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Abstract
The International Conference held in 1884 at Washington defined a universal time as the mean solar time at the Greenwich meridian (GMT). Now, the Universal Time, version UT1, is strictly defined as proportional to the angle of rotation of the Earth in space. In this evolution, the departure of UT1 from GMT does not exceed one or two seconds. This is quite negligible when compared with the departure between the solar time and the legal time of citizens, which may exceed two hours without raising protests.

1. Introduction

The time that governs biological processes at the surface of the Earth follows the apparent motion of the Sun at the location of the beings. Only the diurnal motion of the Sun will be considered in this text. It is described in astronomy by its hour angle, also known as *true solar time*. It is reckoned from the transit at the local meridian, in degrees (or in hours, the hour being here a unit of angle equal to 15°). Considered as a time scale, the true solar time is not convenient because it suffers from various causes of irregularities. One of these, known since Ptolemy, has an annual periodicity with total amplitude of 31 min. It is removed by the *equation of time*, in order to obtain the *mean solar time* at the longitude of the user.

We will start our discussion with the seventh International Geodesic Conference at Rome in October 1883, followed by the *International Conference for the adoption of a unique prime meridian and of a universal day* [1] held at Washington in October 1884 (designated here '1884 Conference'). In fact, the Conference defined a *universal time.* We will recall the various sources of departure of legal time with respect to true solar time.

2. From initial to present definition of universal time

2.1. Classical astrometry

At the Rome Geodetic Conference, a purely scientific meeting, *the delegates began their discussion with admirable dispatch, the scientific objectivity, practical approach, and lack of national prejudice being particularly noticeable* [2]. The meridian of Greenwich, already used by a large majority of navigators, and a universal time based on this meridian were unanimously recommended. Thus, the 1884 Conference, of diplomatic character, seemed at first a pure formality. However, sterile discussions motivated by national pride delayed the conclusions of the conference by one month. These conclusions were finally in conformity with those of the Rome conference.

The 1884 Conference defined the prime meridian by the centre of the Airy meridian instrument of the Royal Greenwich Observatory (RGO), and, implicitly, by the pole of rotation of the Earth. The universal time was defined as the mean solar time at this meridian. These seem to be rigorous definitions. However, a definition should lead to a precise realization, without ambiguity, which was not the case here for the various reasons we will present hereafter, including the magnitude of their effects on time when they can be estimated. We do not follow the chronological order because each topic extended over many years and was treated during overlapping periods.

2.1.1. Precision. The instant of the meridian transit of the Sun cannot be measured with precision. It provides only one measure per clear day. Observation of numerous stars is much more precise, but their position with respect to the Sun is poorly known. The mean solar time thus became a stellar time. The bias may be of the order of 0.1 s.

2.1.2. International cooperation. The realizations of universal time in various observatories are biased by systematic errors coming from their adopted longitude (except in RGO), star positions, personal errors of observers, instrumental errors. At the beginning of the 20th century, the sum of these effects reached several seconds as revealed by radio time signals in 1904 to 1910. This showed a need for coordination and led to the creation of the Bureau International de l'Heure (BIH) in 1912, which began to operate at the Paris Observatory. The BIH developed in 1929 the concept of a *mean observatory* with a coherent system of corrections, so that the average

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of the determinations of universal time was not affected, in principle, by the irregular frequency of the observations. Initially, the mean observatory coincided with the RGO. But subsequently, this condition could not be strictly maintained and the conceptual definition of the time of the prime meridian was lost. For example, in 1930, the adopted correction of Greenwich determinations of universal time was −0.021 s. In 1967, the BIH started to use directly all determinations of universal time, version UT1 (see below), with a stability algorithm described in its Annual Reports for 1967 and 1968. In these developments the continuity of UT1 was preserved, probably at the level of 10 to 20 ms.

2.1.3. Need for a more precise definition. The pole is moving with respect to the Earth. This was demonstrated by measurements made by Küstner [3] in the period 1884 to 1887. The main components are quasi-periodic motions with periods of 1.0 and 1.2 year, and amplitudes of a few metres. A drift of the pole was suspected early, but it was proven only towards 1970: the mean pole moves secularly approximately at the velocity of 10 metres per century along the meridian 80° West. These motions cannot be predicted theoretically: their measurement requires a continuous monitoring which started in 1900, when the International Latitude Service was created. Thus, the prime meridian rotates around the reference point in Greenwich, causing an irregularity in time depending on the declination of the observed bodies of the order of 0.03 s. In 1955, the International Astronomical Union (IAU) officially decided to select a fixed point on the moving equator as the origin of longitude and to call UT1 (Universal Time 1) the universal time referred to this point. A further improvement was a rigorous definition of the location of the equatorial origin based on a concept of *non-rotating origin* [4, 5], which means that the meridian attached to this point has no component of rotation with respect to the Earth when the pole of rotation moves. This new origin was adopted by the IAU in 2000 and named Terrestrial Intermediate Origin (TIO).

