TIME COORDINATION THROUGHOUT THE AMERICAS VIA THE SIM COMMON-VIEW GPS NETWORK

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Abstract

The Sistema Interamericano de Metrologia (SIM) consists of national metrology institutes (NMIs) located in all 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). As the number and the quality of time and frequency standards in the SIM region has increased, it has become more important for SIM nations to be able to compare their standards to each other.

To help advance the state of metrology in the SIM region and to get as many laboratories involved in international time coordination as possible, we have developed a network that provides continuous, near real-time comparisons between the national time and frequency standards located in the SIM region. The network was designed to be low cost and easy to operate, but still capable of providing measurement uncertainties small enough to characterize the best standards in the SIM region. We present the results of comparisons conducted between four participating laboratories: NRC (Canada), NIST (USA), CENAM (Mexico), and CENAMEP (Panama). We discuss the performance of the network and compare SIM results to those published by the BIPM in its monthly Circular-T document. We also discuss the work that is under way to expand the network.

I. INTRODUCTION

The *Sistema Interamericano de Metrologia* (SIM), or Inter-American Metrology System, 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). Its purpose is to ensure the uniformity of measurements throughout the entire OAS region, strengthening traceability back to the International System of units (SI). Although SIM is currently not as well established in the world timekeeping arena as other RMOs such as the European Collaboration in Measurement Standards (EUROMET) and the Asia-Pacific Metrology Programme (APMP), participation from the Americas is on the rise **[1]** and has considerable potential for future expansion.

To encourage cooperation and improve communications between its member nations, SIM has organized metrology working groups (MWGs) in 11 different metrological areas, including one for time and frequency. Table 1 summarizes information collected by the time and frequency MWG regarding the SIM NMIs that currently pursue, or have expressed interest in pursuing, time and frequency metrology. The list currently includes 19 of the 34 SIM nations, and is expected to grow. As of November 2006, nine SIM nations are members of the BIPM's Metre Convention, and four are associates of the General Conference on Weights and Measures (CGPM) **[2]**. Seven submit data to the BIPM and contribute to the derivation of Coordinated Universal Time (UTC), and 12 are known to currently maintain a time and frequency laboratory. At least six other SIM members have expressed interest in starting a time and frequency laboratory in the near future.

Table 1. SIM NMIs that currently pursue or plan to pursue time and frequency metrology.

Country	BIPM/ CGPM Member?	Maintains Time and Freq. Lab?	Maintains ensemble time scale?	Submits to BIPM?
Argentina	Member	Yes	Yes **[3]**	Yes
Brazil	Member	Yes	Yes	Yes
Canada	Member	Yes	Yes	Yes
Chile	Member	Yes	No	Yes
Colombia	No	Yes	No	No
Costa Rica	Associate	Yes	No	No
Dominican Rep.	Member	Unknown	No	No
Ecuador	Associate	Yes	No	No
El Salvador	No	Interested	No	No
Guatemala	No	Interested	No	No
Jamaica	Associate	Yes	No	No
Mexico	Member	Yes	Yes	Yes
Panama	Associate	Yes	No	Yes
Paraguay	No	Interested	No	No
Peru	No	Interested	No	No
Trinidad / Tobago	No	Interested	No	No
United States	Member	Yes	Yes	Yes
Uruguay	Member	Interested	No	No
Venezuela	Member	Yes	No	No

To promote time coordination throughout the Americas and to get as many laboratories involved in international comparisons as possible, the time and frequency MWG has developed a common-view GPS network. This network provides continuous, near-real-time comparisons between the national time and frequency standards located at SIM NMIs. The design objectives were to create a network that was low cost and easy to operate, because resources at many SIM laboratories are very limited and staff sizes are small. At the same time, the network still had to be capable of providing measurement uncertainties that are small enough to characterize the best standards in the SIM region.

