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Atomic time-keeping from 1955 to the present

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Abstract
This paper summarizes the creation and technical evolution of atomic time scales, recalling the parallel development of their acceptance and the remaining problems. We consider a consequence of the accuracy of time measurement, i.e. the entry of Einstein's general relativity into metrology and its applications. We give some details about the method of calculation and the characteristics of International Atomic Time, and we show how it is disseminated at the ultimate level of precision.

1. Introduction

After the construction of the first operational caesium frequency standard at the National Physical Laboratory (UK) in 1955, it was quickly recognized that the selected transition was the best choice and could serve as a reference for *frequencies*, as the angstrom had served for wavelength in the past. The adoption of this transition for the definition of the second was more difficult, but did not raise fundamental objections. In contrast, the time scales built by cumulating atomic seconds were not easily accepted for reasons which are recalled. The algorithm for the calculation of International Atomic Time (TAI) has been designed to guarantee the reliability, the long term stability, the frequency accuracy and the accessibility of the scale. It rests critically on the methods of clock comparison which are still the factor that can act to the detriment of a highly precise time scale. The Bureau International des Poids et Mesures, with the support of the timing community, devotes much effort to developing and improving these methods.

2. Creation and evolution of the TAI, 1955 to present

2.1. Basic time scales in 1955

We first give some indications of the astronomical time scales existing in 1955, in order to show the threshold that needed to be passed for a useful contribution to atomic frequency standards in time-keeping. In those days, the precision of measurements did not require appeal to relativistic theories. The goal of astronomers was to produce a time scale for worldwide use which was the best possible representation of absolute Newtonian time. The lack of uniformity of the realized time is characterized by an estimation of relative variations of rate, denoted by u, over specified intervals. Another important characteristic is the smallest uncertainty ε in assigning a date to an event. An essential property of time scales is, of course, their reliability; in this respect, astronomical times are ideal.

2.1.1. Universal time. Universal Time (UT1) is the name given to the most elaborated form of solar time. It is defined so that it is proportional to the rotation angle of Earth in inertial space [1]. Thus UT1 suffers from the irregularities of the rotation of Earth: a secular deceleration and decade fluctuations. Table 1 gives the corresponding values of u. Shorter-term fluctuations also exist, but they are not considered here because they could be smoothed out by use of good crystal clocks. In particular, a form of Universal Time, UT2, corrected for an annual variation of ±30 ms was defined in 1955. Even today, no theory is available to derive from UT1 a more uniform time. About 1955, the uncertainty of reading stagnated at about 1 ms until it began to decrease in the 1970s and is now $\varepsilon = 10\,\mu\text{s}$. (This progress is due to techniques of observation based on atomic frequency standards.)

2.1.2. Ephemeris time. The irregularities of UT1 have been demonstrated by its shortcomings in modelling the motion of planets and of the Moon. After some 50 years of difficult research, Ephemeris Time (TE), was defined in 1950, on the basis of the orbital motion of Earth. Table 1 gives the order of magnitude of u for TE. Unfortunately, the poor precision in positioning the Sun with respect to the stars made it impossible to exploit the good uniformity of TE in acceptable delays (one needed to wait thousands of years). A better precision of reading was obtained by defining secondary TE*n*s by the motion of the Moon (n being a number specifying the ephemeris in use). But this motion, perturbed by ocean tides and geophysical phenomena, requires an empirical calibration against the fundamental TE which, although it extended over centuries, strongly limits the uniformity.

2.2. The first atomic time scale

In the development of atomic time scales, an essential quality of atomic frequency standards is their accuracy. In this domain, accuracy is defined as the ability of the standard to provide the natural frequency, or a known sub-multiple of the adopted atomic transition for the unperturbed atom. By postulate, this frequency is constant so that the time obtained by integration is uniform. (Strictly speaking this applies at the location of the standard; in relativity, it is *proper time*). A real standard has a defect in accuracy characterized by a relative uncertainty u_{St}. This uncertainty can be seen as the defect of uniformity of the time scale generated by the standard over a very long term, years, decades, etc.

The era of atomic time began in 1955 with the caesium frequency standard built by Essen and Parry at the National Physical Laboratory (NPL) because it was highly accurate and could compete with astronomy [2, 3]. This standard was not a clock, it did not even include a servo loop to steer a quartz oscillator; the standard was used to calibrate the frequency of an external quartz clock at intervals of a few days. The authors estimated that the frequency of the clock was known with a relative standard deviation of 2×10^{-10} in terms of the caesium resonance. However, the frequency of this resonance, referred to the SI second (of UT2), was not precisely known, although early experiments at the National Bureau of Standards (NBS) in 1952 had provided a value. By comparison with UT2, obtained by the Royal Greenwich Observatory (RGO), Essen and Parry adopted a provisional value of the caesium frequency of 9192 631 830 Hz [4]. Essen and Parry had thus developed the first atomic time scale.

Table 1. Relative lack of uniformity, u, and uncertainty of reading, ε, of astronomical time scales (1955).

