SIM Progress in Promoting Time and Frequency Metrology in the Americas

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Overview

The *Sistema Interamericano de Metrologia (*SIM), through its time and frequency metrology working group (TF WG) has developed the SIM Time Network (SIMTN) and SIM Time Scale (SIMT). This work is aligned with the CIPM guidelines, and shares the same goal of the CIPM key comparisons for time and frequency, to improve time and frequency metrology by disseminating the SI unit of time to as many national metrology institutes (NMIs) as possible. The SIMTN automatically compares the national time standards maintained by SIM NMIs. It began operation in May 2005, when comparisons began between the National Institute of Standards and Technology (NIST) of the United States, the Centro Nacional de Metrología (CENAM) of Mexico, and the National Research Council (NRC) of Canada. As of September 2012, 19 SIM NMIs are members of the SIMTN, and contribute data continuously. The SIMTN results are published in near real-time (every 10 minutes) via the Internet. The SIMTN data is used to compute a multi-national, ensemble time scale called SIMT. SIMT became operational in January 2010 and is disseminated every hour via the Internet. It is now used to automatically steer the time standards in four SIM nations.

1. Motivations

A barrier that previously limited the creation of a successful cooperation program for time and frequency metrology within the SIM region was the large dispersion in the size of the economies and population among the SIM countries. However, during the last seven years SIM has established, with high success, a cooperation program in time and frequency metrology within the region that has overcome many of the differences among SIM laboratories with respect to the material and human resources. The program has succeeded by simultaneously satisfying the needs of the established time and frequency laboratories with experienced staffs, as well as the needs of the very small countries, many of whom were attempting to start a time and frequency laboratory with a staff of one person and no budget.

To begin interlaboratory comparisons, it was necessary to develop measurement systems to allow the SIM NMIs to compare their time scales. These measurement systems were built with to meet two requirements. Their measurement uncertainties had to be small enough to be comparable to those reported in the *Circular T* in order to meet the needs of all participating NMIs, and they had to be inexpensive enough to allow small countries to be part of the program.

Low cost equipment was absolutely essential to the success of the program. Participating in the CIPM key comparisons requires the purchase of more than $100,000 USD of equipment – typically about $75,000 USD for a cesium clock and an additional $30,000 to $40,000 for a CGGTTS compatible time transfer receiver. This type of expenditure is simply not possible for many small laboratories. The equipment cost of participating in the SIMTN comparisons is roughly 1/10 of that. The SIM measurement system and a rubidium clock costs about $10,000 USD. This cost is small enough to allow SIM to donate the equipment to NMIs that have no time and frequency budget at all.

2. The SIM Time Network (SIMTN)

Since its inception, the SIMTN has expanded to accommodate all interested SIM NMIs. As of September 2012, 19 NMIs are SIMTN members, as shown in Figure 1.

