Automated Control of National Time Standards via the SIM Time Scale

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***Abstract* — This paper describes a frequency and time control system developed by the Sistema Interamericano de Metrologia (SIM). Due to limited resources, some SIM national metrology institutes maintain a low-cost rubidium clock as their national time standard, instead of the cesium clocks commonly found at larger laboratories. The automated system described here controls the rubidium clocks by adjusting them to agree with the SIM Time Scale (SIMT), which is distributed hourly via the Internet. The system has demonstrated the ability to keep time within ±50 ns of SIMT, with frequency stability near 4 × 10^{-14} after one day of averaging. Due to the inherent stability limitations of the clocks, these performance levels could not be maintained through manual adjustment.**

Keywords — disciplined oscillator, frequency, time, time scale, time transfer

I. INTRODUCTION

Advancements in time and frequency metrology have been made in recent years within the Sistema Interamericano de Metrologia (SIM), a regional metrology organization whose members are the nations of the Organization of American States (OAS). The SIM region includes the national metrology institutes (NMIs) of 34 nations, and covers North, Central, and South America and the Caribbean Islands.

The SIM Time Network (SIMTN) allows NMIs to instantly compare their local time scales through common-view and all-in-view observations of Global Positioning System (GPS) satellites, with the results published via the Internet [1]. The SIM Time Scale (SIMT) processes these time comparisons and generates an international time scale that is also distributed in real time via the Internet and shared by the SIM member nations [2]. The SIMTN has operated continuously since 2005 and SIMT became an operational time scale in 2010. As of March 2013, 19 nations are SIMTN and SIMT participants (Table 1). Measurement results are published in real time at the website of the SIM time and frequency metrology working group (http://tf.nist.gov/sim).

Table 1. SIM Time Network Members.

Country	Year of First Participation	Local Time Scale
United States	2005	Ensemble time scale
Mexico	2005	Ensemble time scale
Canada	2005	Ensemble time scale
Panama	2005	Cesium clock
Brazil	2006	Ensemble time scale
Costa Rica	2007	Cesium clock
Colombia	2007	Cesium clock
Argentina	2007	Cesium clock
Guatemala	2007	GPS clock
Jamaica	2007	Cesium clock
Uruguay	2008	Cesium clock
Paraguay	2008	Rubidium clock
Peru	2009	Cesium clock
Trinidad & Tobago	2009	GPS clock
Saint Lucia	2010	Rubidium clock
Chile	2010	Rubidium clock
Antigua and Barbuda	2011	Rubidium clock
Ecuador	2012	GPS clock
Bolivia	2012	Rubidium clock

SIMT is an ensemble time scale that operates in a similar fashion to the local time scales found at the National Institute of Standards and Technology (NIST) in the United States and at the Centro Nacional de Metrología (CENAM) in Mexico. The clocks in the ensemble are weighted according to their frequency stability, and the average of the weighted clocks is used to generate a composite "clock" that will continue to run even if one or more clocks in the ensemble fails. Unlike the NIST and CENAM time scales, where the members of the ensemble are individual cesium clocks or hydrogen masers, the “clocks” in the SIMT ensemble are the local time scales found at SIM NMIs. Each country is represented by just one NMI, and consequently, by just one “clock”.

