RevMexAA (Serie de Conferencias), **46**, 1–6 (2015)

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TIMEKEEPING IN THE AMERICAS

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RESUMEN

El tiempo y su medida son parte fundamental de la física. Mucho del avance científico y tecnológico está relacionado, de alguna u otra manera, con la medición del tiempo. La medición del tiempo es esencial para la vida diaria lo que la hace la medición más frecuente en las socidades modernas. El tiempo puede ser medido con la incertidumbre más baja y mayor resolución que cualquier otra magnitud física. La medición del tiempo reviste la mayor importancia para muchas aplicaciones, entre otras; sistemas satelitales de navegación global, redes de comunicación, generación de energía eléctrica, astronomía, comercio electrónico y defensa y seguridad nacional. En este artículo discutimos cómo el tiempo es mantenido, coordinado y diseminado en el continente americano.

ABSTRACT

Time and its measurement belong to the most fundamental core of physics, and many scientific and technological advances are directly or indirectly related to time measurements. Timekeeping is essential to everyday life, and thus is the most measured physical quantity in modern societies. Time can also be measured with less uncertainty and more resolution than any other physical quantity. The measurement of time is of the utmost importance for many applications, including: global navigation satellite systems, communications networks, electric power generation, astronomy, electronic commerce, and national defense and security. This paper discusses how time is kept, coordinated, and disseminated in the Americas.

Key Words: astrometry — time

1. INTRODUCTION

This paper is a brief review of timekeeping in the Americas; specifically of the nations located in North, Central, and South America and the Caribbean Islands. In §2 we present a short introduction to atomic timekeeping, including the physics of atomic clocks and how the second is defined in the International System (SI). A summary of timekeeping laboratories in the Americas and the standards that they maintain is provided in §3. International time comparisons are described in §4. §5 discusses international time scales, §6 discusses time dissemination services. Finally, §7 presents a summary.

2. ATOMIC CLOCKS AND THE INTERNATIONAL SYSTEM (SI) SECOND

The current definition of the base unit of time, the second, in the International System (SI) of units was established by the 13th CGPM (Conférence Générale des Poids et Mesures) in 1967. The SI second is defined as the duration of 9 192 631 770 periods of the radiation corresponding to the two hyperfine levels of the cesium 133 atom ground state (CGPM 1967). The definition of the second based on the cesium atom formally marked the beginning of the atomic timekeeping era, after many centuries of referencing time interval measurements to astronomical observations. Time was now kept by first establishing the second by counting oscillations of the electric field asociated to an atomic transition, and then counting seconds to form longer time intervals. The second had previously been defined by first establishing long astronomical intervals, such as the mean solar day and the tropical year, and then dividing to obtain shorter time intervals (McCarthy, D., & Seidelmann, P. 2009), (Audion, C., & Guinot, B. 2001), (Leschiutta, S. 2005).

Once the definition of the atomic second was agreed upon internationally, atomic clocks became the references for the world's timekeeping laboratories. The most common types of atomic clocks utilize the hyperfine transition of the ground state of alkaline atoms, specifically cesium, rubidium and hydrogen. These hyperfine transitions are in the microwave frequency region; approximately 1.420 GHz

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for hydrogen, 6.835 GHz for rubidium and 9.192 GHz for cesium, the frequency used to define the second.

Cesium clocks are the foundation of world timekeeping systems and have been commercially available for more than 50 years (Cutler, L. 2005). They work by locking a local oscillator, typically a quartz oscillator, to the cesium resonance frequency. The exact method can vary, but this is typically done by heating Cs-133 atoms to a gaseous state in an oven, generating a "beam" of atoms that travels through a magnetic field. Here, the beam is split into two atomic beams with different magnetic states. One beam is absorbed by a getter and is of no further interest. The other beam is deflected into a microwave interrogation cavity, commonly known as the Ramsey cavity, where it is exposed to a microwave signal generated by a frequency synthesizer driven by a local oscillator. If this frequency equals cesium resonance (9 192 631 770 Hz), some of the atoms will change their magnetic state. After leaving the Ramsey cavity, the atoms pass through a second magnetic field. These magnets direct only the atoms that changed state to a detector; the other atoms are directed to a getter and absorbed. The magnets located on both sides of the Ramsey cavity serve as a gate, and only the atoms that undergo the desired energy transition are allowed to pass through and reach the detector. The detector sends a feedback signal to a servo circuit that continually adjusts the local oscillator so that the maximum number of atoms reaches the detector. This adjustment keeps the local oscillator locked as tightly as possible to the cesium resonance frequency (Itano, W., & Ramsey, N. 1993), (Major, F. 1998), (Diddams, S., Bergquist, J., Jefferts, S., & Oates, C. 2004).

