SIM Time Scale

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***Abstract*—Time measurement is of great importance for science, technology, and commerce. Among the seven base units of the International System of Units, the second can be realized with the smallest uncertainty, currently reaching parts in 10^{16}. Keeping track of the continuous accumulation of seconds allows the formation of time scales that serve as references for applications that require synchronization to national and international standards. This paper presents and discusses a multinational time scale developed for the Sistema Interamericano de Metrologia (SIM). This time scale, known as the SIM time scale, or SIMT, was developed to complement the official world time scale, Coordinated Universal Time, by providing real-time support to the operational timing systems within the SIM region. SIMT is generated from automated comparisons of time standards in North, Central, and South America, and is believed to be the first operational multinational time scale whose results are continuously published in real time via the Internet.**

***Index Terms*—Atomic clocks, frequency standards, GPS common-view, measurement methods, remote comparisons, time scales.**

I. Introduction

THE second, the base unit of time interval in the International System (SI), is defined in terms of the two hyperfine states of the ground-state energy level of the 133 Cesium atom. This definition has served the metrology community well, and the uncertainty of the best realization of the second achieved by primary frequency standards has improved by a rate of about one order of magnitude per decade since about 1950, reaching a current level of $\sim 4 \times 10^{-16}$ [1]. This continual reduction in uncertainty has increased the level of performance expected from the operational timing systems, including time and frequency transfer systems and the local time scales maintained by national metrology institutes (NMIs).

The Bureau International des Poids et Mesures (BIPM) is responsible for organizing continuous key comparisons of NMI clocks and time scales, processing the results of these comparisons, and maintaining and disseminating the official world time scale, Coordinated Universal Time (UTC) [2]. The BIPM also supports the comparisons organized by regional metrology organizations (RMOs), recognizing that their work is essential to the overall goal for ensuring the worldwide uniformity of measurements through measurement traceability to the SI [3]. In keeping with this effort, an automated time comparison network and time scale have been developed within the Sistema Interamericano de Metrologia (SIM), an RMO whose members are the nations of the Organization of American States. The SIM region includes the NMIs of 34 nations, and covers North, Central, and South America and the Caribbean Islands.

The SIM time network (SIMTN) allows all participating NMIs to instantly compare their local time scales to each other by making the measurement results available through the Internet [4]. The SIM time scale (SIMT) is a multinational time scale that is also disseminated in real time via the Internet. It allows SIM NMIs to easily monitor their local time scales and to quickly detect short-term fluctuations in stability and accuracy. SIMT complements the UTC time scale, which is postprocessed and unavailable in real time, by providing real-time support to the operational timing and calibration systems throughout the SIM region.

This paper presents and discusses the SIMT. Section II briefly addresses the design and the features of the SIMTN and SIMT. Section III presents the SIMT algorithm. Results of the SIMT computation are presented in Section IV. Section V discusses SIMT performance with respect to UTC. Section VI discusses the operational considerations of SIMT, followed by a summary in Section VII.

II. SIMTN and the SIMT Concepts

A. SIM Time Network

The SIMTN continuously compares the time scales of all SIM local time scales with each other and produces measurement results in near real time. The comparisons are performed via the global positioning system (GPS) common-view and all-in-view techniques (the network can be configured to use either method) with multichannel single-frequency (L1 band) receivers. The measurement data are exchanged and published via the Internet [4]. The SIMTN has operated continuously since 2005 [5], and as of December 2012, 19 nations have joined the network (Table I). SIMTN servers located at the National Research Council (NRC) in Canada, the Centro Nacional de Metrología (CENAM) in Mexico, and at the National Institute of Standards and Technology (NIST) in the United States host identical software that processes and displays measurement data whenever requested by a user. All three servers are linked from the SIM time and frequency working group web site: http://tf.nist.gov/sim.

Each server publishes web pages that display a grid containing the most recent time differences between SIM NMIs. The grids are updated every 10 min. When a user clicks a

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TABLE I
SIMTN MEMBERS

Country	Year of First Participation	Time Standard
United States	2005	Ensemble time scale
Mexico	2005	Ensemble time scale
Canada	2005	Ensemble time scale
Panama	2005	Cesium
Brazil	2006	Ensemble time scale
Costa Rica	2007	Cesium
Colombia	2007	Cesium
Argentina	2007	Cesium
Guatemala	2007	GPSDO
Jamaica	2007	Cesium
Uruguay	2008	Cesium
Paraguay	2008	Rubidium
Peru	2009	Cesium
Trinidad & Tobago	2009	GPSDO
Saint Lucia	2010	Rubidium
Chile	2010	Rubidium
Antigua and Barbuda	2011	Rubidium
Ecuador	2012	GPSDO
Bolivia	2012	Rubidium

time difference value displayed on the grid, a phase plot of the comparison will appear. The phase plots can include up to 200 days of data, and the time deviation and Allan deviation values [6] for the selected data are automatically calculated and displayed. The SIMTN also generates a data feed that provides the clock comparison data that the SIMT needs for its time scale computations.

The rapid publication of SIMTN data makes it easy to quickly identify local time scale fluctuations and failures, a key benefit to NMIs that disseminate time or frequency within their countries, or who use their time scale as a reference for calibrations. A complete description of the SIMTN that includes an uncertainty analysis of its comparisons, which is typically less than 15 ns ($k = 2$), is provided in [4]. A discussion of benefits that SIM NMIs receive from the SIMTN is provided in [7].

