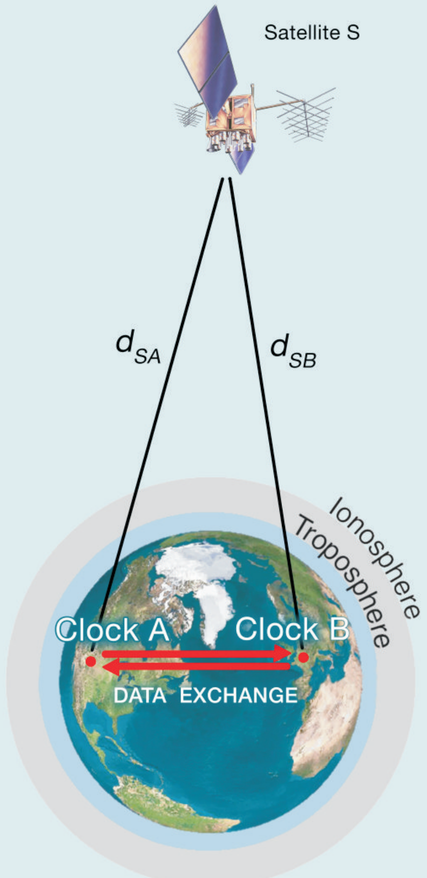


Figure 2. Common-view GPS Measurements.

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 for every SIM system to have well characterized delays 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 SIM measurement system (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 receiver is connected to an aperture coupled slot array antenna designed to mitigate the reception of multipath signals. This “pinwheel” type antenna is smaller and lighter than a choke ring antenna, but rejects multipath signals equally as well [5, 6].

The SIM 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 card connects the system to the network, and participating laboratories must provide an always-on Internet connection. Measurement data are transmitted by use of the file transfer protocol (FTP). Passive mode FTP is used at most sites to avoid problems with firewalls, and the file transfers have been very reliable.

The SIM system measures the time difference between GPS and the local standard every second, and both 1-minute and 10-minute averages are recorded for as many as eight satellites. The system records files that include 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 submitted to the network are in a format that is incompatible with the Consultative GPS and GLONASS Time Transfer Sub-committee (CGGTTS) format used by the BIPM [7]. However, software that converts SIM data to the CGGTTS format has been developed to assist NMIs that need this capability. The native SIM format has the advantage of collecting about 23 % more data than the CGGTTS multi-channel format, as shown in Table 1.

Method	Daily Tracks	Track Length	Satellites	Daily Minutes
CGGTTS single-channel	48	13	1	624
CGGTTS multi-channel	90	13	8 typical	9 360
SIM	144	10	8 max	11 520

Table 1. Comparison of common-view data formats.

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, $\sigma_y(\tau)$ [8], 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 4) that shows the most recent time differences between SIM NMIs. The grid receives new data every ten minutes, and refreshes automatically every five minutes. If a user clicks on one of the time difference values displayed on the grid, a phase plot of the comparison for the current day will appear in their web browser.

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 [9], 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.

SIM Time Scale Comparisons via GPS Common-View

(Time differences in nanoseconds for the 10-minute period ending on 02-14-2008 at 1830 UTC)

SISTEMA INTERAMERICANO DE METROLOGIA	United States UTC(NIST)	Mexico UTC(CNM)	Canada UTC(NRC)	Panama UTC(CNMP)	Brazil UTC(ONRJ)	Costa Rica UTC(ICE)	Colombia UTC(SIC)	Argentina UTC(INTI)	Guatemala UTC(CNMG)	Jamaica UTC(BSJ)
United States UTC(NIST)		40.8	62.3	-118.3	-32.1	-51842455.0	315.4	104.2		65.5
Mexico UTC(CNM)	-40.8		16.7	-161.5	-76.7	-51842495.8	277.0	74.2		24.6
Canada UTC(NRC)	-62.3	-16.7		-179.1	-86.9	-51842510.7	255.8			13.2
Panama UTC(CNMP)	118.3	161.5	179.1		91.2	-51842334.2	440.1	239.8		186.1
Brazil UTC(ONRJ)	32.1	76.7	86.9	-91.2		-51842420.3	349.6	150.9		101.0
Costa Rica UTC(ICE)	51842455.0	51842495.8	51842510.7	51842334.2	51842420.3		51842771.1	51842568.2		51842520.4
Colombia UTC(SIC)	-315.4	-277.0	-255.8	-440.1	-349.6	-51842771.1		-205.4		-250.7
Argentina UTC(INTI)	-104.2	-74.2		-239.8	-150.9	-51842568.2	205.4			-49.2
Guatemala UTC(CNMG)										
Jamaica UTC(BSJ)	-65.5	-24.6	-13.2	-186.1	-101.0	-51842520.4	250.7	49.2		
Last Update (HHMM UTC)	1830	1830	1830	1830	1830	1830	1830	1830		1830

This table was created at 02-14-2008 (MJD 54510) 18:33:26 UTC and will automatically refresh every five minutes.

