Improvements in SIM Time Network and SIM Time Scale Performance

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Abstract: We report recent results achieved within the Sistema Interamericano de Metrología (SIM) regarding the multinational cooperation program in the field of time and frequency metrology. We discuss the performance of the SIM Time Network (SIMTN) and the SIM Time Scale (SIMT). We emphasize results achieved during the time period from May 2013 to May 2014. We found a significant improvement in both accuracy and stability of the SIMT, with results in good agreement with the Rapid UTC (UTCr) time scale published by the Bureau International des Poides et Mesures (BIPM).

1. INTRODUCTION

The *Sistema Interamericano de Metrologia* (SIM) is one of the five major regional metrology organizations (RMOs) recognized by the BIPM. SIM is the largest RMO in terms of land area, and its members are the national metrology institutes (NMIs) located in the 34 nations of the Organization of American States (OAS). The SIM/OAS region extends throughout North, Central, and South America and the Caribbean Islands. For a long time the SIM region faced several barriers that made it difficult to establish a successful cooperation program in time and frequency metrology. These barriers included large differences in both the populations of SIM nations and in the size of their economies. However, during the last decade SIM has established a very successful multinational cooperation program that has overcome these difficulties. The program simultaneously meets the needs of the well-established SIM laboratories, some of them with long international reputations in time and frequency metrology, as well as the needs of very small countries that are just beginning to establish their time and frequency laboratory.

The SIM time and frequency coordination program has developed customized time transfer equipment that allow SIM NMIs to compare their clocks and time scales, by use of the common view and all in view GPS techniques. The development of this equipment and associated software, has enabled the formation of two measurement systems that have unified the time and frequency programs of SIM nations – the SIM Time Network (SIMTN) and the SIM Time Scale (SIMT).

This paper discusses the performance of both the SIMTN and SIMT during the time period from May 2013 to May 2014. Section 2 briefly describes the SIMTN and how measurements of time difference are made, processed and published in real time through the Internet. Section 3 discusses the SIMT computation and its performance. Section 4 briefly discusses how the SIMT scale is computed and how it is used to discipline some SIM national time scales. Finally, Section 5 presents a summary.

2. THE SIM TIME NETWORK (SIMTN)

The SIMTN is a clock comparison network for the SIM region. It was developed by the SIM Time and Frequency Metrology Working Group (SIM TFWG) with support from the OAS. The SIMTN is based on common-view observations of the Coarse / Acquisition (C/A) codes transmitted by Global Positioning System (GPS) satellites on the L1 carrier frequency of 1575.42 MHz. This technique is one of several that the BIPM uses to compare remote clocks and to compute Coordinated Universal Time, UTC. The common-view method is simple but effective. When two clocks are not at the same location, the time difference between them can be measured by simultaneously comparing both clocks to a common GPS satellite signal in “common-view” of both sites. The difference between the two comparisons reveals the time difference between the two clocks. In this case, the GPS signal is simply a vehicle used to transfer time from one location to another.

When the GPS is used, the method involves a GPS satellite (*S*), and two receiving sites (*A* and *B*), each containing a GPS receiver and a local clock. The GPS satellite transmits a signal that is received at sites *A* and *B*, and both sites compare the GPS signal to their local clock. Site A receives the satellite signal, *S*, over the path *SA* that has a delay of δ_{SA}. Measurements at Site *A* of the time difference between clock A and the GPS signal can be written as $\Delta T_A = T_A - T_S - \delta_{SA}$, where T_A and T_S are the Clock *A* time and Satellite *S* time, respectively. Similarly, site *B* receives the satellite signal, *S*, over the path *SB* with a delay δ_{SB} and measures the time difference $\Delta T_B = T_B - T_S - \delta_{SB}$, where T_B is the clock *B* time. Then, the difference between the two measurements ΔT_A and ΔT_B made at site A and site B, respectively, is an estimate of the time differences between the two clocks *A* and *B*. The time difference can be written as

