Challenges in SIM to Create a Coordination Program for Time and Frequency

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Abstract

The Sistema Interamericano de Metrologia (SIM) is one of five major regional metrology organizations (RMOs) recognized by the Bureau International des Poids et Mesures (BIPM). SIM is composed of the national metrology institutes (NMIs) located in the 34 member nations of the Organization of American States (OAS). Its goal is to create a unified measurement network that extends to the entire SIM region, ensuring the uniformity of measurements and strengthening traceability throughout North, Central, and South America back to the International System (SI) of units. To help reach this goal, SIM sponsors working groups in ten different metrological fields, including time and frequency.

Developing a unified time and frequency measurement network in the SIM region has been a challenging task, but much progress has been made in recent years and many obstacles have been overcome. This paper summarizes work done by the SIM Time and Frequency metrology working group from 2004 to 2010. It discusses the challenges faced by the working group, the progress made by individual laboratories, and the important role played by metrology education. It also provides an overview of two major achievements of the working group, the SIM Time Network (SIMTN) and the SIM Time (SIMT) scale.

1. Introduction

The Sistema Interamericano de Metrologia (SIM) covers more land area (Figure 1) than any other regional metrology organization (RMO). The SIM region extends throughout North, Central, and South America and the Caribbean, an area that covers about 27 % of the world's land and includes about 13 % of its population (an estimated 910 million people as of 2009). The residents of the 34 nations in the SIM region experience a wide variety of cultures and speak a wide variety of languages, including Spanish, English, Portuguese, and French. There is also a large variation in both the populations of the SIM nations and the strength of their economies. As of 2009, about two-thirds of the SIM population (approximately 617 million people) resides in the United States, Brazil, or Mexico. In contrast, 11 SIM nations, mostly islands in the Caribbean region, have populations of less than one million. As of 2009, the per capita gross domestic product (GDP) of the United States and Canada exceeded $38 000 USD, but 15 SIM nations had per capita GDPs of less than $10 000 USD [1]. This disparity in population and money directly translates into the level of resources that are made available for metrology. For example, NIST has about 40 full-time professionals employed in its time and frequency division, more than the entire staff at some SIM national metrology institutes (NMIs), which are often small laboratories that pursue just a few areas of metrology to support local industry. In contrast, many SIM NMIs are fortunate if even one metrologist is free to focus on time and frequency measurements.

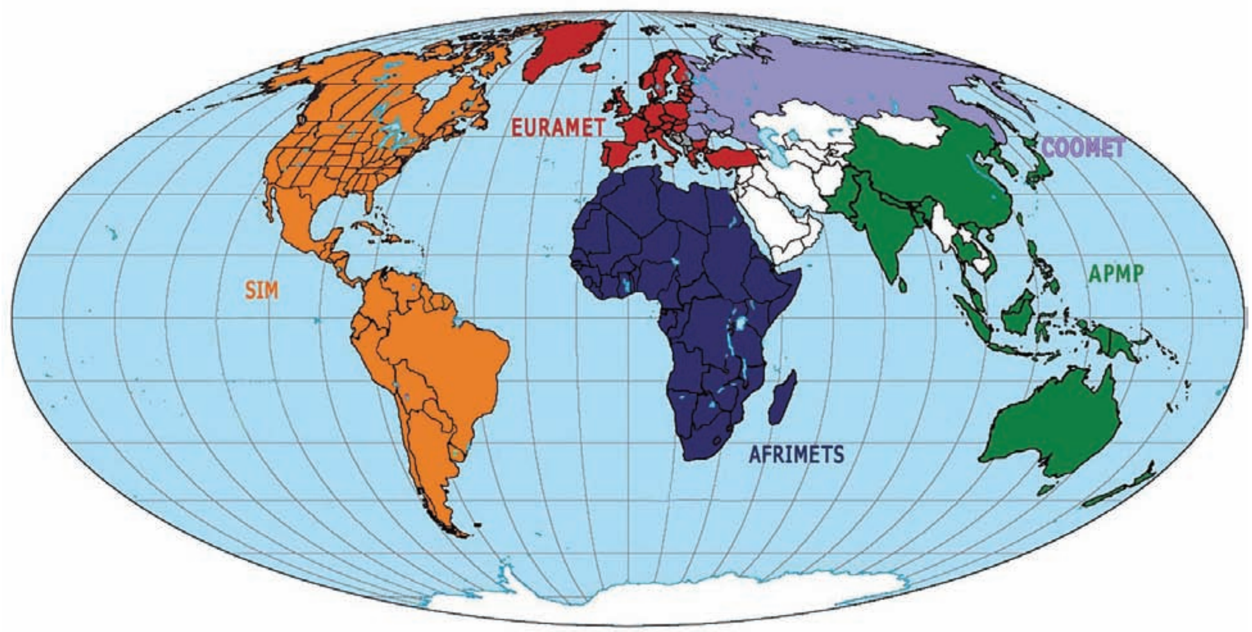

Figure 1. SIM is the largest of the world's five RMOs in terms of land area.