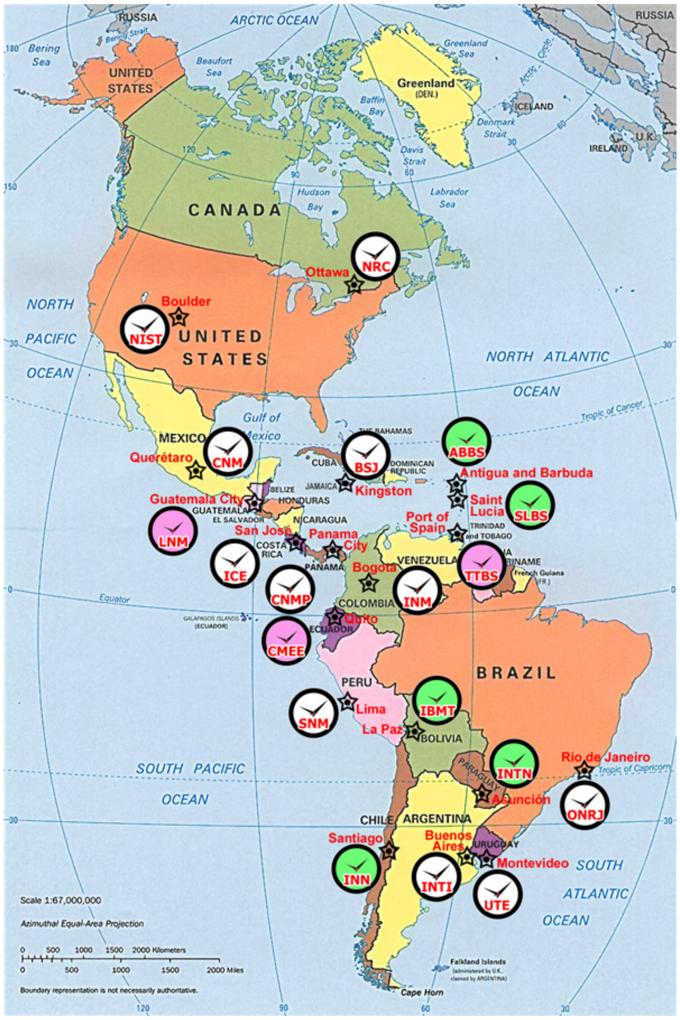

Fig. 1. Map of the SIM region showing “clock” locations.

There are large disparities in resources (staff sizes, equipment, and money) between SIM NMIs and this is reflected in their local time scales, which are divided into four groups. The Group 1 time scales are ensemble time scales that include multiple cesium clocks and/or hydrogen masers, and are allowed to contribute as much as 40 % to the weighted SIMT calculation. The Group 2 time scales each consist of a single cesium clock, and are allowed to contribute as much as 10 % to SIMT. Groups 1 and 2 are indicated by the white clock icons in Fig. 1. The Group 3 time scales are single GPS disciplined clocks (purple clock icons in Fig. 1), and the Group 4 time scales are single rubidium clocks (green clock icons in Fig. 1). Group 3 and Group 4 time scales are not allowed to contribute to SIMT and have a weight of 0 %.

The Group 4 time scales are located in Antigua and Barbuda, Bolivia, Chile, Paraguay, and Saint Lucia. These NMIs currently have limited resources, and their national standards each cost about 1/20 as much as a cesium clock. The frequency stability of the rubidium clocks is limited to a few parts in 10^{12} per day, and they require daily manual adjustment to keep time within 1 µs of SIMT and Coordinated Universal Time (UTC). The control system described in Section II eliminates the need for manual adjustment by keeping the Group 4 time scales synchronized and syntonized to SIMT.

II. Method of Operation

The control system is driven by SIMTN measurements that compare each SIM local time scale to GPS time [1]. New measurements are uploaded every 10 minutes to three Internet servers, located at NIST, CENAM, and at the National Research Council (NRC) in Canada. Each server processes the common-view and all-in-view GPS data and generates a “data feed” upon request. The SIMT computer, which resides at CENAM, accesses each data feed, performs a cross check, and computes the SIMT algorithm [2]. The time differences between SIMT and each local time scale, SIMT – SIMT(k), are computed and uploaded to the NIST server and published via the Internet every hour. Values for SIMT – SIMT(k) are computed for all “clocks”, including the Group 3 and Group 4 clocks that have 0 % weight in the SIMT ensemble. Figure 2 provides a block diagram of the generation of SIMT.

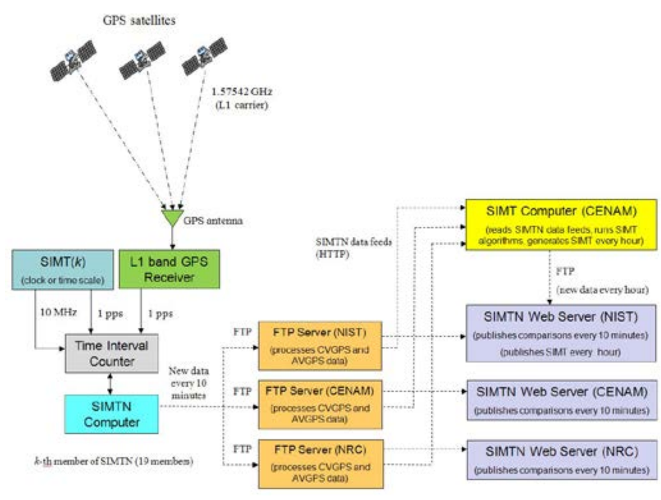

Fig. 2. The generation of SIMT.

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 our system, the rubidium clock is the LO, and the reference source is SIMT.

Each rubidium clock is adjusted by an adaptive proportional-integral-derivative (PID) controller that was implemented in software. A PID controller corrects the error, *e*, between a measured process variable and a desired set point, *SP*. In this case, the desired value of *SP* is 0, because the goal is simply to lock the LO to SIMT. The process variable is *TD*, the last measured time difference between the LO and SIMT. To obtain *TD*, the PID controller invokes a common gateway interface (CGI) applet on the NIST server called *SIMTDIFF*. This applet sends the appropriate SIMT – SIMT(*k*) result through TCP port 80, where it is read by the control software via the hypertext transfer protocol (HTTP). The control software then converts *TD* to a dimensionless frequency correction that is applied to the LO through an RS-232 interface. This process is repeated every hour. Figure 3 provides a block diagram.

