Comparison of the Multinational SIM Time Scale to UTC and UTCr

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***Abstract*— The Sistema Interamericano de Metrología (SIM) is one of the world's five major regional metrology organizations (RMOs) recognized by the International Committee for Weights and Measures (CIPM). To allow SIM National Metrology Institutes (NMIs) to track the performance of their time and frequency standards in almost real-time, the SIM Time and Frequency Metrology Working Group (SIM TFWG) established the SIM Time Network (SIMTN) in 2005. As of 2019, 26 SIM nations participate in the SIMTN. Since 2008, the SIM TFWG has produced the SIM Time Scale (SIMT), a multinational ensemble computed every hour from time difference measurements collected by the SIMTN every 10 min. The SIMT, the first continuously maintained multinational ensemble time scale that is generated and published in near real-time, complements the world's official time scale, Coordinated Universal Time (UTC), by providing real-time support to the operational timing and calibration laboratories at SIM NMIs. The SIMT provides a real-time approximation of UTC with a timing uncertainty near 10 ns. In this article, we present an SIMT evaluation based on data from November 2016 to June 2018 by comparing SIMT performance to that of UTC and rapid UTC (UTCr). We discuss the performance differences between the SIMT, UTC, and UTCr and how that time scales are used in the SIM region.**

***Index Terms*— Atomic clocks, international comparisons, time, time scales.**

I. Introduction

THE generation, measurement, and distribution of accurate time are essential for many strategic infrastructures and systems, including global navigation satellite systems (GNSS), communication networks, electric power grids, transportation systems, financial institutions, stock exchanges, and national defense and security. In developed societies, time is perhaps the most often measured physical quantity and it can be measured with the smallest uncertainty compared with any other physical quantity.

The importance of keeping time in a uniform, consistent, and agreed-upon fashion has long been recognized. Local time scales and timekeeping conventions were originated centuries ago to support commerce and transportation systems [1]. Time scales that were used internationally date back to Greenwich Mean Time (GMT), an astronomical time scale based on the prime meridian at the Royal Observatory Greenwich in London, England. In 1880, GMT was legally adopted as the official time of Great Britain, and numerous other nations legally recognized GMT as official time during the next few decades. Beginning in 1928, at the recommendation of the International Astronomical Union (IAU), GMT became known as Universal Time (UT). Several improved-upon versions of UT, including UT1 and UT2, were in use prior to the advent of atomic timekeeping [2], [3].

The invention of atomic clocks, which first appeared in the late 1940s, soon led to atomic time scales that were far more accurate and stable than the astronomical time scales that preceded them. Coordinated UT (UTC) was a name first used in the early 1960s to refer to an international time scale based on the use of atomic clocks. However, neither atomic time nor our current UTC was internationally accepted that time. In 1967, the International System (SI) second was redefined as 9 192 631 770 periods of the electromagnetic radiation associated with the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom, and 1972 was when the world's current system for keeping official time went into practice; the use of UTC was corrected periodically with integer leap seconds to keep it in phase with astronomical time scales [4].

The Bureau International des Poids et Mesures (BIPM) is the organization responsible for maintaining and disseminating UTC [5]. As of 2019, a total of 83 timing laboratories located in 62 nations contribute data to UTC [6]. The BIPM organizes a key comparison between the atomic time standards of these laboratories and generates UTC from the collected data. The comparisons are based on either passive reception of GNSS time signals or methods involving geostationary satellites that require laboratories to both transmit and receive time signals,

Manuscript received June 11, 2019; revised August 8, 2019; accepted September 10, 2019. Date of publication September 27, 2019; date of current version June 9, 2020. The work of J. M. López-Romero and E. de Carlos-López was supported by CONACyT-Mexico through SNI grants. The work of C. A. Ortiz was supported by Ph.D. grant. The Associate Editor coordinating the review process was Jingyu Hua. *(Corresponding author: J. M. López-Romero.)*

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Digital Object Identifier 10.1109/TIM.2019.2943991

a technique known as two-way satellite time and frequency transfer (TWSTFT). The BIPM publishes the comparison results as the time difference between UTC and each participating laboratory, a measurement known as UTC – UTC(k), in its *Circular T* document. The *Circular T* has been published monthly since 1988 and provides the measurement results at 5-day intervals. In 2013, the BIPM began the weekly publication of rapid UTC (UTCr). The UTCr – UTC(k) measurement results are provided at 1-day intervals [7].

In addition to maintaining UTC based on its key comparison, the BIPM supports supplementary comparisons performed by regional metrology organizations (RMOs). Because their sphere of influence is smaller, the RMOs can often spend more time supporting and working with individual timing laboratories than the BIPM's resources allow. Both the RMOs and BIPM work continuously toward the same goal, which is ensuring worldwide uniformity of measurements by having as many nations as possible establish measurement traceability to the SI.