Time scale	u	ε/s
UT1 secular	5×10^{-11}/year	0.001
decade	4×10^{-8}	
TE (Earth orbit)	$\sim 10^{-11}$	~ 10
TE*n* (Moon orbit)	$\sim 5 \times 10^{-9}$	0.1

It was already admitted that the caesium frequency should be expressed in terms of the second of TE. Markowitz and Hall at the US Naval Observatory (USNO) undertook a precise determination of TE by a worldwide programme of observation with the Markowitz Moon Camera. The value of $\nu_{\mathrm{Cs}} = 9192\,631\,770\,\mathrm{Hz} \pm 30\,\mathrm{Hz}$ was found [5], the uncertainty on the frequency being almost entirely due to TE. As this value of ν_{Cs} was finally adopted for the definition of the SI second in 1967, we use it in the following.

2.3. The era of frequency comparisons, 1955–68

In parallel with research in national metrology laboratories, the National Company, Inc. undertook in 1954 the construction of a commercial caesium clock, known later as Atomichron® [6]. Some 50 of these devices were sold, for military and civil research laboratories. The data of some of them were available for time services as early as mid-1956. On the other hand, new laboratory caesium standards appeared in 1957 (Laboratoire Suisse de Recherches Horlogères (LSRH)), in 1958 (NBS), followed by several others. Figure 1 shows schematically the progress in accuracy of these standards. New commercial

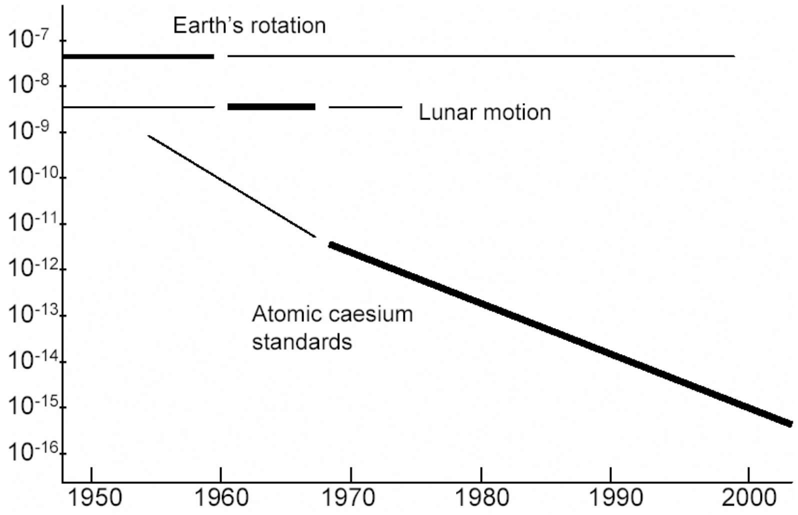

Figure 1. Schematic evolution of the relative accuracy of caesium frequency standards. The figure shows also the relative fluctuations of the duration of the Universal Time second (Earth's rotation) and of the duration of the second of Ephemeris Time, as realized by lunar observations (after 1970 Ephemeris Time is better measured, but cannot compete with atomic time). A thicker line represents the periods of the official definition of the second.

caesium standards appeared in 1964. They were less accurate than laboratory standards, but their very long term stability in frequency was excellent and they were apt for continuous operation as clocks. Several *local independent atomic times* TA(k) (this is an official designation, k being the name of the laboratory producing the scale) were established by integration over frequency, or by use of commercial caesium clocks, or by a combination of the data of both types of instruments. This raised two new problems: (a) how to compare these time scales with an accuracy compatible with that of the standards and (b) how to average them to form a mean atomic time scale ensuring a better uniformity and reliability than individual scales.

The uncertainty of time comparisons based on radio time signals, of the order of 1 ms, corresponds to a frequency uncertainty of a few units of 10^{-11} in relative value over 1 year; this was already much too large to exploit the accuracy of the standards at the end of the 1950s. Better frequency comparisons could be performed by referring the frequency of the standards to a common broadcast frequency at very low frequency (VLF), by measurement of phase variation. It was thus possible to construct a mean frequency standard and, by integration, a mean atomic time. But the uncertainty of time comparison between this mean time scale and local scales remained at the level of ±1 ms. A remarkable advance occurred in 1967 when the firm Hewlett-Packard demonstrated the possibility of using commercial flights to transport its caesium clocks, allowing time transfer with an uncertainty of 1 µs in operational mode. Many calibrations of the VLF links were then performed by clock transportation, mostly by the USNO.