When the SIM Time and Frequency Metrology Working Group (MWG) became active in 2004, its first task was to survey the SIM NMIs to find out who would be interested in participating in the SIM time and frequency effort. A number of SIM NMIs responded and a list of contacts was quickly established. This indicated that there was interest, but the next step was uncertain. It was obvious that a large effort would be needed to unite the SIM NMIs and that it would not happen overnight. To begin with, each SIM NMI was at a different stage of its development. A few NMIs already had well established timing laboratories that participated in Bureau International des Poids et Mesures (BIPM) key comparisons and contributed to the derivation of Coordinated Universal Time (UTC). These labs already had experienced staffs, multiple cesium frequency standards, sophisticated measurement systems, and time transfer equipment including Global Positioning System (GPS) satellite receivers. It was not clear how they would benefit from SIM.

In sharp contrast, other SIM NMIs were starting with nothing other than an interest in pursuing time and frequency metrology. Some had never owned or operated a frequency standard, and had no experience in making time and frequency measurements. They would clearly benefit from the SIM effort, but some lacked the funding to buy even the basic equipment that they needed to get started. The MWG wanted to help, but the SIM budget was small. The limited funds would have to be carefully spent without waste if any progress were to be made.

Thus, the MWG began its work by facing a complex metrology problem. It needed to find a way to get as many SIM NMIs as possible to maintain continuously running time standards. Each

NMI then had to compare its standard to the other time standards in the SIM region. The international comparisons were necessary if all SIM NMIs were to establish metrological traceability to the International System (SI) of units. The problem was part cultural, part logistical, part financial, and part technical, and any proposed solution would have to be practical. The solution was found with the development of the SIM Time Network.

2. The SIM Time Network

The SIM Time Network (SIMTN) became operational in May 2005, when comparisons began between the National Institute of Standards and Technology (NIST), the Centro Nacional de Metrología (CENAM) of Mexico, and at the National Research Council (NRC) of Canada [2]. Since then, the network has expanded to accommodate all interested SIM NMIs [3]. Sixteen laboratories should be participating by the end of 2010, as shown in Figure 2.

Figure 2. The SIM Time Network.

The SIMTN was built by combining two existing technologies, GPS and the Internet. GPS, through a measurement technique called common-view, has long been used to compare high accuracy clocks located at remote sites [4]. The common-view technique requires the measurements made by all of the laboratories involved in a comparison to be gathered in one place before the measurements results can be processed. This data gathering process would have to be automated or the delays would be unacceptable and the work load unsustainable. The use of the Internet solved this problem, providing an ideal medium for the automatic transfer of measurement data. Once the problem of data transfer was solved, there was no reason to delay the publishing of the measurement results, and it was decided to make them available to everyone in real time. The real-time measurement grid (Figure 3) is updated every 10 minutes and shows the current time difference between all of the SIM NMIs. The grid can be viewed at the MWG web site: http://tf.nist.gov/sim