The largest RMO in terms of geographic area is the Sistema Interamericano de Metrología (SIM), which covers about 27% of the Earth's land mass. It includes the 35 member nations of the Organization of American States (OAS), which are located in North, Central, and South America, and the Caribbean Islands. The SIM Time and Frequency Metrology Working Group (SIM TFWG) has been active since 2005 and developed both the SIM Time Network (SIMTN) and SIM Time Scale (SIMT) to encourage and promote uniformity of measurements in time and frequency throughout the Americas. The goal of this article is to discuss the usefulness of the SIMT, a unique multinational time scale produced in real-time, and demonstrate its metrological robustness by comparing its performance to that of UTC and UTCr. We begin with a technical description of the SIMT in Section II. Then, in Section III the performance of the SIMT is compared with UTC and UTCr. Finally, we present a summary and conclusion in Section IV.

II. SIM Time Scale

The clock measurements that form the basis of the SIMT are collected by the SIMTN, which began operation in 2005. That year, real-time common-view Global Positioning System (CVGPS) clock comparisons began between the National Research Council (NRC) in Canada, the Centro Nacional de Metrología (CENAM) in Mexico, and the National Institute of Standards and Technology (NIST) in the USA [8], eventually expanding to its current total of 26 nations. The SIMTN differed from previous CVGPS networks, such as those that collect data for UTC, because the SIMTN measurements are processed and published (https://tf.nist.gov/sim) in near real-time, with new data made public every 10 min [9].

The work on the SIMT, the first multinational time scale whose results are published in near real-time, began in 2008, thus the year 2018 marked its ten-year anniversary. Designed to be a traditional ensemble time scale, the SIMT uses the time scales of SIM laboratories, each designated as SIMT(k), as individual clocks in the ensemble. As is the case with UTC, the output of the SIMT is based on a weighted average, where the sum of the weights of the individual clocks equals 100%. The maximum weight assigned to any SIMT(k) contributor is limited to 40%. The percentage weight of each clock, ω_i, is determined by considering both the inverse of its frequency stability as $1/\sigma_y(\tau)$, where $\sigma_y(\tau)$ is the Allan deviation (ADEV) of the clock at $\tau = 24$ h, and the frequency accuracy of the clock relative to the SIMT frequency. Prior to normalization, the clock weights are estimated as

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

where $\sigma_i(\tau)$ is the ADEV of clock i at $\tau = 24$ h, computed from the 1 h data points collected during the previous 10 days of the SIMTN data, a period deemed long enough to minimize the influence of time transfer noise, and 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. More details are provided in [10]. The weights assigned to the SIMT contributors are updated daily (every 24 h) and published on the website in the interest of full transparency.

In addition, the SIMT will automatically remove a clock from the ensemble if it stops sending data, or if the clock's stability or accuracy is worse than expected. The clocks are monitored by measuring their frequency stability over a 1 h interval. The frequency stability measurement is performed by comparing an individual clock i with the SIMT and the other clocks in the ensemble, and then using the results to help isolate an unstable clock from the others. The required stability is about 7×10^{-12} at $\tau = 1$ h. The instability specifications for low-performance commercial cesium clocks are typically 3×10^{-12} at $\tau = 1$ h, or about a factor of 2 smaller than this requirement. Inaccurate clocks are identified as clocks that differ by more than 25 ns from their expected value. If a clock is known to be unstable or inaccurate, or if a clock stops sending data, its weight is immediately set to 0 and the clock is dropped from the SIMT computation. 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 been normal for at least 27 h. During the first 24 h, the clock is monitored to ensure that it is again behaving normally. Then, the algorithm examines data from the next 3 h to compute the clock's time difference with respect to the SIMT before returning it to the ensemble. These features allow the SIMT to be fully automated and to run unattended without any need for human interaction or for manual adjustments [10]–[12].

Resources among SIM National Metrology Institutes (SIM NMIs) vary widely, and thus not all SIM timing laboratories are able to contribute to the SIMT. Contributions are only accepted from laboratories that have the resources to operate cesium clocks and/or hydrogen masers, a group that currently includes 11 laboratories. Nine of the SIMT contributors also contribute to UTC, with the other two preparing to contribute soon. Most of the remaining SIMT(k) laboratories operate rubidium clocks as their national time standard. In many cases, these rubidium clocks receive hourly corrections via

TABLE I
SIMTN MEMBERS

Nation	Laboratory Acronym	Contributes To SIMT	Locks to SIMT
Antigua and Barbuda	ABBS		✓
Argentina	INTI	✓	
Bahamas	BBSQ		
Belize	BBS		✓
Bolivia	IBMETRO	✓	
Brazil	ONRJ	✓	
Canada	NRC	✓	
Chile	INN		✓
Colombia	INM	✓	
Costa Rica	ICE	✓	
Dominican Republic	INDOCAL		✓
Ecuador	CMEE		
El Salvador	CIM		✓
Guatemala	LNM		
Guyana	GNBS		✓
Haiti	BHN		
Jamaica	BSJ		
Mexico	CENAM	✓	
Panama	CENAMEP	✓	
Paraguay	INTN		✓
Peru	INCP	✓	
St. Kitts and Nevis	SKBS		✓
St. Lucia	SLBS		✓
Trinidad and Tobago	TTBS		
United States of America	NIST	✓	
Uruguay	UTE	✓	

the Internet, based on the measurements of SIMT – SIMT(k). These corrections are automatically applied to their time standard to keep it locked to the SIMT [13]. Thus, the SIMT is useful in several ways. It can monitor the performance of any SIMT(k) laboratory in real-time and serve as an easily accessible reference for calibration and time dissemination systems. It can also discipline oscillators and clocks and serve as an operational timing system that is shared throughout the SIM region. Table I lists (alphabetically by nation) the timing laboratories that send data to the SIMTN. It also indicates whether these laboratories contribute data to the SIMT or lock their time standards to the SIMT. Section III provides data that compare the accuracy and stability of the SIMT to both UTC and UTCr.

