SIM TIME SCALES

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Abstract This paper presents an analysis of the performance of some of the time scales generated in the Sistema Interamericano de Metrologia (SIM) region. We emphasize the first international time scale generated in near real time, the SIM Time scale (SIMT). The SIMT can be used as a reference to evaluate the performance of the other time scales of the region. SIMT is disseminated through the web site of the SIM Time and Frequency Metrology Working Group.

1. INTRODUCTION

Since the beginning of modern science, time measurement has been one of the most important areas of scientific and technological development. Navigation and communications are two areas where progress in the measurement of time has played a key role. The measurement of time has been historically linked to the solution of navigation problems as is well illustrated by the motivations of the Crown of England to establish the Longitude Act during the 18th century [1]. Today, the Global Positioning System (GPS) provides an excellent example of the strong relationship between navigation and time measurement. In addition, the base unit of time interval, the second, is measured with an accuracy superior to any other measurement unit. This fact has made it attractive to redefine other measurement units of the International System of Units (SI) in terms of time and frequency measurements. The definition of the meter, the unit of length, is a good example of this. Another example is the Josephson effect, where the frequency from an atomic clock is converted to a voltage standard. These examples suggest that time and frequency metrology can and should be considered important for both technological and economic reasons.

By analyzing the performance of some of the SIM time scales; this article presents a brief report of the time and frequency measurement capabilities of the SIM region. We emphasize the generation of the first international time scale generated in near real time, the SIM Time scale (SIMT). The SIMT can be used as a reference to evaluate the performance of the other time scales of the region, because it is disseminated through the web site of the SIM Time and Frequency Metrology Working Group (MWG).

Fifteen SIM laboratories are continuously engaged in time and frequency comparisons through the SIM time network (SIMTN). These laboratories are (in geographical order from north to south): the National Research Council (NRC) of Canada, the National Institute of Standards and Technology (NIST) of the United States, the Centro Nacional de Metrología (CENAM) of Mexico, the Laboratorio Nacional de Metrología (LNM) of Guatemala, the Instituto Costarricense de Electricidad (ICE) of Costa Rica, the Centro Nacional de Metrología de Panamá (CENAMEP) of Panama, the Jamaican Bureau of Standards (JBS) of Jamaica, the Trinidad and Tobago Bureau of Standrads (TTBS) of Trinidad and Tobago, the Saint Lucia Bureau of Standards (SLBS) of Saint Lucia, the Superintendencia de Industria y Comercio (SIC) of Colombia, the Observatorio Nacional de Rio de Janeiro (ONRJ) of Brazil, the Instituto Nacional de Competencia y Propiedad Industrial (INDECOPI) of Peru, the Instituto Nacional de Tecnología Industrial (INTN) of Paraguay, the Usinas y Trasmisiones Eléctricas (UTE) of Uruguay and the Instituto Nacional de Tecnología Industrial (INTI) of Argentina.

The creation of a successful program of cooperation for time and frequency metrology within SIM was previously limited by the large differences in both the economies and populations of the participating countries. However, during the last six years (2004-

2010), SIM has been able to establish a cooperative program that has overcome many of the differences in material and human resources. In order for the program to be successful, it was necessary to satisfy the requirements of both the well established laboratories with experienced staffs and the newer, smaller laboratories, some of which were establishing a time and frequency laboratory with just one person, often one with no previous experience in the field.

To allow all SIM laboratories to compare their time scales to each other, it was necessary to install identical measurement equipment in each laboratory. Such equipment must meet two main characteristics: first it must allow measurements with uncertainties comparable to those reported by the BIPM in the *Circular T* in order to meet the needs of the established laboratories. Second, the equipment must be inexpensive enough to allow small countries to be part of the program. The equipment must also require almost no supervision to operate. It was also necessary to implement a training program so that all participants in the coordination program would have a good understanding of the measurements.

Reference [2] presents a discussion about how the SIM time and frequency coordination program was established. As of July 2010, 16 SIM time scales are compared through the SIMTN. Fifteen of these time scales are referred to as SIMT(*k*), where *k* stands for the acronym of the national metrology institute (NMI), the other time scale is SIMT. Reference [3] discusses the measurement uncertainties of the SIMTN. The time differences among the SIMT(*k*) scales are published on the SIM Time and Frequency Metrology Working Group (MWG) web site [4], where a new measurement result appears every ten minutes. These measurement results are accessible to the general public.