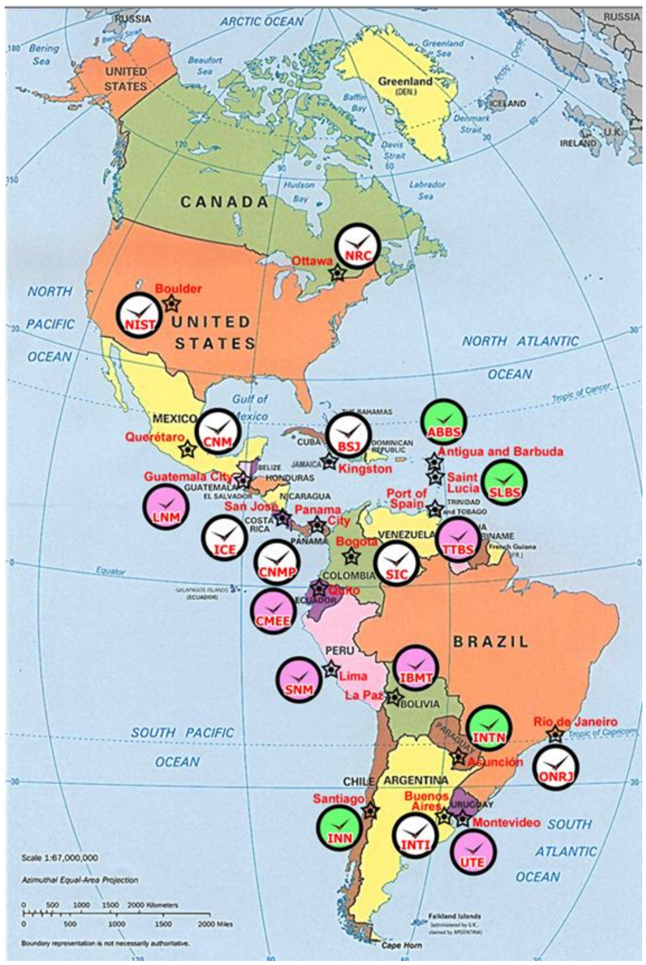
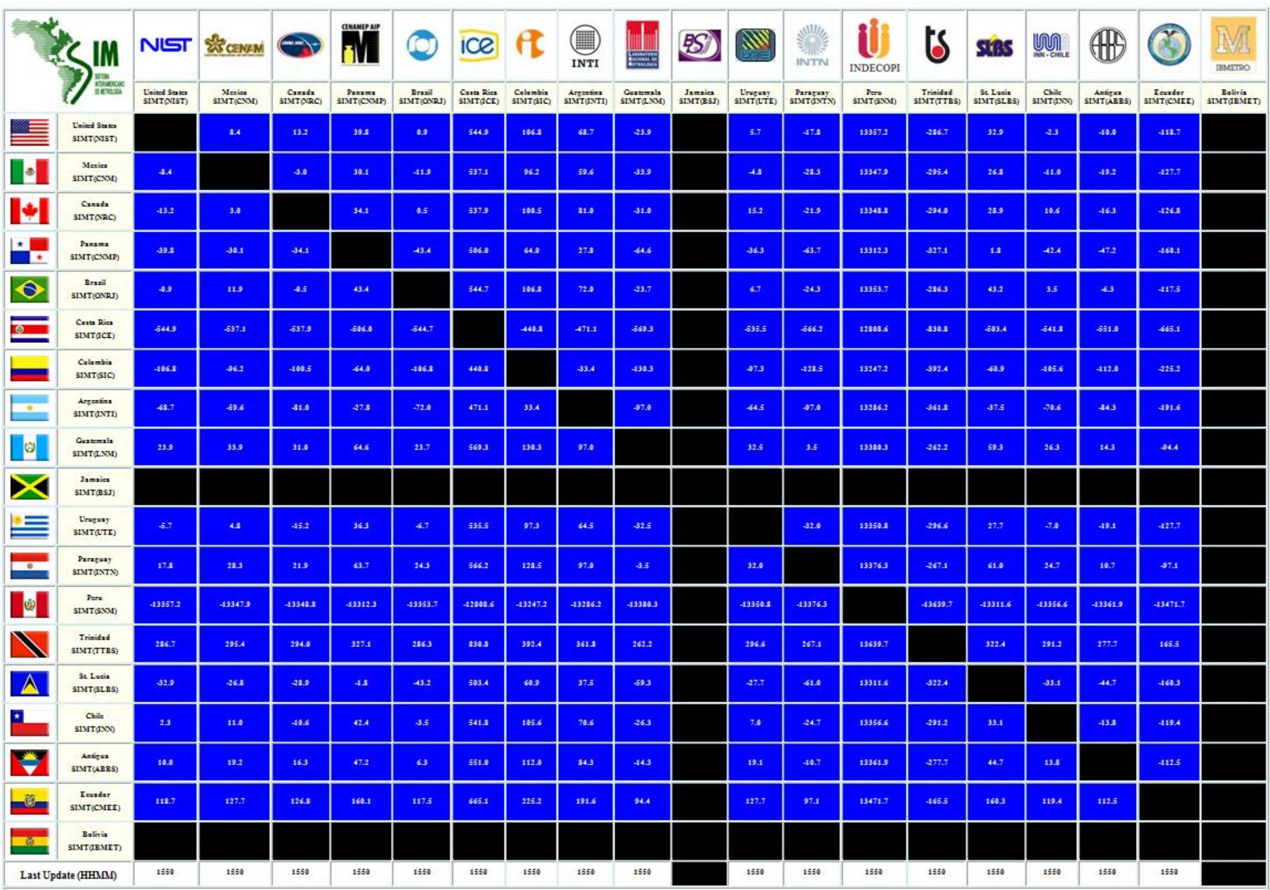


Figure 1. Geographical distribution of SIMTN members. The map shows the locations of the 19 laboratories that participate in the SIM Time Network (SIMTN). The white clocks represent laboratories with cesium clocks that contribute to the calculation of the SIM Time Scale (SIMT), an ensemble time scale that is generated in real-time and updated hourly. The green clocks represent laboratories that operate rubidium clocks that are automatically steered to agree with SIMT. The purple clocks represent laboratories that operate either a GPS disciplined clock or a free running rubidium clock.