III. SIMT Performance Compared With UTC and UTCr

We evaluated the time accuracy and frequency stability of the SIMT by simultaneously comparing the local time scales of five SIM nations to the international SIMT, UTC, and UTCr scales, essentially using the local time scales as common clocks. The five local time scales, listed alphabetically by nation, are located at the National Observatory of Rio de Janeiro (ONRJ) in Brazil, at NRC in Canada, at CENAM in Mexico, at the Centro Nacional de Metrología de Panamá (CENAMEP) in Panama, and at NIST in the USA. Each of these five local time scales contributes to UTC, UTCr, and SIMT, making it possible in each case to obtain measurements of UTC – UTC(k), UTCr – UTC(k), and SIMT – SIMT(k).

The same 1-pps timing signal from the local time scale serves as UTC(k) and SIMT(k) at each of the five laboratories. Thus, there are no differences in the source that is being measured, but there are some important differences in how the measurements are made. First, the SIMT produces a data point at 1-h intervals, as opposed to 1-day intervals for UTCr and 5-day intervals for UTC. Thus, the SIMT data display more dispersion and scatter than the UTC and UTCr data, where short-term data are not available. Second, the SIMT does not issue corrections for the ionosphere or the satellite orbits to the collected time transfer data. For example, the clock comparison data collected for SIMT are obtained via the CVGPS method used by the SIMTN, which uses low-cost single-frequency GPS receivers that do not measure ionospheric delay nor issue any post-processed corrections. Instead, they simply apply the broadcast ionospheric delay model in real-time to every satellite in view. This limits the performance of the SIMT, but not that significantly when 1-day averages are used. For example, for a 10-min average satellite track, the difference between the Klobuchar model and the measured ionospheric delay can sometimes exceed 10 ns, with the worst case being about 20 ns for a satellite that is very close to the horizon ($\sim 10°$ in elevation) during the daytime hours. However, when all satellites in view are averaged for 24 h, as is the case when the daily values of the SIMT and UTCr are compared, the difference between the modeled and measured ionospheric delay is less than 5 ns, with ~ 2 ns being typical. Third, the time transfer equipment used by each of the five laboratories to contribute data to UTC and UTCr is more sophisticated, with smaller measurement uncertainties than the low-cost time transfer equipment used to contribute data to the SIMT. Multifrequency GPS time transfer receivers are in use at CENAM, CENAMEP, NRC, and ONRJ, and the NIST submits its BIPM key comparison data via TWSTFT. The single-frequency SIMTN time transfer systems are typically less stable than the time transfer systems used for the BIPM key comparison and may also differ in their delay calibrations. Finally, the SIMT has access to measurements of far fewer clocks than UTC or UTCr. As indicated in Table I, only 11 laboratories contribute to the SIMT as opposed to 83 for UTC.

A. Use of SIMT for the Evaluation of UTC (CNMP)

With the above factors in mind, we began our evaluation by comparing UTC (CNMP), the national time scale of Panama, to SIMT, UTC, and UTCr (see Fig. 1). The time difference results are shown for the period from 12/30/2016 to 06/13/2018. The SIMT – SIMT (CNMP) comparison agrees well with the UTC and UTCr comparisons, with a slightly larger range and dispersion. This indicates the usefulness of the SIMT as a real-time monitor of the performance of the CNMP time scale. The weight contribution of the CNMP time scale to the SIMT typically ranges from 6% to 7%, whereas its contribution to UTC is small, about 0.1%. The ADEV,

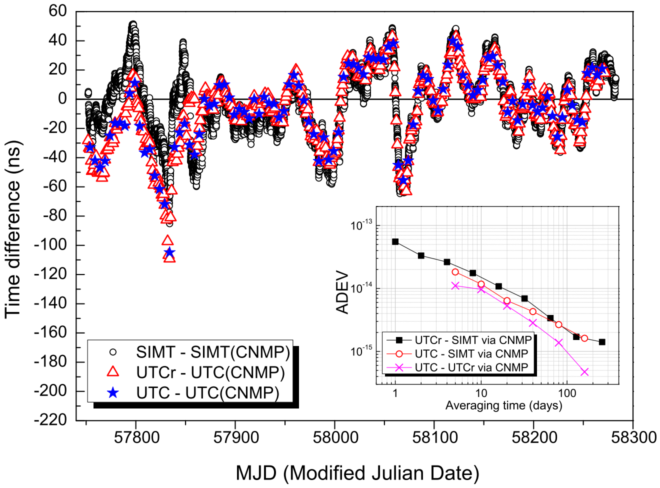

Fig. 1. Time differences of the CENAMEP AIP time scale compared with UTC, UTCr, and SIMT (12/30/2016 to 6/13/2018). Inset: Frequency instability (ADEV) of the SIMT with respect to UTC and UTCr via the CENAMEP AIP time scale.

