SIM Time and Frequency Comparison Network in Near Real Time

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Abstract: A network for time and frequency comparisons within the Inter-American Metrology System (SIM) has been developed. The SIM time and frequency network uses the common-view Global Positioning System (GPS) method to compare frequency and time standards maintained at SIM national metrology laboratories, and comparison results are provided in near real time. Participating laboratories are equipped with a SIM measurement system consisting of an eight-channel GPS receiver coupled to a time interval counter, along with a computer that collects and stores data. Each measurement system then transfers data to a server located at NIST, and the server processes the common-view measurement data of all participating laboratories. Results of comparisons are available via the Internet in near real time (10 minutes of delay). This paper shows results of comparisons conducted for two months between four participating laboratories: NRC (Canada), NIST (USA), CENAM (Mexico) and CENAMEP (Panama). We discuss performance of the network and compare SIM results to those published by the BIPM in its monthly *Circular-T* document.

1. INTRODUCTION

The Inter-American Metrology System (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). Its purpose is to ensure the uniformity of measurements throughout the entire OAS region, strengthening traceability back to the International System of units (SI).

In an effort designed 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 lists the SIM NMIs that currently pursue (or who have expressed interest in pursuing) time and frequency metrology, based on information collected by the time and frequency MWG. The list currently includes 18 of the 34 SIM nations, and is expected to grow. As of May 2006, 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) [1]. Seven submit time measurements 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.

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

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

To help advance the state of metrology in the SIM region and to get as many laboratories involved as possible, the time and frequency MWG has developed a network that provides continuous, near real time comparisons between the national time and frequency standards located at SIM NMIs. The network was designed to be low cost and easy to operate, but still capable of providing measurement uncertainties that are low 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) 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 [2]. The Centro Nacional de Metrología de Panamá (CENAMEP) in Panama was added to the network in December 2005, and the network is expected to soon be extended to include NMIs in South America.

This paper provides a technical description of the network, and presents data collected from comparisons between the national frequency and time standards located in Canada, Mexico, Panama, and the United States. It validates these data by comparing them to data collected from time links previously established by the BIPM, and discusses the measurement uncertainties.

2. DESCRIPTION OF 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 [3]. Since then, it has become the most common comparison technique used by the BIPM when collecting data for the derivation of UTC [4].

The measurement system supplied to SIM laboratories (Figure 1) consists of an industrial rack-mount computer containing a time interval counter with resolution of less than 0.1 ns, and a GPS receiver that can track as many as eight satellites at one time. 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).

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 [5], 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.

Fig. 1 *SIM measurement system.*

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 using 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 unit does not use a satellite tracking schedule. It simply collects and stores data from up to eight visible satellites. This has two advantages: it collects as much data as possible [2], and there is no maintenance 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. The receiver provides information that is used to produce a time offset reading for each individual satellite, and data are averaged for 10 minutes and stored. The daily files created by the SIM system contain a header with the current system settings, followed by a 32×144 matrix containing time measurement data. The

32 columns represent the possible number of GPS satellites, with the column numbers matching the pseudo-random noise (PRN) code of the satellites. The 144 rows represent the number of 10 minute segments in one 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 allows 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* [1], which includes results that are typically two to seven weeks old at the time of publication.

The SIM network reports results in near real time by having all systems upload data every 10 minutes to an Internet server that hosts data reduction and analysis software. This software 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. 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 reduction for each aligned track. The results are graphed as either one hour or one day averages, and the time stability, $\sigma_x(\tau)$, and frequency stability, $\sigma_y(\tau)$ [6], of the entire data set are displayed. In addition, 10 minute, one hour, or one day data can be viewed in tabular form and, if desired, copied into a spreadsheet or other application for further analysis.

3. MEASUREMENT RESULTS

Each of the four laboratories currently participating in the SIM network maintains its own UTC time scale. Three of the time scales are based on an ensemble of atomic oscillators; one is based on a single cesium standard (Table 2). We anticipate that future members of the SIM network will have standards covering an even 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 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 three or four months from the ensemble of clocks.

Figures 2 through 7 show the results of comparisons made during March and April 2006 between the four current members of the SIM network. The blue values in each graph are the results of daily comparisons made via the SIM network; the red values are obtained from the BIPM *Circular-T* and reported at five day intervals (note that several days of SIM data were lost in Panama due to a power outage). The blue values have error bars that reflect the measurement uncertainty (k = 2 coverage factor) for each baseline, as stated in the next section. The BIPM reports uncertainties differently (k = 1), and error bars for the *Circular-T* values are not shown. However, note that all of the red *Circular-T* values fall well within the coverage area, which appears to validate our results and our uncertainty analysis.

