Gianna Panfilo

Temps universel ou temps international ?

Introduction

This article will review the calculation of UTC by pointing out the general concepts of "Universal" and "International"[1]. To highlight these characteristics of UTC it will be presented how it is defined, how it is calculated and how it is used by different communities (communications, space, transport etc.)

The algorithm for the calculation of TAI/UTC has been designed to guarantee the reliability, long-term frequency stability, high frequency accuracy and accessibility of the time scale. It relies on clock readings and is highly dependent on the quality of the clock comparisons. The BIPM, in a coordinated effort with the world timing community, is dedicated to developing and improving these methods.

The BIPM assures the dissemination of UTC through *Circular T*; it is published monthly and today offers complete information for the benefit of National Metrological Institutes (NMIs), observatories and international organizations that contribute to its computation. In *Circular T* is reported the difference between UTC and each UTC(*k*) which is the physical realization of UTC made by each NMI (symbolized here by the letter *k*). This paper also describes the weekly rapid realization of UTC (UTCr). The paper concludes with the application and metrological traceability of UTC. In Figure 1 a scheme of the different time scales and their relations is reported to help the understanding of the paper.

1. The Metre Convention

The Convention to "assure the international unification and improvement of the metric system" and its annexed regulations (commonly known as the "Metre Convention"), was signed on May 20, 1875, and amended in 1921. It is an international treaty, the purpose of which was the creation of an international organization called the BIPM. It is an example of the efforts made by countries in the second half of the 19th century to establish new forms of intergovernmental cooperation.

[1] Panfilo, G., Arias, F., *The Coordinated Universal Time (UTC)*, "Metrologia", Vol. 56, n°4, 2019.

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Since then, the aim of the BIPM continues to be to facilitate the standardization of measurements world-wide by enabling Member States to act together on matters related to measurement science.

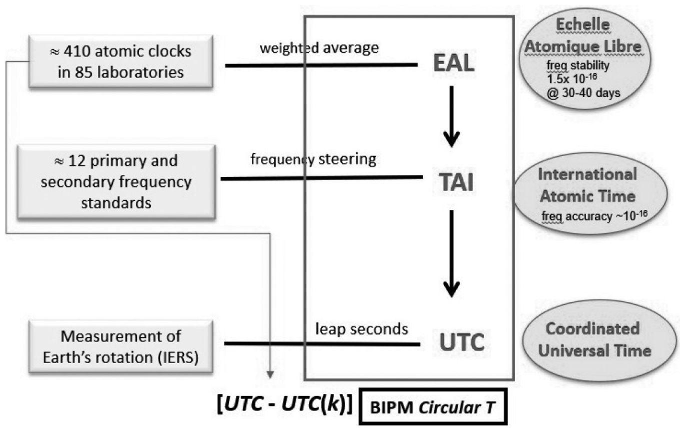


Figure 1. *Representation of EAL, TAI, UTC, UTC(k) and their relations.*

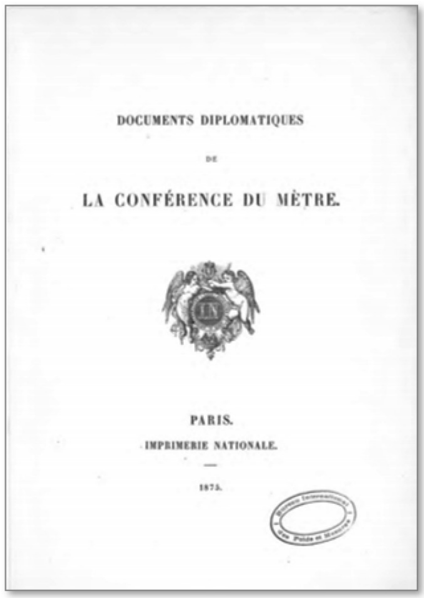
If on May 20, 1875, the Metre Convention was signed in Paris by representatives of 17 States, now the signatories are 64 Member States and 36 Associate States and Economies. The first article of the "Metre Convention" creates the International Bureau of Weights and Measures (BIPM) and the Article 3 states that the BIPM shall operate under the authority of the General Conference on Weights and Measures (CGPM) and the supervision of the International Committee for Weights and Measures (CIPM). In Figure 2 the historical document is reported. The CGPM is composed by official representatives of member states, the CIPM by eighteen individuals of different nationalities elected by the CGPM. The BIPM represents the scientific and technical secretariat dealing with international coordination and liaison, technical coordination by means of technical laboratories and capacity building program. The CIPM works by means of the Consultative Committees from which the CCTF (Consultative Committee for Time and Frequency) deals with the issues linked to the second and UTC.