B. SIM Time Scale

Time keeping for critical applications requires reliability, stability, and accuracy. To meet these requirements, it is customary to develop multiclock, or ensemble time scales that are not dependent on the operation of any single clock. These ensemble time scales are typically generated from a series of time difference measurements made between clocks that are members of the ensemble. By averaging and analyzing these time differences, it is possible to generate a single composite clock. Ensemble time scales always have some constraints and limitations, but in general, the metrological characteristics of the composite clock will be superior to those of any of the individual clocks in the ensemble. Perhaps more importantly, an individual clock failure will not cause an ensemble time scale to fail [8]–[10].

The large number of local time scales in the SIM region made it attractive to generate a composite time scale that could be distributed and shared. Work on SIMT began at CENAM in early 2008 [11] and it has been refined for several years, becoming an operational time scale in 2010. SIMT was designed with several characteristics in mind, specifically: 1) to be a continuously operated time scale that is made publicly available in real time via the Internet; 2) to include local NMI time scales, SIMT(k), as single clocks in the SIMT ensemble; 3) not to be dependent on the clock maintained by any individual NMI; and 4) to provide a traceability path to the SI for smaller laboratories that had not previously engaged in international comparisons.

In particular, SIMT was designed to be an instantly accessible reference standard that can be used to monitor the performance of local SIMTs and operational timing systems in the short, medium, and long terms. The ability of SIMT to detect short-term anomalies is especially useful when compared with UTC, which is not available in real time, and which is insensitive to short-term fluctuations. During the interval while we have worked on SIMT, other NMIs have designed experimental time scales for similar purposes with excellent results [12], [13]. To the best of our knowledge, their data are, however, not made publicly available, nor are they maintained as operational time scales.

III. SIMT ALGORITHMS

Because there are many different applications for time scales, there is no unique best ensemble time scale algorithm. This is well illustrated by the UTC and UTC(k) time scales. UTC is a postprocessed virtual time scale with no associated physical signal. It serves as the ultimate reference for measurements of frequency and time interval, but it has processing delays that are too large to support real-time applications. In contrast, the UTC(k) time scales generated by the NMIs can generate physical signals in real time. Thus, UTC and the various UTC(k) time scales serve different applications, and different criteria are emphasized in their design. These criteria include the models used to predict clock behavior, the weighting procedure, the periodicity used to compute the time scale, the way that the clocks are added to and deleted from the ensemble, and so on.

SIMT is a real-time time scale, such as the UTC(k) time scales. It was designed with algorithms where exponential filtering is used to predict the time and frequency differences of the clocks with respect to the averaged time scale. Clocks are weighted by estimating their frequency instability in terms of the Allan deviation. However, the way that the weights are assigned varies among different time scales. For SIMT, the weighting criteria are based on the inverse of the Allan deviation, $\sigma_y(\tau)$ which is computed by considering the previous 10 days of measurements. A 10-day averaging period was selected to minimize the influence of GPS link noise on the computation of SIMT. Please note that our discussion will use the term clock to refer the local SIMT(k) time scales, because each local time scale is treated as one clock in the SIMT computation. Thus, throughout the rest of this paper, it is important to remember that clock k is equal to SIMT(k). It is also important to note that in the case of the six laboratories that contribute to both UTC and SIMT, SIMT(k) and UTC(k) are generated from the same physical signal and are equivalent in frequency. However, there is sometimes a time bias because of cable delays.

Consider that at the current time t, the prediction $\hat{x}_k(t+\tau)$ for the time difference of the clock k with respect to the SIMT at time $t+\tau$ can be written in terms of a known set of parameters. These parameters include: 1) the time difference $x_k(t)$ of clock k with respect to the SIMT at time t; 2) the fractional frequency difference $y_k(t)$ of clock k with respect to the SIMT at time t; and 3) the parameter D_k that considers the drift of $y_k(t)$ during the time interval $(t, t+\tau)$, as follows:

$$\hat{x}_k(t+\tau) = x_k(t) + [y_k(t) + D_k\tau]\,\tau + \ldots \tag{1}$$

Equation (1) can be easily accepted because it can be seen as a Taylor expansion of the function x_k around the value $x_k(t)$ for a time interval of length τ. Note that the frequency (rate) of SIMT is a free parameter that will drift over time because of measurement noise, and might eventually require steering.

Once the (future) time $t+\tau$ is reached, the time differences between clocks can be obtained in real time from the SIMTN data feed via the Internet, so it is possible to compute SIMT for that $t+\tau$ time. Of course, the predicted value of SIMT, computed at time t for the time $t+\tau$, will not necessarily be equal to the computation of SIMT at time $t+\tau$. However, the SIMT value, predicted at time t for $t+\tau$, can be corrected by the time difference measurements at $t+\tau$ using the defining equation of SIMT scale

$$x_k(t+\tau) = \sum_{j=1}^{N_{\text{Tot}}} \omega_j \left[\hat{x}_j(t+\tau) - x_{jk}(t+\tau)\right] \tag{2}$$

where $x_{jk}(t+\tau)$ is the measured time difference between clock j and k at time $t+\tau$ and N_{Tot} is the total number of clocks.