SIM Time Network

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

	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(INDP)	Trinidad SIMT(TTBS)
United States SIMT(NIST)		-12.0	33.6	-38.8	15.4	279.6	6.5	54.5	-15.9	-70857586.8	25.0	1009.7	12.4	-337.5
Mexico SIMT(CNM)	12.0		45.6	-27.7	20.0	289.3	19.6	64.4	-4.8	-70857576.7	37.0	1017.9	19.9	-326.1
Canada SIMT(NRC)	-33.6	-45.6		-72.3	-18.6	244.4	-27.7	20.6	-49.5	-70857621.5	-8.9	972.3	-21.6	-370.4
Panama SIMT(CNMP)	38.8	27.7	72.3		52.6	316.0	46.6	98.3	23.0	-70857548.2	71.1	1049.3	50.5	-298.3
Brazil SIMT(ONRJ)	-15.4	-20.0	18.6	-52.6		264.8	-1.0	45.3	-27.9	-70857600.7	17.5	996.7	-4.4	-349.3
Costa Rica SIMT(ICE)	-279.6	-289.3	-244.4	-316.0	-264.8		-270.2	-219.1	-294.0	-70857864.2	-246.3	733.7	-266.9	-615.1
Colombia SIMT(SIC)	-6.5	-19.6	27.7	-46.6	1.0	270.2		44.7	-24.2	-70857594.6	17.4	998.6	-1.1	-341.8
Argentina SIMT(INTI)	-54.5	-64.4	-20.6	-98.3	-45.3	219.1	-44.7		-73.6	-70857646.4	-26.1	951.9	-49.2	-386.7
Guatemala SIMT(LNM)	15.9	4.8	49.5	-23.0	27.9	294.0	24.2	73.6		-70857573.0	46.4	1026.6	25.8	-321.9
Jamaica SIMT(BSJ)	70857586.8	70857576.7	70857621.5	70857548.2	70857600.7	70857864.2	70857594.6	70857646.4	70857573.0		70857619.2	70858598.5	70857598.6	70857249.7
Uruguay SIMT(UTE)	-25.0	-37.0	8.9	-71.1	-17.5	246.3	-17.4	26.1	-46.4	-70857619.2		977.9	-24.1	-359.4
Paraguay SIMT(INTN)	-1009.7	-1017.9	-972.3	-1049.3	-996.7	-733.7	-998.6	-951.9	-1026.6	-70858598.5	-977.9		-1001.6	-1340.0
Peru SIMT(INDP)	-12.4	-19.9	21.6	-50.5	4.4	266.9	1.1	49.2	-25.8	-70857598.6	24.1	1001.6		-347.2
Trinidad SIMT(TTBS)	337.5	326.1	370.4	298.3	349.3	615.1	341.8	386.7	321.9	-70857249.7	359.4	1340.0	347.2	
Last Update (HHMM)	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340	2340

This table was created at 03-01-2010 (MJD 55256) 23:41:17 UTC and will refresh every five minutes. Values are in units of nanoseconds.

Click on a time scale or country name to view a **one-way** GPS graph for the current day (GPS-NMI). Click on a number to view a **common-view** graph between two laboratories for the current day.

Figure 3 – The SIM Real-Time Grid.

Participation in the SIMTN requires a SIM measurement system. Interested NMIs can purchase their own system or wait for SIM funding to become available. The cost of building, calibrating, and shipping a system is about $8 000 USD, and the systems are delivered at cost by NIST. So far, the MWG has obtained enough funding to deliver about two systems per year. The systems consist of an industrial rack-mount computer that contains a time interval counter, 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 get the hardware costs down to a reasonable level. The cost of a SIM system is 75 % to 80 % less than the cost of the dual frequency (L1 and L2 band) common-view receivers typically purchased by NMIs that participate in the BIPM key comparisons. It's true that the more expensive hardware has advantages that can reduce the time uncertainty to perhaps 5 ns, but the performance gained from the additional cost and effort is relatively small. Even with its inexpensive hardware, the uncertainty of the SIMTN measurements (k = 2) is typically less than 15 ns and often 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 a few things need to be done; a GPS antenna needs to be mounted on the roof, a 5 MHz or 10 MHz frequency signal and a one pulse per second (pps) signal from the NMI's time standard need to be connected, and the system needs to 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. The three servers each make the SIM grid (Figure 3) available on the web. They also host web-based graphing and data analysis software so that the measurement results can be studied in detail.

Table 1. The SIMTN Participants.

Country	NMI	First SIMTN Participation	National Time Standard	UTC Contributor
Argentina	INTI	January 2008	Cesium	Yes
Brazil	ONRJ	May 2007	Ensemble Time Scale [5]	Yes
Canada	NRC	June 2005	Ensemble Time Scale [6]	Yes
Chile	INN	Late 2010	Rubidium	No
Colombia	SIC	May 2007	Cesium	No
Costa Rica	ICE	March 2007	Cesium	No
Guatemala	LNM	November 2009	GPSDO	No
Jamaica	BSJ	January 2008	Cesium	No
Mexico	CENAM	May 2005	Ensemble Time Scale [7]	Yes
Panama	CENAMEP	December 2005	Cesium	Yes
Paraguay	INTN	February 2009	Rubidium	No
Peru	INDECOPI	September 2009	Rubidium	No
St. Lucia	SLBS	June 2010	Rubidium	No
Trinidad / Tobago	TTBS	November 2009	GPSDO	No
United States	NIST	May 2005	Ensemble Time Scale [8]	Yes
Uruguay	UTE	January 2009	Disciplined Rubidium [9]	No

Table 1 lists the SIMTN participants and the date when they joined the network. It also shows whether the NMI currently participates in the BIPM key comparisons and contributes data to UTC, and the type of time standard that they operate. Most SIM NMIs operate a single clock as their time standard, 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 free run. 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 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.