2. International Atomic Time and Coordinated Universal Time

International Atomic Time (TAI) was established by the Consultative Committee for the Definition of the Second (CCDS) in 1971[2], after the adoption of the

[2] A.A.V.V., *CCDS*, "Metrologia", Vol. 7, 1971, pp. 43-4.

atomic definition of the second by the 13th General Conference on Weights and Measures (CGPM) in 1968[3]. The practical, disseminated reference time scale Coordinated Universal Time (UTC), based on TAI, is equally stable and accurate as TAI, but while TAI is continuous, UTC is affected by one-second discontinuities, known as leap seconds, as a consequence of its definition adopted in 1970[4].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1875.

Figure 2. *The Metre Convention document*

The CGPM at its 15th meeting (1975) noted that Coordinated Universal Time (UTC), derived from TAI, provides the basis of civil time, and strongly endorses this usage. The last recommendation voted during the CGPM in 2018 gives a complete definition of TAI and UTC here reported[5].

– International Atomic Time (TAI) is a continuous time scale produced by the BIPM based on the best realizations of the SI second. TAI is a realization of Terrestrial Time (TT) with the same rate as that of TT, as defined by the IAU Resolution B1.9 (2000)

[3] A.A.V.V., *13th General Conference on Weights and Measures*, “Comptes Rendus de la 13e CGPM (1967/68)”, 1969, p.103; A.A.V.V., *13th CGPM*, “Metrologia”, Vol.4, 1968, p. 43.

[4] A.A.V.V., *ITU-R Recommendations and Reports*, “TF Series. Recommendation ITU-R TF”, 2008, pp. 460-66.

[5] A.A.V.V., *26th CGPM Resolution 2* (https : //www.bipm.org/en/committees/cg/cgpm/26 – 2018/resolution – 2).

– Coordinated Universal Time (UTC) is a time scale produced by the BIPM with the same rate as TAI, but differing from TAI only by an integral number of seconds.

This definition explicitly refers to TAI as a coordinate time, recognizing the need of a relativistic approach. TAI is the basis of realization of time scales used in dynamics, for modelling the motions of artificial and natural celestial bodies, with applications in the exploration of the solar system, tests of theories, geodesy, geophysics, and studies of the environment. Nevertheless, TAI was never disseminated directly and UTC, which was designed to approximate UT1 (a timescale derived from the rotation of the Earth), was chosen as the practical world time reference. At the time of its definition, UTC was the unique means of having real time access to UT1, as needed for some specific applications including astronomical navigation, geodesy, telescope settings, space navigation, satellite tracking, etc. The definition of UTC is based on the atomic second, but the time scale is synchronized to UT1 to maintain |UT1 – UTC| < 0.9 s. Since 1972, UTC differs from TAI by an integral number of seconds, changed, when necessary, by insertion of a leap second, as predicted and announced by the *International Earth Rotation and Reference System Service* (IERS). Since 2017 and until further notice, the offset between TAI and UTC is 37 s. Since 1988 the BIPM is responsible for the computation of TAI and UTC. The phenomenon taken as the basis of a timescale should be reproducible with a frequency that is, ideally, constant. This is never exactly the case, so we must be able to identify the causes of its variation, and to eliminate or at least minimize them. The realizations of the second of the International System of Units (SI) differ from the ideal duration specified in its definition (where the hyperfine splitting of the caesium 133 atom, at rest at a temperature of 0 K, is 9 192 631 770 Hz); in the process of constructing a timescale we should be capable of reducing these differences.

The reliability of a timescale is closely linked with the reliability of the clocks whose measurements are used for its construction; at the same time, redundancy is also required. In the case of the international reference timescale, a large number of clocks are needed; this number is today about 420, most of which are high-performance commercial caesium atomic standards and active hydrogen masers.

The frequency stability of a timescale represents its capacity to maintain a fixed ratio between its unitary scale interval and its theoretical counterpart. The frequency accuracy of a timescale represents the aptitude of its unitary scale interval to reproduce its theoretical counterpart. After the calculation of a timescale on the basis of an algorithm conferring the required frequency stability, the frequency accuracy can be improved by comparing the frequency (rate) of the timescale with that of primary frequency standards (PFS) or another more accurate time scale taken as a reference (for ex. most UTC(k) are steered to UTC; GNSS times are steered to a local UTC(k)), and by applying, if necessary, frequency (rate) corrections.