$$\Delta T_{AB} = (T_A - T_S) - (T_B - T_S) = (T_A - T_B) - (\delta_{SA} - \delta_{SB}), \quad (1)$$

where ΔT_{AB} is the time difference between clocks A and B. Delays that are common to both paths δ_{SA} and δ_{SB} cancel even if they are unknown, but uncorrected delay differences between the two paths add uncertainty to the measurement result. The components that make up the $(\delta_{SA} - \delta_{SB})$ error term include delay differences between the two sites caused by ionospheric and tropospheric delays, multipath signal reflections, environmental conditions, and errors in the GPS antenna coordinates. These factors can be measured or estimated and either applied as a correction to the measurement or accounted for in the uncertainty analysis.

As of May 2014, 19 SIM NMIs have joined the SIMTN (Table 1). The measurements made at each laboratory are transferred via the Internet to three SIM servers. The servers instantly process and publish the data in near real-time. With 19 laboratories participating, the SIMTN is currently publishing 171 ($n^2 - n / 2$, where $n = 19$) bilateral comparisons in real time.

The measurement results can be viewed with any web browser by accessing any of the three SIMTN servers located at the National Institute of Standards and Technology (NIST) in the USA, the National Research Council (NRC) in Canada and the Centro Nacional de Metrologia (CENAM) in Mexico. All three servers are linked from the web site of the SIM TFWG at http://tf.nist.gov/sim. Each server displays a real-time grid that shows the most recent time differences between SIM NMIs. The grids receive new data every 10 minutes, and refresh automatically every five minutes. If a user clicks on a time difference value displayed on the grid, a phase plot of the comparison for the current UTC day will appear in the web browser. The phase plots can be adjusted to include up to 200 days of data at once. The numerical results are also graphed as either one-hour or one-day averages and the time deviation (TDEV) and Allan deviation (ADEV) values for the selected data are automatically displayed. In addition to the graphs, numerical values for 10-minute, one-hour, or one-day averages can be viewed in tabular form or copied to a spreadsheet for further analysis.

Table 1. SIMTN participants as of May 2014

Country	NMI	Year of first participation	Time Standard	UTC participant
Antigua	ABBS	2011	SIMTDO	No
Argentina	INTI	2007	Cesium	Yes
Bolivia	IBMETRO	2012	SIMTDO	No
Brazil	ONRJ	2006	Ensemble time scale	Yes
Canada	NRC	2005	Ensemble time scale	Yes
Chile	INN	2010	SIMTDO	No
Colombia	INM	2007	Cesium	No
Costa Rica	ICE	2007	Cesium	No
Ecuador	CMEE	2012	GPSDO	No
Guatemala	LNM	2007	GPSDO	No
Jamaica	BSJ	2007	Cesium	No
Mexico	CENAM	2005	Ensemble time scale	Yes
Panama	CENAMEP	2005	Cesium	Yes
Paraguay	INTN	2008	SIMTDO	No
Peru	SNM	2009	Cesium	No
St. Lucia	SLBS	2010	SIMTDO	No
Trinidad / Tobago	TTBS	2009	GPSDO	No
United States	NIST	2005	Ensemble Time Scale	Yes
Uruguay	UTE	2008	Cesium	No

The real-time feature of the SIMTN allows all network participants to instantly compare their time standards to each other. This benefits all SIM NMIs, including those that already participate in the CIPM CCTF-K001.UTC unique key comparison for time and frequency and so contributing to the computation of the UTC. The SIMTN members that are UTC contributors can check the performance of their standard without waiting for publication of the BIPM's monthly *Circular-T* report, which includes results that are typically from two to seven weeks old at the time of publication, or for the weekly report of Rapid UTC (UTCr), where the results can be slightly older than one week. Another advantage of the SIMTN is that data are reported every 10 minutes, as opposed to every five days in the case of the *Circular-T*, or every day in the case of reports of the UTCr. This fact makes it much easier to identify short-term fluctuations and to solve measurement problems [1, 2].