CENAM began work on SIMT in 2008. The SIMT algorithm was first published in reference [5] which is similar to the algorithm discussed in [6]. A complete discussion of the SIMT algorithm and an analysis of SIMT performance can be found in [7]. Through the use of the Internet, it is easy to follow the performance of SIMT and the SIM time scales maintained at each laboratory. The data can even be obtained by use of mobile devices such as cellular phones with Internet capability.

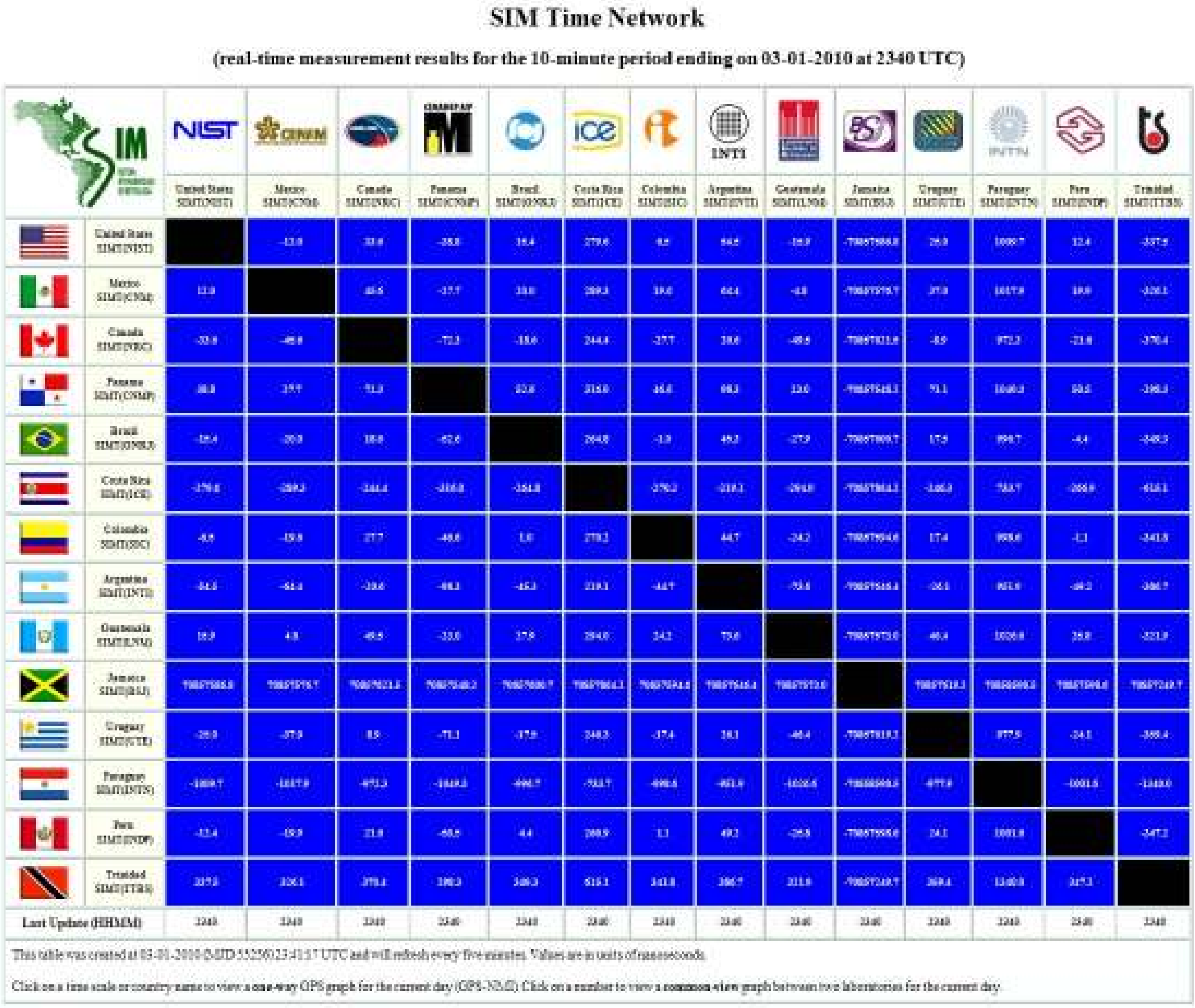
Section 2 briefly describes the SIMTN. Section 3 presents results of the performance of some SIM time scales. Section 4 discusses some aspects of SIMT. Finally, in Section 5, we present a summary and conclusion.