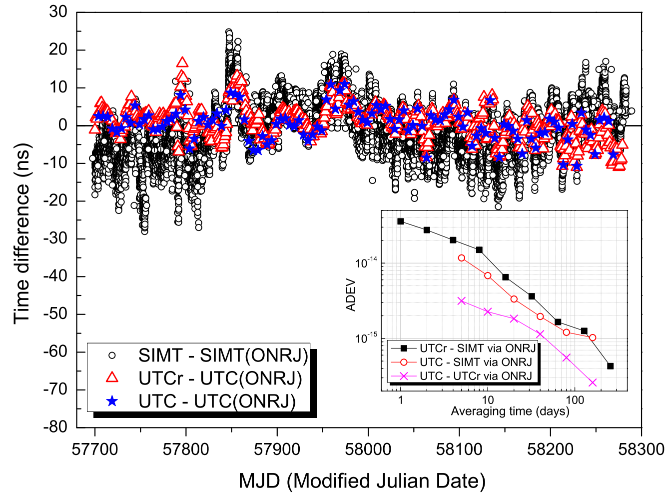

Fig. 2. Time differences of the ONRJ time scale compared with UTC, UTCr, and SIMT (11/8/2016 to 6/13/2018). Inset: Frequency instability (ADEV) of the SIMT with respect to UTC and UTCr via the ONRJ time scale.

$\sigma_y(\tau)$, [14] is used as a standard estimator of frequency stability. At $\tau = 5$ days, when a UTC comparison becomes possible, the instability of the CNMP time scale is essentially the same when compared with all three time scales: 3.69×10^{-14} with respect to UTC, 3.68×10^{-14} with respect to SIMT, and 3.77×10^{-14} with respect to UTCr. Therefore, we conclude that the SIMT essentially works as well as UTC when evaluating CNMP stability at $\tau = 5$ days. The inset of Fig. 1 compares the frequency stability of the SIMT to UTC and UTCr using the CNMP time scale as a common clock. Note that the low noise floor of the UTC – UTCr comparison reflects the strong correlation between those two time scales. The UTC and UTCr comparisons to the SIMT have a slightly higher noise floor, as the SIMT is not as tightly correlated with UTC and UTCr as they are to each other.

B. Use of SIMT for the Evaluation of UTC (ONRJ)

Fig. 2 shows the time difference and frequency stability comparisons to SIMT, UTC, and UTCr, for UTC (ONRJ), the national time scale of Brazil. The comparisons were for the period from 11/08/2016 to 06/13/2018. The weight contribution of the ONRJ time scale to the SIMT typically ranges from 10% to 17%, whereas its contribution to UTC is typically near 0.5%. Fig. 2 also indicates that the SIMT – SIMT (ONRJ) comparison has a relatively large range of about ±25 ns, but also indicates that the UTC and UTCr comparisons fall within its coverage area. At $\tau = 5$ days, when a UTC comparison becomes possible, the instability of the ONRJ time scale is identical when compared with UTC and UTCr, 1.17×10^{-14}, but slightly higher when compared with the SIMT, 1.62×10^{-14}, indicating that the SIMT instability is contributing to the result. The evidence of this is provided in the inset of Fig. 2, which compares the frequency stability of the SIMT to UTC and UTCr using the ONRJ time scale as a common clock. At $\tau = 5$ days, the instability of SIMT with respect to UTC is 1.2×10^{-14}, or roughly equivalent to

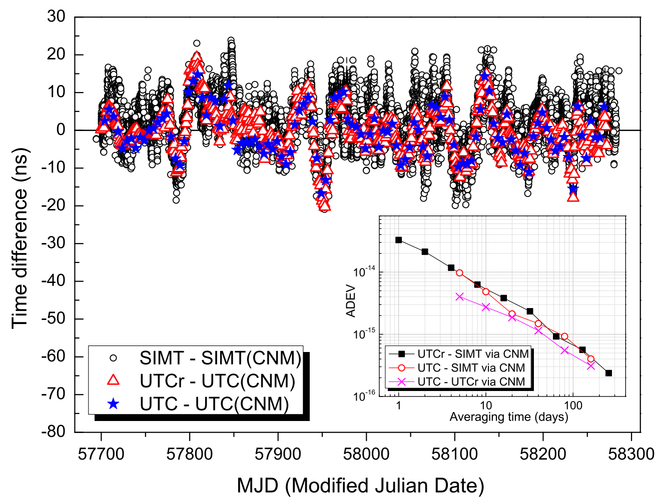

Fig. 3. Time differences of the CNM time scale compared with UTC, UTCr, and SIMT (11/8/2016 to 6/13/2018). Inset: Frequency instability (ADEV) of the SIMT with respect to UTC and UTCr via the CNM time scale.

the stability of the ONRJ time scale when it is also compared with UTC.

C. Use of SIMT for the Evaluation of UTC (CNM)

Fig. 3 shows the time difference and stability comparisons to SIMT, UTC, and UTCr, for UTC (CNM), the national time scale of Mexico.