The stability of a commercially-available cesium clock is typically limited to a few parts in 1×10^{14} per day, which correspondingly limits its timekeeping accuracy to a few nanoseconds per day. These performance limitations can be dramatically reduced if the observation time of the cesium atoms is increased. Cesium fountain clocks accomplish this by laser cooling. Multiple lasers are used to cool the atoms to a temperature of less than 1 μK, near absolute zero. This reduces their velocity to a few centimeters per second or less, a tiny fraction of their $\sim$ 300 m/s speed in Cesium beam clocks. This allows a large sample or cloud of atoms to be gathered together and confined in one place. The cloud of atoms is then launched upwards through a microwave cavity and then falls back through the cavity about one second later under the influence of gravity (Jefferts, S., Heavner, T., & Donley, E. 2004). The best cesium fountain clocks, such as NIST-F2, operated by the National Institute of Standards and Technology (NIST) in the United States, can now realize the SI second with an uncertainty near 1.0×10^{-16} (Heavner, T. et al. 2014), translating to a timekeeping accuracy near 0.01 ns/day, or about 100 times better than commercial cesium clocks. NIST is currently the only timekeeping laboratory in the Americas that has developed operational cesium fountain clocks, but experimental cesium fountains have been constructed in Brazil, Canada, and Mexico.

3. TIMING LABORATORIES IN THE AMERICAS

The number of timekeeping laboratories in the Americas has substantially increased since an earlier study was published in 2006 (Arias, E. 2006), with 29 laboratories participating in international comparisons (Section 4) as of January 2015, as summarized in Table 1. These laboratories can usually be designated as either national metrology institutes (NMIs), assigned by their respective government to provide national standards for many types of measurements, or as designated institutes (DIs). In most cases, the DIs were assigned timekeeping responsibilities because the NMI lacks a timing laboratory, or to provide time for the nation's military.

4. INTERNATIONAL TIME COMPARISONS

To ensure that time is kept correctly, and to establish metrological traceability, all of the timekeeping laboratories in the Americas must participate in international time comparisons. Unlike the intercomparisons of other physical quantities, the measurements of time are automated and continuous. In fact, the measurements never stop unless equipment failures occur.

Official international time comparisons, known as key comparisons, are conducted by the Bureau International des Poids et Mesures (BIPM), located in France. As of January 2015, about 70 timing laboratories participate in these comparisons, including 13 laboratories in the Americas. A cesium clock is required for participation in these comparisons. The pivot laboratory for the BIPM key comparison is the Physikalisch-Technische Bundesanstalt (PTB) in Germany. Most laboratories link to the BIPM by comparing their clocks to PTB via common-view observations of the GPS satellites (several variations of the common-view technique exist) (Defraigne, P., & Petit, G. 2003). However, some laboratories, including NIST and the United States Naval Observatory (USNO) in the Americas, link to the BIPM using a