2. THE SIM TIME NETWORK, SIMT

The SIM Time Network (SIMTN) became operational in May 2005, when comparisons began between NIST, CENAM, and NRC [8]. Since then, the network has expanded to accommodate all interested SIM NMIs. Sixteen laboratories should be participating by the end of 2010.

The SIMTN was built by combining two existing technologies: GPS common-view time transfer and the Internet. The GPS common-view technique has long been used to compare high accuracy clocks located at remote sites [9]. The measurements made by all of the laboratories involved in a comparison need to be gathered in one place before the measurement results can be processed. The Internet provides an ideal medium for the automatic transfer of measurements and for displaying measurement results. Once the problem of data transfer was solved, there was no reason to delay the publishing of the measurement results, and the MWG decided to make them publicly available via the Internet. The measurement grid (Figure 1) is updated every 10 minutes and it shows the current time difference between all of the participating SIM laboratories. The grid can be viewed at: http://tf.nist.gov/sim

Participation in the SIMTN requires a SIM measurement system. The SIM measurement systems consist of an industrial rack-mount computer that contains a time interval counter with single shot resolution of less than 0.1 ns, an eight-channel L1 band, C/A code GPS receiver, and software developed by NIST. The use of a single frequency (L1 band) GPS receiver made it possible to maintain the hardware costs down to a reasonable level. The uncertainty of the SIMTN measurements (k = 2) is typically less than 15 ns and often only about 10 ns, and the SIMTN results are similar to those published by the BIPM [3]. To help reduce the need for training, the SIM systems were designed to be very easy to install and use. Only four things are necessary; i) a GPS antenna needs to be mounted on the roof, ii) a 5 MHz or 10 MHz signal is required as a counter time base, iii) one pulse per second (pps) signal from the NMI's time standard need to be connected, and iv) the system must be connected to the Internet. Once the system has been installed, the time difference between GPS and the local time standard is measured every second, and the measurements are uploaded every 10 minutes to three file servers. The servers are located at NIST, CENAM, and NRC. Each of the three servers make the SIM grid (Figure 1) available on the Internet. They also host web-based graphing and data analysis software so that the measurement results can be studied in detail.



SIM Time Network

(real-time measurement results for the 10-minute period ending on 03-01-2010 at 2340 UTC)

Figure 1. The SIM real-time grid.

3. SIM TIME SCALES

Most SIM NMIs operate a single clock as their time scale, with perhaps another clock available as a backup. This clock is either a cesium, a rubidium, or a GPS disciplined oscillator (GPSDO). However, the more advanced laboratories operate an ensemble time scale that consists of multiple cesium or hydrogen maser standards. In an ensemble time scale, the individual clocks are not adjusted, but instead are allowed to run freely. The free running clocks are measured, and the clock measurements are used (normally as a weighted average) to adjust the time scale output, which could be a master clock, a synthesizer, or a phase stepper. The four ensemble time scales in the SIM region already represent a significant percentage of the ensemble time scales that currently exist worldwide, and at least three other SIM labs (Colombia, Jamaica, and Panama) plan to build ensemble time scales in the future. An ensemble time scale is the preferred way of doing things among the major timing laboratories, but the cost of both the equipment and the labor is too high for many SIM laboratories. Having at least one cesium clock is desirable and is required if the laboratory wishes to participate in the BIPM key comparisons. However, a rubidium or a GPSDO is all that is necessary to participate in the SIMTN and establish traceability back to the SI. If the NMI does not have a frequency standard, the MWG uses funding obtained from SIM to provide a rubidium oscillator, which is an ideal entry level standard.