The comparisons were for the period from 11/08/2016 to 06/13/2018. The weight contribution of the CNM time scale to the SIMT typically averages about 12%, whereas its contribution to UTC is typically in the range of 0.5%–1%. Fig. 3 indicates that the range of SIMT – SIMT (CNM) is about ±20 ns and shows that the UTC and UTCr comparisons fall well within its coverage area. At $\tau = 5$ days, when a UTC comparison becomes possible, the instability of the CNM time scale is 1.25×10^{-14} and 1.30×10^{-14}, respectively, when compared with UTC and UTCr, and insignificantly higher (by

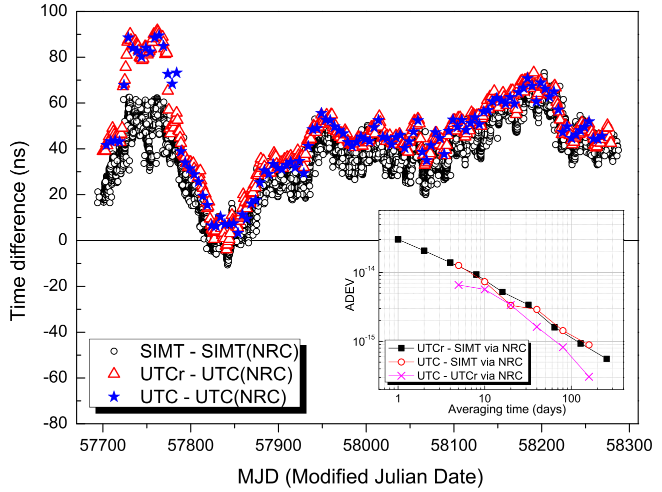

Fig. 4. Time differences of the NRC time scale compared with UTC, UTCr, and SIMT (11/8/2016 to 6/13/2018). Inset: Frequency instability (ADEV) of the SIMT with respect to UTC and UTCr via the NRC time scale.

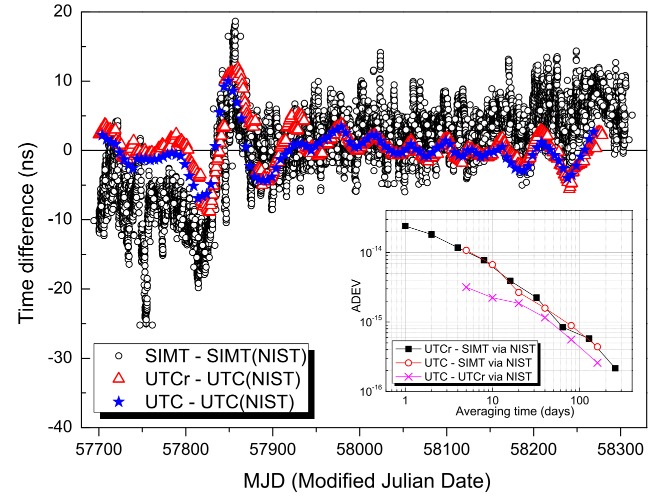

Fig. 5. Time differences of the NIST time scale compared with UTC, UTCr, and SIMT (11/8/2016 to 6/13/2018). Inset: Frequency instability (ADEV) of the SIMT with respect to UTC and UTCr via the NIST time scale.

$\sim$2 parts in 10^{15}) when compared with the SIMT, 1.45×10^{-14}. The inset of Fig. 3 compares the frequency stability of the SIMT to UTC and UTCr using the CNM time scale as a common clock. At $\tau = 5$ days, the instability of the SIMT with respect to UTC is 0.97×10^{-14}, or smaller than the stability of the CNM time scale when it is also compared with UTC.

D. Use of SIMT for the Evaluation of UTC (NRC)

Fig. 4 shows the time difference and stability comparisons to SIMT, UTC, and UTCr, for UTC (NRC), the national time scale of Canada, for the period from 11/08/2016 to 06/13/2018. The weight contribution of the NRC time scale to the SIMT is typically near 20%, whereas its contribution to UTC is typically near 0.5%. Fig. 4 shows the phase steps of $\sim$30 ns in the UTC – UTC (NRC) comparison (between MJD 57720 and MJD 57790) that are not present in the SIMT – SIMT (NRC) comparison. The anomaly was caused by a time transfer equipment problem. After this problem was corrected, the UTC, UTCr, and SIMT comparisons are in close agreement. At $\tau = 5$ days, when a UTC comparison becomes possible, the instability of the NRC time scale is smallest when compared with UTCr, or 1.28×10^{-14}, and higher when compared with UTC or SIMT, 1.41×10^{-14} and 1.58×10^{-14}, respectively. The inset of Fig. 4 compares the frequency stability of the SIMT to UTC and UTCr using the NRC time scale as a common clock. At $\tau = 5$ days, the instability of the SIMT with respect to either UTC or UTCr is identical, 1.26×10^{-14}, or essentially the same as the best estimate of the NRC time scale stability at the same interval.