Mean atomic time scales based on international clock data were established at the USNO (scale A1, which became later a purely local atomic time) and at the Bureau International de l'Heure (BIH). We consider here the BIH scale which became the TAI in 1972. This scale is continuous since July 1955, although the methods of computation were adapted to the changing techniques of frequency and time comparisons. Let us give first a definition. Any oscillator has a real frequency, which is a function of time t, $\nu(t)$ and a nominal frequency ν_0. Its *relative frequency offset* is $y(t) = \nu(t)/\nu_0 - 1$. During the period 1955–69, the BIH centralized the phase comparisons of VLF emissions and of several local caesium standards k. It also referred these emissions to a good crystal clock of the Paris Observatory (then a rubidium clock), denoted R, providing time T_{R}. Then by integration of $[y_{\mathrm{k}}(t) - y_{\mathrm{R}}(t)]$ and after the choice of time origins, $[T_{\mathrm{k}} - T_{\mathrm{R}}]$ were obtained, where T_{k} are local time scales, *as obtained by the BIH*. An average of the $y_{\mathrm{k}}(t)$, denoted $y_{\mathrm{m}}(t)$, was also formed, leading to a mean atomic time scale, T_{m}, by $[T_{\mathrm{m}} - T_{\mathrm{R}}]$ and to $[T_{\mathrm{k}} - T_{\mathrm{m}}]$. At first sight, each T_{k} seems to provide an access to the mean time scale, T_{m}. However, the integrations made at the BIH did not correspond to the individual integrations made by the laboratories, i.e. $T_{\mathrm{k}} \neq$ TA(k), the causes being the uncertainties of phase measurement and the differences in integration methods. In order to obtain a unique mean time scale, the BIH arbitrarily considered that R was the unique point of access of T_{m}. The lack of symmetry and the privileged role of the Paris Observatory was a major defect of this procedure.

In its work, the BIH set the origin of T_{k} and of its mean scale, T_{m}, by coincidence with UT2 on 1 January 1958, 0 h UT2. Initially, the data of all available caesium standards received the same weight in the average. However, it was recognized in 1963 that only the standards built in the metrology laboratories NBS, LSRH and NPL should be considered as primary standards. Consequently, the BIH scale was based on these standards and named A3, corrections to the previous results being issued [7]. The name A3 was retained when other primary standards joined the initial group in 1966.

2.4. The era of precise time comparisons, 1969–72

In 1967/68 a major advance in time-keeping was introduced by the LORAN-C system of navigation. This system is based on the synchronized emission of signals from networks of a minimum of three stations. Over distances up to about 1000 km, signals emitted at 100 kHz travel by ground wave, the delay of propagation between an emitting station and a fixed point being constant at the microsecond level. Progressively, the LORAN-C networks were synchronized between themselves, first across the North Atlantic, then in other parts of the world. For time services, it was thus equivalent to receiving any station of any network to perform time comparisons. However, the time links using LORAN-C had to be calibrated by clock transportation on commercial flights. This being done, LORAN-C brought unification of time at the microsecond level in its area of coverage, leading to an improvement of the order of 1000 with respect to the classical radio time signals.

At the same time, Czech scientists had the idea of using the signals of commercial television as a means of synchronization [8]. These time links, useful up to a few hundred kilometres, were stable at the level of 0.1 µs to 1 µs, depending on the distance. They also required calibration by clock transportation.

With these new tools, the BIH adopted at the beginning of 1969 a new method for establishing its mean atomic time by directly averaging local independent atomic times. It named this scale TA(BIH), without introducing time discontinuity. TA(BIH) was initially based on three TA(k), those of the Physikalische Technische Bundesanstalt (PTB), the Commission Nationale de l'Heure of France (F) and the USNO. In the course of 1969 this group was extended to include the RGO, the National Research Laboratory of Canada (NRC), the NBS and the Observatoire de Neuchâtel (ON) in Switzerland. The BIH method of computation avoided steps in phase and frequency when introducing new participants. Thus TA(BIH) was keeping the memory of the mean frequency of the initial group of three time scales.

On the other hand, a time scale approximating UT1, called Coordinated Universal Time (UTC), has been in use since 1962. In 1965, UTC was mathematically linked to TA(BIH). Several laboratories were keeping approximations to UTC, termed UTC(k). The access to TA(BIH) was provided by the TA(k) and UTC(k) through the publication, by the BIH, of values of [TA(BIH) − TA(k)] and of [UTC − UTC(k)] at 10-day intervals, the uncertainties being of the order of 1 µs for laboratories receiving LORAN-C, 10 µs for VLF. This publication had the form of monthly circulars providing data with a delay ranging from 1 to 2 months. With this new method, the BIH time scale became truly international, with multiple accesses, the symmetry between participants being respected. In 1971 the TA(BIH) was renamed TAI (see section 3.2).

2.5. *The era of precise time comparisons, 1973 to present*

The BIH considered that the direct use of individual atomic clocks would be preferable to the averaging of time scales for the following reasons:

- the possibility of defining the criteria for TAI independent of those for TA(k)s, which differed from each other for specific local needs, and devising an algorithm to fulfil them,
- the inclusion of small groups of caesium clocks not used for local TA(k)s,
- the increase in the number of points of access to TAI/UTC,
- the creation of a worldwide community of laboratories participating in TAI.

An organization was set up for transmission of data to the BIH, in a unified format, initially by Telex and by the General Electric Mk III system. An algorithm called Algos was first tested on the French clocks and then in 1972/73 on international data. It began to be used operationally on 26 June 1973. The first description of Algos appeared in the *Rapport Annuel du BIH pour 1973*. Since 1973, Algos has been modified several times to keep up with the progress of clocks, frequency standards and time comparison means; however, its basic principles have not changed. They are discussed in section 5.