The SIM time scales are referred to as SIMT(*k*), where *k* is the acronym of the NMI. If a SIMTN member, let us say lab *k*, is also a UTC contributor (see Table 1), then the time scales UTC(*k*) and SIMT(*k*) are the same at their origin, that is, both of them are produced with exactly same clocks and algorithm but could differ in the point within the laboratory where they are defined. In other words, UTC(*k*) and SIMT(*k*) are equivalent in frequency, however, there may be a time bias between them due to cable delays.

As an example of the data that the SIMTN produces, Figure 1 shows the time difference between the NIST and the NRC time scales as measured by the SIMTN from MJD 56600 to MJD 56800. Figure 1 also includes the time difference between NIST and NRC time scales when UTC and UTCr are used as common references. It must be mentioned that there is a systematic time difference between UTC(NRC) and SIMT(NRC) of about 13 ns. Such systematic time difference has been corrected in data shown in Figure 1. We have not found another systematic time difference between UTC(*k*) and SIMT(*k*) for $k \neq NRC$. As can be noticed from Figure 1, SIMTN time difference data are in good agreement with those derived from the UTC and UTCr BIPM time scales. SIMTN produces similar time differences for any pair of SIM NMIs and those also are in good agreement with time differences when using UTC or UTCr data, if available.

2.1. SIMTN data accessibility

As mentioned earlier, SIMTN data can be accessed through three servers located at NRC, NIST and CENAM. The servers are linked at a single web site (tf.nist.gov/sim). In addition to the measurement results, the site offers free downloads of all publications related to the activities of the working group, and information about past and future working group meetings and workshops.

The web site was redesigned in the early part of 2014 to be HTML5 compatible, which eliminated the need for a Java browser plug-in. The Java plug-in formerly required by the web site was not compatible with many mobile devices, including Android tablets and smartphones, Apple iPads and iPhones, Google's Chrome operating system, and so on. The redesigned web site allows the SIM data to be viewed and graphed from any mobile device, allowing staff members at SIM NMIs and other interested parties to check the performance of their time scale from any place at any time.

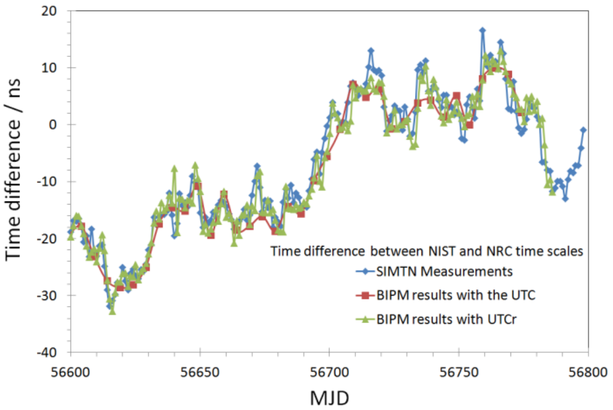

Figure 1. Time difference between the NIST and NRC time scales as measured by SIMTN, BIPM through the UTC and UTCr.

3. THE SIM TIME SCALE (SIMT)

Time keeping for critical applications, such as the generation of the UTC(*k*) time scales, requires reliability, accessibility, stability and accuracy. In order to generate a reliable time scale that is protected against the failure of any single clock, it is common practice to maintain a set of clocks, usually referred to as an ensemble time scales, whose time output is based on the weighted average of the individual clocks. In addition to being immune to a single point of failure, an ensemble of clocks can be used to generate a time scale with metrological characteristics superior to those obtainable from any single clock.

CENAM began work on SIMT in 2008 and it became an operational time scale in 2010. Reference [3] presents a complete discussion of the SIMT algorithm and an analysis of its performance.

