COORDINATED UNIVERSAL TIME UTC : HISTORICAL BACKGROUND AND PERSPECTIVES

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ABSTRACT. The system of Coordinated Universal Time, UTC, was initially conceived at the beginning of the 1960's as a means of improving the dissemination of Universal Time, UT1, and to make available the stable frequency of atomic standards in a single time signal emission. It gradually evolved by relaxing the tolerance on UT1 and in 1971 reached the form we know to-day. In spite of its success, borne out by 33 years of existence, the present system suffers increasingly from the inconvenience of leap seconds. The number of users in need of a continuous time scale is increasing, and as a consequence there is a proliferation of scales built for specific purposes due to the fact that UTC is not satisfactory for their applications. Global Navigation Satellite Systems time scales are examples of this situation. These notes bring together some astronomical elements that should be kept in mind in any proposed revision of the UTC system and give our views on a new system of time dissemination.

1. BIRTH AND EVOLUTION OF UTC

1.1 The pre-atomic time era

Regular emissions of intercontinental radio time signals began in 1910 in France, Germany and USA, with important applications in geodesy and especially positioning at sea. A need of coordination appeared immediately, which led to conceive the Bureau International de l'Heure (BIH) in 1912/1913. The Bureau was officially created in 1919, as a service of the International Astronomical Union, but has begun to work towards 1913. Although this early coordination, which involved the solution of many scientific and technical new problems, is interesting, the history considered here begins in 1955, just before the advent of caesium time standards.

In 1955, about 30 time services measured Universal Time UT and about 25 stations emitted radio time signals to disseminate UT. [The distinction UT0/UT1/UT2 was introduced in January 1956. At the BIH, UT was an average of the UT0's of the participating observatories. In January 1955, UT2 began to be used.] There was a great variety of operational modes, however, a typical mode was as follows. Astronomical determinations of UT were referred to a master clock (pendulum or crystal clocks, diapasons) which was then used to extrapolate UT in order to steer signal emission. Also reception times of a huge number of time signals were referred to the master clock. The data of all time services were then centralized at the BIH where they were processed to issue, with a delay of about one year, the *definitive* corrections to the nominal times of emission of the signals.

Let us mention some statistics, for January 1955. Daily corrections for 228 emissions were published. These corrections were ranging from -189 ms to +116 ms, with a majority between +/− 50 ms. Main sources of errors were: wrong values of astronomical longitudes, uncertainties of determinations of UT (10 to 20 ms), periods of bad weather, instability of clocks.

1.2 Atomic time and coordination of time signals

In July 1955, the first operational caesium frequency standard appeared at the National Physical Laboratory (UK) (Essen and Parry, 1955). It was soon followed by others, either laboratory instruments or industrially made ones (”Atomichron”). Some of these standards were used for short periods of time and were used to calibrate the frequency of crystal clocks. Others operated continuously. It was thus possible to construct *integrated* atomic time scales. At the US Naval Observatory (USNO) the frequency of the caesium transition was determined in 1957 by comparison with Ephemeris Time (Markowitz et al., 1958). This value was adopted for the atomic time A1 of USNO and for other integrated atomic times. Then, in 1967, it became the defining value for the definition of the SI second. In 1961, the BIH assigned a common origin to these time scales by coincidence with UT2 on the 1^{st} of January 1958 (Stoyko, 1961). The same origin was used for the BIH mean atomic time.

The divergence of these early atomic times was slow when compared to the divergence of the best clocks. Their largest difference at the end of 1958 was 5 ms and at the end of 1957 it was 7 ms. Then it increased at a much slower rate, following the rapid progress of the frequency standards (1 ms per year corresponds to $3 \text{x} 10^{-11}$ in relative frequency, level of the frequency inaccuracy of caesium standards in 1960/1961). These time scales brought much improved bases for the extrapolation of UT and the possibility of synchronizing time signal emissions within a few milliseconds.

In 1956, the time signals WWV of the National Bureau of Standards (now National Institute of Standards and Technology) of the USA began to be emitted on an uniform time scale, the deviation with respect to UT2 being corrected by time steps of 20 ms. In 1958, this uniform time scale was obtained from atomic time using a constant frequency offset of about $-100 \text{x} 10^{-10}$ in order to follow approximately UT2, with time steps of 20 ms when needed.