Section 4 discusses SIMT in detail, but here we present in advance the results obtained when comparing some of the SIM time scales to SIMT. Figure 2 shows the time differences of the scales of NIST, CENAM, NRC, CENAMEP, ONRJ and SIC with respect to SIMT, from April 19th, 2009, to April 1st, 2010. In Figure 3 the frequency stabilities obtained from such comparisons are presented. It must be mentioned that in Figure 3 no corrections on stabilities were made due to correlation between SIM(k) time scales and SIMT. The GPS link noise contribution to the stability, which typically has a one day period, can be seen in Figure 3. We estimate conservatively that the uncertainty of the time differences between SIMT(*k*) and SIMT scales is near 8 ns.

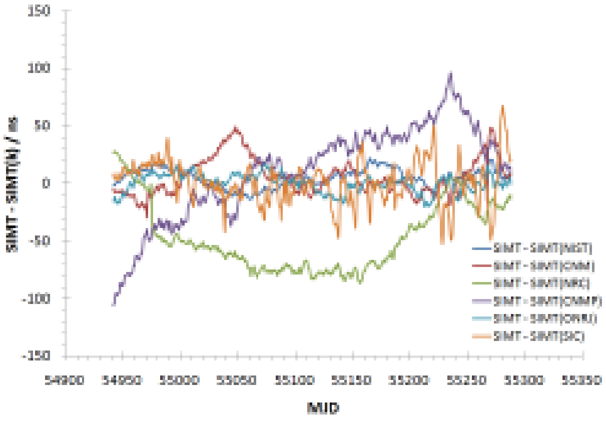


Figure 2. *Time differences between some SIM time scales with respect to the SIMT.*

Most SIM time scales are maintained in a way that keeps the time differences between them to within less than 100 ns. About half of the SIM time scales are within 50 ns of each other most of the time.

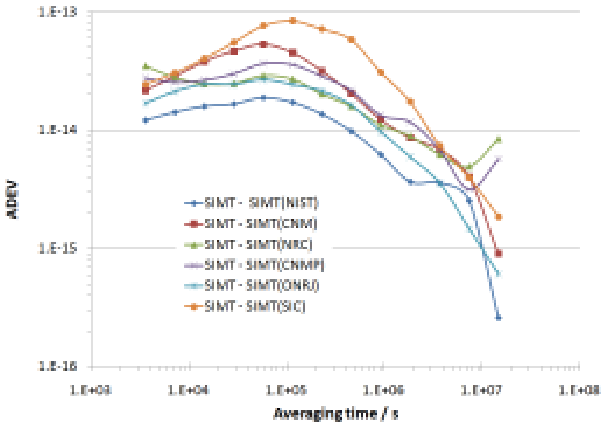


Figure 3. *Frequency stability of some SIM time scales.*

4. THE SIM TIME SCALE, SIMT

The SIMTN participants operate about 25 industrial Cesium clocks and nine active Hydrogen Masers. This large number of atomic oscillators, along with the SIMTN capabilities, made it very attractive to generate SIMT. Nine time scales currently contribute to SIMT, and each contributor has one or more Cesium clocks and/or Hydrogen Masers. The nine contributors are NRC, NIST, CENAM, ICE, CENAMEP, BSJ, SIC, ONRJ and INTI. The activities that led to the generation of SIMT date back to early 2008 at CENAM [5]. The SIMT algorithm is similar to the one used at NIST [10] and CENAM [6] to generate the UTC(NIST) and UTC(CNM) time scales, respectively.

Both the NIST and CENAM algorithms use exponential filtering to predict the time and frequency differences of the clocks with respect to the averaged time scale. Also, in both algorithms the weighting procedure is a dynamic process where the frequency instability of clocks is measured in terms of the Allan deviation. However, some slight differences in the criteria of NIST and CENAM are to be mentioned regarding the weight assignments. For the SIMT scale, similarly to the CENAM time scale, the weighting criteria is related to the inverse of the Allan variation, which is computed from the previous 10 days of SIMTN measurements. The use of a 10-day period reduces the contribution of time transfer noise to the SIMT uncertainty.

Figure 4 presents a schematic representation of the SIMT generation process. The solid lines are intended to represent the comparison among SIM time scales (“clocks”), which is performed in near real time (one measurement every 10 minutes) based on the GPS common-view technique. A further discussion about the way these data are processed to determine the time differences between clocks and their associated uncertainties can be found in reference [3]. All measurement data are made available from three servers located at NRC, NIST and CENAM through the Time and Frequency Metrology Working Group web site: http://tf.nist.gov/sim

Notice that in the SIMT algorithm the complete SIMT(k) scale is used as a “single clock”, and no distinction is made with respect to the individual clocks participating on the SIMT(k) generation. This differs from UTC, where each individual clock is used in the computation. The dashed lines in Figure 4 represent the comparison of the clocks with respect to the SIMT. We use dashed lines in order to represent the virtual character of such comparisons, because the SIMT is a virtual time scale that produces no physical signal. The time difference measurements produced by dashed lines are also published in real time in a way similar to those produced by solid lines through the MWG web site [11].

