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ORIGINAL PAPER

Automated Clock Comparisons and Time Scale Generation in the SIM Region

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Abstract: The second, the base unit of time interval in the International System, is defined in terms of the two hyperfine states of the Cesium atom ground-state energy level. This definition has so far served the metrology community well, and the uncertainty of the best realization of the second has improved by a rate of about one order of magnitude per decade over the past 50 years, reaching a current level of a few parts in 10^{16} [1]. This continual reduction in uncertainty has increased the level of performance expected from both time and frequency transfer systems and from the time standards maintained by national metrology institutes (NMIs). During recent years, an automated time comparison network has been developed within the *Sistema Interamericano de Metrologia* (SIM), a regional metrology organization. The SIM Time Network (SIMTN) allows NMIs to compare their time scales via the Global Positioning System common-view and all-in-view time transfer techniques, and makes results available through the Internet in near real time [2]. The SIMTN has proven to be robust and reliable, and the uncertainty of its comparisons is similar to the uncertainty of the key comparisons published by the Bureau International des Poids et Mesures in its monthly *Circular T* document. The large number of geographically dispersed clocks measured by the SIMTN made it attractive to develop a SIM time scale (SIMT), which is computed in near real time and immediately made available to the general public via the Internet. This rapid computation allows contributing laboratories to easily monitor their time scales, and to quickly detect short term fluctuations in stability and accuracy. This paper discusses both the SIMTN and the SIMT, focusing primarily on the SIMT algorithm and the results of its performance.

Keywords: International comparisons; Time; Time scales; Time transfer

1. Introduction

1.1. The SIM Time Network

The *Sistema Interamericano de Metrologia* (SIM) includes the 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. The SIM Time Network (SIMTN) was developed by the SIM Time and Frequency Metrology Working Group (SIM TFMWG) to allow as many of these NMIs as possible to participate in international comparisons of time and frequency. Seventeen, or exactly half of the 34 SIM nations, are participating in the SIMTN as of October 2011.

Three Internet servers, located in Canada, Mexico, and the United States, host identical software that processes time transfer data "on the fly" whenever requested. The measurement results can be viewed with any web browser by accessing any of the three servers. No special software is needed and no specific training is required to access the comparison data. 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 min, 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

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[2]. The numerical results are graphed as 1-h or 1-day averages, and the Time deviation and Allan deviation values [3] for the selected data are automatically displayed. In addition to the graphs, numerical values for 10-min, 1-h, or 1-day averages can be viewed in tabular form or copied to a spreadsheet for further analysis.

The real-time measurements allow SIM NMIs to instantly compare their time standards to each other. This benefits all participants, including those laboratories that already participate in the BIPM key comparisons (CCTF-K001.UTC) and contribute to the computation of Coordinated Universal Time (UTC). The UTC contributors can use the SIMTN to immediately check the performance of their standards without waiting for publication of the BIPM's monthly *Circular T* report, which historically has included results that are from 2 to 7 weeks old at the time of publication. Another benefit is that the SIMTN reports new data every 10 min, as opposed to every 5 days in the case of the *Circular T*. The additional data makes it much easier to identify short-term fluctuations and to solve measurement problems [2].

The combined resources of the SIMTN include about 25 Cesium clocks and nine Hydrogen masers. This large number of atomic oscillators, along with the large volume of real-time data generated by the SIMTN, made it attractive to generate an international time scale for the SIM region, known as the SIM Time Scale (SIMT).

1.2. Time Scales

Time keeping for critical applications requires reliability, accessibility, stability, and accuracy. To meet these requirements, many NMIs develop time scales that contain multiple clocks, and are thus not dependent on the operation of any single clock. These multi-clock or ensemble time scales are typically generated from a series of time difference measurements that are made between clocks in the ensemble. By averaging and analyzing these time differences, it is possible to generate a time scale whose metrological characteristics are superior to those of any single clock in the ensemble [4, 5].