To filter the GPS link noise, (2) is transformed as follows:

$$\begin{aligned} x_k(t) &= \sum_{j=1}^{N_{\text{Tot}}} \omega_j \left[\hat{x}_j(t) - x_{jk}(t)\right] \approx \sum_{j=1}^{N_{\text{Tot}}} \omega_j \left[\hat{x}_j(t) - \left\langle x_{jk}(t)\right\rangle\right] \\ &\approx \sum_{j=1}^{N_{\text{Tot}}} \omega_j \left[\hat{x}_j(t) - \left\langle x_{jk_0}(t-\tau_0)\right\rangle - \left\langle x_{k_0k}(t-\tau_0)\right\rangle\right] \end{aligned} \tag{3}$$

where $\left\langle x_{jk}(t)\right\rangle$ is the average of $x_{jk}(t)$ during the previous 3 h. Here, k_0 is the pivot laboratory, which is usually NIST or CENAM, but can be configured in software to be any of the contributing NMIs.

The prediction $\hat{y}_k(t+\tau)$ of the fractional frequency deviation of clock k with respect to SIMT, at time $t+\tau$, is made according to

$$\hat{y}_k(t+\tau) = \frac{\hat{x}_k(t+\tau) - x_k(t)}{\tau}. \tag{4}$$

To minimize the GPS link noise when computing the frequency prediction, (4) is transformed in

$$\hat{y}_k(t) = \frac{\hat{x}_k(t) - x_k(t-\tau)}{\tau} \approx \langle m_k \rangle \tag{5}$$

where $\langle m_k \rangle$ is the 10-day average of the fractional frequency difference m_k of clock k with respect to the SIMT frequency.

When the (future) time $t+\tau$ is reached, the correction for the frequency prediction can again be made through an exponential filtering defined by

$$y_k(t+\tau) = \frac{1}{1+\alpha_k}\left[\hat{y}_k(t+\tau) + \alpha_k y_k(t)\right] \tag{6}$$

where α_k is a parameter that brings information about the averaging period when reaching the floor noise in clock k, given by the relation [14]

$$\alpha_k(\tau) = \frac{1}{2}\left[\sqrt{\frac{1}{3} + \frac{4}{3}\frac{\tau_{\text{min},\,k}^2}{\tau^2}} - 1\right]. \tag{7}$$

Here, $\tau_{\text{min},\,k}$ is the integration period at which the noise floor of clock k is reached. For weights ω_i, the condition of normalization is, of course, kept as follows:

$$\sum_{i=1}^{N_{\text{Tot}}} \omega_i = 1. \tag{8}$$

To have a mechanism that increases or decreases the weight for a single clock according to its frequency stability, we have defined the clock weights to be inversely proportional to the frequency stability, which is estimated in terms of the Allan deviation. Thus, the basic SIMT criteria for clock weighting is defined by

$$\omega_i \propto \frac{1}{\sigma_i(\tau)} \tag{9}$$

where $\sigma_i(\tau)$ is the Allan deviation of the clock i for $\tau = 1$ h, computed from the previous 10 days of SIMTN data. This long integration period was selected to minimize the influence of the GPS time transfer noise that is inherent in the SIMTN data, and thus to provide a truer picture of the actual performance of the clocks.

To improve the accuracy of SIMT, the weighting method was modified in February 2012 to include an accuracy factor

$$\omega_i \propto \frac{1}{\sigma_i(\tau)} \times \frac{1}{|\langle \Delta f \rangle|} \tag{10}$$

where $|\langle \Delta f \rangle|$ is the absolute value of the previous 240-h average of the relative frequency offset Δf of the contributing clock with respect to the SIMT frequency. The weighting computation is made every 24 h, at 0-h, 0-min UTC. Thus, the weighting factor assigned to a clock remains constant throughout the UTC day.

Clock weights are computed in several steps. The first consists in computing the preweights with

$$\omega'_k(t) = \frac{1}{\sigma_k(\tau')\times |\langle m_k \rangle|} \tag{11}$$

where $|\langle m_k \rangle|$ is the absolute value of the 10-day average of the fractional frequency deviation of clock k respect to SIMT. Second, to keep valid (8) preweights are normalized as follows:

$$\omega_k(t) = \frac{1}{\sum_j \omega'_j(t)} \times \frac{1}{\sigma_k(\tau') \times |\langle m_k \rangle|} \tag{12}$$

To prevent failed clocks from disturbing SIMT, the performance of each clock is continuously monitored. That monitoring is achieved through the computation for the values of $\sigma_i(\tau_0)$, where τ_0 is 1 h. This frequency stability is computed by comparing an individual clock i with SIMT and other clocks in the ensemble, and the three-cornered hat method [15] is used to help in isolating the behavior of the bad clock. When a clock exhibits anomalous behavior or stops sending data to the SIMTN, its weight is immediately set to 0 and it is dropped from the ensemble.

The criteria in SIMT algorithm to detect anomalous behavior in clocks is based on the relation $\left|\langle \hat{x}_k(t) - x_k(t)\rangle\right| \geq 25$ ns, thus if the time difference of clock k with respect to SIMT differs by >25 ns from its expected value, its weight is set to 0 and it is removed from the time scale computation. This criteria corresponds to a frequency instability of 7×10^{-12} at $\tau = 1$ h. Stability specifications for low-performance commercial Cesium clocks are typically 3×10^{-12} at $\tau = 1$ h, or about a factor of two smaller than the restriction used by the SIMT algorithm. When a clock's weight is set to 0, the weight that it previously held is automatically reassigned to other clocks. The SIMT algorithm continues to monitor the failed clock, and automatically restores it to the ensemble when its behavior has returned to normal for at least 27 h of operation; 27 h is the sum of 24 + 3 h. Once a clock on SIMTN has been recovered from a failure, we observe it during 1 day (24 h) to be sure that the clock is effectively recovered from the failure. If the clock meets that condition then we use data during the next 3 h to compute the time difference with respect to SIMT.