The SIMTN was built by combining two 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 but requires measurements made by all of the laboratories involved in a comparison to be collected in one place before the measurements results can be processed. The Internet provides an ideal medium for the automatic transfer of measurements. Once the data transfer problem was solved, there was no reason to delay publication of the measurement results, and SIM decided to make them available to everyone in real time.

Each participant in the SIMTN operates a measurement system consisting of an industrial rack-mount computer that contains a time interval counter with single shot resolution of less than 0.1 ns, an L1 band, C/A code GPS receiver, and software developed by NIST. The units are assembled and calibrated at NIST before shipment to the host NMI. To reduce the need for training, the SIM systems were designed to be very easy to install and use.

The uncertainty of the SIMTN measurements (k = 2) is typically less than 15 ns and often about 10 ns, comparable to many of the CPIM key comparison links. Every 10 minutes each system uploads its measurements to three file servers, located at NIST, CENAM, and NRC. The three servers make the SIM grid (Fig. 2) available on the Internet. The grid can be viewed at: http://tf.nist.gov/sim



	United States SIMT(NIST)	Mexico SIMT(CNM)	Canada SIMT(NRC)	Panama SIMT(CNMP)	Brazil SIMT(ONRJ)	Costa Rica SIMT(ICE)	Colombia SIMT(SIC)	Argentina SIMT(INTI)	Guatemala SIMT(LNM)	Jamaica SIMT(BSJ)	Uruguay SIMT(UTE)	Paraguay SIMT(INTN)	Peru SIMT(SNM)	Trinidad SIMT(TTBS)	St. Lucia SIMT(SLBS)	Chile SIMT(INN)	Antigua SIMT(ABBS)	Ecuador SIMT(CMEE)	Bolivia SIMT(IBMET)
United States SIMT(NIST)		8.4	13.2	39.8	0.9	544.9	106.8	68.7	-23.9		5.7	-17.8	13357.2	-286.7	32.9	-2.3	-10.0	-118.7	
Mexico SIMT(CNM)	-8.4		-3.0	30.1	-11.9	537.1	96.2	59.6	-33.9		-4.8	-28.3	13347.9	-295.4	26.8	-11.0	-19.2	-127.7	
Canada SIMT(NRC)	-13.2	3.0		34.1	0.5	537.9	100.5	81.0	-31.0		15.2	-21.9	13348.8	-294.0	28.9	10.6	-16.3	-126.8	
Panama SIMT(CNMP)	-39.8	-30.1	-34.1		-43.4	506.0	64.0	27.8	-64.6		-36.3	-63.7	13312.3	-327.1	1.8	-42.4	-47.2	-160.1	
Brazil SIMT(ONRJ)	-0.9	11.9	-0.5	43.4		544.7	106.8	72.0	-23.7		6.7	-24.3	13353.7	-286.3	43.2	3.5	-6.3	-117.5	
Costa Rica SIMT(ICE)	-544.9	-537.1	-537.9	-506.0	-544.7		-440.8	-471.1	-569.3		-535.5	-566.2	12808.6	-830.8	-503.4	-541.8	-551.0	-665.1	
Colombia SIMT(SIC)	-106.8	-96.2	-100.5	-64.0	-106.8	440.8		-33.4	-130.3		-97.3	-128.5	13247.2	-392.4	-60.9	-105.6	-112.0	-225.2	
Argentina SIMT(INTI)	-68.7	-59.6	-81.0	-27.8	-72.0	471.1	33.4		-97.0		-64.5	-97.0	13286.2	-361.8	-37.5	-70.6	-84.3	-191.6	
Guatemala SIMT(LNM)	23.9	33.9	31.0	64.6	23.7	569.3	130.3	97.0			32.5	3.5	13380.3	-262.2	59.3	26.3	14.3	-94.4	
Jamaica SIMT(BSJ)																			
Uruguay SIMT(UTE)	-5.7	4.8	-15.2	36.3	-6.7	535.5	97.3	64.5	-32.5			-32.0	13350.8	-296.6	27.7	-7.0	-19.1	-127.7	
Paraguay SIMT(INTN)	17.8	28.3	21.9	63.7	24.3	566.2	128.5	97.0	-3.5		32.0		13376.3	-267.1	61.0	24.7	10.7	-97.1	
Peru SIMT(SNM)	-13357.2	-13347.9	-13348.8	-13312.3	-13353.7	-12808.6	-13247.2	-13286.2	-13380.3		-13350.8	-13376.3		-13639.7	-13311.6	-13356.6	-13361.9	-13471.7	
Trinidad SIMT(TTBS)	286.7	295.4	294.0	327.1	286.3	830.8	392.4	361.8	262.2		296.6	267.1	13639.7		322.4	291.2	277.7	165.5	
St. Lucia SIMT(SLBS)	-32.9	-26.8	-28.9	-1.8	-43.2	503.4	60.9	37.5	-59.3		-27.7	-61.0	13311.6	-322.4		-33.1	-44.7	-160.3	
Chile SIMT(INN)	2.3	11.0	-10.6	42.4	-3.5	541.8	105.6	70.6	-26.3		7.0	-24.7	13356.6	-291.2	33.1		-13.8	-119.4	
Antigua SIMT(ABBS)	10.0	19.2	16.3	47.2	6.3	551.0	112.0	84.3	-14.3		19.1	-10.7	13361.9	-277.7	44.7	13.8		-112.5	
Ecuador SIMT(CMEE)	118.7	127.7	126.8	160.1	117.5	665.1	225.2	191.6	94.4		127.7	97.1	13471.7	-165.5	160.3	119.4	112.5		
Bolivia SIMT(IBMET)																			
Last Update (HHMM)	1550	1550	1550	1550	1550	1550	1550	1550	1550		1550	1550	1550	1550	1550	1550	1550	1550	