Because there are many different applications for time scales, there is no unique "best" time scale algorithm. That fact is well illustrated by the UTC and UTC(k) time scales. UTC, calculated by the BIPM, is a virtual time scale (that is, it has no associated physical signal). It is produced by use of a post processing scheme that has delays in its calculation that are mostly due to the delays in data collection. The UTC(k) time scales generated by the NMIs are local time scales that generate a physical signal in real time. Thus, UTC and the various UTC(k) time scales serve different applications, and different criteria are emphasized in their design. These criteria include the models used to predict clock behavior, the weighting procedure, the periodicity used to compute the time scale, the way that clocks are added to and deleted from the ensemble, and so on.

1.3. The SIM Time Scale

The SIM time scale (SIMT) had several design requirements: (i) it was to be generated in near real time, (ii) it was to be a virtual time scale that generated no physical signal (as is the case with UTC), (iii) the "clocks" of the ensemble would be the time scales of the individual SIM NMIs, (iv) the clock measurements would be the time differences between SIM NMIs that are reported by the SIMTN, and (v) it would not intentionally be steered to UTC or to any other "external" reference. The SIMT was designed to be a convenient way for SIM NMIs to monitor the performance of their time scales, because it would not have the long processing delays of UTC. In addition, it would produce more data than the UTC scale, which is insensitive for short term (shorter than 5 day) fluctuations in the UTC(k) scales and thus cannot detect short term instabilities.

2. SIM Time Scale Algorithm

2.1. The SIM Time Scale Algorithm

The development of the SIMT algorithm began at the Centro Nacional de Metrología (CENAM) in early 2008 [6]. The algorithm used in SIM to generate the SIMT scale is similar to those algorithms used at the National Institute of Standards and Technology (NIST) [7] and CENAM [8] to generate the UTC(NIST) and UTC(CNM) time scales. In such algorithms, 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 instability in terms of the Allan deviation. However, the way that weights are assigned can vary from time scale to time scale. For SIMT, the weighting criteria are based on the inverse of the Allan deviation, $\sigma_y(\tau)$ 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 the SIMT. Because most of the other properties of the exponential algorithm have been discussed in the time scale literature (for examples, see Refs. [4] and [5]), we comment here on only the most relevant features of the SIMT algorithm. Note that our discussion will use the term "clocks" to refer to the individual local time scales that participate in the SIMTN comparisons.

In the SIMT algorithm we consider that at the current time t, the prediction $\hat{x}_k(t+\tau)$ for the time difference $\hat{x}$ of the clock k with respect to the SIMT at time $t+\tau$ can be written in terms of a known set of parameters. These parameters include: (i) the time difference of clock k with respect to the SIMT at time t, $x_k(t)$, (ii) the fractional frequency difference $y_k(t)$ of clock k with respect to the SIMT at time t, and (iii) the parameter D_k which takes into account the drift of $y_k(t)$ during the time interval $(t, t + \tau)$, as follows:

$$\hat{x}_k(t+\tau) = x_k(t) + [y_k(t) + D_k\tau]\tau + \cdots. \tag{1}$$

Equation (1) can be easily accepted because it can be seen as a Taylor expansion of the function x_k around the value $x_k(t)$ for a time interval of length τ.

Once the (future) time $t + \tau$ is reached, time differences among clocks can be obtained through the SIMTN, so it is possible to compute the value of the time scale SIMT for that $t + \tau$ time. Of course, the predicted value of the SIMT scale computed at time t for the time $t + \tau$ will not necessarily be equal to the computation of SIMT at time $t + \tau$. Under this assumption, the SIMT value, predicted at time t for $t + \tau$, can be corrected by the time difference measurements at $t + \tau$ by using the relation

$$x_k(t+\tau) = \sum_{j=1}^{N} \omega_j[\hat{x}_j(t+\tau) - x_{jk}(t+\tau)]. \tag{2}$$

where x_{jk} is the measured time difference between clock j and clock k at time $t + \tau$.