The SIM time and frequency network began operation in June 2005, continuously comparing the national time scales of the Centro Nacional de Metrologia (CENAM, abbreviated as CNM) 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 **[4]**. The Centro Nacional de Metrología de Panamá (CENAMEP, abbreviated as CNMP) in Panama was added to the network in December 2005. A SIM measurement system was shipped to the Observatorio Nacional in Rio De Janeiro (ONRJ) in Brazil in October 2006, and data collection should begin soon. The locations of the five laboratories currently in the network are shown in Figure 1. Future expansion of the SIM network into Colombia, Costa Rica, and Guatemala is now being discussed, and should occur by the end of 2007.

There are 10 baselines between the five laboratories, shown as dotted lines in Figure 1. Note the large geographic area covered by SIM. The length of the baseline from NIST to ONRJ is about 9500 km, longer than the baselines between NIST and most of the EUROMET laboratories. It is the longest baseline in the SIM network now, and will be nearly the longest even if all member nations eventually participate.

The following sections provide a technical description of the SIM network, and present data collected from continuous comparisons between the national standards located in Canada, Mexico, Panama, and the United States. We compare the SIM results to data collected from time links previously established by the BIPM, and then discuss the measurement uncertainties.

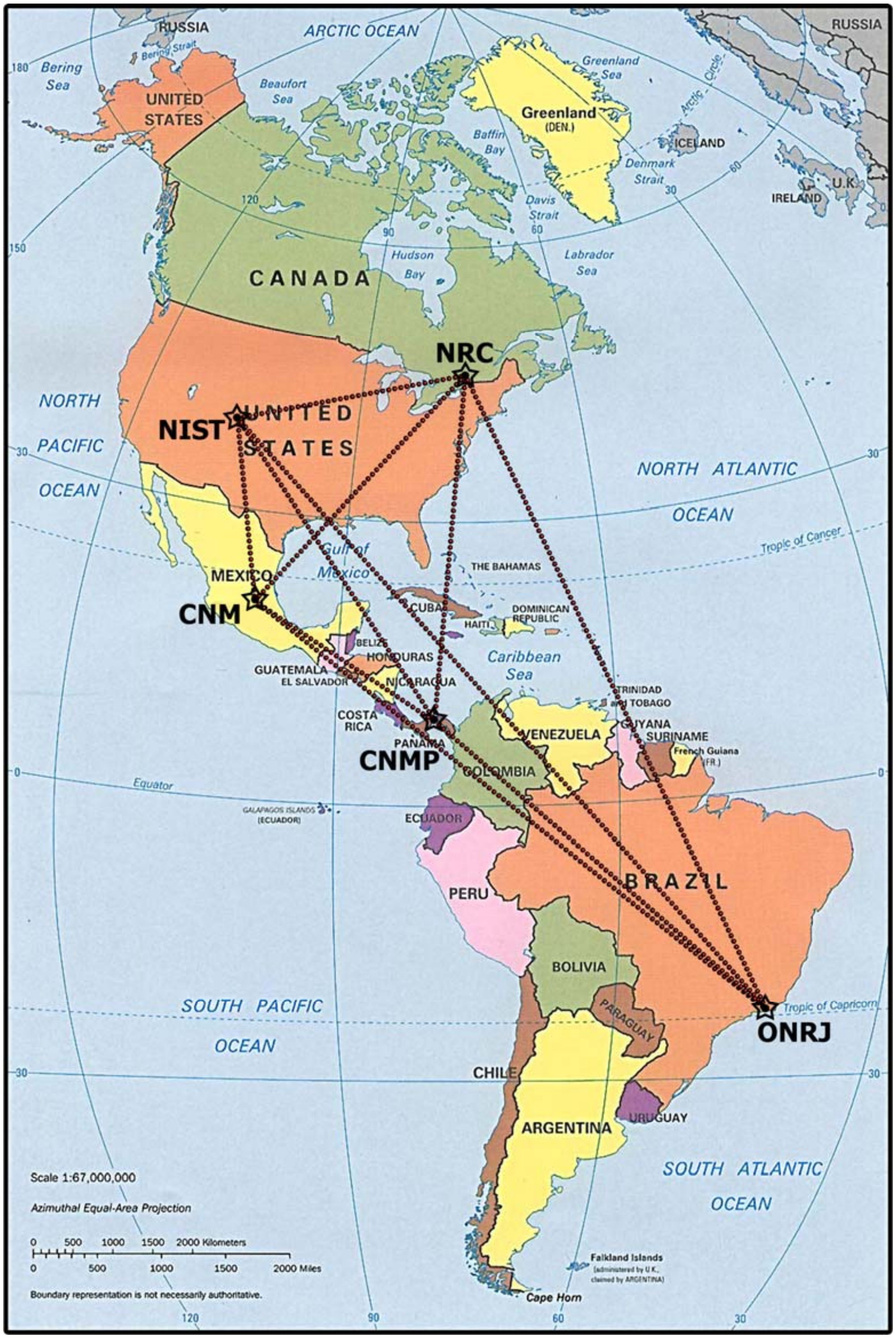

Figure 1. Map of the SIM region, showing the NMIs currently participating in the network.

II. DESCRIPTION OF SIM NETWORK

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 for remote comparisons of clocks and oscillators shortly after the first GPS satellite was launched **[5]**. Since then, it has become the most common comparison technique used to collect data for the derivation of UTC **[6,7]**.

The measurement system supplied to SIM laboratories (Figure 2) consists of an industrial rack-mount computer containing a time-interval counter with 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 UTC time scale. 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 all connections to avoid problems with firewalls, and the file uploads have been very reliable.

The eight-channel GPS receiver is identical to receivers used in other common-view systems that submit data to the BIPM for the derivation of UTC **[8]**, and thus the performance of the SIM system is similar to those units. The receiver provides 5 V dc to an active antenna through the antenna cable. A patch antenna was originally used, but we have recently begun using an aperture-coupled slot array antenna that was designed to mitigate multipath (Figure 3). This "pinwheel" type antenna is smaller and lighter than a choke ring, but provides comparable performance **[9]**.