Figure 2. The SIMTN grid.

The grids are updated every 10 minutes. When a user “clicks” a 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 for the selected data are automatically calculated and displayed. The SIMTN also generates a “data feed” that provides the clock comparison data that SIMT algorithm needs for SIMT values computation.

The SIMTN allows all SIM NMIs to check the performance of their local time scales whenever necessary. The rapid publication of data has made it easy to quickly identify local time scale fluctuations and failures, a key benefit to NMIs who use their time scale as a reference for calibrations or as the source of the official time in their country.

3. The SIM Time Scale (SIMT)

The Bureau International des Poids et Mesures (BIPM) recently began a pilot experiment to publish the *Rapid* Coordinated Universal Time, UTCr, every week as opposed to the UTC computation which is published every month. The UTCr computation is made with the aim to explore the possibility to compute the UTC with increasing accessibility to this international time reference. The SIM TFMG has emphasized time scale accessibility for a number of years, beginning in 2005 when the SIMTN was developed, as described in Section 2. In 2008 the CENAM Time and Frequency Division started the work to generate the SIM time scale, the first multi-national ensemble time scale whose values are disseminated in real time. The SIMT scale has been operational since January 2010, and its values are disseminated every hour via the Internet (Fig. 3).

SIM Time Scale

(SIMT - SIMT(*k*) for the 1-hour period ending on 2012-08-30 at 17:20:00 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)		-2.32	38.65 %	Uruguay SIMT(UTE)		-3.82	0.00 %
Mexico SIMT(CNM)		-11.48	17.37 %	Paraguay SIMT(INTN)		0.78	0.00 %
Brazil SIMT(ONRJ)		-12.94	14.06 %	Peru SIMT(SNM)		-11814.78	0.00 %
Canada SIMT(NRC)		-2.70	8.44 %	Trinidad SIMT(TTBS)		266.48	0.00 %
Panama SIMT(CNMP)		-40.14	8.01 %	St. Lucia SIMT(SLBS)		16.18	0.00 %
Colombia SIMT(SIC)		-123.31	7.88 %	Chile SIMT(INN)		-3.52	0.00 %
Argentina SIMT(INTI)		-59.89	5.59 %	Antigua SIMT(ABBS)		1.38	0.00 %
Jamaica SIMT(BSJ)		---	0.00 %	Ecuador SIMT(CMEE)		112.58	0.00 %
Costa Rica SIMT(ICE)		74.88	0.00 %	Bolivia SIMT(IBMET)		---	0.00 %
Guatemala SIMT(LNM)		7.08	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 17:45:49 UTC and refreshes every 30 minutes.