The prediction $\hat{y}_k(t+\tau)$ of the fractional frequency deviation of clock k with respect to SIMT, at time $t + \tau$, is made according to

$$\hat{y}_k(t+\tau) = \frac{\hat{x}_k(t+\tau) - x_k(t)}{\tau}. \tag{3}$$

Once again, when the (future) time $t + \tau$ is reached, the correction for the frequency prediction can be made through an exponential filtering defined by

$$y_i(t+\tau) = \frac{1}{1+m_i}[\hat{y}_i(t+\tau) + m_i(\tau)y_i(t)], \tag{4}$$

where m_i is a parameter that bring information about the averaging period when reaching the floor noise in clock i, given by the relation [9]

$$m_i(\tau) = \frac{1}{2}\left[\sqrt{\frac{1}{3} + \frac{4}{3}\frac{\tau_{\min,i}^2}{\tau^2}} - 1\right]. \tag{5}$$

Here $\tau_{\min,i}$ is the integration period at which the noise floor of clock i is reached. For weights ω_i, the condition of normalization is, of course, kept. That is

$$\sum_{i=1}^{N} \omega_i = 1. \tag{6}$$

In order to have a mechanism that increases or decreases the weight for a single clock according to its frequency stability, we have defined the clock weights to be inversely proportional to the frequency stability, which is estimated in terms of the Allan deviation. Thus, the SIMT criteria for clock weighing is defined by

$$\omega_i \propto \frac{1}{\sigma_i(\tau)}, \tag{7}$$

where $\sigma_i(\tau)$ is the Allan deviation of clock i for an integration period of 10 days. The proportional constant is set by the normalization condition on weights (Eq. 6). As noted earlier, this long integration period was selected to minimize the influence of the GPS time transfer noise that is inherent in the SIMTN data, and thus to provide a truer picture of the actual performance of the clocks. The SIMTN data from the previous 50 days are used to compute the stability of clocks in order to determine the weighting factors. This computation is made every day at 0 h, 0 min UTC. Thus, the weighting factor assigned to a clock remains constant during a UTC day. Because clock failures can occur at any time, and because we want to prevent failed clocks from disturbing SIMT, the performance of each clock is automatically monitored in real time. That monitoring is achieved through the computation of the values of $\sigma_i(\tau_0)$, where τ_0 is 1 h. This frequency stability is computed by comparing an individual clock i to the SIMT. If a clock exhibits unexpected and anomalous behavior, its weight is immediately set to zero and it is dropped from the ensemble. The SIMT algorithm automatically restores the clock to the ensemble when its behavior has returned to normal. It was also necessary to provide an upper limit for the clock weights. For example, the NIST time scale is typically the most stable in the SIM region, and thus will normally receive the highest weight. However, to prevent the time scale of any nation from dominating SIMT, we limit the contribution of each clock to 40%. This limit will probably be further reduced as more nations contribute to SIMT.

SIMT is calculated every hour at minute 20, and the time differences between SIMT and each contributing clock are published on the SIM TFWG web site at minute 30. The process that generates SIMT is completely automated, and no human intervention is needed for its computation and dissemination.

2.2. SIM Time Scale Generation

As of October 2011, nine NMIs are contributing to the SIMT. Each of these laboratories maintains either an ensemble time scale or a single cesium clock time scale. Laboratories whose time scale consists of a rubidium oscillator or a GPS disciplined oscillator are currently not allowed to contribute, but the SIMT algorithm has been developed in a way that will allow these laboratories to be