Algos was introduced without frequency and time steps. Initially, 56 caesium clocks in 25 laboratories participated, the values of [UTC − UTC(k)] being provided as previously with the same uncertainty. These data were published as previously, with a larger number of UTC(k)s.

In the period 1973–present, the main developments of TAI are:

- The number of participating laboratories has increased to more than 50 at present. The participating clocks include mostly commercial caesium standards and also hydrogen masers, the total number reaching about 300.
- The primary frequency standards of NBS, PTB and NRC revealed in the 1970s that the relative frequency of TAI was too high by about 1×10^{-12}. It was decided to correct it by exactly -10.0×10^{-13} on 1 January 1977. Subsequently, the agreement with the primary frequency standards has been maintained by a *frequency steering* as explained in section 5.2. This frequency steering compensates a trend to a decrease in the frequency of industrially made caesium clocks, which persists up to the present and remains unexplained.
- The reception of the signals from the Global Positioning System (GPS) in 1983 and the use of telecommunication satellites reduced the uncertainties of time comparisons in the range of 10 ns to 1 ns.
- In 1988, in a global reorganization of international services of Earth rotation and time, the BIH was dissolved and the responsibility of TAI was transferred to the Bureau International des Poids et Mesures (BIPM).
- Since 1996 the values of [UTC − UTC(k)] have been published monthly at 5-day intervals.

About 1980, high accuracy primary caesium standards were being operated continuously as clocks at the PTB and the NRC. As these standards were the main contributors to the frequency steering of TAI, it was suggested that TAI could rest solely on them and future similar devices. In the subsequent discussions, it was recognized that the existing organization, which uses them to steer the frequency of TAI, offered better guarantees of perennial TAI.

The present characteristics of TAI and UTC are detailed in section 5.

3. The acceptance of atomic time

3.1. *Definition of the second*

In 1955, the SI second was still defined tacitly as the second of mean solar time, or more precisely of UT2. To avoid its variations of 10^{-7} to 10^{-8} in relative value, the astronomers suggested a new definition of the second to be based on the orbital motion of Earth [9]. Following declarations of the International Astronomical Union (IAU) in 1952 and 1955, the International Committee of Weights and Measures (Comité International des Poids et Mesures, CIPM) decided in 1956 to define the second, the *ephemeris second*, as a fraction of the tropical year. This decision was ratified in 1960 by the General Conference of Weights and Measures (Conférence Générale des Poids et Mesures (CGPM)), 5 years after the birth of the first caesium frequency standard.

We can now consider the adoption of the ephemeris second as an unnecessary step towards the *atomic second*. The rational explanation is that it was not certain, at this epoch, that the caesium transition was the best choice and that all the corrections due to the perturbations of the atoms were taken into account; indeed, a small correction due to black body radiation was applied much later. The possibility that atomic time differed from dynamical time was also raised—a problem which remains open. Less rational was the ancestral feeling that the motion of celestial bodies is time. Nevertheless, under pressure from physicists a value of the frequency for caesium standards was *suggested for temporary use* by the CIPM in 1964. In 1967/68, this value was adopted for a new definition of the second, the current one, and the definition of the ephemeris second was abrogated.

3.2. *Adoption of TAI*

Much more controversial was the adoption of atomic time scales. A fundamental problem is that atomic time results from integration over frequency and that uncertainties are also integrated. This leads to an unlimited departure from an ideally integrated time. In contrast, astronomical times are based on observations of positions of celestial bodies, with limited uncertainties, decreasing as a consequence of observational progress. At some time, the error on atomic time exceeds that on the reading of astronomical time. As an example, the error cumulated on TAI since 1977 may be of the order of 20 µs; the uncertainty on UT1 is now 10 µs. However, we have to also consider the accuracy of the theory of motion of celestial bodies and the spectra of the uncertainties. In the example of UT1, the uncertainties of TAI which have long term variations, say over decades, do not matter because the long term irregularities of UT1 have no precise theoretical modelling. A more critical example is that of rapid pulsars whose pulse reception times are measured with uncertainties of the order of 1 µs. The frequency of rotation is very stable and, here, the uncertainties on TAI may be a limitation in understanding these bodies. However, pulsars cannot replace atomic clocks because of their decelerating rotation and other poorly modelled phenomena [10].

At present, astronomers studying planetary motions date their observations in TAI, and then they construct ephemerides to model these motions. However, they do not consider these ephemerides as a prediction of the positions in terms of TAI. Instead, they consider that an ephemeris generates its own dynamical time scale. After relativistic transformations (see below), this scale is close to TAI, but distinct from it. Will it be possible some day to use a new form of ephemeris time to replace the atomic time? We do not see at present how astronomical time could challenge the precision of reading, the convenience and the accuracy of the scale unit of atomic time—qualities which are continuously improving.