2.1.4. Deformations of the Earth. The expression 'rotation of the Earth' is used for the sake of brevity, but it means the rotation of a reference system attached statistically to the Earth's crust which is deformable at the level of some centimetres per year.

2.2. Space geodesy techniques

Until about 1970, all determinations of UT1 were based on astronomical longitude and latitude, i.e. on the direction of the local vertical (plumb line). The worldwide system of longitude referred to the Greenwich meridian was realized by the unification of the values of UT1. Then new techniques of measurement became operational:

- laser ranging to artificial satellites and to the Moon (SLR, LLR),
- measurements of the Doppler effect on frequencies between satellites and the ground,
- radio-interferometry on quasars with baselines reaching several thousand kilometres (VLBI).

All these techniques, designated as *space geodesy techniques*, refer the positions of the observation sites to the true figure of the Earth instead of the verticals. In combination they provide realizations, named *frames*, (a) of a geocentric reference system, homogeneous on the whole Earth designated the International Terrestrial Reference System (ITRS), (b) of a Geocentric Celestial Reference System (GCRS) system in space, (c) of parameters describing the relative orientation of these two frames. These latter, known as Earth Orientation Parameters (EOP), are the instantaneous positions of the pole in the two frames and an angle of rotation of the Earth. But the initial orientation of the reference frames was not precisely defined.

The services developing these new techniques used provisional reference frames and sent their results to the BIH in the form of values of the coordinates of the pole and UT1. The BIH adjusted these provisional references so that there were no discontinuities of UT1 and in the coordinates of the instantaneous pole in the terrestrial frame. This decision had two major consequences.

1. UT1 remained close to the Greenwich Mean Time.
2. The prime meridian is not in conformity with the definition given by the 1884 Conference. It passes now at about 100 metres East of the Airy transit circle and moves towards the East at a velocity of about 1.5 cm/year, as a result of tectonic drift.

Let us conclude this discussion, without making reference to the intricacy of astronomical and geodetic considerations which may confuse the reader.

Strictly speaking, the Universal Time, version UT1, is not a solar time. It is a parameter which, jointly with the coordinates of the moving pole of rotation of the Earth, describes the rotation of the surface of the Earth in space. The knowledge of these parameters is essential for all space techniques with multiple applications, both practical and scientific, of the utmost importance.

However, all decisions taken until now preserved the role of UT1, the representation of the mean solar time at the Greenwich meridian as defined by the 1884 Conference, with a departure which may reach one to two seconds.

3. Irregularities of UT1

The long term irregularities of UT1 were demonstrated during the first half of the 20th century, by comparison with a time scale based on the orbital motions in the solar system, called Ephemeris Time TE. It was also possible to obtain information on the rotation of the Earth in antiquity by the location of solar eclipses. Over hundreds of millions years, palaeontology reveals the number of days in the year, whose duration is almost invariant, by the study of the growth of corals and other organisms, and of sedimentary layers. The reference currently used is atomic time. From all these studies, it appears that the main components of the irregularities are as follows.

- A slowing down of the rotation is caused partly by dissipation of rotational energy in oceanic tides, partly by a transfer of energy to the lunar orbital motion.

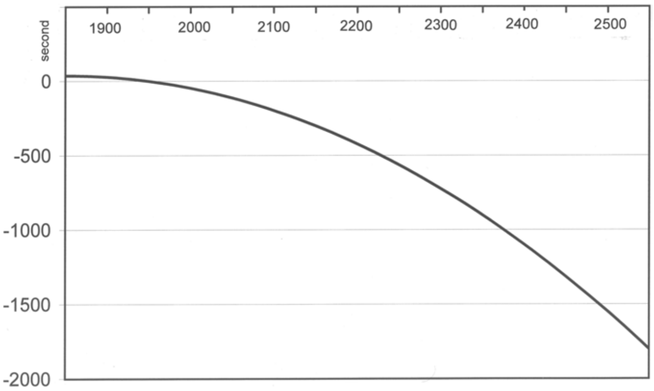

Figure 1. Extrapolated secular variation of $UT1 - TAI$, for the years 1850 to 2550.

