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THE IBEROAMERICAN CONTRIBUTION TO INTERNATIONAL TIME KEEPING

E. F. Arias[1,2]

RESUMEN

Las escalas internacionales de tiempo, Tiempo Atómico Internacional (TAI) y Tiempo Universal Coordinado (UTC), son elaboradas en el Bureau Internacional des Poids et Mesures (BIPM), gracias a la contribución de 57 laboratorios de tiempo nacionales que mantienen controles locales de UTC. La contribución iberoamericana al cálculo de TAI ha aumentado en los últimos años. Diez laboratorios en las Américas y uno en España contribuyen a la estabilidad de TAI con el aporte de datos de relojes atómicos industriales; una fuente de cesio mantenida en uno de ellos contribuye a mejorar la exactitud de TAI. Este artículo resume las características de las escalas de tiempo de referencia y describe la contribución de los laboratorios iberoamericanos.

ABSTRACT

The international time scales, International Atomic Time (TAI) and Coordinated Universal Time (UTC), are elaborated at the Bureau International des Poids et Mesures (BIPM), thanks to the contribution of 57 national time laboratories that maintain local realizations of UTC. The Iberoamerican contribution to TAI has increased in the last years. Ten laboratories in America and one in Spain participate to the calculation of TAI , increasing its stability with the data of industrial atomic clocks and improving its accuracy with frequency measurements of a caesium source developed and maintained at one laboratory. This paper summarizes the characteristics of the reference time scales and describes the contributions of the Iberoamerican time laboratories to them.

Key Words: **TIME — REFERENCE SYSTEMS**

1. GENERAL

International time keeping started in 1912 with the creation of the Bureau International de l'Heure (BIH) at the Paris Observatory. Until the beginning of the 70's, the reference time scales were based on the motions of the Earth; its rotation provided Universal Time, and later, its translation was used to construct Ephemeris Time (ET), the dynamical time scale that represented the uniform time until 1971.

The assertion that an atomic transition could be at the basis of the measurement of time and the development of the first atomic caesium clocks in 1955 by Essen & Parry (1957) put time keeping in the hands of metrology. In 1958, at the USNO, Markowitz & Hall (1958) determined the frequency of the caesium in terms of the second ET as the result of a programme of worldwide observations with the Markowitz Moon camera.

The ephemeris second had been defined as a fraction of the tropical year 1900, thus in retrospect and not susceptible of being reproduced; this was a clear drawback. In 1967, the 13th Conférence Générale de Poids et Mesures (CGPM) adopted a new definition of the second (Metrologia 1968), by now called the SI second, using the value of the caesium frequency in terms of the ephemeris second determined by Markowitz & Hall. In 1971, the 14th CGPM recognized TAI as the continuous, reference time scale (Metrologia 1972) to be used for scientific applications; UTC has been defined as the practical time scale, of atomic nature, differing from TAI in an integer number of seconds originated in the application of leap seconds to UTC to keep it within a tolerance of 0.9 s with respect to UT1 (Universal Time corrected for the effects of polar motion).

In 1986, the Bureau International des Poids et Mesures (BIPM) assumed the responsibility of maintaining and disseminating TAI and UTC by an enterprise of international cooperation with time laboratories in metrology institutes and astronomical observatories that realize local atomic time scales. 57 institutions participate today for the calculation of the reference time scales at the BIPM, 11 of them in Iberoamerican countries. Most of them disseminate local approximations of UTC at different levels of precision, from those demanding some nanoseconds (satellite navigation as an example) to those

[1]Bureau International des Poids et Mesures, Sèvres, France.

[2]Associated astronomer to Paris Observatory, France.

less exigent, at the level of the millisecond or even less.

2. REFERENCE TIME SCALES: TAI AND UTC

TAI and UTC are calculated at the BIPM on the basis of data contribution from time laboratories in metrology institutes and astronomical observatories worldwide spread. The time laboratories maintain atomic clocks that serve to provide local realizations of UTC, named UTC(lab) for laboratory 'lab'. Making use of their clock data, the BIPM calculates a time scale that is a weighted average of clock readings with an algorithm known as Algos (Guinot & Thomas, 1988; Audoin & Guinot, 2001).

Some 300 atomic clocks installed in 57 time laboratories are used in 2005 for the calculation of the reference time scales. Algos is based mainly on clock differences, making necessary the use of techniques of clock comparison at distance. Industrial caesium clocks in time laboratories realize the atomic second with a relative frequency accuracy in the range 10^{-12} - 10^{-13}, depending on the model. They are characterized by a long-term frequency stability of order 10^{-14}. In addition to caesium standards, active hydrogen masers are installed in many laboratories; they are highly stable in frequency, but over a shorter averaging interval (sometimes better than 1 x 10^{-15} over one day). Both types of clocks are used as the time reference in laboratories; hydrogen masers are used as the reference for frequency comparisons of primary frequency standards. Both caesium and hydrogen maser standards contribute data for TAI, and they serve to the reliability and the frequency stability of the scale. They do not contribute to the realization of the unit that relies on the primary standards developed and maintained by a few laboratories. The quality of the clocks requires the availability of very high performance techniques of time transfer to compare them.

By making use of the satellites of the GPS (Global Positioning System) constellation, time transfer at nanosecond level is possible, and even better, when dual-frequency GPS receivers are used. The technique of common-view (Allan and Weiss, 1980) is used; it consists in simultaneously comparing clocks in two laboratories to the clock on board the same GPS satellite, thus cancelling the effects of the satellite clock. A two-way method of clock comparison (Two Way Satellite Time and Frequency Transfer, TWSTFT) is used by some laboratories for clock comparison. Clocks in two laboratories are simultaneously compared at both ends by transferring the signals through a telecommunications satellite. While the ionospheric effects are the main source of uncertainty in time transfer by single-frequency GPS, they are almost cancelled when using the TWSTFT, due to the fact that it is a two-way technique with slightly different frequencies for the up and down signals. In the best conditions, when clocks are compared by TWSTFT with a sub-daily frequency, the uncertainty goes down to a fraction of a nanosecond.