E. Use of SIMT for the Evaluation of UTC (NIST)

Fig. 5 shows the time difference and stability comparisons to SIMT, UTC, and UTCr, for UTC (NIST), the national time scale of the USA, for the period from 11/08/2016 to 06/13/2018. The weight contribution of the NIST time scale to the SIMT typically ranges from 30% to 35%, whereas its contribution to UTC usually exceeds 5%.

Fig. 5 also shows that the range of the UTC – UTC (NIST) comparisons is at least a factor of 2 larger than the SIMT – SIMT (NIST) comparisons, but that the comparisons are in phase with each other and overlap. The inset of Fig. 5 compares the frequency stability of the SIMT to UTC and UTCr using the NIST time scale as a common clock. At $\tau = 5$ days, when a UTC comparison becomes possible, the instability of the NIST time scale is just 0.14×10^{-14} when compared with UTC and 0.32×10^{-14} when compared with UTCr, but more than a factor of 3 higher or 1.09×10^{-14} when compared with the SIMT. The inset of Fig. 5 compares the frequency stability of the SIMT to UTC and UTCr using the NIST time scale as a common clock. At $\tau = 5$ days, the instabilities of the SIMT with respect to either UTC or UTCr are almost identical, 1.08×10^{-14} and 1.06×10^{-14}, respectively, with both values being about the same as the SIMT – SIMT (NIST) result. This indicates that a stability comparison between SIMT (NIST) and SIMT at $\tau = 5$ days reports the instability of SIMT, rather than the instability of the NIST time scale.

F. Summary and Analysis of SIMT Performance

To summarize the time accuracy results, Fig. 6 shows the time differences between UTC and SIMT for the period from 11/12/2016 (MJD 57704) to 05/26/2018 (MJD 58264) with respect to CNM, CNMP, NRC, ONRJ, and NIST. With the notable exception of some anomalies recorded during the early part of this interval (cropped at 20 ns), nearly all comparisons show that the SIMT and UTC are within $\pm$10 ns of each other. Some of the differences appear to be systematic biases that can be attributed to the differences in delay calibrations of the separate time transfer systems that contribute data to UTC and SIMT.

The systematic biases could be potentially accounted for and removed by performing periodic relative delay calibrations between the UTC and SIMT time transfer systems, and then correcting the calibration of the inferior system so that the two

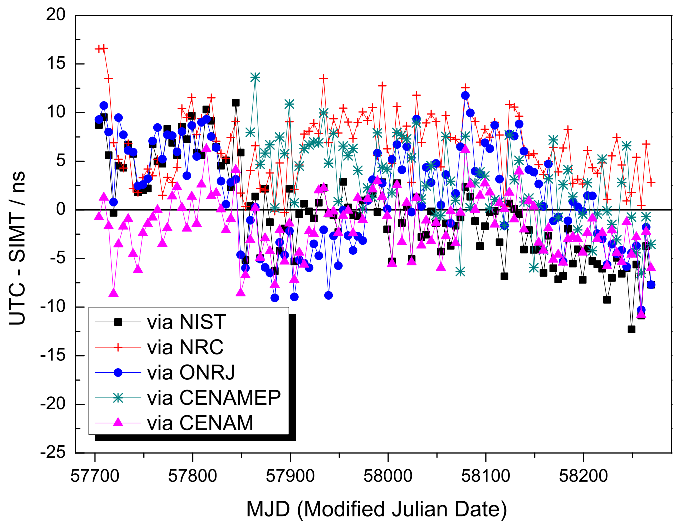

Fig. 6. Time difference comparisons between UTC and SIMT via CNM, CNMP, NRC, ONRJ, and NIST. Note: Some data from NRC and ONRJ were not included in this graph because they are not representative of the NRC and ONRJ time scales' performance.

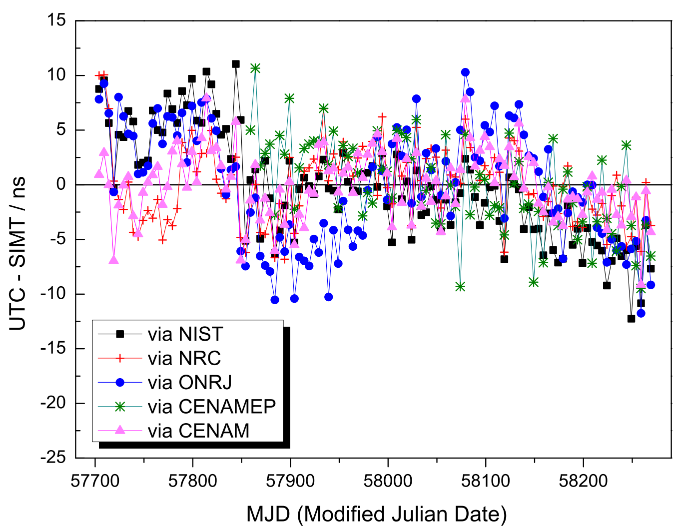

Fig. 7. Zeroing out the time differences in UTC – SIMT comparisons performed via several SIM laboratories. Offsets (in nanoseconds) of −0.3, 6.5, 1.4, 2.9, and −1.6 were removed from NIST, NRC, ONRJ, CNMP, and CNM data, respectively. Note: some data from NRC and ONRJ were not considered in this graph because they are not representative of the NRC and ONRJ time scales' performance.