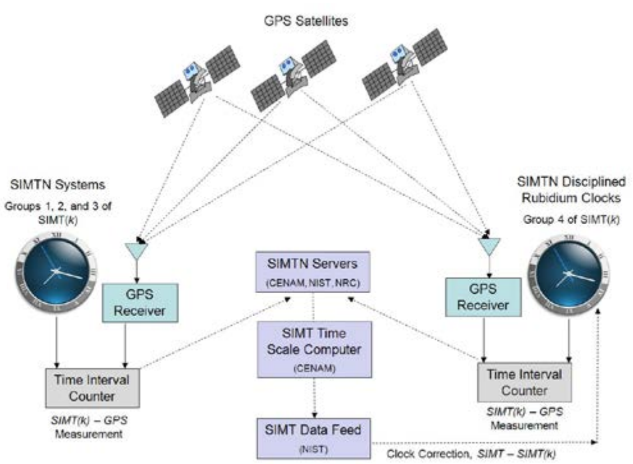

Fig. 3. Simplified diagram of SIMT disciplined oscillator approach.

The control software indicates a lock condition when the LO is accurate to within 50 ns of SIMT and stable to within 10 ns as estimated with the time deviation, $\sigma_x(\tau)$ [3], at $\tau = 10$ minutes. Internally, however, the software distinguishes between a "soft lock" based on the 50/10 criteria, and a "hard lock," which is reached when the accuracy is within 30 ns and the time deviation is less than 5 ns.

The frequency corrections are recorded and stored. If the rubidium clock loses lock due to an Internet or SIMT outage, its 1 pulse per second (pps) timing output can be resynchronized to SIMT, and its frequency can be restored to the last "hard lock" condition when the outage ends. During reacquisition, the PID controller is disengaged until the LO reaches a steady state condition with respect to SIMT, at which point frequency corrections are resumed.

One limitation of this method is that the LO will rapidly lose lock if SIMT is not accessible, so it is imperative for SIMT and the various network connections to be reliable. The noise floor of the LO, as estimated with the Modified Allan deviation, *Mod* $\sigma_y(\tau)$ [3], is near 4×10^{-13} at $\tau = 1$ hour and about a factor of five worse 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. Thus, an unlocked clock rapidly accumulates both a frequency and time error. This problem was, of course, more severe when the clocks were manually adjusted at irregular intervals, and even intermittent SIMT availability provides much better performance.

Another limitation involves latency. There is a 35 minute interval between the measurement of the LO and the time when the SIMT – SIMT(*k*) values are made available to the control software. The values refer to the previous hour, but SIMT is computed 20 minutes after the hour and published 30 minutes after the hour. To allow for processing delays, the control software does not retrieve the values or issue frequency corrections until 35 minutes after the hour. Due to this latency, the LO can be locked more tightly to the time scale of another NMI [4] than it can be to SIMT. However, for a variety of reasons (some metrological, some political) it is preferable to control national time standards with a shared SIM resource, rather than with an NMI time scale.

III. Results

The control system was first installed at the St. Lucia Bureau of Standards (SLBS) in June 2012 and most recently at the Instituto Boliviano de Metrologia (IBMETRO) in January 2013. Since its inception, there have been frequent SIMT outages, along with power and Internet outages at some SIM laboratories. For these reasons, it has not been possible to record long data runs where a rubidium clock has remained locked to SIMT. However, each failure results in more robust software being written and the reliability is gradually improving. The results when the control system is working properly are encouraging, and examples are provided in the following sections.

A. Time Accuracy Results

Figure 4 shows the results of a 60-day time comparison between SIMT and the rubidium clock located at the Antigua and Barbuda Bureau of Standards (ABBS) in St. Johns, Antigua. The comparison took place between July 25th and September 22nd, 2012, Modified Julian Dates (MJD) 56133 to 56192. The hourly time variations remained within ±50 ns of SIMT and the average time offset was -0.5 ns.