The medium-term stability of EAL, expressed in terms of an Allan deviation, is estimated to be 0.5 x 10^{-15} for averaging times from 20 to 40 days.

The accuracy of TAI is assured by the primary frequency standards developed in some laboratories reporting their frequency measurements to the BIPM. Ten primary frequency standards that include five caesium sources have contributed, more or less regularly, in the last two years to TAI. In 2005, the definition of the second of the SI is realised, at best, by the primary frequency standards with an accuracy of order 10^{-15}.

3. THE IBEROAMERICAN TIME LABORATORIES

The participation of laboratories in the Americas and Spain has increased in the last years. Six laboratories from South and Central America provide clock data to TAI: Observatorio Naval de Buenos Aires (ONBA, Argentina), Instituto Geográfico Militar (IGMA, Argentina), Observatorio Nacional de Rio de Janeiro (ONRJ, Brazil), Centro Nacional de Metrología (CNM, México), TIGO Concepción (TCC, Chile), y Centro Nacional de Metrología (CNMP, Panamá). North America is represented by the National Institute of Standards and Technology (NIST, USA), the US Naval Observatory (USNO, USA), the Applied Physics Laboratory (APL, USA) and the National Research Council (NRC, Canada). The Spanish contribution is made by the Real Instituto y Observatorio de la Armada (ROA, Spain). These laboratories realize local independent time scales denominated UTC(lab). They are equipped with caesium clocks and hydrogen masers, and time transfer devices. Table 1 describes the equipment of the laboratories. They have, within their respective countries, different kind of responsibilities that demand traceability to the reference time scale UTC. Some of them are responsible for the maintenance and dissemination of the national time. TCC has been installed in Chile to provide a time reference to the German geodetic station TIGO from IFAG (Federal Agency for Cartography and Geodesy). IGMA is a tracking station for the GPS satellite constellation. The USNO maintains more than 80 atomic clocks that serve to the steering of the GPS time to

TABLE 1

EQUIPMENT, UNCERTAINTY OF [UTC-$UTC(LAB)$], TIME SIGNALS AND TIME DISSEMINATION SERVICES AVAILABLE IN TIME LABORATORIES

Laboratory	Clocks Cs	H-m	pfs	Time comparison	Uncertainty [UTC-$UTC(lab)$]	Time signals	Time diss. services
APL	3	2	-	GPS	5.5	-	-
CNM	3	1	-	GPS	20.9	-	Yes
CNMP	2	-	-	GPS	8.2	-	-
IGMA	3	-	-	GPS	20.5	-	-
NIST	5	5	1	GPS, TWSTFT	4.9	Yes	Yes
NRC	2	3	3	GPS	15.1	Yes	Yes
ONBA	1	-	-	GPS	8.8	Yes	Yes
ONRJ	3	-	-	GPS	21.2	-	Yes
ROA	5	-	-	GPS, TWSTFT	5.3	Yes	Yes
TCC	3	1	-	GPS	21.0	-	-
USNO	72	20	-	GPS, TWSTFT	1.7	-	Yes

'H-m' stands for hydrogen-maser, 'pfs' stands for primary frequency standard, uncertainty unit is ns.

UTC(USNO). UTC(USNO) is the best approximation to UTC, it represents UTC within less than 2 ns. The time scale of APL serves to the space research. CNM, CNMP, NIST, NRC are national metrology laboratories; they are in charge of the maintenance of the national standards and of the establishment of their equivalences to the international standards.

3.1. *Local realizations of UTC reference time scale*

Stations in Iberoamerica and Spain are equipped with GPS receivers, and three of them (NIST, USNO and ROA) operate also TWSTFT stations and perform observations with a sub-daily frequency (refer to Table 1 for laboratory equipment). The NIST and the NRC develop and maintain primary frequency standards. Only the NIST contributes with frequency measurements of its caesium source to the accuracy of TAI. The laboratories maintain local representations of UTC, either coming from the master clock of the station or from the average of a clock ensemble. These realizations are compared to UTC and the results are published monthly in the BIPM Circular T. Table 1 gives the uncertainty of the differences [UTC-$UTC(k)$] as published on April 2005.

3.2. *Time signal emissions and dissemination services*

Some laboratories provide time signals in the UTC system, in accordance with the recommendations of the International Telecommunications Union. They transmit second pulses of the local UTC in different frequencies, the value of DUT1, that is, the difference between UT1 and UTC to the tenth of a second. Time dissemination services by telephone line and/or networks have been settled in some laboratories. Table 1 indicates the laboratories responsible for time signal emissions and time dissemination services.

4. CONCLUSION

The elaboration of the reference time scales is a task undertaken at the BIPM jointly with national laboratories and observatories distributed worldwide. The Iberoamerican clocks represent about 40% of the total of clocks in TAI, where the USNO is the first contributor with more than 80 clocks. New timing stations were established in the last years; this is the case of the CNMP in Panama and of TCC in Chile. APL restarted the cooperation with the BIPM after some years of interruption. The impact of time metrology in the different aspects of human life (science, space and air navigation, communications, transportation, and many more applications) stimulates an increase in the number of organisations needing traceability in time, and stimulates the already established laboratories to update their equipments.

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