SIMT was designed with several characteristics in mind, specifically i) to be a continuously operated time scale, that is made freely available in real time via the Internet, ii) to include local NMI time scales, SIMT(*k*), as single “clocks” in the SIMT ensemble, iii) to not be dependent on the clock maintained by any individual NMI, and iv) 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 SIM time scales and operational timing systems in the short, medium and long term. The ability of SIMT to detect short term anomalies in SIMT(*k*) scales is particularly useful when compared to UTC, which is not available in real time, and which is insensitive to short term fluctuations.

SIMT is a real-time time scale, like the local representations of UTC, UTC(*k*), that are generated by individual timing laboratories. 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 stability in terms of the Allan deviation. For SIMT, the weighting criteria are based on the inverse of the Allan deviation, which is computed by taking into account 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. Note that in our discussion we use the term “clock” to refer to the local SIMT(*k*) time scales, because each local time scale is treated as one clock in the SIMT computation. It is also important to note that in the case of the six SIM laboratories that contribute to both UTC and SIMT, SIMT(*k*) and UTC(*k*) are generated from the same physical signal but a time bias may exist due to cable delays.

Here we will mention that on 56400 MJD (April 18, 2013) we changed the criteria to assign weights of the SIM NMIs on their participation on SIMT computation. Before April 18, 2013, weights in SIMT were computed as: $\omega_i \propto {}^{1}\!/_{\sigma_i(\tau)}$, where ω_i is the weight of the clock *i* and $\sigma_i(\tau)$ is the stability of clock *i* measured in terms of the Alan deviation. τ is an averaging period of 1 day. After April 18, 2013, we added a frequency accuracy term to the weighting algorithm. Currently, the weights on SIMT algorithm are computed according to $\omega_i \propto \left[{}^{1}\!/_{\sigma_i(\tau)}\right] \times \left[{}^{1}\!/_{|\langle\Delta f_i\rangle|}\right]$, where $|\langle\Delta f_i\rangle|$ is the absolute value of the frequency difference of the clock *i* with respect to SIMT frequency. This simple change helped to significantly improve both the accuracy and stability of SIMT. The original model of weights $\omega_i \propto {}^{1}\!/_{\sigma^2{}_i(\tau)}$ was not the best option for SIMT for several reasons. One of these reasons is that the frequency stabilities of SIMT(*k*) scales have a large dispersion among them and using Allan variance instead of Allan deviation for weights assignment would effectively eliminate contributions from most of SIMT(*k*) in SIMT, a trend we aim to avoid.

We can analyze the performance of SIMT by comparing it to UTC and UTCr. Figure 2 shows the time differences of the NRC time scale with respect to GPS time, SIMT, UTC, and UTCr from 56413 MJD to 56790 MJD. From this figure we can notice that SIMT stability, for averaging periods of a month or longer, approaches the stability of UTCr. Time differences of SIMT with respect to UTC seem to be smaller than 10 ns. When analyzing the time differences of the NIST time scale (Figure 3) with respect to the GPS time, SIMT, UTC and UTCr, we arrive at similar conclusions.

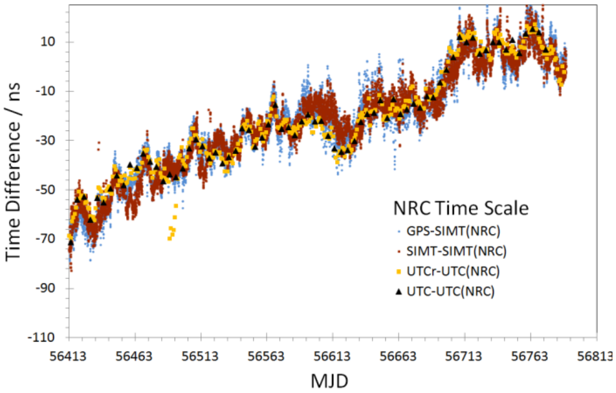

Figure 2. Time differences of the NRC time scale with respect to GPS time, SIMT, UTC and UTCr from 56413 MJD to 56790 MJD.