This is shown by figure 1, using the deceleration of the rotational velocity R, $\mathrm{d}R/\mathrm{d}t = -5.5 \times 10^{-22}\,\mathrm{rad\,s^{-2}}$, estimated by Lambeck [6] with an uncertainty of about 10%. Equivalently, in more familiar units, the duration of the UT1 day (usually designated as the *length of the day, lod*) increases by 2.06 ms per century. For historical reasons, the SI second, in its present definition, has approximately the mean duration of the second of the mean solar time during the 19th century: we assumed that equality took place in 1850. We also adjusted the secular term so that it be equal to TAI, and therefore to UT1, in 1958. These decisions are somewhat arbitrary, because the decade fluctuations of the Earth's rotation, mentioned below, make a rigorous treatment impossible. However, this has no consequences in the context of this discussion.

- Decade fluctuations have a typical period of 30 to 40 years and an amplitude of several seconds. They are not theoretically predictable, but smooth enough for an empirical prediction to less than ±1 s over 3 years. They are attributed to interaction between the core and the mantle of the Earth. Figure 2 shows the values of $UT1 - TAI$, after removal of the secular effect mentioned above and of a linear function of time.
- An annual term, with total amplitude 60 ms, is mainly attributed to the atmosphere. This term is barely visible in figure 2.
- Other terms are due to tides, to oceanic currents and to the atmosphere with Fourier frequency larger than once per year, and amplitudes of a few milliseconds.

The two first irregularities are of major concern in this discussion.

4. Availability and prediction of UT1

As this subject is developed by D Gambis and B Luzum in this issue of *Metrologia*, we give here only brief indications.

The development of atomic frequency standards since 1955 led to two forms of atomic time scales: the International Atomic Time TAI and the Coordinated Universal Time UTC (UTC disseminates UT1 within ±0.9 s, see below). Precise values of UT1, as well as preliminary values and predictions, are obtained through the daily values of $UT1 - UTC$, available on the web: http://www.iers.org/. The delays and uncertainties are indicated below.

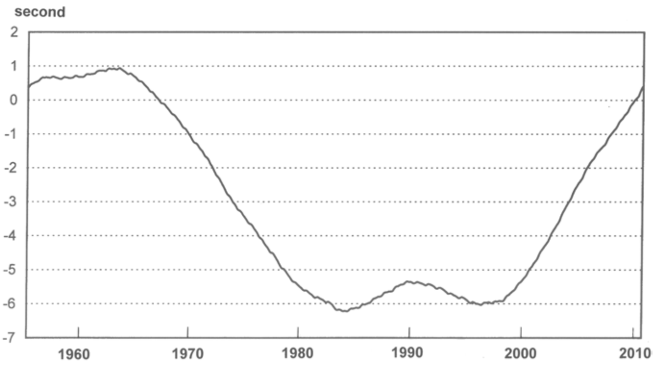

Figure 2. Observed variation of $UT1 - TAI$ after removal of the secular trend.

Definitive values Monthly Circular B, IERS EOP Centre	delay: from 1 to 2 months	uncertainty 5 µs to 10 µs
Preliminary extension Monthly Circular B	delay: from 0 to 1 month	uncertainty <30 µs
Prediction updated weekly Circular A, IERS Rapid Service and Prediction Center	for example: over 40 days	uncertainty <4 ms

Tests on real data from 1955 to the present, made by the author, have shown that a linear prediction based on one year of values of $UT1 - TAI$ led to a maximum error less than 0.6 s in two years after the last observed values. After three years, the maximum was 1.0 s.

5. International Atomic Time (TAI) and Coordinated Universal Time (UTC)

5.1. *History and present definition of UTC*

The concept of atomic time was born in July 1955, as a first application of the caesium frequency standard built by Essen and Parry [7] at the National Physical Laboratory in the United Kingdom. Following the development of other caesium standards, mean atomic time scales were constructed by integration over the frequency. One of these time scales, established by the BIH, was adopted by the 14th Conférence Générale des Poids et Mesures (CGPM) in 1971, as the International Atomic Time (TAI)—a name we apply retroactively since 1955 to the BIH time scale.

TAI has now a strict definition in the context of General Relativity (see, for example, [8]). It is based on the atomic definition of the second adopted in 1967. Its time origin is defined by giving the same date in TAI and UT1 on 1958

January 1 d 0 h 0 m 0 s exactly. Subsequently, TAI and UT1 diverge as a consequence of the irregularities of the rotation of the Earth. At the beginning of 2011, $UT1 - TAI$ reached -34.1 s.