This new system was not unanimously approved, probably because it accepted deliberately a departure with respect to UT2. Nevertheless, its advantages incited several observatories and laboratories to adopt it and to synchronize their emissions of time signals. In 1960 the International Union of Radiosciences recommended that the BIH, after consulting the concerned parties, announce the value of the frequency offset to be used during the following year and suggested that the nominal value will not change during the year. Later, the BIH also announced the date of introduction of time steps which were raised to 50 ms in August 1962 then to 100 ms in November 1963.

The name of Coordinated Universal Time UTC appeared in the early sixties at the International Radio Consultative Committee (CCIR) of the International Telecommunications Union (which became IUT-R Working Party 7A).

At the BIH, the acronym UTC was used for the first time in January 1964, with the empirical definition of a time scale deduced from the average time of emission of coordinated time signals. For these signals, the BIH began to publish the monthly averages of the difference E = UTC - Time of emission of the coordinated time signals, which remained fairly constant at the millisecond level (Guinot, 1964). For the best coordinated signals E amounted to a few milliseconds; for the others, E was progressively reduced.

A fundamental change occurred in January 1965: the BIH defined UTC by applying strictly the international frequency offset and time steps to its own atomic time scale, which became in 1972, TAI (Guinot, 1965). Thus, the transformation of UTC from a system of coordination of time signals into a time scale was achieved.

1.3 The present UTC

Most radio time signals had their carrier frequency in constant ratio with the second pulses. Therefore, the change of the frequency offset of UTC required physical adjustments at the emitting stations. With the increasing use of stable frequencies, especially for broadcasting and television stations, many users were also disturbed by the changes of the carrier frequency that they used as standard. This led to abandon a fine tuning of the UTC frequency on that of UT and to keep as long as possible a constant frequency offset, at the cost of an increased number of 100 ms time steps.

At the end of the 1960s, the demand for dissemination of frequencies in conformity with the definition of the second was becoming more pressing. Legal aspects were also evoked. These matters were mainly considered by the CCIR which prepared in 1969 a new definition of UTC without frequency offset and with time steps of one second, to be applied on 1972 January 1^{st}. In the meantime, from the beginning of 1970, two emissions (DCF77, Germany and WWVB, USA) broadcasted signals on a system known as TAS (Stepped Atomic Time). TAS had no frequency offset and a time step of 200 ms was applied at the end of a month when needed to maintain $[\,UT1\text{-}TAS\,]$ within ± 200 ms.

The first version of CCIR Recommendation 460-1 (1970) stipulates that TAI and UTC differ by an integral number of seconds, adjusted when necessary at the end of December or of June by introduction of positive or negative *leap seconds*. [This required on 1972 January 1 a time step of UTC of -0.1077580 s.] The maximum departure $|\,UT1\text{-}UTC\,|$ should not exceed 0.7 s. At the end of 1972, it was realized that it was not possible to comply with this rules and the BIH was faced to the choice of exceeding the tolerance of 0.7 s either on 1973 January 1 or 1973 July 1. Consequently, the tolerance was set to 0.9 s and the possibility of introducing a leap second at the end of any month was open. For those who needed the accuracy on UT1 provided by the previous form of UTC, an audible code disseminated $[\,UT1\text{-}UTC\,]$ to the nearest 0.1 s.

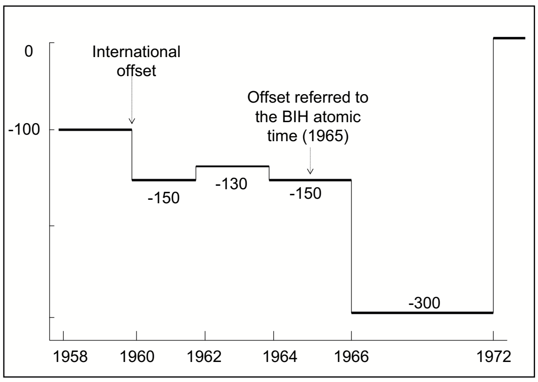

Figure 1: UTC frequency offsets (unit is 10^{-10}).

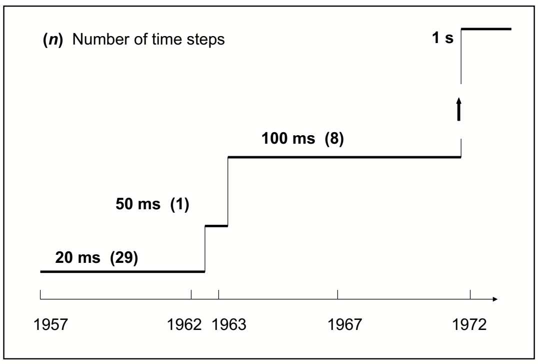

Figure 2: Evolution of UTC time steps.