It was also necessary to provide an upper limit for the clock weights. Contributors to SIMT are divided in three groups: 1) group 1 consists of NMIs that operate ensemble time scales; 2) group 2 includes laboratories that operate time scales based on a single Cesium clock; and 3) finally, group 3 includes laboratories that operate time scales based on a rubidium clock or a GPS disciplined clock. To prevent the time scale of any individual nation from dominating SIMT, we have limited the contribution of each clock in group 1 not to exceed 40%. For SIM laboratories in group 2, the weight limit cannot exceed 10%. Group 3 laboratories are not allowed to contribute to SIMT and have a weight of 0. The limit values will probably be reduced as more nations contribute to the SIMT computation. The algorithm to assign the final weights is as follows. Consider the next three sets of weights Ω_{Scales}, Ω_{Cs}, and Ω_{Rb}

$$\begin{aligned} \Omega_{\text{Scales}} &= \{\omega_k \,|\, k = 1, 2, 3, \ldots, N_{\text{Scales}}\} \\ \Omega_{Cs} &= \left\{\omega_j \,\middle|\, j = 1, 2, 3, \ldots, N_{Cs}\right\} \\ \Omega_{Rb} &= \{\omega_l = 0 \,|\, l = 1, 2, 3, \ldots, N_{Rb}\} \end{aligned} \tag{13}$$

where N_{Scales}, N_{Cs}, and N_{Rb} are the number of laboratories in group 1, 2 and 3, respectively. It is possible that when computing (12) that some weights will exceed 40%. To prevent that occurrence, weights are rescaled as follows. Consider the next set of weights

$$\Omega^a_{\text{Scales}} = \left\{\omega_{k_1}, \omega_{k_2}, \ldots, \omega_{k_n}\right\} \subset \Omega_{\text{Scales}} \tag{14}$$

where $k_n \leq N_{\text{Scales}}$. We will write $\omega_{k_i} = \omega_{\text{Scales}} + \delta\omega_{k_i}$ with $i = 1, 2, \ldots, n$ and where $\delta\omega_{k_i} \geq 0$ where $\omega_{\text{Scales}} = 40\%$.

Now, we define

$$\delta\omega_{\text{Scales}} = \sum_{\omega_i \in \Omega^a_{\text{Scales}}} \delta\omega_i. \tag{15}$$

Let Ω^b_{Scales} be the complement of Ω^a_{Scales}, i.e., $\Omega^a_{\text{Scales}} \cap \Omega^b_{\text{Scales}} = 0$ and $\Omega^a_{\text{Scales}} \cup \Omega^b_{\text{Scales}} = \Omega_{\text{Scales}}$. Then, for each weight $\omega_i \in \Omega^b_{\text{Scales}}$, the next ratio is computed as follows:

$$r_i = \frac{\omega_i}{\sum\limits_{\omega_j \in \Omega^b_{\text{Scales}}} \omega_j}. \tag{16}$$

Finally, weights in sets Ω^a_{Scales} and Ω^b_{Scales} are transformed as follows, respectively:

$$\omega_{k_\alpha} \to \omega^f_{k_\alpha} = \omega_{\text{Scales}} = 40\% \tag{17}$$

$$\omega_{k_\beta} \to \omega^f_{k_\beta} = \omega_{k_\beta} + r_{k_\beta}\delta\omega_{\text{Scales}}.$$

If some of the new weights $\omega^f_{k_\alpha}$ are >40%, the process is repeated. Similarly, weights for group 2 are also rescaled.

SIMT is calculated every hour at minute 20 with data of minute 0, and the time differences between SIMT and each contributing clock are published on the web site at minute 30. The process is completely automated, and no human intervention is needed for the computation and dissemination of SIMT.

IV. SIMT Generation

As of December 2012, four local SIMTs are generated by multiclock ensembles; located in Brazil Observatorio Nacional de Rio de Janeiro (ONRJ), Canada (NRC), Mexico (CENAM), and the United States (NIST). These clocks form group 1, and are allowed to have a weight as large as 40% in the SIMT computation. The single-clock time scales, are allowed to have a weight as large as 10%, if they meet the group 2 requirement of having a cesium clock. Six local SIMTs are currently in group 2; Argentina Instituto Nacional de Tecnología Industrial (INTI), Columbia Secretaría de Industria y Comercio (SIC), Costa Rica Instituto Costarricense de Electricidad (ICE), Jamaica Bureau of Standards of Jamaica (BSJ), Panama Centro Nacional de Metrología de Panamá (CNMP), and Peru Servicio Nacional de Metrología (SNM). The remaining local SIMTs currently consist of single rubidium clocks (in some cases disciplined to an external reference). These time scales are not allowed to contribute to the SIMT computation.

Fig. 1 shows the SIMT generation process. It is important to remember (as noted previously) that each clock that contributes to SIMT is actually a local SIMT(k) time scale, which includes one or more actual clocks. The solid lines represent the comparisons among clocks [the SIMT(k) time scales] through the SIMTN to a pivot laboratory. New results are available every 10 min. The software allows any SIM NMI to be selected as the pivot. The dashed lines represent