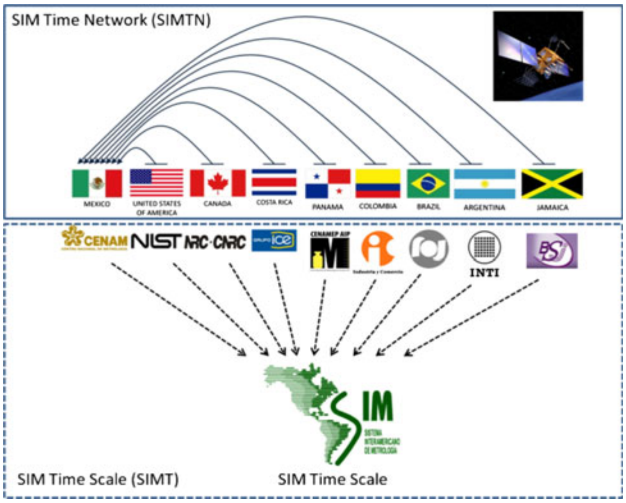

Fig. 1 A block diagram of the SIMT generation

easily added if they obtain the necessary hardware in the future.

Figure 1 shows a block diagram of the SIMT generation. The solid lines in Fig. 1 represent the clock comparisons made via GPS techniques through the SIMTN. A detailed discussion of how these comparisons are processed in real time and an analysis of their uncertainty can be found in [2]. The dashed lines in Fig. 1 represent the comparisons between SIMT and each of its contributing clocks, SIMT–SIMT(*k*). The dashed lines, of course, represent "virtual" comparisons, because like UTC, SIMT is a virtual time scale that does not produce a physical signal. The SIMT–SIMT(*k*) data have been published since April 2010 in near real time by the same web site (http://tf.nist.gov/sim) that distributes the SIMTN data. At the time of publication of this article, SIMT is generated only at CENAM. However, we plan to add the SIMT software to the servers at NIST in the United States and at the National Research Council (NRC) in Canada in 2012. The eventual simultaneous generation of SIMT in three different countries will make SIMT more reliable and accessible, two very important characteristics for a time scale.

3. Results

To estimate the performance of the SIMT scale, this section provides measurements of the NIST and CENAM time scales with respect to SIMT, UTC and GPS time for the 200 day period that began on March 26, 2011 (55646 MJD), and ended on October 10, 2011 (55845 MJD). This period was selected because 200 days corresponds to the longest range of data that the SIMTN software can display at once, and because it was the most recent data available at the time of this report.

Figure 2 shows the time differences between the NIST and CENAM time scales when we use SIMT, GPS time and UTC as our references. The data points are 1-day averages, except for time differences involving UTC, which provides only one data point every 5 days. The three comparisons are in relative agreement, but the comparison involving UTC appears to have a systematic bias of about 10 ns. This is probably due to a calibration bias in one or more of the systems that NIST and CENAM use to contribute to UTC and SIMT. Both NIST and CENAM contribute to SIMT by use of the single frequency common-view GPS measurement system that is provided to all members of the SIMTN [2]. However, NIST contributes data to UTC with a two-way satellite time transfer system, and CENAM contributes data to UTC with a dual frequency GPS time transfer receiver.

Figure 3 shows the time differences of the NIST and CENAM time scales with respect to both SIMT and UTC. There is a fairly high degree of correlation when the CENAM time scale is measured against either SIMT or