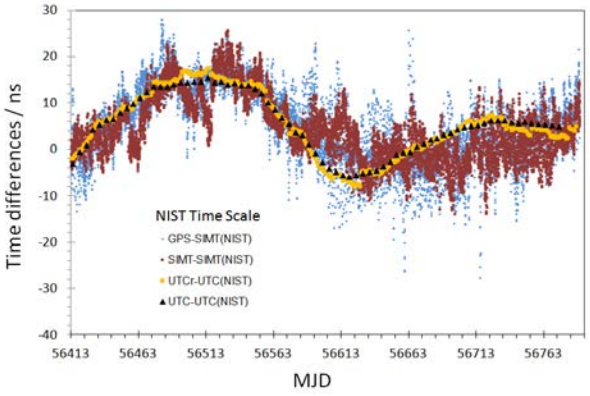

Figure 3. Time differences of the NIST time scale with respect to GPS time, SIMT, UTC and UTCr from 56413 MJD to 56790 MJD.

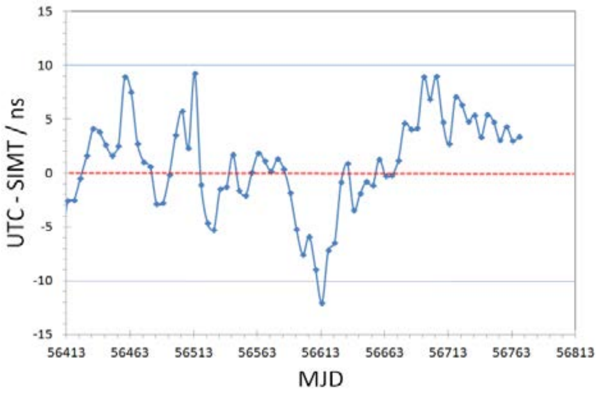

Figure 4. Time differences of SIMT with respect to UTC when the NIST time scale is used as a “common clock”.

If we compute the time difference of the SIMT with respect to UTC when the NIST time scale is used as a common “clock”, we find that $|\text{UTC} - \text{SIMT}| \leq 10$ ns for most of the time (Figure 4). Figure 5 shows the frequency stability of the time differences UTC – SIMT when the NIST time scale is used as the common reference.

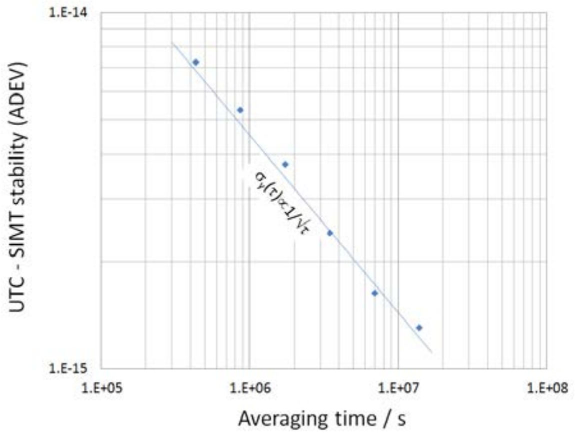

Figure 5. SIMT frequency stability when compared to UTC. The NIST time scale is used as a “common clock”.

4. SIMT disciplined clocks

The resources available to be devoted to frequency and time metrology are very limited at many SIM NMIs, and as a result, some laboratories operate rubidium clocks as their national frequency reference. The frequency stability of these clocks is limited to a few parts in 10^{12} per day, and as a result they require daily manual adjustment to keep time within 1 µs (1000 ns) of SIMT and UTC. To eliminate the need for manual adjustment, a control system has been implemented to keep these rubidium clocks synchronized and syntonized to SIMT [4].