The accessibility/universality to a world-wide timescale represents its aptitude to provide a way of dating events for everyone. This depends on the precision that is required. We consider here only the ultimate precision, which necessitates an observation of a few tens of days for reducing time transfer noise and profiting from the stability of the participating clocks. The long-term frequency stability required for a reference timescale in such a way is reached.

The instability of TAI, estimated today as 1 part in 10^{16} for averaging times of about 30 days, is obtained by processing clock and clock comparison data at 5-day intervals over a monthly analysis, with a delay to publication of less than ten days after the last date of data reported in the official document called BIPM *Circular T*[6].

By analyzing the acronym's UTC and TAI we can find the characteristics previously described:

UTC – Coordinated Universal Time

– *Coordinated* – it means that UTC is coordinated by means of (broadcasted) time signals.

– *Universal* – it is an heritage of the previous astronomic definition – Universal Time but it means also

– that is universally valid, universally used in many applications. However, the time is only "universal" at the very close vicinity of the equipotential surface corresponding to the sea level. In consequence, according to Einstein's relativity, time cannot be universal.

– *Time* refers to the scale interval that is SI second TAI – International Atomic Time.

– *International* – that it has been adopted internationally.

– *Atomic* – that the definition of the second is based on universal (quantum) properties of atoms.

– *Time* refers to the scale interval that is SI second.

3. Computation of UTC and TAI

Different algorithms can be considered depending on the requirements of the scale. For an international reference such as UTC, the requirement is extreme reliability and long-term frequency stability. UTC therefore relies on the largest possible number of atomic clocks of different types, located in different parts of the world and connected via a network that allows precise time comparisons between remote sites. Each month the differences between the international time scale UTC and the local time scales UTC(*k*) maintained at the contributing time laboratories are reported at 5-day intervals in an official document called BIPM *Circular T*[7]. The various time laboratories worldwide achieve a stable local time scale based on individual atomic clocks or a clock ensemble. The clock readings reported by these laboratories are then combined at the BIPM through an algorithm designed to optimize the frequency stability and accuracy as well as the reliability of the time scale beyond the level

[6] Circular T: https://www.bipm.org/en/time-ftp/circular-t.
[7] *Ibidem*.

of performance that can be realized by any individual clock in the ensemble. The BIPM Time Department uses an appropriate algorithm [1,10] to generate the international reference UTC each month[8]. The calculation of UTC is carried out in three steps as illustrated in Figure 1:

– The free atomic time scale EAL is computed as a weighted average of about 420 free-running atomic clocks distributed world-wide. A clock weighting procedure has been designed to optimize the long-term frequency stability of the scale.

– The frequency of EAL is steered to maintain agreement with the definition of the SI second, and the resulting time scale is TAI. The steering correction is determined by comparing the EAL frequency with that of the PFS/SFS.

– Leap seconds are inserted to maintain agreement with the non-uniform time derived from the rotation of the Earth. The resulting time scale is UTC.

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In Figure 3 the geographical representation of the laboratories participant in UTC is reported.