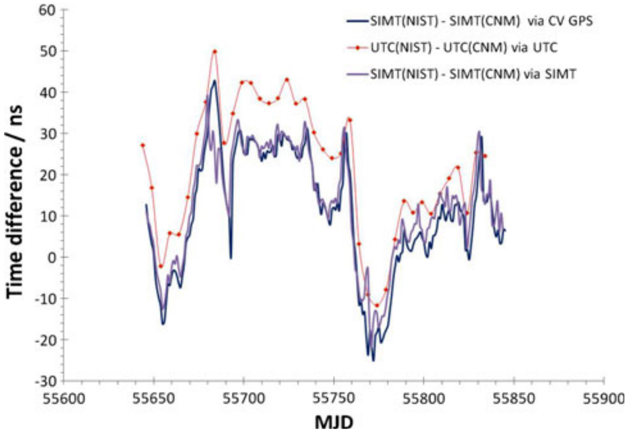

Fig. 2 Direct comparison of NIST and CENAM time scales using different methods

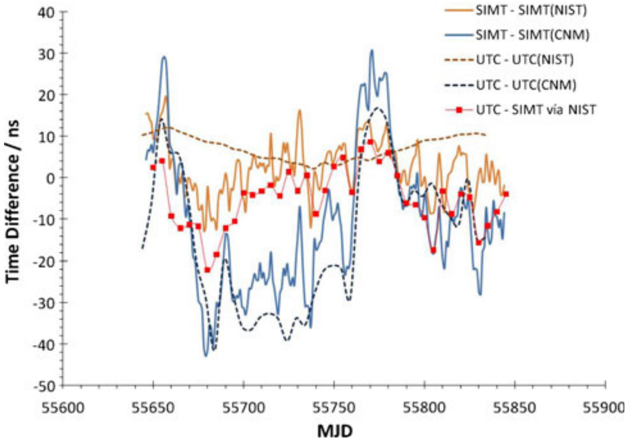

Fig. 3 Comparison of NIST and CENAM time scales to SIMT and UTC

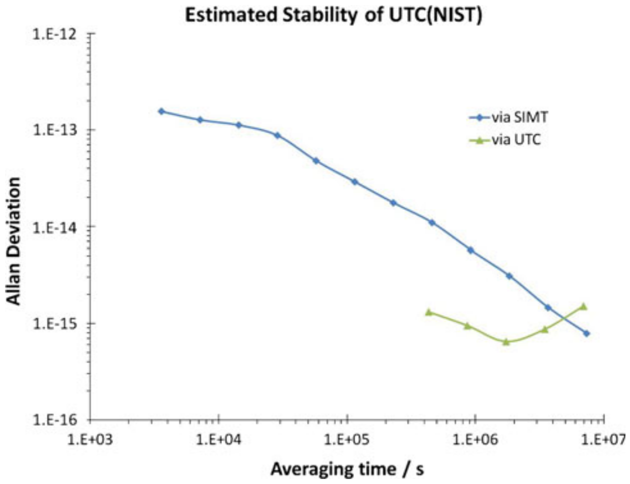

Fig. 4 The estimated stability of UTC(NIST) when using SIMT and UTC as references

UTC. There is less correlation when measuring the NIST time scale, probably because SIMT is not stable enough to accurately measure UTC(NIST) in the short and medium term. It should also be noted that because SIMT has a relatively small number of participants, that both NIST and CENAM are given much more weight in the SIMT computation than they are in the UTC computation. Figure 3 also shows the difference between UTC and SIMT when the NIST time scale is employed as a "common clock". The peak-to-peak variation between SIMT and UTC over the 200-day period is about 30 ns.

Figure 4 estimates the stability of UTC(NIST) by comparing it to both SIMT and UTC. Note that short term estimates of stability are not obtainable when UTC is the reference because τ_0 is equal to 5 days for UTC, as opposed to 1 h for SIMT. At $\tau = 5$ days, the UTC(NIST) stability estimate is about one order of magnitude lower when UTC is used as the reference. The two stability estimates are not equivalent until after about 6 weeks of averaging. Note, however, that the NIST time scale is typically the most stable in the SIM region, and the shortcomings of SIMT are the most obvious in a NIST comparison. Most SIMTN participants have less stable and less accurate time scales than NIST or CENAM, and are currently not UTC contributors. Therefore, SIMT serves nicely as a nearly equivalent and more accessible reference for those laboratories.

4. Conclusions

The automated clock comparisons performed by the SIMTN have directly led to the automated generation of SIMT. The SIMT scale is generated by a fully automated system that obtains its measurement data from the SIMTN. The SIMTN and SIMT now act in concert to monitor the performance and improve the quality of time and frequency standards throughout the SIM region.

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