Figure 3. The SIMT grid.

SIMT is computed from the contributions of the local SIM time scales, SIMT(*k*). If a SIM NMI contributes to both SIMT and UTC, then SIMT(*k*) and the UTC(*k*) scales can be considered as equivalent at their source, because they are generated with the same clocks, algorithms, and equipment. However, there can be a time offset between SIMT(*k*) and UTC(*k*), due to delays introduced by cables, as a consequence of the different physical points within the laboratory where the time scales are defined. It is also important to emphasize that the laboratories that contribute to both SIMT and UTC operate two separate time transfer systems, and a lower-noise system is often used for the UTC contribution.

SIMT was constructed with specific requirements: i) to be generated in real time, ii) to use the local time scales of the SIM NMIs, SIMT(*k*), as the "clocks" of its ensemble, and iii) to avoid dependence on any single contributor. It is instantly accessible reference that monitors and supports the performance of local SIM time scales and operational timing systems in the SIM region. Figure 4 illustrates how SIMT is generated. Note that the generation of SIMT is automatic. There is no post processing, and no human interaction is required.

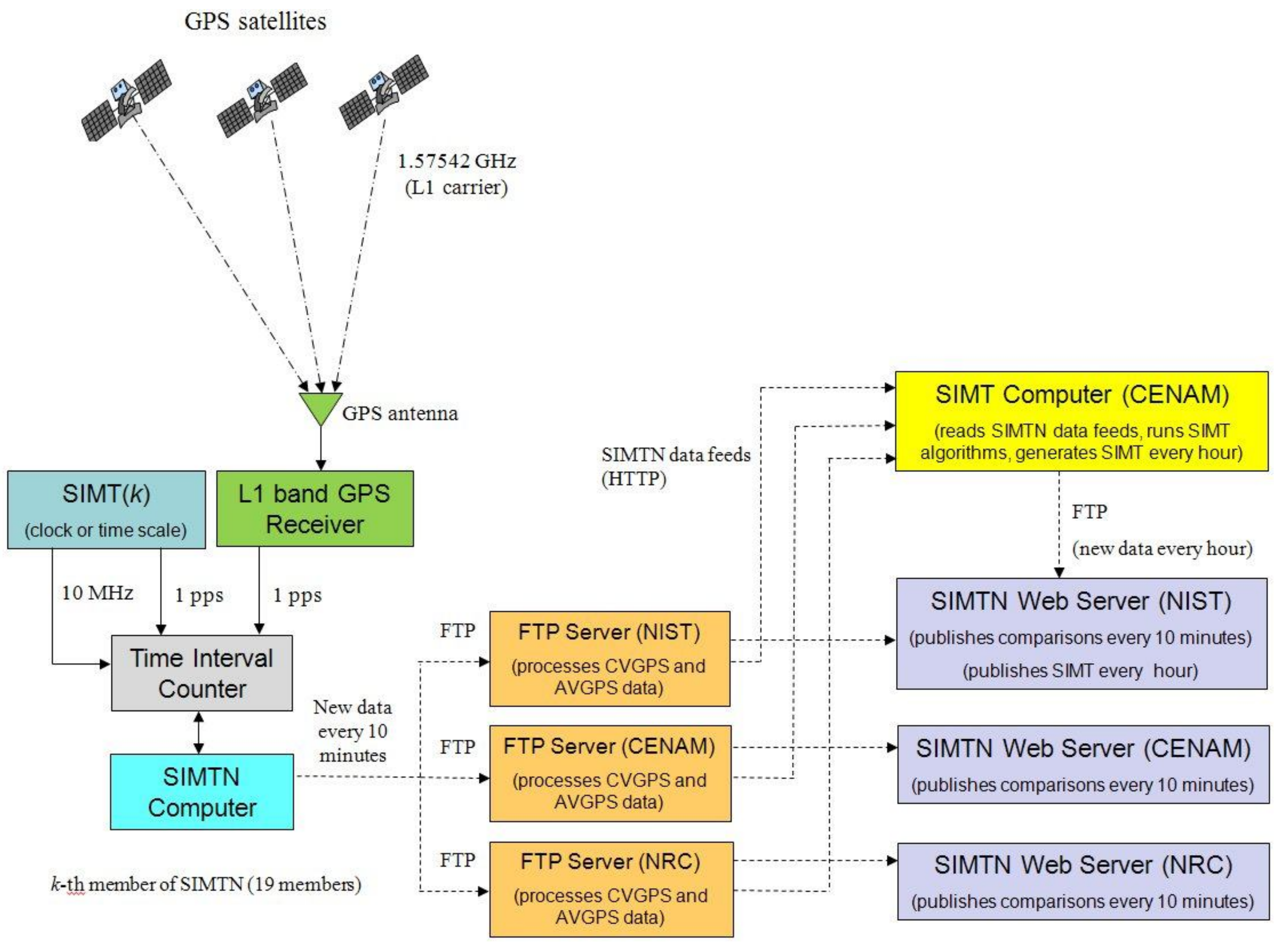


Figure 4. The generation of SIMT.

SIMT weights clocks by estimating their frequency instability in terms of the Allan deviation. However, the way that weights are assigned varies among different time scales. 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. The basic SIMT criteria for clock weighting were originally defined (from January 1, 2010 to February 8, 2012) as:

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

where $\sigma_i(\tau)$ is the Allan deviation of the clock i for τ = 10 days, computed from the previous 50 days of SIMTN data. This long integration period was selected to minimize the influence of the common-view time transfer noise that is inherent in the SIMTN data, and thus to provide a truer picture of the actual performance of the clocks.