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TABLE 1

TIMEKEEPING LABORATORIES IN THE AMERICAS THAT PARTICIPATE IN INTERNATIONAL COMPARISONS

Laboratory	Country	NMI or DI	Time Scale	UTC contributor	Link to UTC	SIM Time Network	Radio Time Services	Internet Time Services
ABBS	Antigua & Barbuda	NMI	SIMTDC	N	—	Y	N	N
INTI	Argentina	NMI	Cesium	Y	GPS	Y	N	N
ONBA	Argentina	DI	Cesium	Y	GPS	N	N	N
IGNA	Argentina	—	Cesium	Y	GPS	N	N	N
IBMETRO	Bolivia	NMI	SIMTDC	N	—	Y	N	Y
ONRJ	Brazil	DI	Ensemble	Y	GPS	Y	Y	Y
INXE	Brazil	NMI	Cesium	Y	GPS	N	N	N
NRC	Canada	NMI	Ensemble	Y	GPS	Y	Y	Y
TCC	Chile	—	SIMTDC	N	GPS	N	N	N
INN	Chile	DI	SIMTDC	N	—	Y	N	N
INM	Colombia	NMI	Cesium	N*	GPS*	Y	N	Y
ICE	Costa Rica	DI	Cesium	N*	GPS*	Y	N	Y
CMEE	Ecuador	DI	GPSDC	N	—	Y	N	Y
CIM	El Salvador	NMI	SIMTDC	N	—	Y	N	N
LNM	Guatemala	NMI	GPSDC	N	—	Y	N	N
GNBS	Guyana	NMI	SIMTDC	N	—	Y	N	N
BSJ	Jamaica	NMI	Cesium	N	—	Y	N	N
CENAM	Mexico	NMI	Ensemble	Y	GPS	Y	Y	Y
CENAMEP	Panama	NMI	Cesium	Y	GPS	Y	N	Y
INTN	Paraguay	NMI	SIMTDC	N	—	Y	N	Y
SNM	Peru	NMI	Cesium	N*	GPS*	Y	N	Y
SLBS	Saint Lucia	NMI	SIMTDC	N	—	Y	N	Y
SKNBS	St. Kitts & Nevis	NMI	SIMTDC	N	—	Y	N	N
TTBS	Trinidad & Tobago	NMI	GPSDC	N	—	Y	N	N
NIST	United States	NMI	Ensemble	Y	TWSTFT	Y	Y	Y
USNO	United States	—	Ensemble	Y	TWSTFT	N	Y	Y
NRL	United States	—	Ensemble	Y	GPS	N	N	N
APL	United States	—	Ensemble	Y	GPS	N	N	N
UTE	Uruguay	DI	Cesium	N*	GPS*	Y	N	Y

*Expected to become a UTC contributor in 2015

technique called Two-Way Satellite Time and Frequency Transfer (TWSTFT) that requires signals to be transmitted and received through a geostationary satellite (Piester, D., Bauch, A., Breakiron, L., Matsakis, D., Blanzano, B., & Koudelka, O. 2008). Results from the BIPM key comparison are published monthly in a document called Circular T with one value provided for each laboratory every five days.

A much faster system for international comparisons within the Americas is the SIM Time Network (SIMTN). SIM is the Sistema Interamericano de Metrologia, one of the five major regional metrology organizations (RMOs) recognized by the BIPM. Supported by the Organization of American States (OAS), the SIM region includes 34 nations of North, Central, and South America and the Caribbean Is-