Other objections to the acceptance of atomic time included its possible lack of reliability and its artificial character (it was said that it was not God's time!).

In spite of objections, atomic time was increasingly used. The unification of time on the basis of the atomic time scale of the BIH was recommended by the International Astronomical Union (IAU, 1967), the International Union of Radio Sciences (URSI, 1969) and the International Radio Consultative Committee of the International Telecommunication Union (CCIR, 1970). The ultimate consecration came from the official recognition by the 14th CGPM in 1971, which introduced the designation *International Atomic Time* and the universal acronym TAI (that can be used for designating the BIH atomic time since 1955).

Nevertheless, TAI was never disseminated directly, and UTC, approximating UT1, continues to rule the world because it is needed in real time for some specific applications including astronomical navigation, geodesy, telescope settings, space navigation and satellite tracking. The definition of UTC evolved with an increasing tolerance for the time offset [UT1 − UTC]. Since 1972, UTC differs from TAI by an integral number of seconds, changed when necessary by insertion of a *leap second* to maintain $|\mathrm{UT1} - \mathrm{UTC}| < 0.9$ s. Although this system works well, leap seconds are increasingly cumbersome and introduce an ambiguity in dating events when they occur. This leads to the fact that continuous time scales parallel to TAI, but with a time offset of an integral number of seconds, have been created, which puts at risk the unification of time. With the progress of communications, other means of providing UT1 in real time can be conceived and the future of UTC is being discussed [11, 12].

TAI and UTC have numerous applications in time synchronization at all levels of precision: from the minute needed by the general public to the nanoseconds required in the most demanding applications. The case of the GPS is typical. The time scale of the system may be totally independent of TAI; however, the GPS authorities found it convenient to narrowly synchronize the GPS time with UTC(USNO) modulo 1 s, hence with TAI modulo 1 s; since 1998 the time offset has mostly been between −30 ns and +20 ns, with excursions up to +40 ns. In addition, GPS disseminates a good approximation to UTC, easily available at all levels of precision from the second to a few nanoseconds. Similar features will be adopted for Galileo, the future European satellite positioning system.

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. In all these applications, relativistic effects are important.

4. General relativity and atomic time, definition of TAI

In the 1960s, Einstein's general relativity was still a rather esoteric theory, except for a few specialists and cosmologists. A consequence of the accuracy of frequency standards is that this theory is now in current use in many applications. It has also led to a general reflection on metrology in the framework of general relativity [13]. We relate here how this theory was progressively accepted in time-keeping and related fields.

One of the precursors was G Becker, from the PTB, who clearly defined in 1967 the relation between the proper unit of time for local use and the time coordinate (*coordinate time*) in extended domains [14]. However, the insertion of TAI in this general scheme was slow. Although the need to correct the frequency of standards to refer them at sea level was recognized (the correction is about 1×10^{-13} per kilometre of altitude in relative value, for clocks fixed on the surface of Earth), it was generally, but wrongly, considered that TAI had the form of a proper time [15]. In 1980, the Consultative Committee for the Definition of the Second (CCDS) declared that TAI is coordinate time defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit. The IAU did not accept this definition at its General Assembly of 1982 and preferred to wait for a global treatment of space–time reference systems. This was accomplished in the framework of general relativity in 1991, after many controversies, with the adoption of a specified metric [16]. In 2000, a metric extended to higher order terms was adopted by the IAU [17]. In these developments, several theoretical coordinate times were defined, for use in the vicinity of Earth and for the dynamics of the solar system. All these coordinate times are realized on the basis of TAI after relativistic transformations. TAI itself appears as a realization of an ideal terrestrial time TT (a designation proposed by Becker in 1967!). Terrestrial time is obtained from a geocentric coordinate time TCG by a linear transformation chosen so that the mean rate of TT is close to the mean rate of the proper time of an observer located on the rotating geoid.

The necessity for a relativistic treatment of time comparisons was demonstrated in a spectacular way in 1972 by an around-the-world transportation of caesium clocks [18]. The basic formulae for various types of time comparisons were developed in the 1970s by several authors. The formulae are based on a convention for synchronization, which was made explicit later and which is now known as *coordinate synchronization*.

In general relativity, local physics keeps its familiar form, provided that the effects of special relativity are taken into account. It is, however, important to note that the progress of atomic time standards narrows the limits of 'local'. We arrive at a situation where the structure of an atomic clock cannot be seen as local. The modelling of a frequency standard itself in the framework of general relativity is becoming a necessity [19]. In applications, the need for a relativistic treatment appears as a consequence of precise measurement techniques based on atomic time and frequency standards: telemetry by lasers and radars and angular measurements by very long baseline interferometry. The fields which are involved include celestial and terrestrial reference systems, geodesy, geophysics, positioning by satellite systems and dynamics in the solar system (motion of planets, satellites, space probes). Originally, the relativistic treatment often took the form of relativistic corrections to the Newtonian model. Subsequently, the work of experts in general relativity who have undertaken an educational effort [20, 21] has led to a much more satisfactory comprehensive treatment.