With the aim to improve the stability of SIMT, the weighting algorithm was modified on February 9, 2012, to include an “accuracy factor” as follows:

$$\omega_i \propto \frac{1}{\sigma_i(\tau)} \times \frac{1}{\Delta f_i}, \tag{2}$$

where Δf_i is the relative frequency offset of the contributing clock with respect to the SIMT frequency. The weighting computation is made every 24 hours, at 0 hours, 0 minutes UTC. Thus, the weighting factor assigned to a clock remains constant throughout the UTC day.

The NMIs that operate ensemble time scales are allowed to have a weight as large as 40 %. This arbitrary weight limit was set to prevent any single NMI from dominating SIMT. The laboratories that operate time scales consisting of a single cesium clock have a weight limit of 10 %. NMIs without cesium clocks are not allowed to contribute to SIMT (their weight is 0). However, a time difference for all NMI time scales, SIMT – SIMT(k), is computed and published every hour, regardless of whether they contribute or not.

Figure 5 shows two measurements of SIMT – SIMT(NIST) that each cover an interval of 90 days. The first measurement (blue color trace) corresponds to the period from February 23, 2011, to May 23, 2011, when the original weighting algorithm (Eq. 1) was in use. The second measurement (red color trace) corresponds to the period from February 9, 2012, to May 9, 2012, when the new weighting algorithm (Eq. 2) was in use. The results show that the dispersion of values was reduced with the new algorithm.

Figure 6 shows the Allan deviation of SIMT – SIMT(NIST) before and after the new algorithm was implemented, showing visible improvement at all averaging intervals. We assume that the SIMT(NIST) scale had the same frequency stability in 2011 and 2012, and that the improvement shown with the new algorithm in 2012 is due to an improvement in the stability of SIMT.