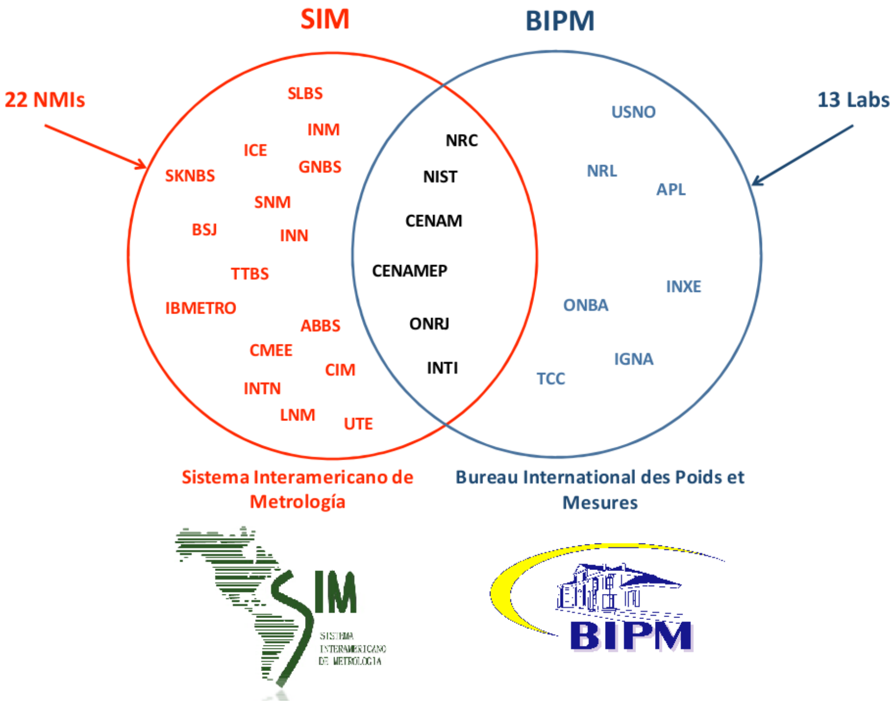

Fig. 1. Schematic of timekeeping laboratories engaged in SIM and BIPM comparisons. Acronyms are as follow: Saint Lucia Bureau Standards (SLBS) from Saint Lucia, Instituto Nacional de Metrologia (INM) from Colombia, Instituto Costarricence de Electricidad (ICE) from Costa Rica, Guyana National Bureau of Standards (GNBS) from Guyana, Saint Kitts National Bureau of Standards (SKNBS) from Saint Kitts, Sistema Nacional de Metrología (SNM) from Peru, Jamaica Bureau of Standards (BSJ) from Jamaica, Instituto Nacional de Normalización (INN) from Chile, Trinidad & Tobago Bureau of Standards (TTBS) from Trinidad & Tobago, Instituto Boliviano de Metrología (IBMETRO), Antigua & Barbuda Bureau of Standards (ABBS), Centro de Metrología del Ejercito Ecuatoriano (CMEE) from Bolivia, Centro Investigaciones en Metrología (CIM) from El Salvador, Usinas Tecnológicas de Electricidad (UTE) from Uruguay, National Research Council Canada (NRC) from Canada, National Institute of Standards and Technology (NIST) from the USA, Centro Nacional de Metrología (CENAM) from Mexico, Centro Nacional de Metrología de Panamá (CENAMEP) from Panama, Observatorio Nacional de Rio de Janeiro (ONRJ) from Barzil, Instituto Nacional de Tecnología Industrial (INTN) from Paraguay, US Naval Observatory (USNO) from the USA, National Reserach Laboratory (NRL) from the USA, Applied Physics Laboratory (APL) from the USA, Instituto Nacional de Metrología (INXE) from Brazil, Observatorio Naval de Buenos Aires (ONBA) from Argentina, Instituto Geofísico y Marítimo de Argentina (IGNA) from Argentina.

lands. Currently, 22 of these nations have joined the SIMTN and continuously compare their time standards by utilizing both the GPS common-view and all-in-view techniques and transferring data in real-time via the Internet. A cesium clock is not required for the SIMTN; laboratories with limited resources can participate with a rubidium clock disciplined to an external source (see Table 1). Three servers (located in Canada, Mexico, and the United States) process the clock comparisons and publish new results every 10 minutes at http://tf.nist.gov/sim.

Most of the participants in the SIMTN routinely keep time within 100 ns of each other. The uncertainty of the SIMTN measurements for most of the laboratory links is about 12 ns (2σ), which is similar to the uncertainty of the BIPM key comparison links. Its chief advantage is the rapid publication of new measurements, which makes it far more useful than the BIPM key comparisons for identifying short-term fluctuations and failures in national time scales, and allowing these problems to be quickly resolved (Lombardi, M. et al. 2011).

Figure 1 shows a schematic that lists the 29 laboratories that participate in the BIPM key comparisons and the SIMTN. The overlapping part of the circles lists the six laboratories that participate in both systems. As indicated in Table 1, four additional laboratories now in the SIMTN are expected to begin participation in the BIPM key comparisons in 2015.