Click on time scale names or country names to view **one-way** GPS data. Click on time difference values to view **common-view** comparisons between laboratories.

Figure 4. The SIM Real-Time Measurement Grid.

CURRENT AND FUTURE MEMBERSHIP

As of September 2008, 12 NMIs have been sent SIM measurement equipment, which allows them to participate in the network. Four additional NMIs have formally expressed interest in joining the network, and will be added when resources become available (Table 2).

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	Yes	Rubidium
Peru	INDECOPI	Future	Rubidium
St. Lucia	SLBS	Future	Rubidium
Trinidad / Tobago	TTBS	Future	Rubidium
United States	NIST	Yes	Time Scale
Uruguay	UTE	Yes	Cesium

Table 2. Current and Future SIM Network Members.

A map of the SIM region showing the current and known future members of the network is provided in Figure 5. We anticipate that other SIM NMIs will also be interested in establishing a time and frequency laboratory, and that additional requests to join the network will eventually be received.

As shown in Table 2, four SIM NMIs operate time scales composed of an ensemble of cesium oscillators and/or hydrogen masers as their national standard. Six operate a single cesium oscillator. The remaining NMIs will use rubidium oscillators, at least initially, 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 cesium oscillators needed to build an ensemble time scale. This progression has already begun. Three SIM laboratories have purchased cesium oscillators in 2008: SIC in Colombia, INTI in Argentina, and ICE in Costa Rica.

Figure 5. 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 network measurements involves evaluating both the Type A and Type B uncertainties as described in the ISO standard [10]. Uncertainties are combined with the root sum of squares method, where *k* is the coverage factor (Eq. 2):

$$U_c = k\sqrt{U_a^2 + U_b^2} \tag{2}$$

To evaluate the Type A uncertainty, we use the time deviation, $\sigma_x(\tau)$, at an averaging time of one day. The time deviation [8] is a metric calculated automatically by our web-based software that estimates the amount of time transfer noise. For most SIM baselines, $\sigma_x()$ at 1 day is typically about 1.5 ns. 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 6. The time deviation will probably never exceed 5 ns if each of the two laboratories involved in a given comparison has a cesium oscillator (for comparisons involving rubidium oscillators, $\sigma_x(\tau)$, is likely to be dominated by oscillator noise and can be much larger).

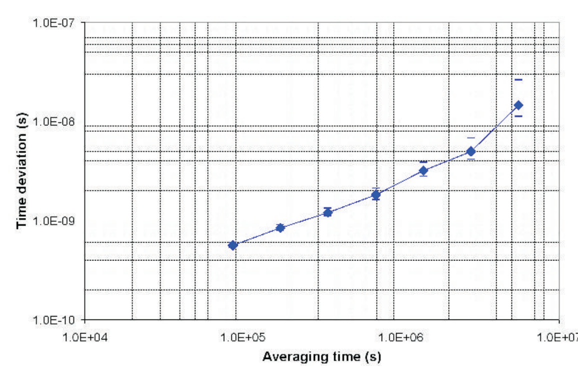


Figure 6. Time deviation of NIST-NRC link for the period from January through August, 2007.

To evaluate the Type B uncertainty, we have identified seven components that can potentially introduce systematic errors in the time measurements 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 by several nanoseconds. However, the use of the pinwheel antennas [5] described earlier, along with high quality antenna cable and connectors, has improved the repeatability of the calibrations. This is illustrated in Figure 7, 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 was 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.

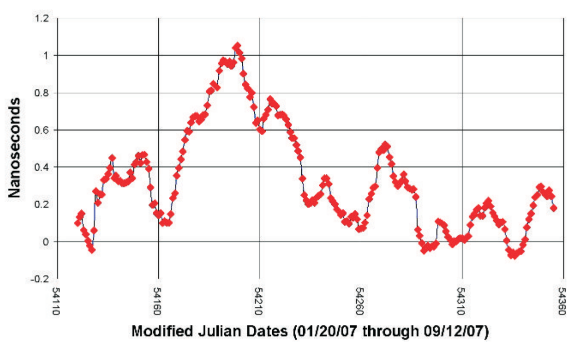


Figure 7. Time variation in 235 consecutive 10-day calibrations between SIM measurement units.

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 can typically determine the antenna's horizontal position (latitude and longitude) 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 slightly more than 2 ns per meter. For this reason, elevation is often obtained through an independent survey, often with a dual frequency geodetic GPS receiver.

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 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. When possible, SIM NMIs mount their antennas in an area with a clear, unobstructed view of the sky on all sides, and the antenna was designed to mitigate multipath [5, 6]. 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 delay. 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 [11]. 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 a one-time measurement made with a time interval counter that typically has a Type B uncertainty of 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 is 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 for some baselines. 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.

Uncertainty Component	Best Case	Worst Case	Typical
U_A, $\sigma_x(\tau)$, $\tau = 1$ 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

Table 3. Measurement Uncertainties (nanoseconds).