Then the UTC system functioned without difficulties. Up to now, all leap seconds were positive. At the beginning, their rhythm was one per year. Since 1999, the rate of UT1 is close to that of TAI and no leap second has been introduced (October 2004).

The CCIR gave rules to date events without ambiguity when a leap second occurs. However, in case of positive leap second this is valid only in the system of hour, minute, second. In other systems two events one second apart receive the same date during the positive leap second.

Figures 1 and 2 show the evolution of the frequency offsets and time steps of UTC.

2. LONG TERM VARIATIONS OF UT1

In the long term the variation of [*UT1-TAI*] is dominated by the deceleration of the Earth rotation (fig. 3). [*UT1-TAI*] could reach half an hour in 2700, one hour towards 3000. Figure 4 shows the corresponding rate of introduction of leap seconds in the present UTC. Decade variations are superimposed to the secular terms and introduce variations in rate of order of one to two seconds per year, according to our experience since the 19^{th} century. Such variations referred to TAI are shown in fig. 5.

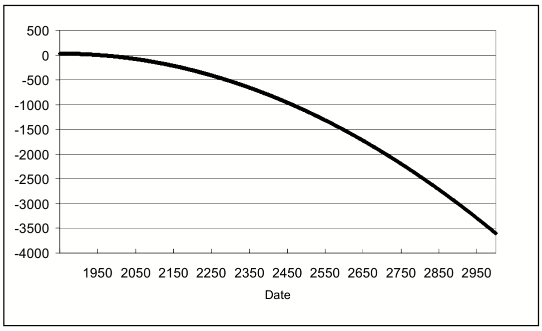

Figure 3: Secular term of [*UT1-uniform time*], in seconds.

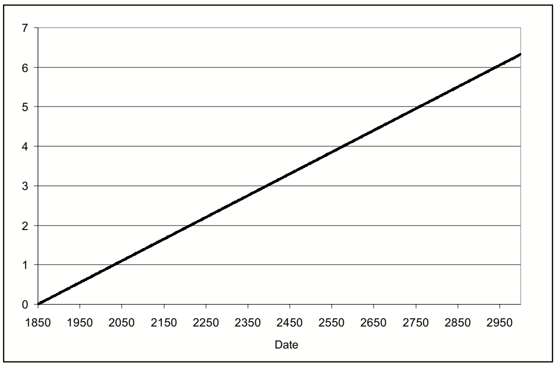

Figure 4: Number of leap seconds per year.

3. PERSPECTIVES

The UTC system has been in use for more than 30 years, and seems to be, a priori, a good compromise. However, the requirements for time keeping have evolved since the definition of UTC. The necessity of a uniform time scale, without the discontinuities introduced by the leap seconds is increasing.

TAI is, according to its first definition (Metrologia, 1971), the reference time coordinate established by the Bureau International de l'Heure (the BIPM at present) on the basis of readings of clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units. This definition evolved to be inserted in the context of general relativity, and TAI became the coordinate scale defined in a geocentric reference frame with SI second as realized on the rotating geoid as the scale unit (Metrologia, 1981). TAI is the uniform conventional time scale, but it is not distributed directly in every-day life. The time in common use (broadcast by different means) is referred to UTC, as recommended by the 15^{th} CGPM in 1975 and defined by the ITU. UTC provides the basis of civil time, it is associated to the legal time of most countries. Local realizations of UTC in time laboratories all over the world guarantee the dissemination of a time scale that represents UTC at the level of some tens of nanoseconds. These local physical realizations, named UTC(k) (k representing the laboratory) are provided by clocks.

In lack of a disseminated uniform time scale, and responding to the request of groups of users or services providers, a diversity of continuous time scales proliferated, constructed in most cases from ensembles of clocks, and differing between them in a number of seconds (see fig. 6). TAI is the uniform time scale, time dissemination responds to the UTC scale, offset by 32 s from TAI at present. GPS time, the scale for internal use in the GPS system is 19 s behind TAI (a constant amount) and 13 s ahead UTC today, this value increasing with the occurrence of positive leap seconds. The Glonass time is traceable to UTC through its Russian realization; it is directly affected by the introduction of a leap second. The future Galileo system plans to avoid the leap second by steering Galileo time to a uniform conventional time scale, namely TAI, but operatively to a sort of "leap second deprived UTC". In any case, the final decision is on hold of a recommendation concerning the definition of UTC. Besides these time scales there are many more designed for different applications, most of them absent in our records (telecommunications, banking, etc.). Should we think that the role of UTC in its present definition is to serve as the link between users of the different scales, each adopting a continuous scale to operate and transforming to UTC in a last step to follow the conventions?