At the time of publication of this article, the SIMT scale is generated only at CENAM in Mexico. However, in the near future SIMT will also be generated at NIST in the United States and at the NRC in Canada. In such a way, the SIMT scale will be fully generated automatically, with almost no human intervention, in three different locations. This method provides SIMT with high reliability and accessibility, two characteristics that are very desirable for a time scale with demanding applications.

SIMT has been generated in real time without interruptions since the second half of 2009. Here we present results for SIMT that were obtained in a post processed scheme with data collected from April 2009 to April 2010. A further discussion of results for SIMT in both post processed and real time generation schemes is presented in reference [7].

Figures 5, 6 and 7 show the time differences of the NIST, CENAM and ONRJ time scales with respect to the SIMT and UTC time scales. The solid blue color lines in the graphs correspond to the time differences with respect to the SIMT; the dashed light blue color lines correspond to the uncertainty bars for the time difference with respect to the SIMT. The red color lines are for the data published in *Circular T* for the time differences of UTC(NIST), UTC(CNM) and UTC(ONRJ) with respect to UTC. Finally, the figures also include the time differences with respect to the GPS time as measured by the SIM GPS systems. As can be noticed from the graphs, UTC and SIMT scales agree within the estimated uncertainties of the comparisons most of the time.

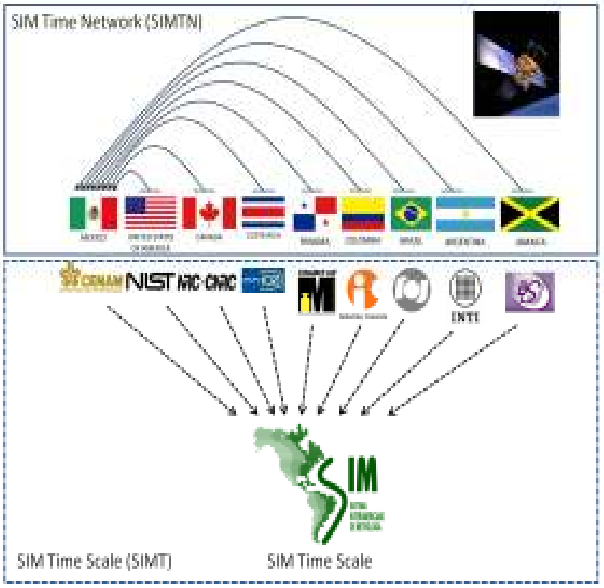


Figure 4. *Schematic of the participation of nine SIM laboratories in the generation of SIMT.*

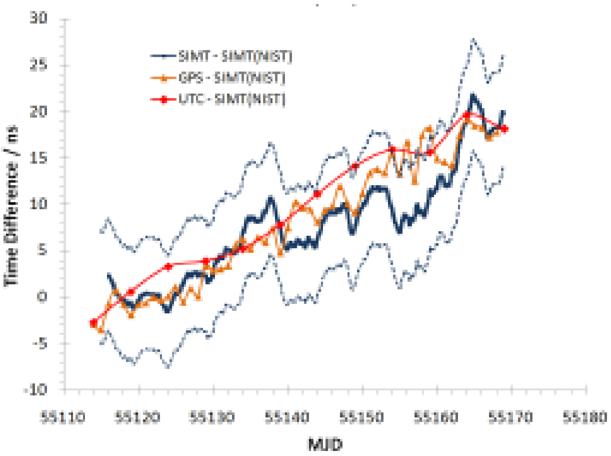


Figure 5*. Time differences between the NIST time scale with respect to the SIMT, UTC and GPS time scales.*