One of the early applications of atomic time, in 1960, was to improve the coordination of the emissions of radio time signals of the UK and USA for disseminating UT1, needed for geodesy (at the better level of precision, about 1 ms) and, in real time, for navigation (±1 s). The basis of this coordination was derived from atomic clocks with a frequency offset, in order to interpolate and extrapolate UT1. The frequency offset was kept constant as long as possible, but could be changed at the end of a year if necessary. In the meantime, time steps could be introduced at agreed dates to maintain time signals within ±20 ms of UT2 (UT2 is a regularized form of UT1, by correction for the annual term). This system, based on a discontinuous time scale, named Coordinated Universal Time, was rapidly adopted by several countries and its management was entrusted to the BIH in 1962. In 1965, the BIH took the initiative to base the coordination on its atomic time scale TAI by the definition of UTC as a linear function of TAI.

The definition of UTC evolved rapidly because the frequency offset required modifications of some devices and because the frequency dissemination was not in agreement with the SI definition of the second. First, the number of frequency adjustments was reduced at the cost of an increased tolerance in $UT2 - UTC$. Then in 1972 the frequency offset was cancelled, the time steps were settled at 1 s. This system is currently in use. It is defined by

$$UTC = TAI + n \text{ seconds}, \qquad n \text{ being an integer},$$
$$|UT1 - UTC| < 0.9 \text{ s},$$

n being changed by insertion or deletion of a *leap second* (respectively positive or negative) when necessary at the end of any month, with first preference in June or December, and second preference in March or September (Recommendation IUT-R TF, 460-6). In addition, an audible code was inserted in the emission of radio time signals, giving access to UT1 with an uncertainty of ±0.1 s. This code was little used and was removed later from some emissions.

The maximum departure of 0.9 s of UTC from UT1 was chosen because it was acceptable for astronomical navigation at sea.

The frequency of occurrence of leap seconds has ranged up to now from one per year to one in 7 years, depending on the irregularities of the Earth's rotation.

5.2. Remarks on the present role of UTC

(a) Initially conceived as a means to improve the dissemination of UT1, UTC shifted towards a form of atomic time giving easy access to TAI and disseminating the unit of time, without corrections other than those required by the relativistic effects. Nevertheless it still represents the Greenwich mean solar time as defined by the 1884 Conference within about 1 s. This approximation is sufficient for most practical purposes, including astronomical navigation if still needed.

(b) However, UT1 is often required with full accuracy and is now easily available by other means, in real time, on the Web. It can be predicted empirically with an uncertainty smaller than one second over 3 years (a sufficient delay and precision for printed tables such as Nautical Almanacs, ephemerides for public use).

(c) UTC provides with full accuracy of reading the TAI, which remains in the background.

(d) Among the drawbacks of UTC, considered in this issue of *Metrologia* by other authors, we mention one fact (not a judgment): UTC is not a time scale on account of its discontinuities. In particular, in the case of positive leap seconds (a negative leap second has not yet occurred and their probability is low), the date of an event may be ambiguous. When UTC was defined by the International Telecommunication Union (ITU), the ambiguity was removed by introducing a second labelled 60 for the positive leap second, the succession of dates ending by 58 s, 59 s, 60 s, 00 s, 01 s. In addition to the fact that no machines include the possibility of displaying a second 60, most scientific and technical systems use a decimal fraction of the minute, or of the hour, or of the day. In all these cases, two different events separated by one second receive the same date when a positive leap second occurs. It is not a simple drawback; it may be a danger, for example when launching a rocket. (At least one space agency systematically avoids launches at the possible dates of insertion of a leap second.)

6. Legal time, time in use, social aspects

We consider now the departure D between true solar time and the time read by citizens on their watches. It is not a matter of seconds as previously discussed, but a matter of hours.

Equation of time. As mentioned above, it contributes up to 16 min to D.

Time zones. This well known system was conceived as a consequence of the development of railways. In principle, each zone extends by 7.5° East or West of a central meridian of longitude $N \times 15°$, N being an integer negative or positive, or zero. The time in use should be UTC corrected by N hours. Inside a theoretical zone, the contribution to D ranges from -30 min to +30 min. In practice the time zones follow the frontiers of states or groups of states, with possible additional departures. In Europe, for example, most countries have adopted the Central Europe Time CET which is UTC +1 h; the contribution to D reaches 1.5 h in some regions of Spain.