We can now say that general relativity is accepted as a 'new classical' framework for metrology, geodesy and fundamental astronomy, which is a consequence of atomic time-keeping.

In the following section, we use the language of Newtonian mechanics for the sake of simplicity; however, it must be understood that a relativistic treatment is strictly applied.

5. Present realization of TAI and UTC

TAI is the reference time scale, defined in the context of general relativity as seen previously. Since 1988 it has been calculated at the BIPM as a result of international cooperation. The algorithm Algos [22–24], developed at the BIH in 1973, has fixed the principles of the construction of TAI. After numerous tests and some improvements, it remains the basis of the calculation.

UTC is calculated as derived from TAI by the application of leap seconds. The dates of leap seconds of UTC are decided and announced by the International Earth Rotation and Reference Systems Service (IERS). At present (March 2005), the difference between TAI and UTC amounts to 32 s.

TAI is the uniform time scale that provides a precise reference for scientific applications, whereas UTC is the time scale of practical use that serves for international coordination in time-keeping and for the definition of legal national times.

The requested properties of TAI. A time scale is characterized by its reliability, frequency stability and accuracy, and accessibility. The algorithm for calculation will depend on what is required of these characteristics.

The *reliability* of a time scale 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 time scale, a large number of clocks are required; this number is today about 300, most of them high performing caesium atomic standards and active auto-tuned hydrogen masers.

The *frequency stability* of a time scale is the capacity to maintain a fixed ratio between its unitary scale interval and its theoretical counterpart. A means of estimating the frequency stability of a time scale is by calculating the Allan variance, which is the two-sample variance designed for statistical analysis of time series, and depends on the sampling interval.

The *frequency accuracy* of a time scale is the aptitude of its unitary scale interval for reproducing its theoretical counterpart. After the calculation of a time scale on the basis of an algorithm conferring the required frequency stability, the frequency accuracy is improved by comparing the frequency of the time scale with that of primary frequency standards and by applying, if necessary, frequency corrections.

The *accessibility* to a worldwide time scale is its aptitude for providing a way of dating events for everyone. It depends on the precision which is required. We consider here only the ultimate precision, which, as we shall see, requires a delay of a few tens of days in order to reach the long term frequency stability required for a reference time scale. Besides, the process needs to be designed in such a way that the measurement noise is eliminated or at least minimized, this requiring a minimum of data sampling intervals. The instability of TAI, estimated today as 0.5×10^{-15} for averaging times of 20–40 days [25], is obtained by processing clock and clock comparison data at 5-day intervals over a monthly analysis, with a delay of publication of about 15 days after the last date of data report. In the very long term, over a decade, the stability is maintained by primary frequency standards and is limited by the accuracy at the level of 10^{-15}, assuming that the present performances are constant.

5.1. An essential tool: clock comparisons

The calculation of a time scale on the basis of the readings of clocks located in different laboratories requires the use of methods of comparison of distant clocks. A prime requisite is that the methods of time transfer do not contaminate the frequency stability of the clocks, and in fact they often were in the past a major limitation in the construction of a time scale.

The uncertainty of clock comparison is today between a few tens of nanoseconds and a nanosecond for the best links, *a priori* sufficient for comparing the best atomic standards over integration times of a few days. This assertion is strictly valid for frequency comparisons, where only the denominated statistical uncertainty (Type A) affects the process. In the case of time comparisons, the systematic uncertainty (Type B), coming from the calibration, should be considered in addition. In the present situation, calibration contributes with an uncertainty that surpasses the statistical component, and that can reach 20 ns for non-calibrated equipment (see table 2). It can be inferred that repeated equipment calibrations are indispensable for clock comparison.

A network of international time links has been established by the BIPM to organize these comparisons (see figure 2). It is a star-like scheme with links from laboratories to a pivotal laboratory in each continent and long baselines providing the links between the pivotal points.

It should be noted that participating laboratories provide time transfer data in the form of a comparison of their UTC(k)s with respect to another time scale or to another local realization of UTC.

Table 2. Characteristics of some of the time links in TAI. The technique is indicated as follows: GPS MC for GPS common-view multi-channel C/A data; GPS SC for GPS common-view single-channel C/A data; GPS P3 for GPS common-view multi-channel dual-frequency P code data; TWSTFT for two-way satellite time and frequency transfer data. Uncertainties u_A, u_B are described in the text. Under 'Calibration type' EC indicates equipment calibration, LC (technique) is for a link calibrated using the mentioned 'technique' and NA stands for 'not available'. Conventional acronyms for the laboratories are provided in the BIPM reports.