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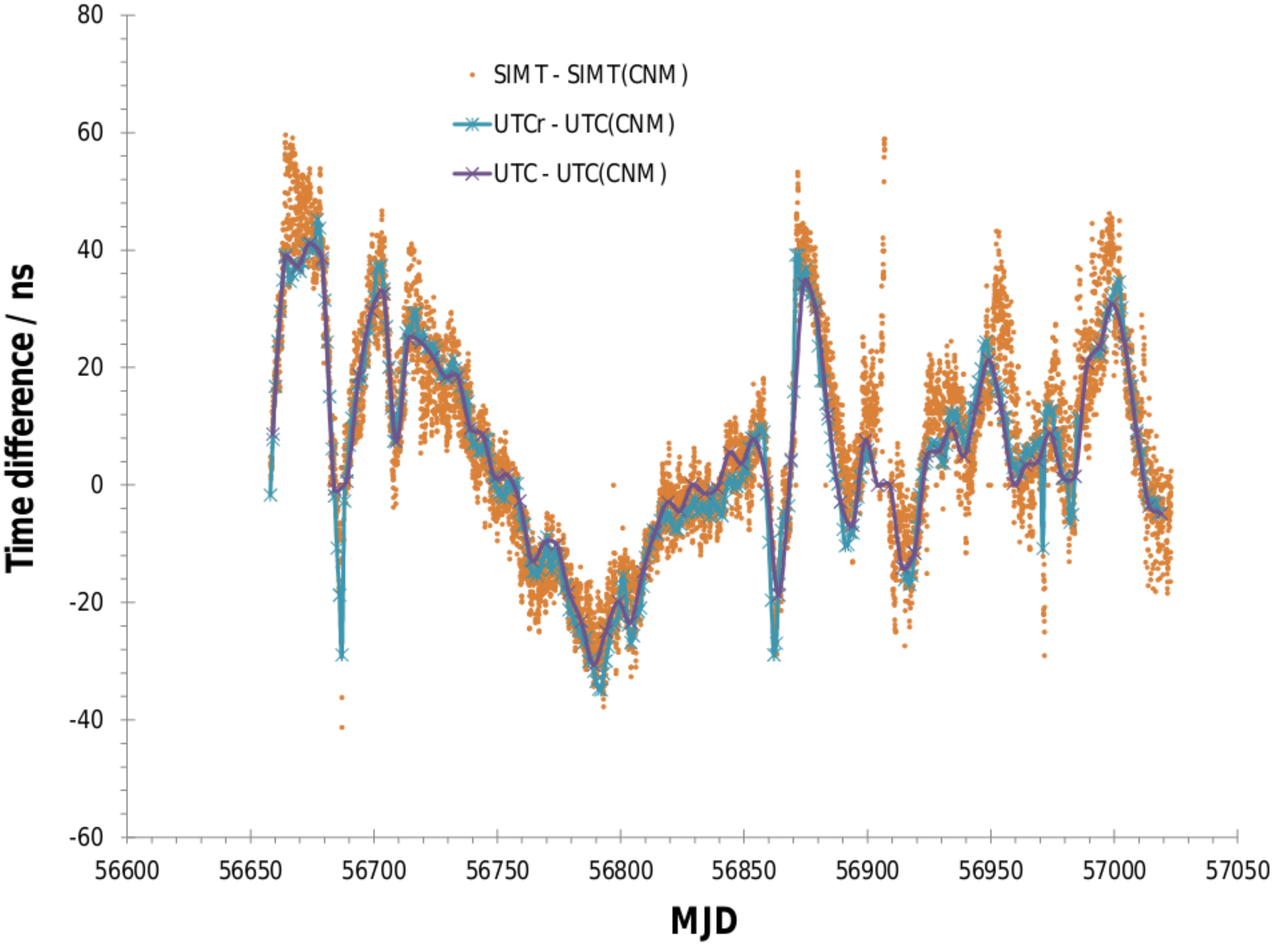

Fig. 2. A long-term comparison of the time scale at CENAM in Mexico to UTC, UTCr, and SIMT.