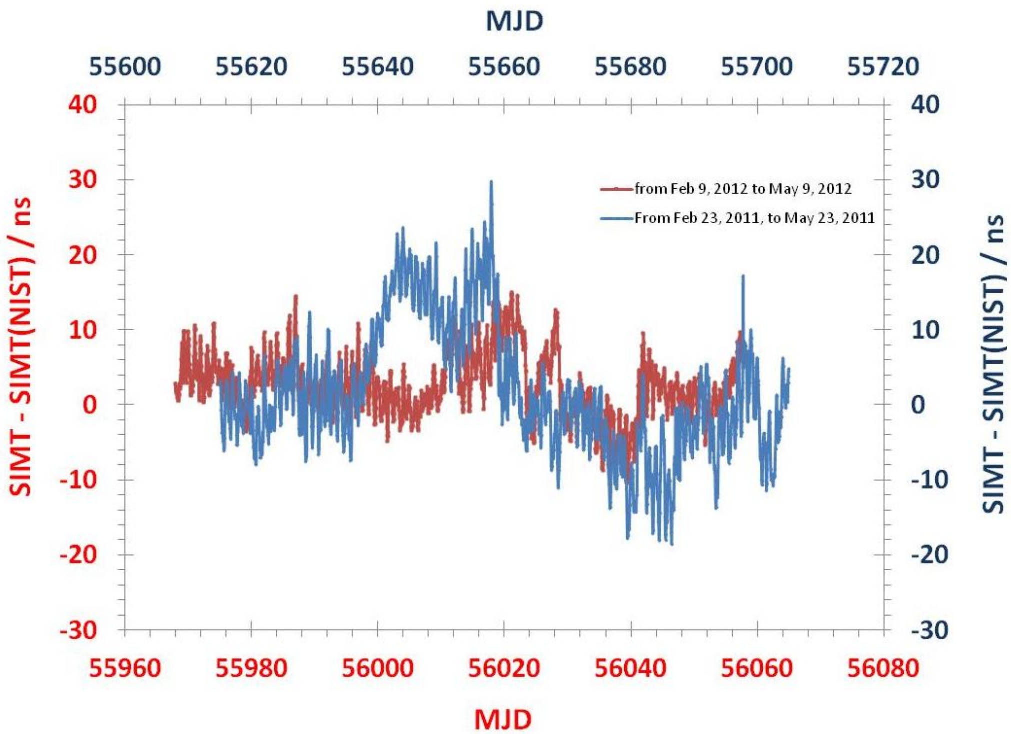


Figure 5. SIMT – SIMT(NIST) time differences. The blue trace was recorded with the original weighting algorithm, the red trace with the new algorithm.

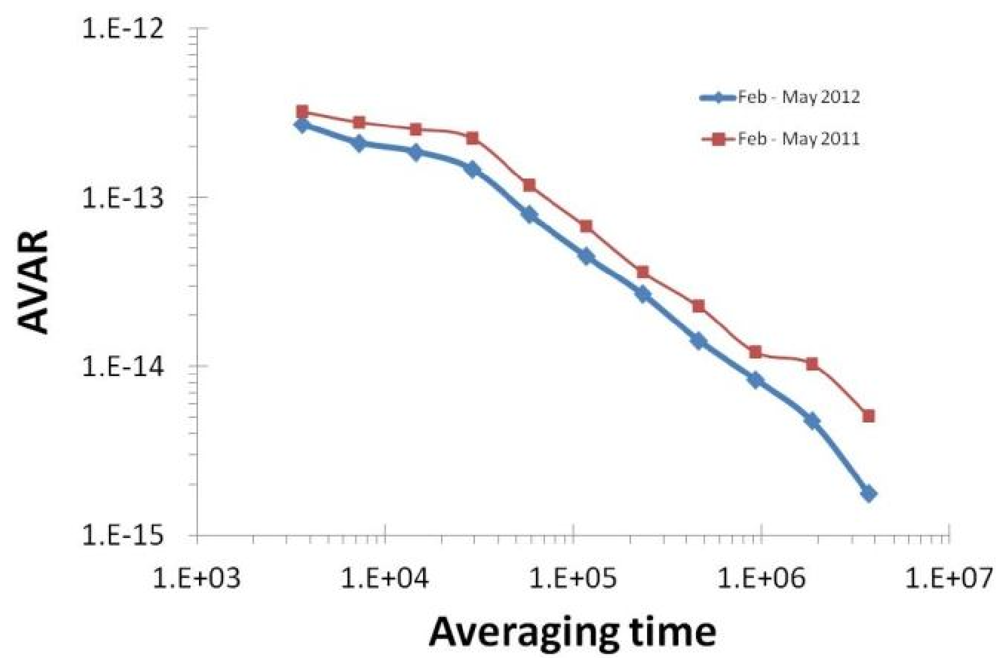


Figure 6. SIMT – SIMT(NIST) frequency stability. The red trace was recorded with the original weighting algorithm, the blue trace with the new weighting algorithm.

4. Remote realization of SIMT

Nine of the current 19 SIMTN members operate a cesium clock as their local time and frequency reference. The other ten members operate either a GPS disciplined clock or a rubidium clock. The rubidium clocks were formally manually steered, which was labor intensive and which made it difficult to maintain synchronization to within better than a few microseconds of SIMT. To improve both, the frequency and time accuracy and stability of the references of such laboratories, the SIM TFWG has recently implemented an automatic frequency steering algorithm in four of those laboratories. Such automatic steering process can be seen also as a physical realization of the SIMT scale in remote locations. Once the Rb clock is successfully locked to SIMT, the average time difference between SIMT and the local SIMT(k) over long intervals is near 0, as shown in Fig. 7.