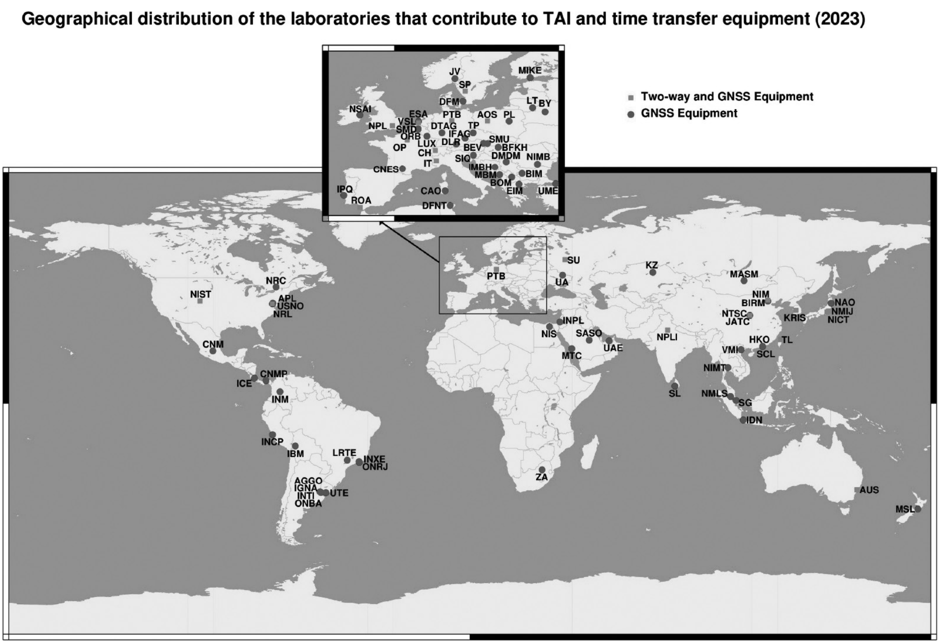

Figure 3. *Geographical representation of the laboratories participant in UTC.*

[8] Panfilo, G., Arias, F., *op. cit.*; Panfilo, G., *The Coordinated Universal Time*, “The IEEE Instrumentation and Measurement Magazine”, Special Issue on “Women Contributions”, Vol. 19, n°3, June 2016, pp. 28-33.

3.1 Atomic clocks, Time Links and Primary and Secondary Frequency Standards

To contribute to UTC the time laboratories sent to the BIPM different data; atomic clocks, time links and one part of them Primary and Secondary Frequency Standard (PSFS) evaluation. In this section is reported a short description of these different contribution to UTC. The atomic clocks used in UTC calculation are about 420 from which 180 Caesium clocks, 180 Hydrogen Masers and 5 Rubidium fountains. In Figure 4 the total clocks (black line), the Hydrogen masers (gray line) and caesium clocks (dark gray line) are reported. As it can be observed in Figure 4, in the last 2 years the number of Hydrogen Masers is increased of about 20 as the number of Caesium clocks is decreased of about the same number; this guarantees a stable number of clocks participating in UTC calculation.

The network of UTC time links until now is supported by two independent techniques, the two-way satellite time and frequency transfer (TWSTFT, or shorter, TW) and those based on GNSS observations.

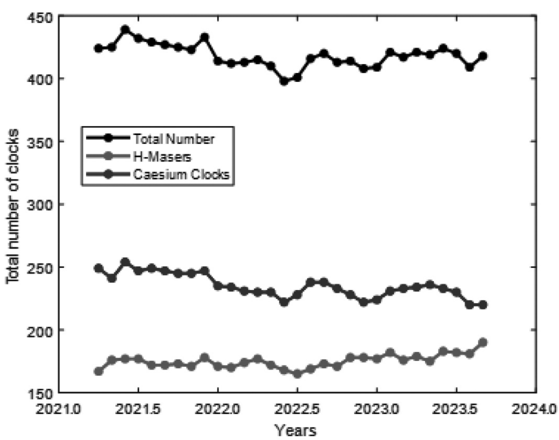

Figure 4. *The total clocks (black line), the Hydrogen masers (gray line) and Caesium clocks (dark gray line) participating in UTC.*

Several types of measurements exist for GNSS time transfer, e.g. single frequency code, dual frequency code, dual frequency code and phase for GPS. Moreover, new satellite systems as Galileo (European), GAGAN (Indian) and BeiDou (Chinese) will provide in the next future a very important number of measurements. For the TW in Europe, in North America and in Asia a complete set of redundant measurements is available. A global use of this ensemble of measurements will optimize the impact of the time links in UTC calculation by improving its metrological properties. Currently in UTC one pivot is used to compare clocks, the German laboratory PTB.

About 11 laboratories operate PSFS and contribute to the steering of EAL by submitting their data to the BIPM. In Figure 5 we can see the graphical representation of PSFS reported to the BIPM since Circular T 190. If the Cs Fountains (in the middle) contribute regularly since more then 10 years, we can observe then Optical clocks (on top) start to contribute in a regular way since 2020.