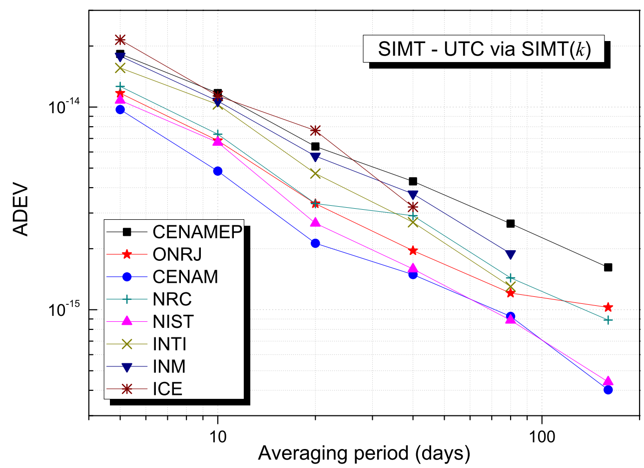

Fig. 8. Frequency instability of the SIMT with respect to UTC when compared via several SIM laboratories.

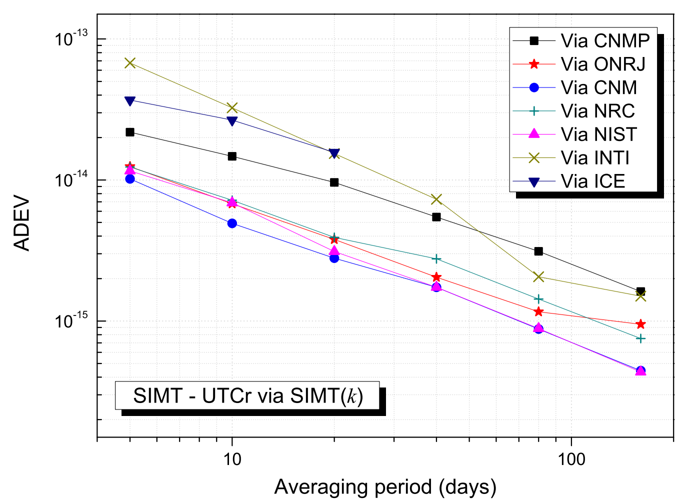

Fig. 9. Frequency instability of the SIMT with respect to UTCr when compared via several SIM laboratories.

systems agree. Relative delay calibration would be possible to perform at 9 of the 11 laboratories that contribute to the SIMT, because they also contribute to UTC; however, they are currently performed at only one or two laboratories. We plan to do a better job of conducting relative delay calibrations in the future.

When data shown in Fig. 6 are used to correct the systematic errors on the SIM GPS system calibrations, that is, when Fig. 6 is used to zero out the curves (see Fig. 7), the time offsets (in nanoseconds) are found for NIST, NRC, ONRJ, CNMP, and CNM: −0.3, 6.5, 1.4, 2.9, and –1.6, respectively. The instability of the SIM GPS receivers accounts for some of this variation, as their time deviation, $\sigma_x(\tau)$, at $\tau = 1$ day, typically ranges from 0.5 to 1.0 ns.

Figs. 8 and 9 summarize the frequency stability of the SIMT – UTC and SIMT – UTCr comparisons computed via several SIM laboratories (previously shown in the insets to Figs. 1–5). In both cases, the frequency stability estimates for the several SIM laboratories at $\tau = 5$ days are within a factor of 2.

Finally, Fig. 10 shows the frequency stability of the UTC – UTC(k) and SIMT – SIMT(k) time differences for CENAMEP, ONRJ, CENAM, NRC, and NIST for the period from 11/08/2016 to 06/13/2018. Fig. 10 also includes the frequency stability of SIMT – UTC when NIST is used as the pivot laboratory. As shown, this last frequency stability is better than the UTC – UTC(k) stability for $k \neq$ NIST.

To summarize the frequency stability results, we conclude that the stability estimates of the CNM, NIST, NRC, and ONRJ time scales performed with the SIMT as the reference would be limited by the stability of the SIMT at $\tau = 5$ days, the interval where the first UTC values are reported. These four local time scales are the primary contributors to the

TABLE II

AVERAGE VALUE OF UTC – UTC(k), UTCR – UTC(k), AND SIMT – SIMT(k) WHEN USING LOCAL SIMT AS COMMON CLOCK. ADEVS AT 5 DAYS OF THE TIME DIFFERENCES SIMT – UTC, SIMT – UTCR, SIMT – SIMT(k), UTC – UTC(k), UTCR – UTC(k). WEIGHTS OF EACH SIM LABORATORY IN SIMT AND UTC FORMATION