Figure 2. SIM measurement system.

Figure 3. GPS "pinwheel" antenna.

2.1. SYSTEM CALIBRATION

Each measurement system is assembled and calibrated at NIST in Boulder, Colorado, prior to being shipped to the participating SIM laboratory. The system under test (SUT) is calibrated with the same antenna and cable that will be sent to the participating laboratory. The SUT is compared to the NIST SIM unit over a 6 m baseline, with UTC (NIST) serving as a common clock. During the test, the SUT uses previously surveyed antenna coordinates with an estimated uncertainty of 20 cm. The calibration lasts for 10 days, and produces an average delay number that is entered into the measurement system prior to shipment.

2.2. GPS DATA COLLECTION

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 **[4]**, and no maintenance is required because tracking schedules never need to be updated or changed. The time interval between GPS and the local UTC time scale is measured every second, and 10-minute averages are recorded for as many as eight satellites. The SIM files contain the current system settings, followed by a 32 × 144 matrix containing the time 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 1 day.

2.3. NEAR-REAL-TIME REPORTING OF RESULTS

As listed in Table 1, seven SIM laboratories already contribute to UTC, but most do not. The SIM laboratories that do not contribute to UTC will benefit greatly from joining the network, because it will allow them (for the first time) to establish measurement traceability to the SI units of time and frequency by providing links to laboratories that do contribute. The seven UTC contributors also benefit because the SIM network processes measurement results in near real-time. This allows all participants to instantly compare their time scales to each other, without waiting for the BIPM's *Circular-T* **[2]**, which includes results that are typically 2 to 7 weeks old at the time of publication.

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 from a participating laboratory. Requests are usually processed within a fraction of a second, and made with any Java-enabled Web browser from any Internet connection. No special software is needed, and no training is required. The system is democratic and does not favor any laboratory or nation. All members can view the results of all comparisons, and no laboratory acts as the hub.

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 1-hour or 1-day averages, and the time deviation, $\sigma_x(\tau)$, and Allan deviation, $\sigma_y(\tau)$ **[10]**, of the entire data set are displayed. In addition, 10-minute, 1-hour, or 1-day averages can be viewed in tabular form and, if desired, copied into a spreadsheet or other application for further analysis.