The control system is currently implemented in Antigua and Barbuda, Bolivia, Chile, Paraguay, and Saint Lucia. The control system is driven by the SIMTN and SIMT. Once the SIMT – SIMT(*k*) time differences are known, it becomes possible to lock the frequency and time outputs of the rubidium clocks to agree with SIMT by employing basic disciplined oscillator techniques. Disciplined oscillators allow accurate frequency and time signals, controlled by a common reference, to be simultaneously generated at multiple sites. They work by continuously measuring a local oscillator (LO) against a reference source, converting the difference between the LO and the reference to a frequency correction, and then applying this frequency correction to the LO. By continuously repeating this process, a LO is disciplined so that it replicates the performance of the reference. In this system, the rubidium clock is the LO, and the reference source is SIMT.

The frequency stability of a typical Rb clock is near 4×10^{-13} at $\tau = 1$ hour and about a factor of five worse (a few parts in 10^{12}) at $\tau = 1$ day, due to frequency drift and aging. Both the short and long-term stability can be much worse than anticipated at some locations due to poor laboratory temperature control. As example of this SIMT discipline process, Figure 6 presents the time difference from 56650 MJD to 56805 MJD of the SIMT(ABBS) time scale in Antigua with respect to SIMT scale after the disciplining process has been implemented.

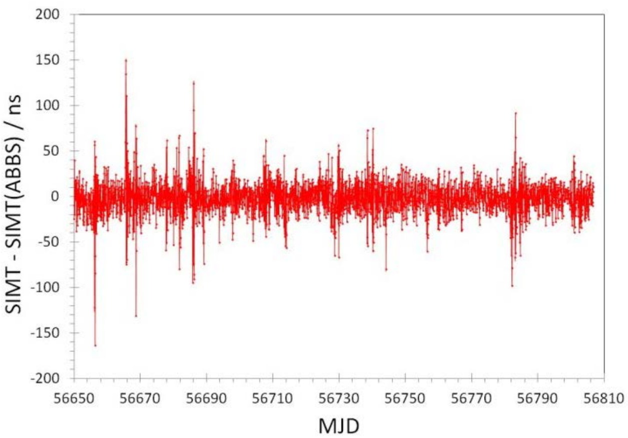

Figure 6. Time difference of the SIMT(ABBS) respect to SIMT after the SIMT disciplining process.

Figure 7 shows the frequency stability of data in Figure 6. Both graphs are typical for any SIMT(*k*) time scale based on a single rubidium clock, if the SIMT disciplining system is implemented.

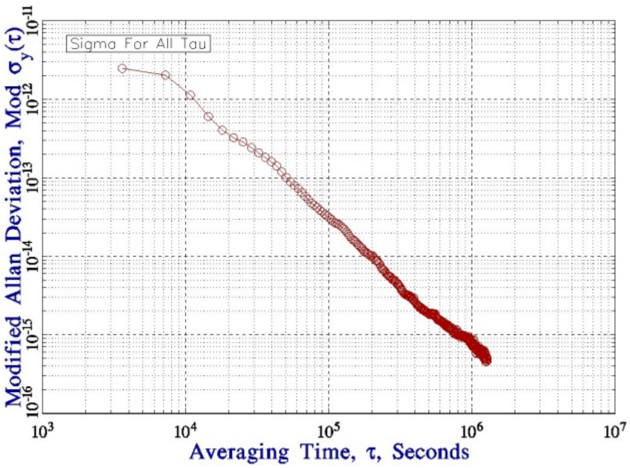

Figure 7. Typical frequency stability for a rubidium clock when it is disciplined to the SIMT scale.

5. Summary

The *Sistema Interamericano de Metrologia* (SIM) has developed a number of measurement systems that are designed to coordinate frequency control and timekeeping throughout the Americas. These systems include the SIM Time Network (SIMTN), the SIM Time Scale (SIMT), and the control system for SIMT disciplined clocks. The performance of each of these systems continues to improve, and the results of recent SIMT measurements are in good agreement with published measurements of UTC and UTCr.

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