The SIMTN was designed to remove as many barriers to entry as possible. 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 (about $4 000 USD) to provide a rubidium oscillator, which is an ideal entry level standard.

3. The SIM Time Scale

Another major development of the MWG is SIM Time (SIMT), which is a time scale generated from the SIMTN data [10]. Work on the SIMT algorithms began at CENAM in late 2008. The SIMT scale is a weighted average of the local time scales, known as SIMT(*k*), kept at the various SIM NMIs (Figure 4). It is generated from the SIMTN data and is updated every hour with estimates of SIMT – SIMT(*k*) displayed on the web. As of May 2010, all nine of the NMIs (Table 1) with either ensemble time scales or cesium clocks are contributing to SIMT. These NMIs can now compare their standards not only to each other, but also to SIMT. Along with a similar time scale developed between four NMIs in Asia [11], the SIMT scale is one of the only international time scales generated in real time.

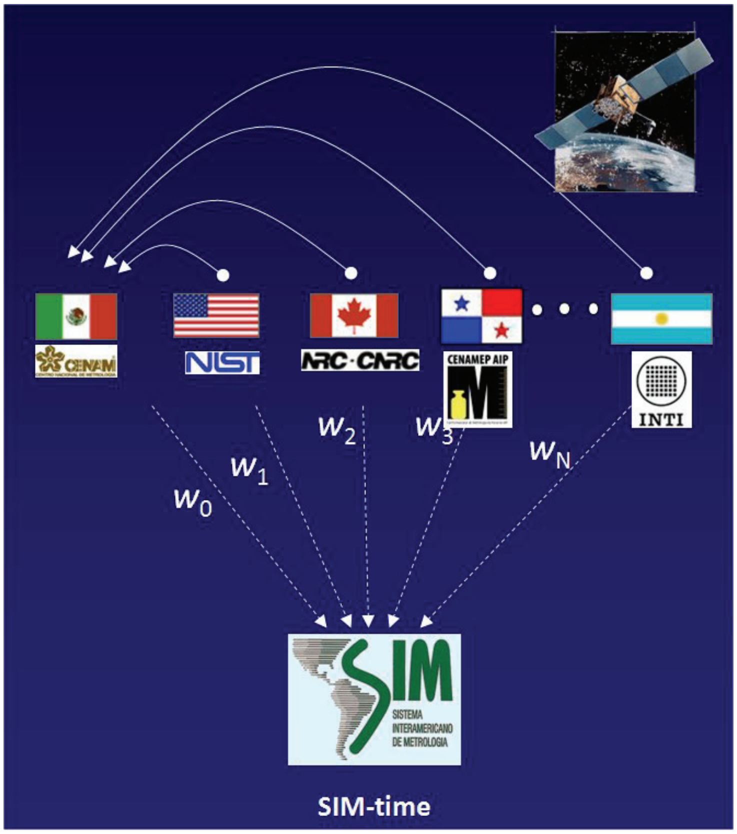

Figure 4. The SIM time scale.

4. Metrology Education

It is hard to overestimate the value of metrology education, or the experience and sense of purpose that metrologists gain from working with their colleagues. The staff members at small and recently established NMIs obviously benefit from the experience of their colleagues at more established laboratories, but all NMIs have unique experiences that they can share with the others. To further the cause of metrology education, the MWG has conducted three four-day time and frequency training classes, with each well attended by metrologists from both NMIs and industry. The first was held in Asunción, Paraguay in December 2005, the second was in Buenos Aires, Argentina in February 2008, and the third in Lima, Peru in March 2010. The training effort goes on continuously through emails, phone conversations, and laboratory visits.

The field of time and frequency metrology is highly specialized, and its jargon can be arcane and intimidating to newcomers, even if they are well versed in another area of metrology. Time and frequency metrology is not simple; it involves atomic clocks, satellites, and sophisticated electronic instruments, and new advancements such as optical clocks are always pushing the field rapidly along. In addition, non-classical statistics that are not taught in school are used to quantify measurement uncertainty, such as the Allan deviation and the Time deviation. A thorough understanding of the field typically requires years of study, but the MWG has tried to shorten the learning curve by distributing training materials that provide an introduction. Slide presentations that cover the topics listed in Table 2 have been developed for SIM training courses and are made freely available at the MWG web site: http://tf.nist.gov/sim

Table 2. Subject Areas of Time and Frequency Metrology Addressed by the MWG.