III. MEASUREMENT RESULTS

The four laboratories that currently contribute data to the SIM network maintain UTC time scales. Three of the time scales are based on an ensemble of atomic oscillators; one is based on a single cesium oscillator (Table 2). The newest member, ONRJ in Brazil, also maintains a time scale based on an ensemble of atomic oscillators [**11**], and will begin contributing data soon. We anticipate that future members of the SIM network will have standards covering a broader range. Laboratories that are just beginning to establish a capability in time and frequency will perhaps use a single rubidium oscillator as their national standard, but will still be able to establish traceability to the SI at a known uncertainty.

Table 2. Description of SIM time scales.

Time Scale	Description
UTC (CNM)	The output of a high performance commercial cesium standard called Master Clock, which is steered based on results from internal comparisons made between four cesium standards and one hydrogen maser.
UTC (CNMP)	The output of a single, free-running commercial cesium standard.
UTC (NIST)	An ensemble of six commercial hydrogen masers, and four commercial cesium standards, with rate corrections provided by primary frequency standards, including NIST-F1, a cesium fountain built at NIST. The output of the time scale is provided by a synthesizer referenced to a hydrogen maser, and steered by a weighted average of the clocks in the ensemble.
UTC (NRC)	An ensemble of three hydrogen masers (two NRC-built and one commercial), two cesium beam tubes built by NRC, and two commercial cesium standards. One of the cesium-beam tubes feeds a frequency offset generator that provides UTC (NRC). The applied frequency offset is calculated every 3 or 4 months from the ensemble of clocks.

Figures 4 through 6 show the results of comparisons made from March through October 2006 (8 months) between CNM, NIST, and NRC. All three laboratories maintain UTC time scales based on an ensemble of multiple clocks. The blue values in Figure 4 though 6 are the results of daily comparisons made via the SIM network; the red values are obtained from the *Circular-T* and reported at 5-day intervals. The blue values have error bars that reflect the measurement uncertainty (k = 2 coverage factor), as explained in the next section. The *Circular-T* reports uncertainties as k = 1, and error bars for the red values are not shown. However, note that nearly all of the red *Circular-T* values fall within the stated uncertainty of the SIM measurements, which helps to validate the SIM results.

Figure 7 shows comparisons of the single cesium standard of CNMP to the three ensemble time scales via both the SIM network and the *Circular-T*. No error bars are shown in Figure 7, but the various comparisons produce nearly identical results, and indicate that the CNMP standard has a frequency offset near 7×10^{-14} with respect to all of the ensemble time scales.

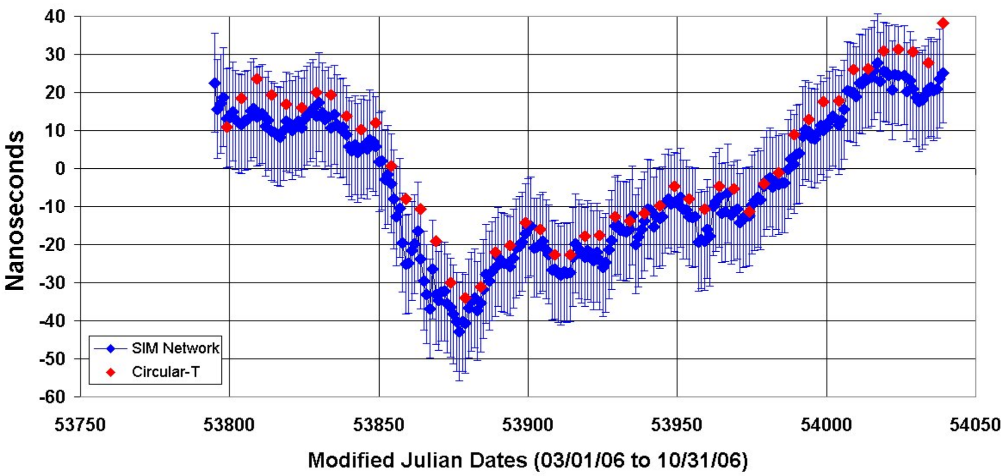

Figure 4. UTC (NIST) – UTC (CNM).