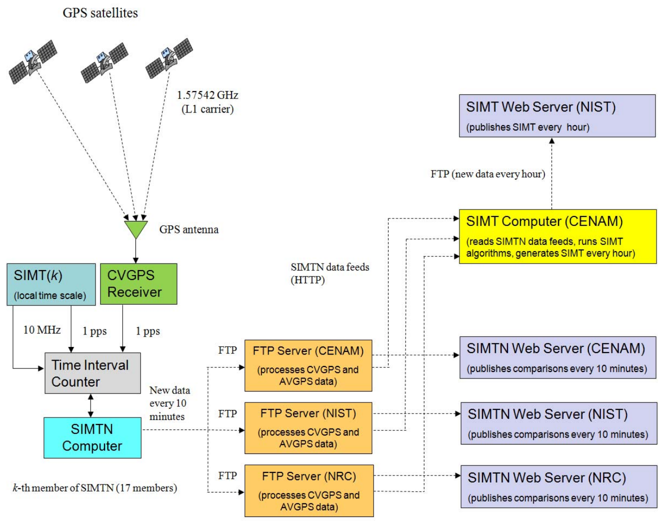
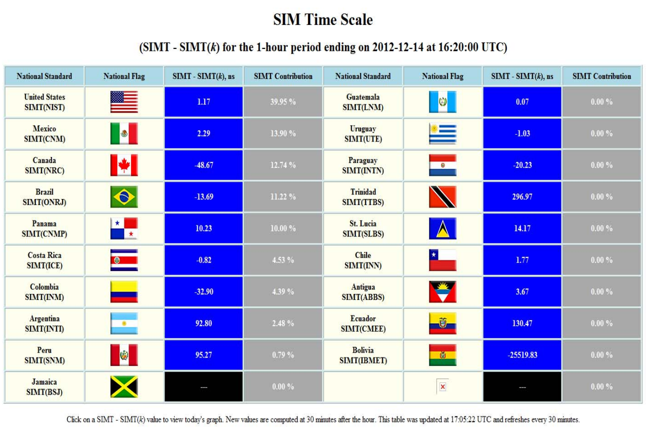


Fig. 1. Block diagram of SIMT generation.



SIM Time Scale

(SIMT - SIMT(k) for the 1-hour period ending on 2012-12-14 at 16:20:00 UTC)

National Standard	National Flag	SIMT - SIMT(k), ns	SIMT Contribution	National Standard	National Flag	SIMT - SIMT(k), ns	SIMT Contribution
United States SIMT(NIST)		1.17	39.95 %	Guatemala SIMT(LNM)		0.07	0.00 %
Mexico SIMT(CNM)		2.29	13.90 %	Uruguay SIMT(UTE)		-1.03	0.00 %
Canada SIMT(NRC)		-48.67	12.74 %	Paraguay SIMT(INTN)		-20.23	0.00 %
Brazil SIMT(ONRJ)		-13.69	11.22 %	Trinidad SIMT(TTBS)		296.97	0.00 %
Panama SIMT(CNMP)		10.23	10.00 %	St. Lucia SIMT(SLBS)		14.17	0.00 %
Costa Rica SIMT(ICE)		-0.82	4.53 %	Chile SIMT(INN)		1.77	0.00 %
Colombia SIMT(INM)		-32.90	4.39 %	Antigua SIMT(ABBS)		3.67	0.00 %
Argentina SIMT(INTI)		92.80	2.48 %	Ecuador SIMT(CMEE)		130.47	0.00 %
Peru SIMT(SNM)		95.27	0.79 %	Bolivia SIMT(IBMET)		-25519.83	0.00 %
Jamaica SIMT(BSJ)		---	0.00 %			---	0.00 %

Click on a SIMT - SIMT(k) value to view today's graph. New values are computed at 30 minutes after the hour. This table was updated at 17:05:22 UTC and refreshes every 30 minutes.

Fig. 2. Real-time grid for SIMT dissemination.

the comparisons of the local SIMT(k) scales with SIMT. The dashed lines also represent the virtual character of the SIMT(k) – SIMT comparisons. As is the case with UTC, SIMT is a virtual time scale and produces no physical signal.

SIMT has been generated as an operational time scale since January 2010, although software changes have been made when necessary to improve reliability and performance. The time differences between all local SIMT time scales and SIMT, SIMT(k) – SIMT, are published every hour (http://tf.nist.gov/sim) even if the local time scale does not contribute to SIMT. The SIMT grid (Fig. 2) shows the SIMT(k) – SIMT time difference for every laboratory that is currently sending data via the SIMTN. It also shows the percentage weight that each local time scale is currently contributing to SIMT.

V. RESULTS

This section presents SIMT data collected during a 350-day interval, from December 5, 2011 [55900 Modified Julian Date (MJD)] to November 19, 2012 (56250 MJD). To evaluate SIMT performance, we compared SIMT with the six

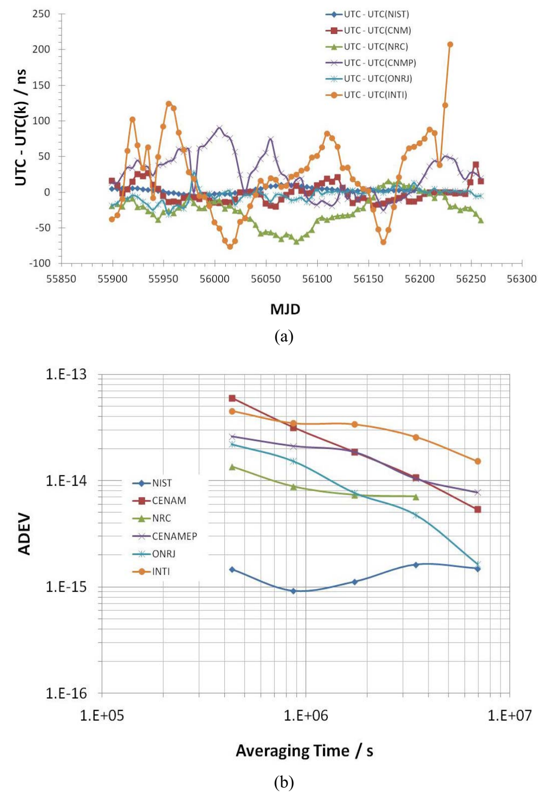


Fig. 3. (a) Time differences of the six SIM NMIs that contribute to both SIMT and UTC. (b) Frequency stability of the six SIM NMIs that contribute to both SIMT and UTC.