SIM Lab (k)	Average time offset value (ns) 500 days approx.			ADEV at 5 days ($\times 10^{-14}$)					Typical weight (%)	
	UTC - UTC(k)	UTCr - UTC(k)	SIMT - SIMT(k)	SIMT - UTC	SIMT - UTCr	SIMT - SIMT(k)	UTC - UTC(k)	UTCr - UTC(k)	UTC	SIMT
NIST	-0.18	0.47	-0.16	1.08	1.06	1.09	0.14	0.32	5.0	35.5
NRC	46.71	46.96	36.86	1.26	1.26	1.58	1.41	1.28	0.5	17.4
CNM	-0.47	0.01	1.20	0.97	1.06	1.46	1.25	1.30	0.5	16.7
ONRJ	0.53	0.95	-1.25	1.17	1.82	1.62	1.17	1.17	0.5	9.6
CNMP	-6.16	-6.37	-2.06	1.83	2.36	3.68	3.69	3.77	0.1	5.4
ICE	-13.81	-21.88	-8.58	2.15	2.52	2.19	2.26	2.38	< 0.1	5.2
INTI	55.43	50.57	57.20	6.89	5.26	2.11	2.29	2.40	< 0.1	4.5
INM	-9.46	—	-4.95	1.78	—	4.89	4.63	—	—	3.2
INACAL	—	—	141.37	—	—	5.65	—	—	—	1.7
UTE	—	—	117.55	—	—	11.2	—	—	—	0.5
IBMET	—	—	-8687.50	—	—	8.72	—	—	—	0.3

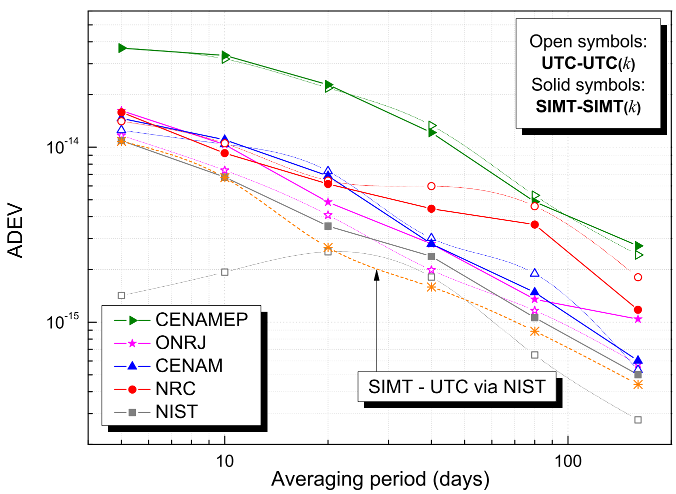

Fig. 10. Frequency instabilities of the time differences UTC – UTC(k) and SIMT – SIMT(k) for CENAMEP, ONRJ, CENAM, NRC, and NIST. The frequency instability of the time differences SIMT – UTC via NIST is also included.

SIMT scale and typically contribute about 75%–80% of its weighted average. Our results indicate, however, that an accurate stability estimate of the CNMP time scale can be made at $\tau = 5$ days with the SIMT. This implies that the SIMT can accurately evaluate the time scale stability of the remaining SIMTN members, most of them are not currently UTC contributors and have less stable time scales than CNMP, at $\tau = 5$ days or even at shorter intervals.

Table II provides the ADEV at 5 days for SIMT – UTC and SIMT – UTCr when different SIM laboratories are used as the pivot laboratory. These data were previously shown graphically in Figs. 1–5. The stability data for SIMT – SIMT(k), UTC – UTC(k), and UTCr – UTC(k) are also included. In addition, Table II shows the average value of SIMT – SIMT(k), UTC – UTC(k), and UTCr – UTC(k) from MJD 57700 to MJD 58270. Finally, the approximate weights of each SIM laboratories in SIMT and UTC formation are also included in Table II.

Despite the previously discussed constraints, we feel that the performance of SIMT can be improved. Recalibrating the SIMTN time transfer receivers would likely reduce the SIMT and UTC time differences to well below 10 ns, because many of the receivers have not been recalibrated since they were originally installed. Because the SIMT now runs without frequency corrections, its frequency stability could potentially be improved by periodic frequency calibrations performed with respect to a primary frequency standard. A cesium fountain clock at CENAM [15] is currently under full evaluation and could be used in the future to calibrate SIMT.

Currently, the SIMT is a free running time scale in the sense that there is not a primary frequency standard used to calibrate it. However, CENAM's cesium fountain clock (CENAM CsF_1) is now under evaluation to determine its systematic frequency shifts. Once the CENAM CsF_1 performance has been evaluated, we plan to use it to calibrate the frequency rate of the SIMT scale. In a second stage, we plan to use CENAM CsF_1 to steer SIMT to keep it as close as possible to UTC. It may also be possible to use the other fountain clocks in the SIM region (at NIST and NRC) to calibrate the SIMT scale but, as a first approach, the use of CENAM CsF_1 clock is easier to implement because it is in the same location where the SIMT is computed.

IV. SUMMARY AND CONCLUSION

Since beginning continuous operation a decade ago, the SIMT has proven to be a useful and easily accessed multinational time scale that provides good performance without human interaction or manual adjustments. It complements UTC and UTCr by continuously monitoring the performance of SIMT(k) time scales in real-time and serves as a frequency and time reference that is freely shared among SIM laboratories. As such, the SIMT has had a large role in the success of the recent time and frequency coordination effort in the Americas.

ACKNOWLEDGMENT

This article is a partial contribution of the U.S. government and is not subject to copyright.

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