Link lab 1/lab 2	Technique	u_A/ns	u_B/ns	Calibration type lab 1/lab 2	Distance/km (approx)
AOS/PTB	GPS MC	1.5	5.0	GPS EC/GPS EC	450
AUS/NICT	GPS MC	3.0	5.0	GPS EC/GPS EC	7300
BEV/PTB	GPS MC	1.5	5.0	GPS EC/GPS EC	600
CSIR/PTB	GPS MC	3.0	20.0	NA/GPS EC	8100
ONBA/USNO	GPS MC	5.0	7.0	GPS EC/GPS EC	7800
NMIJ/NICT	GPS SC	2.5	5.0	GPS EC/GPS EC	70
CAO/PTB	GPS SC	7.0	20.0	NA/GPS EC	1500
NICT/PTB	GPS P3	1.5	5.0	LC(GPS MC)	8300
NIMT/NICT	GPS P3	1.0	20.0	LC(GPS MC)	4500
ORB/PTB	GPS P3	0.7	5.0	GPS EC/GPS EC	450
IEN/PTB	TWSTFT	0.5	1.0	LC (TWSTFT)	830
NIST/PTB	TWSTFT	0.5	5.0	LC(GPS SC)	7500
TL/NICT	TWSTFT	1.5	5.0	LC(GPS SC)	2100

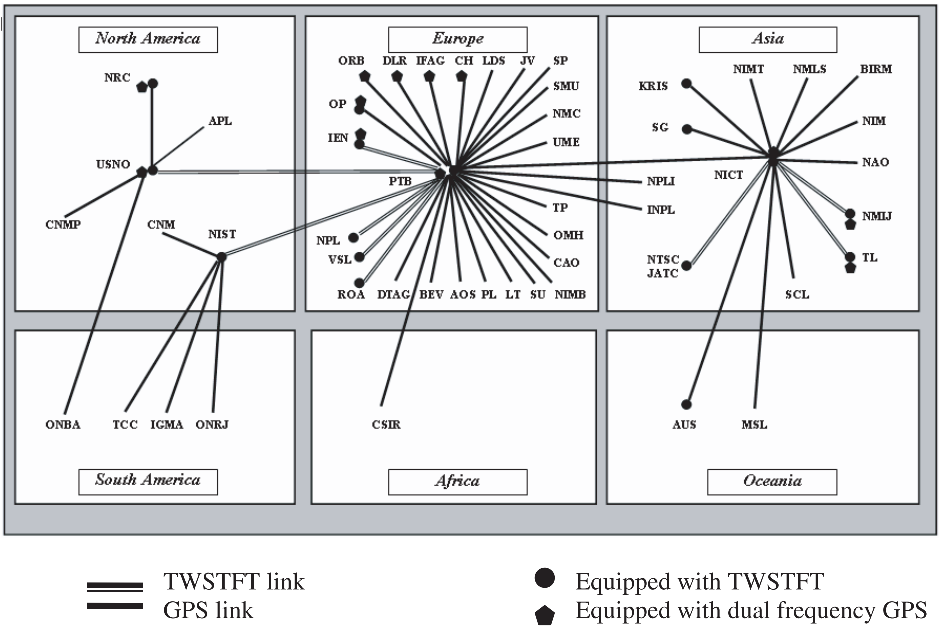

Figure 2. Network of international time links for TAI as in December 2004.

5.1.1. Use of GPS for time transfer. The use of GPS satellites in time comparisons introduced a major improvement in the construction and dissemination of time scales. It consists of using the signal broadcast by GPS satellites, which contains timing and positioning information. It is a one-way method, the signal being emitted by a satellite and received by specific equipment installed in a laboratory. For this purpose, GPS receivers have been developed and commercialized to be used specifically for time transfer. The common-view method proposed in the 1980s by Allan and Weiss [26] consists of reception of the same emitted signal. It is still in use for clock comparison because it eliminates the instability of the satellite clocks.

The Russian satellite system of global navigation GLONASS is not used for time comparison in TAI on a routine basis, since the satellite constellation is not yet complete and stable. Nevertheless, studies conducted at the BIPM and in other laboratories prove [27] that the system is potentially useful for accurate time transfer.

The Consultative Committee for Time and Frequency (CCTF; formerly CCDS) set up a working group to establish a common format, standard formulae and parameters to facilitate data exchange for time dissemination and transfer (CCTF Working Group on GNSS time transfer standards (CGGTTS)). Modern GPS and GPS/GLONASS receivers installed in national time laboratories that contribute to the calculation of TAI provide in an automated way time transfer data accordingly to the directives of CGGTTS [28]. GPS transfer data are provided in the form of the difference between a clock in a laboratory (generally the one realizing UTC(k)) and the GPS time.

Thanks to new hardware and to improvements in data treatment and modelling, the uncertainty of clock synchronization via GPS fell from a few hundreds of nanoseconds at the beginning of the 1980s to 1 ns today. Old single-channel, single-frequency C/A-code receivers are being replaced in time laboratories by multi-channel receivers, which allow simultaneous observation of all satellites over the horizon. The effects of ionospheric delay introduce one of the most significant errors in GPS time comparison, in particular in the case of clocks compared over long baselines. Dual-frequency receivers installed in some of the participating laboratories permit the removal of the delay introduced by the ionosphere, thus increasing the accuracy of time transfer. GPS observations with single-frequency receivers used in regular TAI calculations are corrected for ionospheric delays by making use of ionospheric maps produced by the International GPS Service (IGS) [29]. All GPS links are corrected for satellite positions using IGS post-processed precise satellite ephemerides.