SIMT(k) time scales that also contribute to the UTC calculation. These time scales (listed alphabetically by acronym) are located at CENAM in Mexico, Centro Nacional de Metrología de Panamá (CENAMEP) in Panama, INTI in Argentina, NIST in the United States of America, NRC in Canada, and ONRJ in Brazil. To show the performance of these time scales, Fig. 3(a) shows the time differences of each scale at five-day intervals, as published by the BIPM in its monthly Circular T document. The time differences are an indication of accuracy, and Fig. 3(b) shows the corresponding frequency stability.

As shown in Fig. 3, the NIST time scale is the most accurate and stable time scale in the SIM region. The time differences and frequency stability of the NIST time scale with respect to both SIMT and UTC are shown in Fig. 4(a). The blue line corresponds to the UTC – UTC(NIST) time differences as published in Circular T. The green line represents the time differences of SIMT – SIMT(NIST) with one point every hour. The red line is the 5-day average of the SIMT – SIMT(NIST) values that are computed to align with the Circular T data. The stability graph in Fig. 4(b) shows that the stability of the SIMT – SIMT(NIST) comparisons is about one order of magnitude worse than the stability of the UTC – UTC(NIST) comparisons at $\tau = 5$ days (120 h), and remains a factor of three worse at $\tau = 1000$ h. The short-term stability is not shown in the graph, but the stability of SIMT with respect to SIMT(NIST) is $\sim 2 \times 10^{-13}$ at $\tau = 1$ h, improving by about one order of magnitude at $\tau = 1$ day. The weight contributed to SIMT by SIMT(NIST) is typically near 40%, the maximum weight allowable. The stability

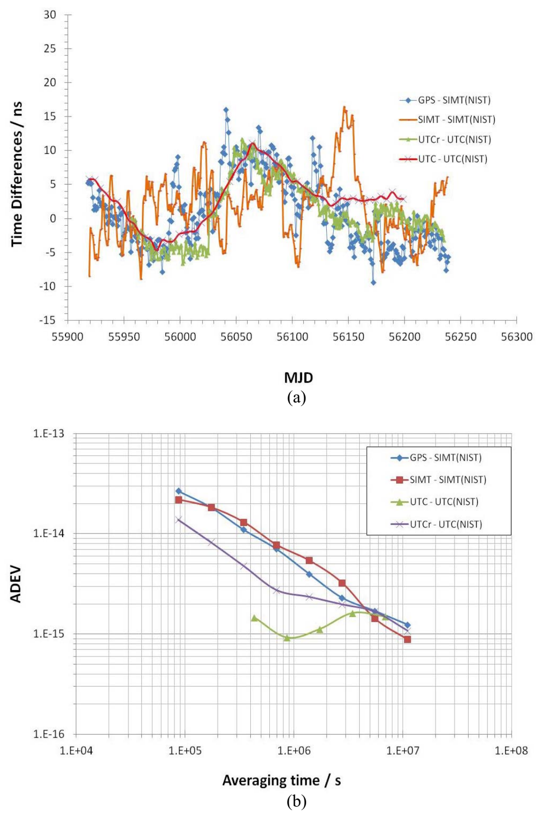


Fig. 4. (a) Time differences of the NIST time scale with respect to SIMT and UTC. (b) Frequency stability of the NIST time scale with respect to SIMT and UTC.

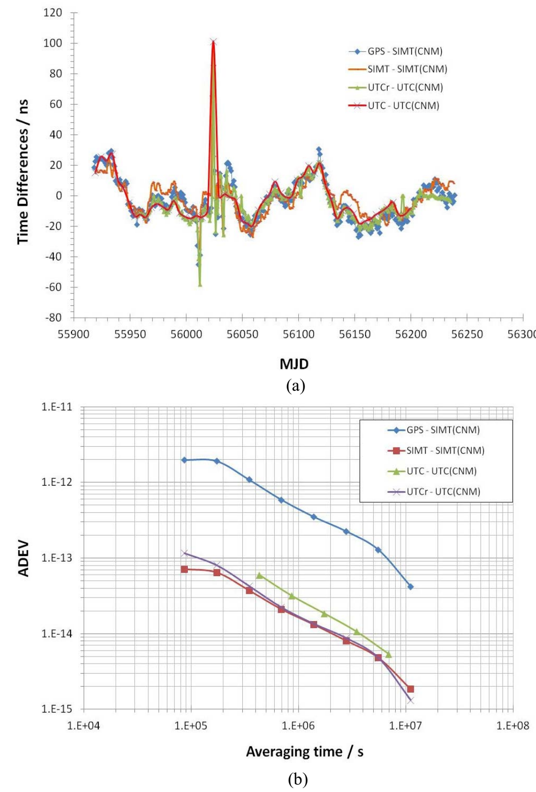


Fig. 5. (a) Time differences of the CENAM time scale with respect to SIMT and UTC. (b) Frequency stability of the CENAM time scale with respect to SIMT and UTC.

of SIMT would improve if this arbitrary weight restriction was increased, but it would make SIMT more dependent upon the contributions of a single clock, defeating one of our design objectives.