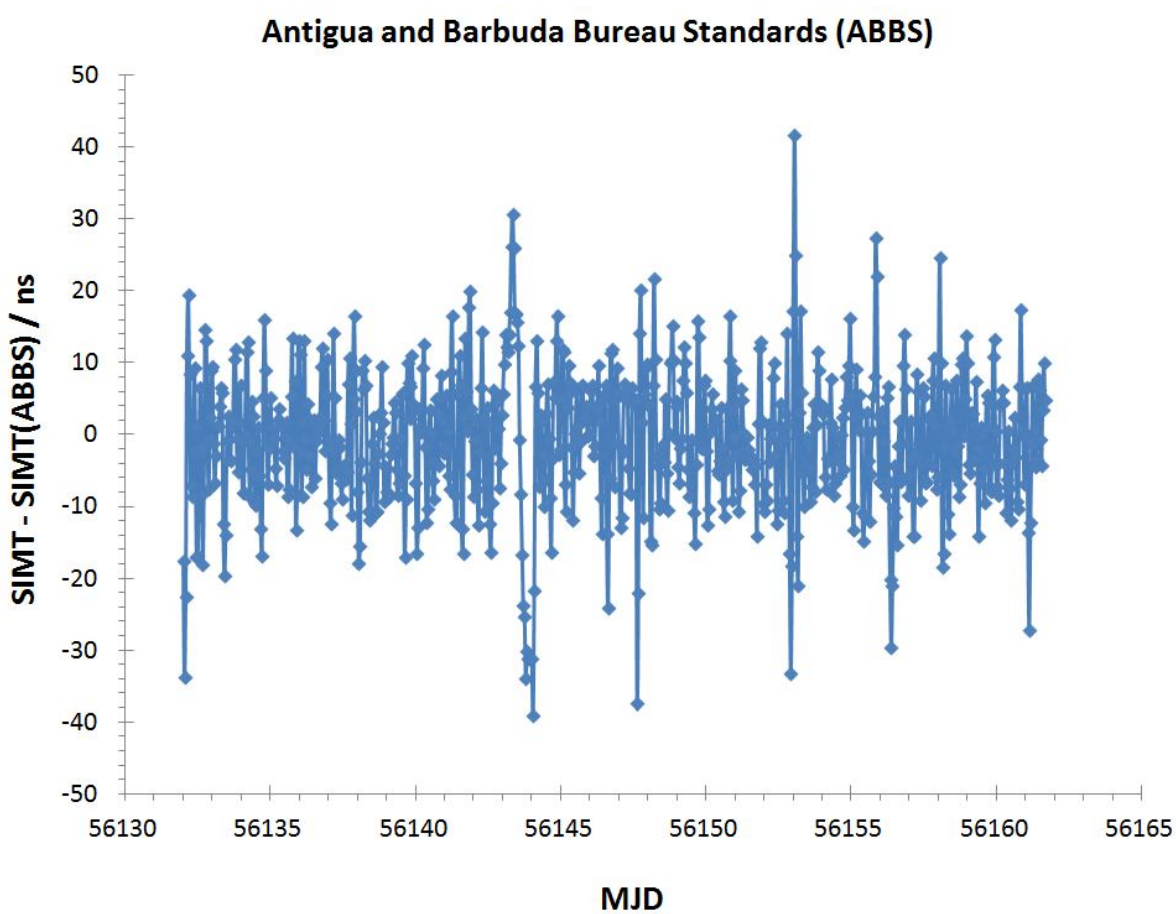


Figure 7. SIMT – SIMT(SLBS) time difference. These time differences correspond to 30 days time interval during which the SLBS rubidium clock was steered to agree with SIMT.

5. Future work

There are many items to address in the near future related with the SIMTN and SIMT. Considering that stability of SIMT is not yet as good of NIST time scale stability, we want to improve SIMT stability. Studies to reduce the instabilities on SIMT will be conducted during the coming months. To improve the accessibility and reliability of SIMT, actions are under progress to simultaneously compute SIMT at two more different locations apart from CENAM, namely, at NRC and the NIST. There are also plans to include a fourth SIMTN server at the Observatorio de Rio de Janeiro in Brazil.

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