Summer time or light saving time. In many countries, an hour is added to watches during part of the year, for convenience and for saving energy.

6.1. An example

As an example, we show in figure 3 the departure between the true solar time and the legal time in France at Paris. We also mention the correction to apply in order to get the departure in Strasbourg and Brest. We observe that the range for a fixed

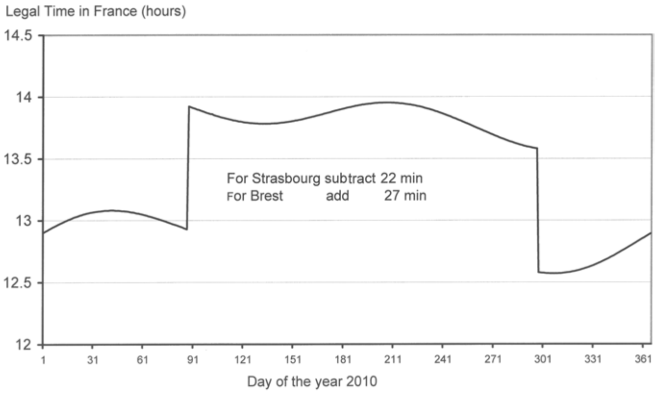

Figure 3. Legal time at noon, true solar time, at Paris.

observer is 1 h 23 min. The total range over the country is 2 h 12 min.

6.2. The reaction of citizens

My direct experience on this subject results from messages I received during the interval 1964 to 1988 when I was the director of the BIH. Indeed these reactions were very few. Almost all of them emanated from astrologers, who wanted to locate celestial bodies at crucial instants and needed information on legal time. When astrology was not explicitly mentioned, I used to satisfy their request without paying much attention to the author. Once I received as thanks a dedicated book of a well known writer: he had wanted to avoid inaccuracy in one of his books. When introducing atomic time, I also received a letter of complaint (only one) saying that we should not use atomic time, because the solar time is God's time.

7. Terminology

Ideally we should distinguish the theoretical definition of a *time* from its realization, a *time scale*, by an appropriate notation. For example, a *Terrestrial Time*, TT, has a rigorous definition and is realized as TT(X), where X is an acronym designating its mode of realization. When it is based on TAI, one writes $TT(\mathrm{TAI}) = TAI + 32.184\,\mathrm{s}$. The BIPM produces series of TT(BIPMXY) where XY are the two last digits of the year of production. But such a distinction is too complicated for scales used commonly.

The name of a time and of a time scale either indicates its goal (such as Universal Time) or the mode of construction (such as Ephemeris Time), or both (such as International Atomic Time). Universal Time is a nice name, although stamped with the grandiloquence of the 19th century, because it indicates the goal of its definition, not the technique to build the time scale. But the need to distinguish versions of UT adorned its acronym with suffixes: Universal Time has versions UT0, UT1, UT2, UTR, UTC. As shown by Sadler [9] this situation is far from being satisfactory.

I do not believe that it would be possible to rationalize all these denominations. But we should take advantage of any opportunity to simplify them.

8. Conclusion

Universal Time UT1 is now strictly proportional to the angle of rotation, designated by θ, between the celestial and the terrestrial reference systems. Its definition does not refer to the Sun, but the link with θ has been carefully established to ensure practically the conformity with the definition of the *universal hour* of the 1884 Conference, probably at the level of about 1 s.

Coordinated Universal Time UTC, in its present definition, disseminates UT1 with a possible offset of 0.9 s, at the cost of steps in time of 1 s. It disseminates also International Atomic Time TAI, with full accuracy, after correction by a variable integral number of seconds. The goal of this compromise between UT1 and TAI, adopted in 1972, was mainly the need for UT1 for astronomical navigation at sea.

After the progress of the Internet, of improved communications, of the Global Navigational Satellite Systems, we may ask ourselves if it is still useful to accept the inconvenience of a leap second. Our goal, in this paper, was essentially to introduce some elements into this discussion. We especially wished to show that the public accepts a departure of the legal time with respect to solar time by an amount reaching hours and, in many countries, time steps of one hour twice a year. Compared with this offset, the abandonment of leap seconds would introduce possible offset of 3 or 4 min by 2100, and half an hour between 2500 and 2600. It would be quite sufficient, for many centuries, to have a unique, continuous and uniform world time and to adjust legal times according to the wishes of citizens by steps of one hour, exactly as is already done twice a year.

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