MEASUREMENT RESULTS

Figure 8 shows the results of a comparison between the ensemble time scales of CENAM and NIST across a 2199 km baseline for the one year period beginning June 1, 2007 and ending May 31, 2008. The daily values from the SIM network include error bars showing the estimated uncertainty *(k = 2)* of 12 ns. Values from the BIPM *Circular-T* are shown at five-day intervals, and fall well within this uncertainty. Note that the difference between the two time scales never exceeded 50 ns.

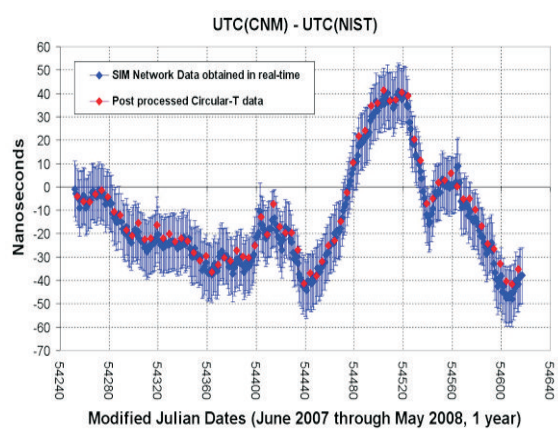


Figure 8. One year comparison between the CENAM and NIST time scales.

Figure 9 indicates how well all of the SIM standards are performing by looking at a five day block of data from August 2008. For this comparison, NIST was arbitrarily chosen as the pivot laboratory, and the other eight SIM standards were compared to UTC(NIST). The largest frequency offset of any of the eight standards was about 2×10^{-13}, and the largest time offset was less than 400 ns. Although there is room for further improvement, these results indicate that national time and frequency standards are now tightly controlled throughout the SIM region.

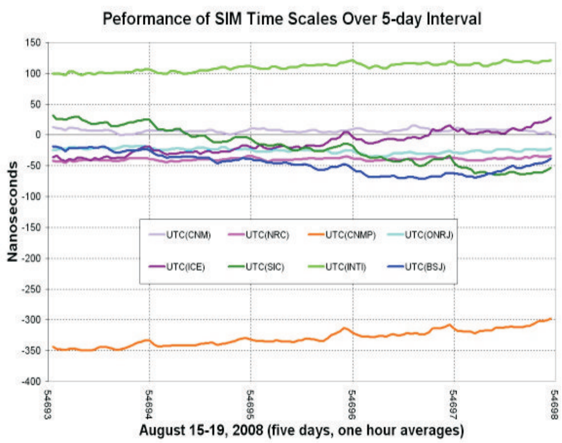


Figure 9. Five-day comparison between UTC(NIST) and eight other SIM standards.

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

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

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), *REFGPSi(A)* is the series of individual satellite tracks recorded at site A, *REFGPSi(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).

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, no satellites are in common-view about 10 % of the time, and on average, only 1.4 satellites are simultaneously visible at both sites [11]. 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 [12]. Instead, the averages of the *REFGPSi(A)* and *REFGPSi(B)* data series are calculated, and the time difference *TD* is the difference between the two averages:

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

The utility of the all-in-view method is well established, and was used to collect the data in Figure 9. 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. 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 [12].

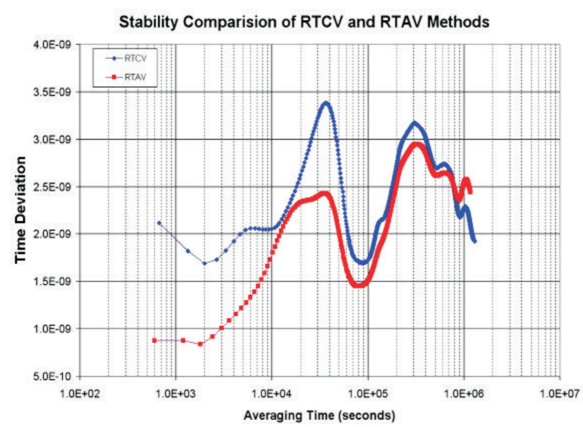


Figure 10. Time deviation graph comparing the RTCV and RTAV methods over a long baseline.

Figure 10 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 [11]. Of course, the greatest virtue of the RTAV method is simply that it always works, even when no satellites are in common view.

ESTABLISHMENT OF A SIM TIME SCALE

In mid-2008, work began at CENAM on the development of algorithms for a SIM time scale, to be known as *SIM-Time*, or UTC(SIM). This time scale will accept the real-time inputs from each of the participating laboratories, assign a weighted average to each contributor, and then generate a near real-time version of UTC(SIM). When this work is completed, it will be possible for all laboratories in the SIM network to compare their standards not only to each other, but also to UTC(SIM) [13].

SUMMARY AND CONCLUSION

The SIM time and frequency network began operation in June 2005, and systems have been delivered to 12 NMIs as of September 2008. The network should eventually expand to 16 laboratories. The SIM 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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