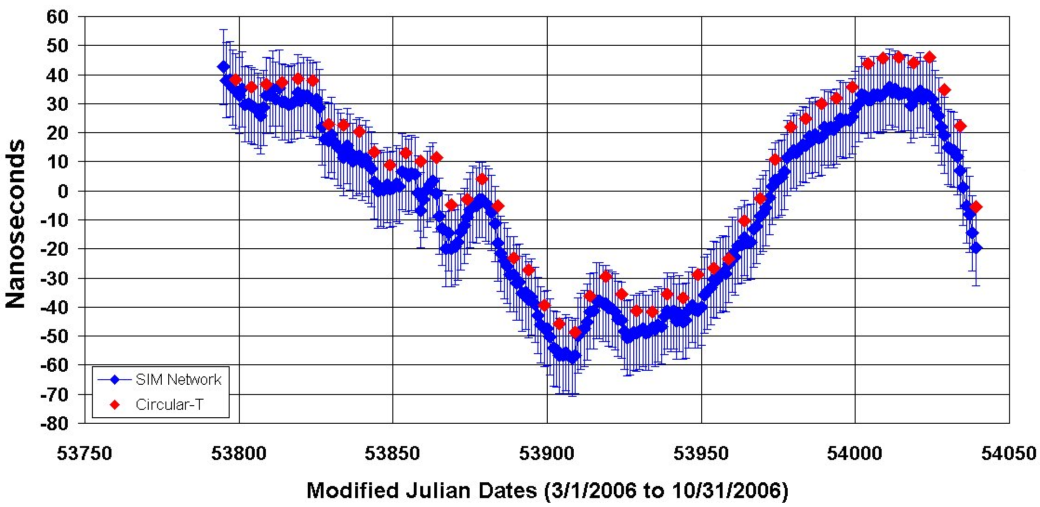

Figure 5. UTC (NIST) – UTC (NRC).

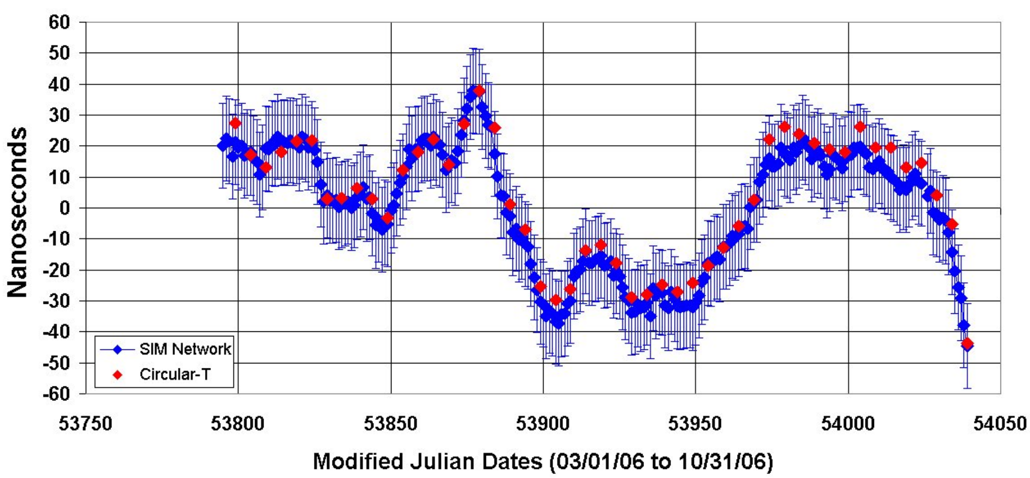

Figure 6. UTC (CNM) – UTC (NRC).