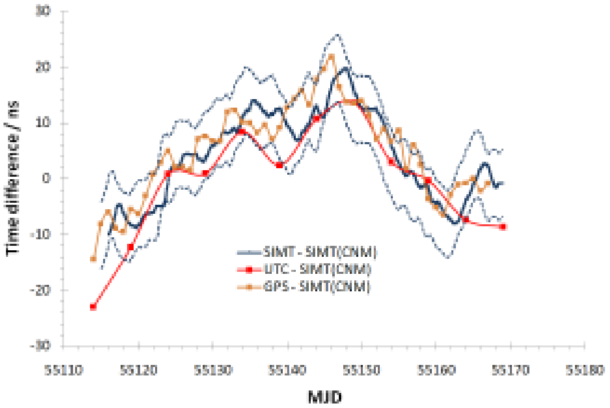


***Figure 6**. Time differences between the CENAM time scale with respect to the SIMT, UTC and GPS time scales.*

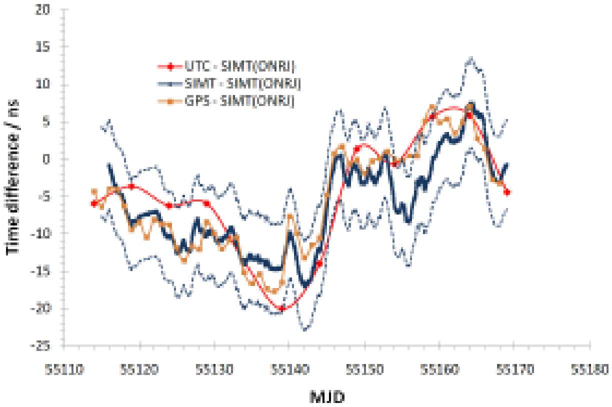


***Figure 7**. Time differences between the ONRJ time scale with respect to the SIMT, UTC and GPS time scales.*

We must mention that the SIMT data presented in this paper was generated with a post processed scheme that included data from the NIST, CENAM, NRC, CENAMEP, ONRJ and SIC time scales. Figure 8 shows the weights assigned to each SIM time scale in the SIMT computations. The NIST time scale is the most stable in the SIM region, and thus receives the highest weight. To prevent an individual time scale from dominating SIMT, the MWG has decided to establish a limit of 40 % for the contribution of a single SIM time scale to SIMT.

Figure 9 shows the time differences of the SIMT scale with respect to UTC and GPS time. The graph also includes the time differences of the UTC(USNO) with respect to UTC as published in the *Circular T*. The time differences of the SIMT scale with respect to UTC are computed when the NIST time scale is considered as a common clock that contributes to both UTC and SIMT. A similar procedure was followed to compute the time difference of the SIMT with respect to GPS time.

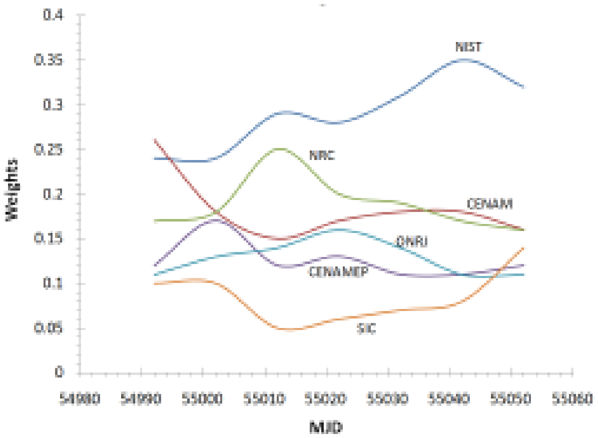


***Figure 8**. Weights assigned to SIM time scales during the generation of SIMT.*

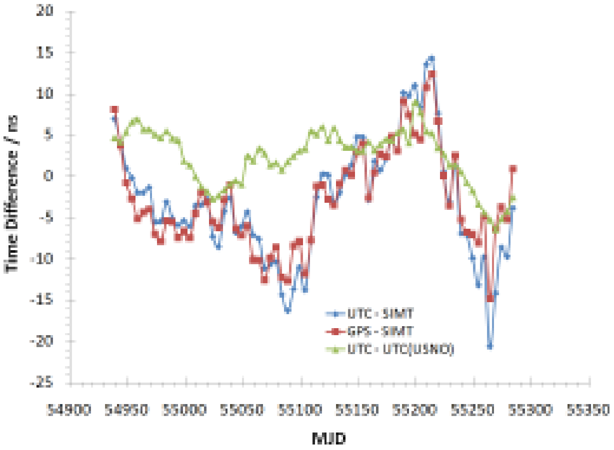


***Figure 9**. Time differences of SIMT with respect to the UTC and GPS time scales along with the UTC – UTC(USNO) time difference.*