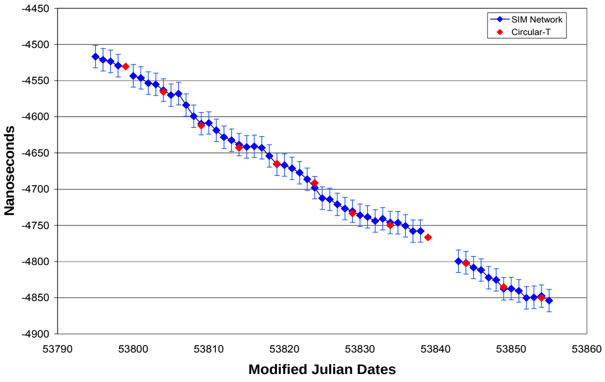

Fig. 2 *UTC(CNM) – UTC(CNMP).*

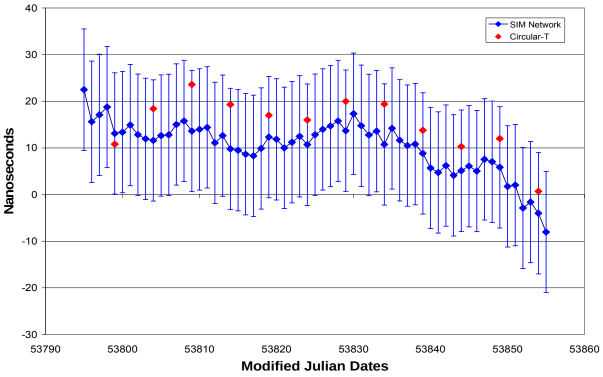

Fig. 3 *UTC(NIST) – UTC(CNM).*

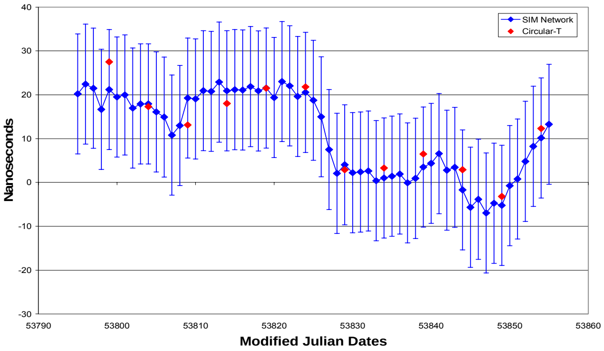

Fig. 4 *UTC(CNM) – UTC(NRC).*

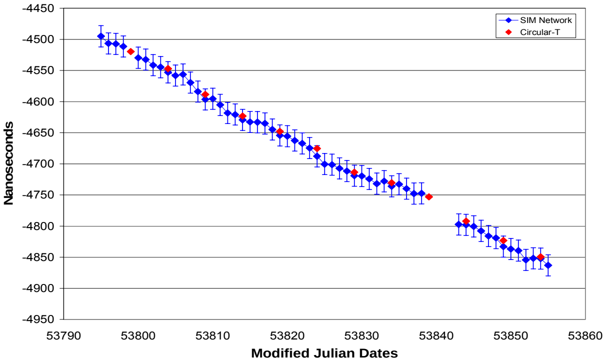

Fig. 5 *UTC(NIST) – UTC(CNMP).*

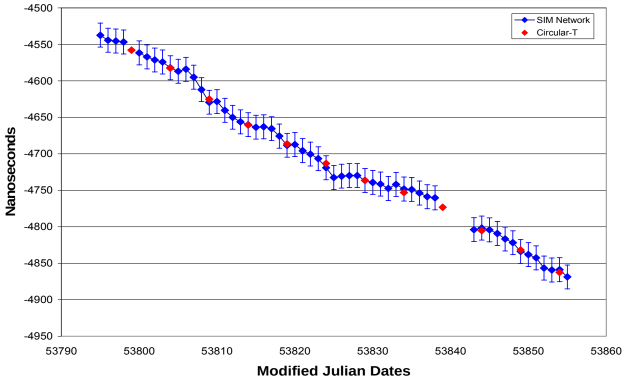

Fig. 6 *UTC(NRC) – UTC(CNMP).*

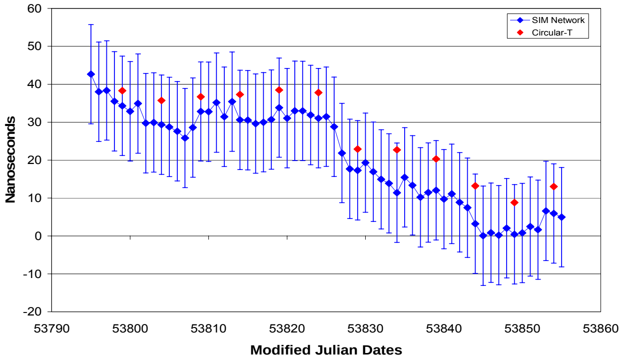

Fig. 7 *UTC(NIST) – UTC(NRC).*

4. 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 [7]. To evaluate the Type A uncertainty, we use the time deviation statistic, $\sigma_x(\tau)$, at an averaging time of one day. The time deviation is an industry standard for estimating time stability [6] that is calculated automatically by our web-based software.

To evaluate the Type B uncertainty, we have identified seven components that can potentially introduce systematic errors (Table 3). Most of the Type B uncertainties have uniform distributions that we have conservatively estimated in some cases, making them large enough to cover all scenarios. However, because the SIM network uses modeled, rather than measured, ionospheric delay corrections, we use uncertainty estimates for ionospheric delay that are baseline dependent [8]. Also, we assume that each laboratory will be able to survey their antenna coordinates to within one meter, which is typically the case. However, if this is not true, the uncertainty component for coordinates will increase by two to three nanoseconds for each meter of error.

***Table 3.** Summary of results and uncertainties (in nanoseconds) for all six comparisons (March-April 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	-6.7×10^{-14}	-2.8×10^{-15}	-4.8×10^{-15}	-7.0×10^{-14}	-6.3×10^{-14}	-7.7×10^{-15}
Mean Time Offset	–4690.4	+10.3	+11.0	–4680.7	–4702.8	+21.2
U_A, $\sigma_x(\tau)$	4.2	1.4	1.5	5.0	4.5	1.5
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	15.5	13.0	13.7	17.0	16.4	13.1

As shown in Table 3, the combined time uncertainty, U_c, ranges from 13.0 to 17.0 nanoseconds for the six baselines. The frequency uncertainty (k = 2) is typically less than 1×10^{-13} at an averaging time of one day, reaching 1×10^{-14} at about one month, if not limited by noise from the standards.

5. CONCLUSIONS

The SIM time and frequency network began operation in June 2005, and four NMIs now participate. The network is expected to advance the state of 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 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.

REFERENCES

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

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