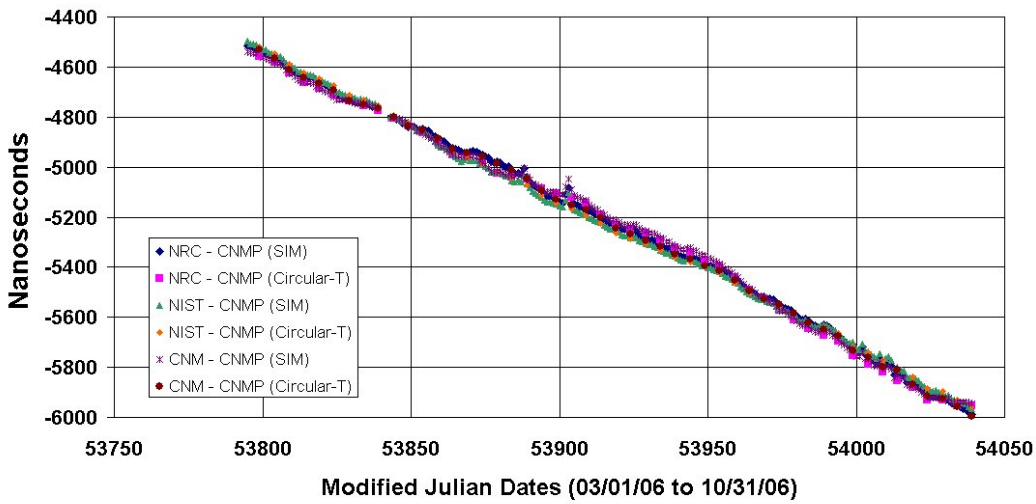

Figure 7. UTC (CNMP) as compared to three SIM time scales.

IV. MEASUREMENT UNCERTAINTIES

Estimating the uncertainty of the SIM measurements involves evaluating both the Type A and Type B uncertainties as described in the ISO standard **[12]**. To evaluate the Type A uncertainty, we use the time deviation, $\sigma_x(\tau)$, at an averaging time of 1 day. The time deviation **[10]** is a metric calculated automatically by our Web-based software that indicates the amount of time transfer noise.

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 (Table 3). This differs from the BIPM method of computing uncertainties for the *Circular-T*, where the uncertainty of the calibration, with some allowance for seasonal delay changes, is the only Type B uncertainty that is considered **[13]**. Note that the SIM network uses modeled, rather than measured, ionospheric delay corrections. This makes real-time processing possible, but introduces uncertainties that are baseline-dependent and that have been removed from the BIPM links **[13,14]**. Also, note that we assume that each laboratory has surveyed their antenna coordinates to within 1 m, a conservative assumption for the existing sites. However, if it is not true for future antenna sites, the uncertainty component for coordinates will increase by more than 2 ns for each additional meter of error. As shown in Table 3, the combined time uncertainty, U_c ($k = 2$), ranges from 13.0 to 17.2 ns for the six baselines. The CNM, NIST, and NRC time scales remained within ±50 ns of each other for nearly the entire 8-month interval, and the average time offset was less than 5 ns.

V. SUMMARY

The SIM time and frequency network began operation in June 2005, and five NMIs now participate. The network is advancing the state of time coordination and time and frequency metrology throughout the SIM region, by providing 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.

Table 3. Results and uncertainties (in nanoseconds) for six baselines (March-October 2006).

	CNM – CNMP	NIST – CNM	CNM – NRC	NIST – CNMP	NRC – CNMP	NIST – NRC
Baseline (km)	2544.0	2198.9	3520.7	4194.9	3989.0	2471.3
Mean Freq. Offset	-7.0×10^{-14}	5.1×10^{-16}	-7.8×10^{-16}	-6.9×10^{-14}	-6.9×10^{-14}	-2.0×10^{-16}
Mean Time Offset	−5235.5	−4.3	+0.7	−5243.7	−5240.1	+3.5
U_A, $\sigma_x(\tau)$	5.1	1.5	1.5	5.2	5.1	1.3
U_B, Calibration	4	4	4	4	4	4
U_B, Coordinates	3	3	3	3	3	3
U_B, Environment	3	3	3	3	3	3
U_B, Multipath	2	2	2	2	2	2
U_B, Ionosphere	2	1.5	2.5	3	3	1.5
U_B, Ref. Delay	0.5	0.5	0.5	0.5	0.5	0.5
U_B, Resolution	0.05	0.05	0.05	0.05	0.05	0.05
U_C, k = 2	16.5	13.1	13.7	17.2	17.1	13.0

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