The frequency of occurrence of positive leap seconds will increase, although slowly, in the long term (fig. 4), superimposed to decade fluctuations of the Earth rotation which may well lead in the near future to two leap seconds per year; this could increase the risk of omissions and errors in the files giving the information on [*UTC-TAI*].

An important fact is that dating in UTC is ambiguous when a positive leap second occurs in systems other than those using hours, minutes and seconds; in this latter system the use of the second "60", recommended by the ITU, may be a cause of difficulty. One of the most important role of a time scale is to provide an unambiguous way of dating events. In our opinion, the shortcomings of the present UTC in this respect suffice to condemn the system.

Based on these remarks, it seems that we should move towards the adoption of a world-wide, continuous time scale provided that enough time allowed to the users to prepare for the change. Taking into account that in some national legislations it is established that UTC serves as the basis of the official time, it should be convenient to maintain the same name and acronym. TAI should be preserved as it is; no more leap seconds would be added to UTC, freezing its difference to TAI at its value at the moment of application. Nevertheless, to avoid that the offset between TAI and UTC increase indefinitely, a leap hour could be added when necessary sometime in the far distant future. This proposal does not satisfy the condition of continuity, but the leap hour should not occur before about year 2700.

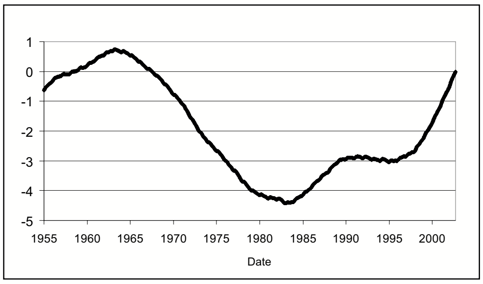

Figure 5: [*UT1-TAI*] corrected for secular variation.

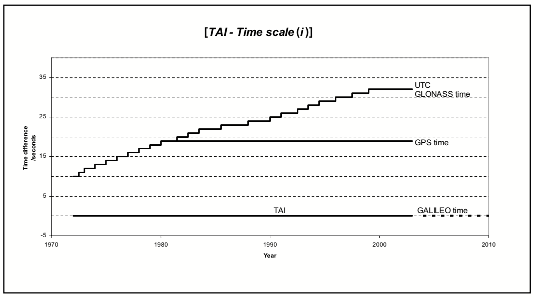

Figure 6: Differences between the various time scales and TAI.

4. ACCESS TO UT1

The dissemination of data depending on UT1 is and will remain essential. The critical case is that of annual ephemeredes for astronomical navigation (sea, air), for public use (sunrise, sunset, visibility of stars, planets, etc.) which require a precision of order of 1 second. It has been shown that a prediction of [*UT1-TAI*] within ±1 second is possible over two or three years. These ephemeredes should be based on this prediction, and expressed directly with UTC as time argument. The authorities responsible for the monitoring of the Earth rotation (at present the IERS) should be in charge of the prediction of [*UT1-TAI*] needed for preparation of the ephemeredes.

The other needs of UT1 would be satisfied as they are presently, by dissemination of [*UT1-TAI*], either predicted for real time, or observed for deferred time. One can conceive improvements of the dissemination of these quantities, when needed, for example by satellite navigation systems.

5. REFERENCES

Essen L, Parry J.V.I, 1957, Phil. Trans. R. Soc. London, Series A, **250**, 45-69.

Guinot B., 1964, Buletin Horaire du BIH, Série J, n ° 1.

Guinot B., 1965, Buletin Horaire du BIH, Série J, n ° 7. Markowitz W, Hall R.G., Essen L., Parry J.V.I., 1958, Phys. Rev. Lett.,**1**, 105-107.

Metrologia, 1971, **7**, 43.

Metrologia, 1981, **17**, 70.

Stoyko A., 1961, Bulletin Horaire du BIH, Série G, 241-245.