A Historical Perspective of Time Measurement
The Second and the International System of Units
General Concepts of Time and Frequency Metrology
Traceability
Quartz Oscillators
Atomic Oscillators (Rubidium, Cesium, and Hydrogen Masers)
The Global Positioning System (GPS)
Time Transfer Methods, including GPS common-view
Disciplined Oscillators
Time Domain Measurements
Frequency Domain Measurements
Measurement Uncertainty
The Statistics of Time and Frequency (Allan deviation and Time deviation)
Ensemble Time Scales
Frequency Combs, Optical Clocks, and the Future of the SI Second

5. Progress and Developments at SIM NMIs

The timing labs of the SIM region have made rapid progress in recent years. In addition to establishing traceability, SIM NMIs have developed the ability to do more types of calibrations and have reduced their measurement uncertainties. Lab personnel have also developed new data acquisition and measurement control systems. The SIMTN and metrology education have played a role in this progress, as has the addition of new laboratory equipment. Figure 5 shows the standards and instrumentation in four SIM timing laboratories.

Figure 5. SIM Timing Labs (Colombia, Costa Rica, Panama, Uruguay, clockwise from top left)

A goal of the MWG is to have all NMIs develop quality systems and to submit their calibration and measurement capabilities (CMCs) to the BIPM Key Comparison Database (KCDB) so that their calibrations can be recognized worldwide. When the MWG was first established, none of the SIM NMIs were included in the KCDB for time and frequency. The first to be included was CENAMEP of Panama in August 2006. As of March 2010, five SIM timing laboratories (CENAM, CENAMEP, ONRJ, NIST, and NRC) were among the 40 timing laboratories included in the KCDB. Several other SIM NMIs are now working on their submissions.

A goal of many NMIs is to become the official timekeeper for their country, an important responsibility. Some SIM NMIs earned this distinction long ago; for instance NRC has been Canada's official timekeeper since 1970. However, new NMIs must first establish name recognition within their countries, demonstrate the ability to maintain an internationally recognized time standard, and then begin the legislative process required to obtain official timekeeper status. The documented measurements provided by the SIMTN make this effort easier. INTN became Paraguay's official timekeeper by presidential decree in December 2009. SIC had fulfilled the responsibility of being Colombia's official timekeeper since 1992, but received legal confirmation of this function (decree 3523) in 2009. The NMIs in Costa Rica, Jamaica, Panama, Peru, and Trinidad & Tobago, are now working toward the goal of becoming their nation's official timekeeper and expect to be successful. In addition, UTE is now working on an agreement to audit the agency responsible for the official time in Uruguay.

The MWG has also indirectly helped SIM laboratories to develop new time broadcast services. For example, many SIM labs operate network time protocol (NTP) servers that broadcast time over the Internet, and these labs can now all be confident that the time they distribute is accurate and traceable. Web clocks, a convenient way to distribute time-of-day to the general public, are now operated by seven SIMTN participants (Table 3), and several other participants have announced plans to develop them.

Table 3. Web Clocks Operated by SIM NMIs

Country	**URL**
Brazil	http://pcdsh01.on.br/HoraLegalBrasileira.asp
Canada	http://time5.nrc.ca/webclock_e.shtml
Colombia	http://horalegal.sic.gov.co/
Mexico	http://www.cenam.mx/hora_oficial/
Panama	http://horaexacta.cenamep.org.pa/
Peru	http://www.indecopi.gob.pe
United States	http://nist.time.gov

The work of the MWG has also helped launch new calibration services that support local industry. NIST launched its Time Measurement and Analysis Service (TMAS), a remote calibration service intended for metrology laboratories and research facilities, by utilizing technology and experience gained from the SIMTN [12] and a similar service is operated at CENAM. The SIMTN experience also allowed CENAM and NIST to collaborate on a project to synchronize the clocks in the TELMEX communications network in Mexico to CENAM time. TELMEX is the largest telephone provider in Mexico, and their telephone network includes eight cesium primary reference clocks, located in four different cities in Mexico. These clocks are now continuously compared to the national time standard in Mexico with a network that is similar to the SIMTN. ICE is doing similar work, and is monitoring clocks in the telecommunications synchronizing network in Costa Rica. CENAMEP of Panama and ICE of Costa Rica have organized a stopwatch comparison where two travelling stopwatches will be sent around the SIM region for measurement. Eleven SIM NMIs will participate in this comparison beginning in the summer of 2010.

In short, the efforts of the MWG have been successful. Much has been accomplished, but perhaps the best thing about the SIM effort is that the communication between SIM NMIs has been excellent.   Many friendships have been formed, many challenges have been overcome, and a healthy spirit of cooperation exists. Although challenges will always continue to exist, the future of time and frequency metrology in the SIM region looks brighter today than ever before.

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