UTC(USNO) and GPS time are not equivalent time scales. However, if we make the assumption that they are nearly equivalent, then we can apply the three cornered hat method [12] to the Figure 9 measurements to roughly estimate the frequency stability of SIMT. This is done by:

$$\sigma_{12}^2(\tau) = \sigma_1^2(\tau) + \sigma_2^2(\tau) \qquad (1)$$

$$\sigma_{13}^2(\tau) = \sigma_1^2(\tau) + \sigma_3^2(\tau) \qquad (2)$$

$$\sigma_{23}^2(\tau) = \sigma_2^2(\tau) + \sigma_3^2(\tau) \qquad (3)$$

where σ_{ij} are indicated on Figure 10.

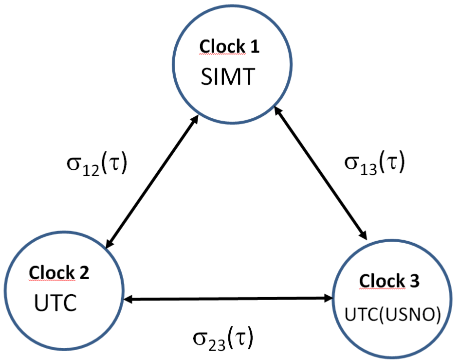


***Figure 10**. Schematic of the comparison among the SIMT, UTC and UTC(USNO) time scales.*

Equations (1), (2) and (3) strictly hold for uncorrelated oscillators. However, a correction factor can be applied to account for the correlation between UTC(USNO) and UTC. This correction factor can be written as 1/(1 - *w*), where *w* is the contribution of UTC(USNO) to the computation of UTC, which is near 50 %.

Figure 11 shows the solution of the previous equations in which the correlation between UTC(USNO) and UTC has been taken into account. The frequency stability of SIMT can be approximately described by the relation

$$\sigma_{SIMT}(\tau) \approx \frac{4\times10^{-12}}{\sqrt{\tau}} \ . \qquad (4)$$

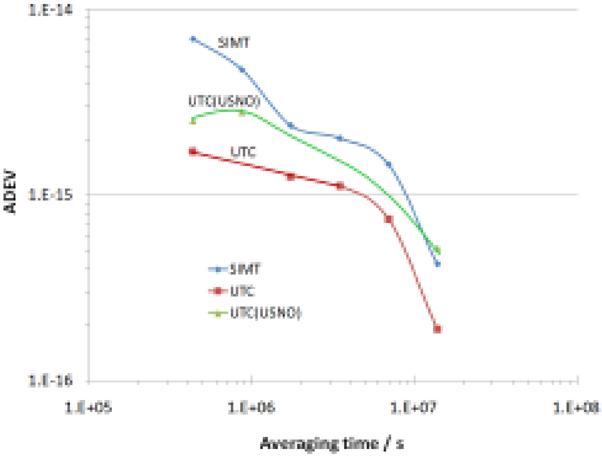


***Figure 11**. Estimated frequency stability of the SIMT, UTC and UTC(USNO) time scales.*

5. SUMMARY AND CONCLUSIONS

The SIM Time Network (SIMTN) began in 2005, and now continuously compares the time standards of 15 SIM laboratories and publishes the results in near real-time on the Internet. The SIMTN reports results every 10 minutes, which makes it easy to identify short-term frequency and time fluctuations and to solve measurement problems.

Since 2008, the SIMTN data has been used to generate the SIM Time scale (SIMT). Since the second half of 2009, SIMT has been continuously generated in a fully automated scheme with the results published in real time via the Internet. The frequency stability of the SIMT can be estimated as $4 \times 10^{-12} / \tau^{1/2}$. Currently SIMT is generated at CENAM; however, it is expected to be simultaneously generated at CENAM, NIST, and NRC in the near future. This will make SIMT even more reliable and accessible, two characteristics that are very desirable for a time scale with demanding applications.

Acknowledgements

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