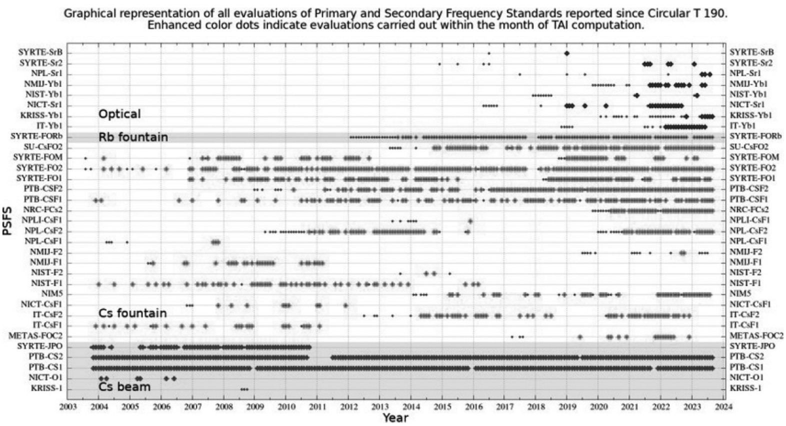

Figure 5. *The PSFS contributing to the steering of EAL to obtain TAI.*

4. UTCr

Considering the evolving needs of time metrology and the convenience of allowing the contributing laboratories access to a realization of UTC more frequently than through the monthly *Circular T*, the BIPM Time Department started in 2012 to implement the computation of UTCr[9], a rapid realization of UTC published every week and based on daily data submitted daily. After 18 months of pilot experiment, UTCr has been declared operational and is now an official publication of the BIPM. Since 1988, UTC has been calculated with one-month data batches at five-day intervals. Extrapolation of values over 10 to 45 days based on prediction models is necessary to many applications. UTC, as published today, is not adapted for real and quasi-real time applications and it was recognized that a more rapid realization would be of benefit to a variety of applications. For these reasons, the BIPM provides UTCr, a new realization of UTC available with a shorter delay. The stability of UTCr was expected to be about comparable to that of UTC, albeit slightly worse because the number of participating clocks would necessarily be smaller and because, in general, a deferred solution (here UTC) is expected to be better than a rapid solution (UTCr). In order to achieve a similar performance, it

[9] Petit, G., Arias, F., Harmegnies, A., *et. al.*, *UTCr: a rapid realization of UTC*, "Metrologia", Vol. 51, 2014, pp. 33-39.

was decided to use the same algorithm (frequency prediction, weighting scheme) and to apply it in a similar manner with a calculation interval covering approximately one month. UTCr was designed to be a realization of UTC, i.e. in practice the goal is to minimize the time difference [UTCr-UTC]. For this purpose, a steering algorithm has to be implemented. In October 2023, 62 laboratories representing 74% of the clock weight in UTC participate to UTCr calculation. In Figure 6 the difference between UTC and UTCr is reported.

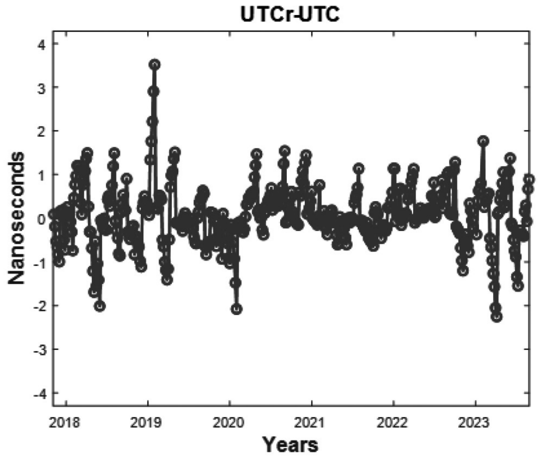

Figure 6. *Difference between UTC and UTCr.*

5. Application of UTC – traceability

UTC is the word reference universally used in the word for many applications, to facilitate the standardization of measurements and timing. Here some of the application domains of UTC are listed; Earth and space sciences need precise timing for observation, research, and modelling in the fields of geodesy, geophysics and astronomy; telecommunications are based on precise network synchronization; telecommunication techniques allow UTC dissemination. UTC is the reference for financial market coordination and cross-border energy transmission. Global Navigation Satellite Systems (GNSS) are based on precise timing and are synchronized to UTC; civil time keeping, and legal times are based on UTC. From the metrological point of view UTC gives traceability through the NMI's to the users as illustrated in Figure 7[10].