Time differences and frequency stability graphs for CENAM, NRC, CENAMEP, INTI, and ONRJ, as compared with both SIMT, UTC and rapid UTC (UTCr) [16], are shown in Figs. 5–8, respectively. Each figure follows the same convention. The blue line represents SIMT − SIMT(k) with one data point every hour. The red line represents the 5-day average of SIMT − SIMT(k), and the green line represents UTC − UTC(k) as published in Circular T. It is noticeable from these figures that the SIMT − SIMT(k) time differences are in close proximity to UTC − UTC(k) for the same time scale. The frequency stabilities of the two comparisons are also in close agreement, with the exception (Fig. 8) of the comparisons involving the NRC time scale. Here, the frequency stability of UTC − UTC(NRC) shows better stability than the stability of the SIMT − SIMT(NRC) at $\tau = 5$ days by about a factor of two, but converges at longer averaging periods.

The results shown in Figs. 4–9 suggest that SIMT serves as a nearly equivalent reference to UTC for stability measurements for most SIM NMIs. UTC, the official world time scale, has many technical advantages that make it more stable than SIMT, including more clocks, lower noise time transfer links, and frequency corrections that are applied from cesium fountain primary standards. The performance

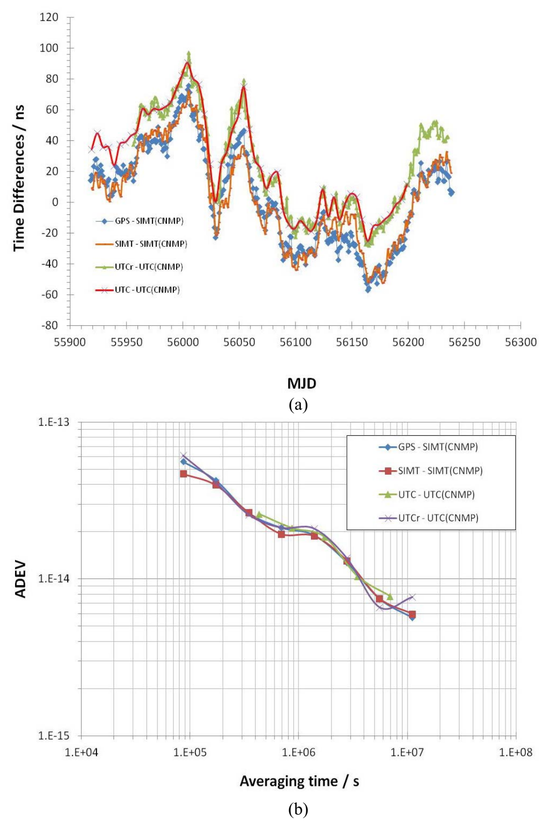


Fig. 6. (a) Time differences of the CENEMEP time scale with respect to SIMT and UTC. (b) Frequency stability of the CENAMEP time scale with respect to SIMT and UTC.

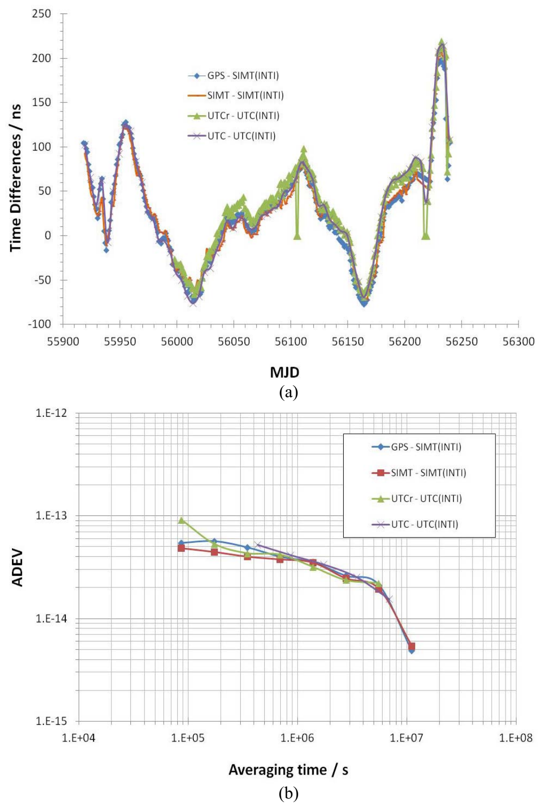


Fig. 7. (a) Time differences of the INTI time scale with respect to SIMT and UTC. (b) Frequency stability of the INTI time scale with respect to SIMT and UTC.

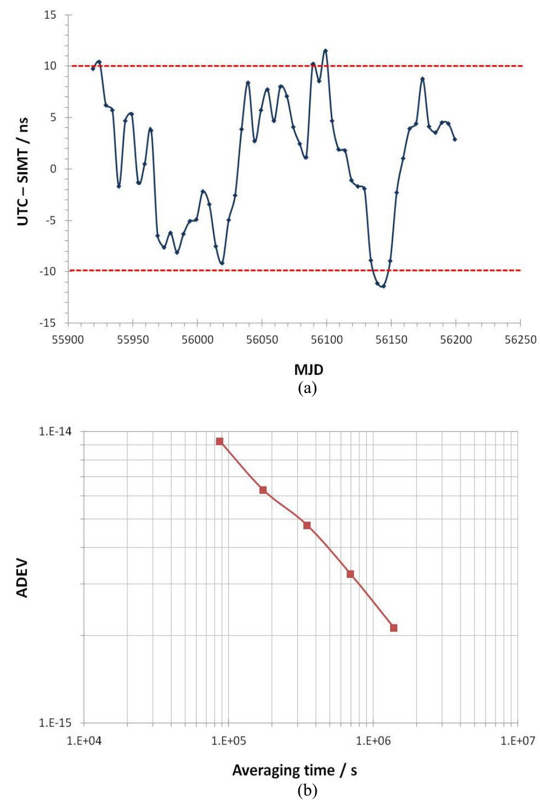


Fig. 9. (a) UTC–SIMT time difference. (b) Frequency stability of the UTC–SIMT time differences.