5. COORDINATED UNIVERSAL TIME (UTC) AND SIM TIME (SIMT)

The official world time scale is Coordinated Universal Time, UTC, which is computed by the BIPM. UTC is processed from the clock comparison data collected during the BIPM key comparisons discussed in Section 4. Each laboratory that submits clock data to the BIPM is a UTC contributor. UTC produces no physical signal, and the local realizations of UTC maintained by timing laboratories are referred to as UTC(k), where k is the acronym of the laboratory. The monthly Circular T document lists measurements of [UTC – UTC(k)] at five-day intervals for each of the laboratories that participated in the BIPM key comparison (Defraigne, P., & Petit, G. 2003). To make UTC more accessible, the BIPM now produces UTCr, or rapid UTC, which is published weekly with measurements provided at one-day intervals (Petit, G., Arias, F., Harmegnies, A., Panfilo, G., & Tisserand, L. 2014). As of January 2015, 13 laboratories in the Americas are contributing to UTC, and nine of those laboratories also contribute to UTCr.

Beginning in 2008, a time scale developed by the Centro Nacional de Metrología (CENAM) in Mexico has been automatically generated from the clock comparison data collected by the SIMTN. This time scale, known as the SIM Time Scale or SIMT, is computed every hour, and new measurements of [SIMT – SIMT(k)] are published via the Internet at http://tf.nist.gov/sim. The SIMTN members that operated either ensemble time scales or cesium clocks (see Table 1) are allowed to contribute to the calculation of SIMT, and the remaining laboratories can utilize SIMT as another source of comparison (Lopez-Romero, J., Lombardi, M., Diaz-Muñoz, N., & de Carlos-Lopez, E. 2013). Like UTC, SIMT is computed from a weighted average, and the most stable contributing clocks are assigned the most weight in the calculation. Unlike UTC, SIMT is usable for near real-time applications. As of January 2015, eight recently established timing laboratories in the Amer-

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icas operate rubidium clocks disciplined to SIMT (Lopez-Romero, J., Lombardi M., Diaz-Muñoz, N., & de Carlos-Lopez, E. 2014) as their national time standard (Table 1).

Figure 2 shows a long-term comparison of the CENAM time scale, the national time standard for Mexico, with UTC, UTCr, and SIMT for the year 2014 (MJD 56658 to MJD 57022). The results show that all three international time scales are in close agreement, with differences seldom exceeding 20 ns.

6. TIME DISSEMINATION SERVICES

After a laboratory has established a time scale and engaged in international comparisons, it is customary to establish time dissemination services that make the national time accessible to the general public. Time can be disseminated through a variety of mediums, including radio broadcasts, telephone lines, and via the Internet. Radio stations dedicated to time dissemination in the Americas include the shortwave stations WWV and WWVH in the United States, and CHU in Canada. The 60 kHz station WWVB in the United States is the synchronization source for many millions of low-cost radio controlled clocks in North America (Lombardi, M., & Nelson, G. 2014). The most common time dissemination services in the Americas now utilize the Internet, providing time via the network time protocol (NTP) at accuracies of a few milliseconds or less for hundreds of millions of computers. As of 2014, a number of laboratories that participate in the SIMTN also now participate in a similar network that compares the time that they disseminate via NTP (Lombardi, M. et al 2014). Table 1 summarizes the laboratories that provide radio or Internet time services.

7. SUMMARY

The number of timekeeping laboratories in the Americas has increased in recent years, and their capabilities have been enhanced. There are currently 29 timing laboratories in the Americas now participating in international time comparisons programs, conducted by either the BIPM or SIM, with an increasing number of laboratories now participating in both comparisons. Most of these laboratories maintain time scales that are synchronized to within 100 ns of both UTC and SIMT, and many of them now disseminate time to the general public through calibration and time synchronization services. This expansion is expected to continue, perhaps reaching the point when all 34 nations of the OAS maintain their own time scales, participate in international comparisons, and disseminate accurate time to their nation's citizens.

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