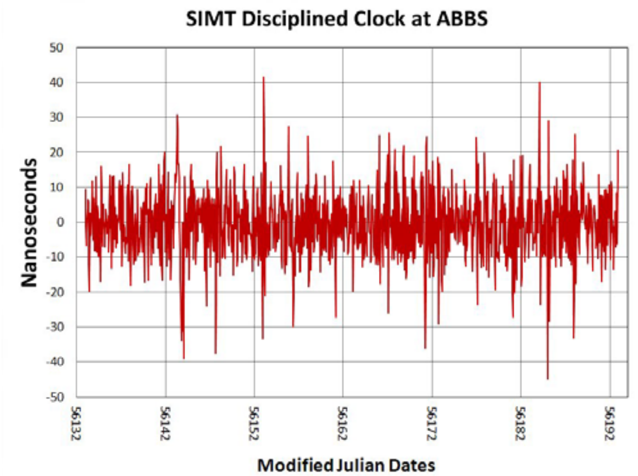

Fig. 4. Time accuracy of SIMT disciplined clock (1 h averages).

When a SIMT outage occurs, the rubidium clocks run without adjustment until the outage is over, and require multiple hours to relock. Figure 5 shows the performance of a clock located at SLBS before, during, and after a 41-hour SIMT outage. The relock period lasted for about 8 hours. During the outage, the clock's time offset exceeded ±2 µs.

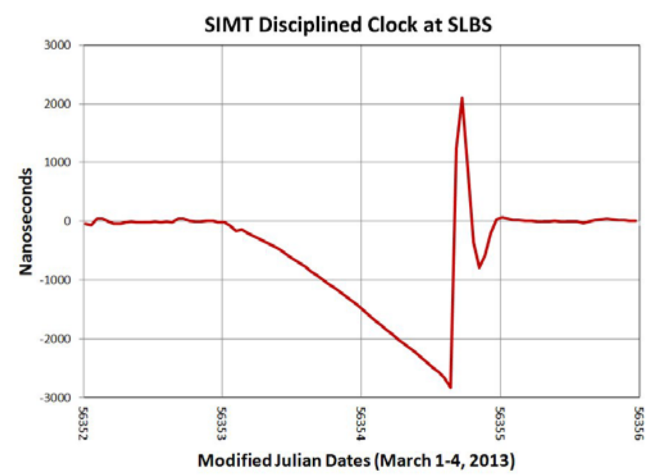

Fig. 5. Clock accuracy before, during, and after a SIMT outage.

B. Frequency Stability Results

Figure 6 shows the frequency stability of the clock at ABBS estimated with *Mod* $\sigma_y(\tau)$ [3] for the same 60-day period graphed in Fig. 4. The stability is about 4×10^{-14} at $\tau = 1$ day, almost two orders of magnitude better than an undisciplined rubidium clock, and drops below 1×10^{-15} at $\tau = 10$ days. Note that SIMT was the reference for the Fig. 6 measurements and also controls the rubidium clock, so there is correlation between the device under test and the reference that makes the results continuously improve without ever reaching a noise floor. Ideally, statistics such as *Mod* $\sigma_y(\tau)$ are applied to free running, rather than disciplined oscillators, whose stability is limited mostly by the uncertainty of the clock corrections. Even so, they are useful for determining how closely a disciplined oscillator replicates its reference frequency [4].

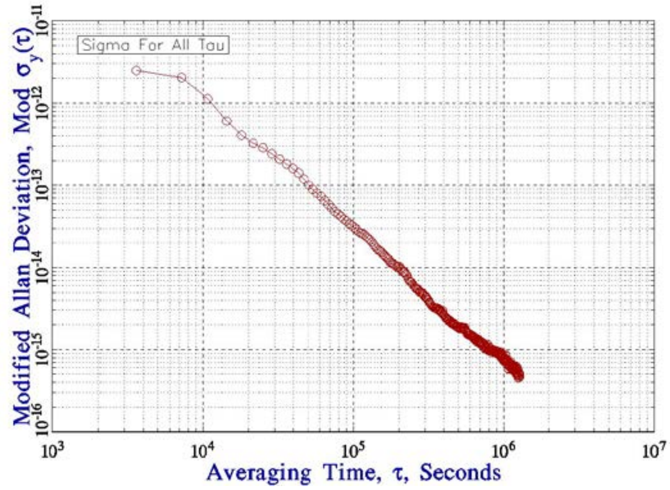

Fig. 6. Frequency stability of SIMT disciplined oscillator.

IV. Conclusions

We have developed and demonstrated a system to control the low-cost rubidium clocks that serve as national time standards in some SIM countries. The system automatically disciplines the clocks to agree with SIMT. Our initial results are promising, but more work is needed to improve the reliability of SIMT and to optimize the clock disciplining method.

Acknowledgements

We thank Anselm Gittens of the St. Lucia Bureau of Standards (SLBS), Alan Michael of the Antigua and Barbuda Bureau of Standards (ABBS), Raúl González of the Instituto Nacional de Tecnologia Normalizacion y Metrologia (INTN) in Paraguay, and Franklin Espejo Alcazar of the Instituto Boliviano de Metrologia (IBMETRO), for their enthusiastic participation and assistance.

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