[10] A.A.V.V., *CCTF WGMRA Guideline 9. CCTF criteria for obtaining traceability in time and frequency* (https://www.bipm.org/utils/common/pdf/CC/CCTF/CCTF – WGMRA – Guideline 9.pdf)

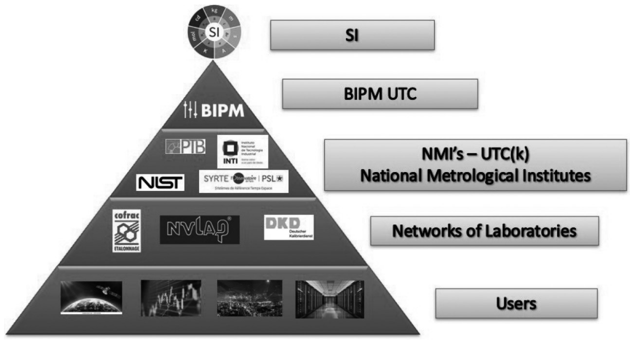

Figure 7. *The traceability chain of UTC.*

6. UTC – International and Universal

In this article UTC has been presented as international (internationally adopted) and universal (universally valid), but another extremely important concept is its being "natural". With the atomic definition of the second on the one hand this "natural" aspect has been lost because the definition is no longer tied to the earth-sun cycles, but on the other hand the second has been made more universal in the sense that in any part of the universe the definition could be reproduced because it is not tied to a single earth phenomenon. In any part of the universe the second can thus be defined and not just on earth. However, the atomic definition is less natural because it requires a high level of technology and higher than that required by a definition based on astronomical observation (accessible even without modern technology, with degradation of accuracy). A distinction needs to be made, to avoid ambiguity about the concept of universality, between the definition of the second in term of frequency and in time. If we consider the definition of the second in terms of frequency the second can be reproduced in any part of the universe, when we consider UTC (a time quantity) we need to specify that it remains valid only on the gravitational equipotential surface corresponding to what is commonly known as sea level. Indeed, as relativity shows that time is a relative concept, no time scale can be described as universal. While the decisions related to the definition of UTC/TAI certainly have a political key, one of the phenomenotechnical reasons (cf. Bachelard) related to the decision to have a single reference time scale is related to the physics of the system. In fact, the noise characterizing atomic clocks is a Brownian motion and from mathematical theory it is known that two long-term Brownian motions diverge thus the need to have one as a reference (on which to steer the other time scales). Another point to be made is that the advent of information technology means that, for the moment, time is defined and realized by humans, but the process is speed up with the help of machines; with the advent of artificial intelligence's it is not excluded that the algorithms needed to generate UTC can be completely realized by machines. To finish there is certainly an important weight from the geopolitical point of view for the choices made regarding UTC by the BIPM since these choices favor technologies or infrastructures of some countries over others. An example are the definition of the unit of time (the technology to achieve it may be held in priority by certain countries rather than others) and the continuity of the scale (leap second) more or less compatible with different satellite navigation systems.

7. Conclusions

In this paper the definition and the calculation of UTC has been presented to highlight his international role as word reference in time. A big effort made by the time laboratories located all over the word, with the coordination of the BIPM, allows for years to have an international reference like UTC that shows high level metrological properties as long-term stability, accuracy and reliability. The BIPM thanks all the laboratories participating in UTC for their continues support and involvement. The general concept of universality has been dealt with in the document by emphasizing the difference between defining the second in terms of "frequency" and in terms of "time – time scale – UTC", which gives rise to a completely different universality property for the second and UTC; from another point of view, it is also possible to say that UTC is universally used in many applications.

Gianna Panfilo
International Bureau of Weights and Measures (BIPM)
gpanfilo@bipm.org

Bibliography

A.A.V.V., CCDS, "Metrologia", Vol. 7, 1971, pp. 43-4.

A.A. V.V., *13th General Conference on Weights and Measures*, Comptes Rendus de la 13e CGPM (1967/68), 1969, p.103.

A.A.V.V., *13th CGPM*, "Metrologia", Vol. 4, 1968, p. 43.

A.A.V.V., *ITU-R Recommendations and Reports*, "TF Series. Recommendation ITU-R TF", 2008, pp. 460-66.

A.A. V.V., *26th CGPM Resolution 2* (*https://www.bipm.org/en/committees/cg/cgpm/*26 – 2018/ *resolution* – 2)

Panfilo, G., "The Coordinated Universal Time", *The IEEE Instrumentation and Measurement Magazine*, Special Issue on "Women Contributions", Vol. 19, n°3, June 2016, p 28-33.

Panfilo, G., Arias, F., *The Coordinated Universal Time (UTC)*, "Metrologia", Vol. 56, n°4, 2019.

Petit, G., Arias, F., Harmegnies, A., *et. al.*, "UTCr: a rapid realization of UTC", *Metrologia*, Vol. 51, 2014, pp. 33-39.

Petit, G., Arias, E.F., Panfilo, G., *International atomic time: status and future challenges*, "Comptes *rendus*

Physique", Vol. 16, n°5, 2015, pp. 480-488.