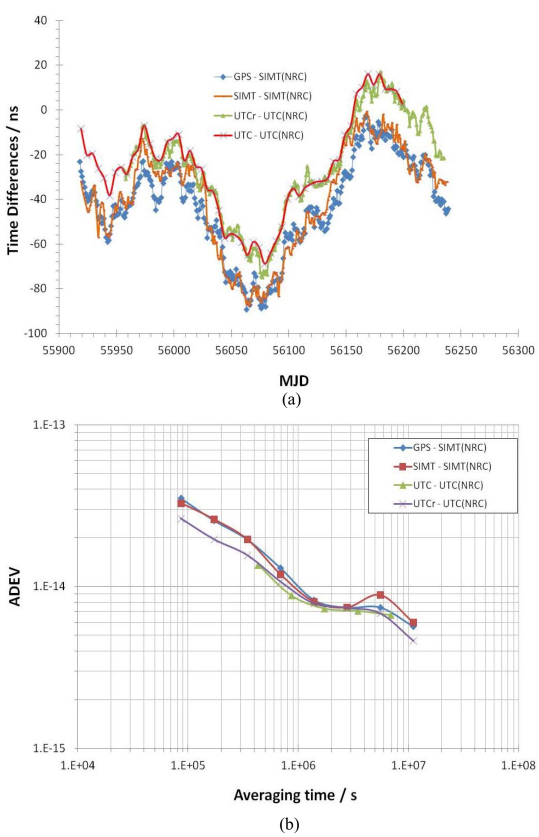


Fig. 8. (a) Time differences of the NRC time scale with respect to SIMT and UTC. (b) Frequency stability of the NRC time scale with respect to SIMT and UTC.

advantages of UTC are most obvious in the NIST comparison (Fig. 4). Note, however, that some of the advantages of UTC are indirectly passed to SIMT, through the contributions of SIMT(k) time scales that are being periodically steered to agree with UTC. This ensures homogeneity between the work done by SIM and the work of the BIPM.

SIMT also provides a reasonably good approximation for the accuracy of UTC. Fig. 9(a) shows UTC − SIMT time differences that were computed using the NIST and CENAM time scales as common clocks for the 500-day interval from MJD 55400 to MJD 55900. For example, a point using NIST as the common clock is computed as [SIMT − SIMT(NIST)] − [UTC − UTC(NIST)]. Values are shown every five days to match the reporting interval of the Circular T. As shown by the dashed lines, the difference between the two time scales is usually within ± 15 ns. Fig. 9(b) shows that the stability of the comparison is $\sim 1 \times 10^{-14}$ at $\tau = 10$ days, averaging down as a white noise process to $\sim 1 \times 10^{-15}$ at $\tau = 100$ days. Note that even though SIMT(k) and UTC(k) are equivalent at their source in the case of both CENAM and NIST, different time transfer links are employed to contribute to SIMT and UTC, respectively, and that the differences in calibration and transfer noise between these links influences the Fig. 9 results. Both CENAM and NIST use the SIMTN to contribute to SIMT, but CENAM uses the GPS all-in-view multichannel technique to contribute to UTC, whereas NIST contributes to UTC via two-way satellite time and frequency transfer.

VI. Operational Considerations of SIMT

We are working to improve all aspects of SIMT reliability. The reliability of SIMT depends upon several factors, including the reliability of the SIMT software, the reliability of the local time scales, and the reliability of Internet servers and the network itself. On numerous occasions, a local SIM scale has stopped sending data because of a time scale failure or a network outage. These outages can last for hours or days, but SIMT will continue to be generated as long as a sufficient number of clocks are available. The SIMTN data feed at a given location has also failed at times, but it is available from three servers (at CENAM, NIST, and NRC), and has never simultaneously failed at all three sites. The SIMT software has failed on occasion because of programming errors, or when encountering situations that had not previously arisen (either with the clock data or with the network connections), but SIMT has become a more reliable time scale with each software revision. In fact, SIMT is now being used to discipline group 3 three rubidium clocks at SIM NMIs located in Antigua, Paraguay, Saint Lucia, and Bolivia. Thus, SIMT disciplined devices now serve as national standards of frequency and time in several nations.

VII. Conclusion

The SIMT is continuously generated from automated comparisons of time standards in North, Central, and South America, and is believed to be the first multinational time scale whose results are published in real time via the Internet. SIMT is not a substitute for UTC. Instead, its role is to complement UTC within the SIM region by providing real-time support to the operational timing and calibration systems. SIMT is sufficiently stable to measure the stability of most SIM local time scales and provides a good approximation of UTC timing accuracy ($\pm$10 ns). The reliability, accuracy, and stability of SIMT are expected to continue to improve.

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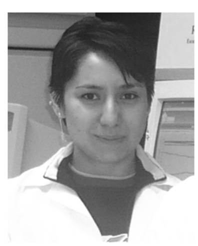

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