A pilot project conducted jointly by the BIPM and the IGS between 1998 and 2002 focused on the feasibility of making accurate time and frequency comparisons using GPS phase and code measurements [30]. As a conclusion of some studies conducted during this project, precise-code data from GPS geodetic-type, multi-channel, dual-frequency receivers have been introduced since June 2004 in the calculation of TAI [31]. These links, denominated by GPS P3 links, provide ionosphere-free data and allow clock comparisons with nanosecond uncertainty or better.

5.1.2. Two-way satellite time and frequency transfer. After about 25 years of experimentation, the method of two-way satellite time and frequency transfer (TWSTFT) started to be extensively used in TAI at the beginning of the 21st century [32]. The TWSTFT technique utilizes a telecommunication geostationary satellite to compare clocks located in two receiving–emitting stations. Two-way observations are scheduled between pairs of laboratories so that their clocks are simultaneously compared at both ends of the baseline. The clocks are directly compared, using the transponder of the satellite. It has the advantage of a two-way method over the one-way method of eliminating or reducing some sources of systematic error such as ionospheric and tropospheric delays and uncertainty in the positions of the satellite and the ground stations. The differences between two clocks placed in the two stations are directly computed. The first TWSTFT link was introduced in TAI in 1999 [33]. Since then, the number of laboratories operating two-way equipment has increased, allowing links within and between North America, Europe and the Asia–Pacific region. Until mid-2004, intervals of 5 min measurements were made 3 days per week, impeding the technique from reaching its highest potential performance, which is sub-nanosecond uncertainty. With the installation of automated stations in most laboratories, some of the TWSTFT link observations in TAI are at daily or even sub-daily intervals, with the consequence of setting the uncertainty below the nanosecond.

5.1.3. Calibration of time transfer equipment and link uncertainties. Calibration of the laboratory's equipment for time transfer is fundamental to the stability of TAI and to its dissemination. Campaigns of GPS time equipment differential calibration are organized by the BIPM to compensate for internal delays in laboratories by comparing their equipment with travelling GPS equipment. Successive campaigns with BIPM travelling receivers have been conducted since 2001, with the result that more than 50% of the GPS equipment used in TAI has been calibrated [34–36]. The situation for the TWSTFT links is rather different; the laboratories organize with the support of the BIPM calibrations of the TWSTFT equipment [37–40]. While waiting to have all stations thus calibrated, two-way links in TAI are calibrated at the BIPM by using the corresponding GPS link.

The BIPM estimates Type A and Type B uncertainties of all time links in TAI [41]. Some links have been selected to show examples of their values in table 2, and they are indicated with u_A and u_B, respectively. The statistical uncertainty, u_A, is evaluated by taking into account the level of phase noise in the raw data; u_B is the uncertainty on the calibration.

For two decades, GPS C/A-code observations have provided a unique tool for clock comparison in TAI, rendering impossible any test of its performance with respect to other methods. The present situation is quite different; the introduction of the TWSTFT technique has allowed the opportunity of comparing the results of clock comparisons traditionally obtained with the GPS common-view technique with those coming from an independent technique, and made the system more reliable. For the links where the two techniques are available, both GPS and TWSTFT links are computed, the better being used in the calculation of TAI, the other kept as a backup. The GPS P3 links have further increased the reliability of the system of time links, providing a method of assessing the performance of the TWSTFT technique. Comparison of results obtained on the same baselines with the different techniques shows equivalent performances for GPS geodetic-type dual-frequency receivers and TWSTFT equipment, when the two-way sessions have a daily regularity (1 ns or less).

At the moment, 80% of the links in TAI are obtained by using GPS equipment (65% with GPS time-receivers; 15% with GPS geodetic-type receivers) and about 14% of the links are provided by TWSTFT observations. There still remain a small number of laboratories equipped with old-type receivers not adapted to provide data in the CGGTTS standard format.

5.2. The algorithm Algos

5.2.1. The general scheme. In the establishment and dissemination of time scales the quantities which intervene are only time and frequency differences at dates which can be loosely specified because these quantities vary slowly. In each participating laboratory k the approximation to UTC, denoted UTC(k), serves as the reference for local clock differences and frequencies. Comparisons between laboratories j and k have the form of [UTC(j) − UTC(k)]. The dissemination of a global time scale T takes the form of time series of [T − UTC(k)] at selected dates.

Making use of the clock and time transfer data, Algos calculates an averaged time scale called *Free Atomic Time Scale* denoted EAL. This scale has an optimized frequency stability for a selected averaging time, but its frequency is not constrained to be accurate. Then, TAI is obtained by application of frequency corrections to EAL based on the data of primary frequency standards (PFS). The next step is to produce UTC by addition to TAI an integral number of seconds (negative for the time being). The output of the process is [UTC − UTC(k)].

5.2.2. Clocks in TAI. A total of 56 time laboratories from 41 countries participate in the calculation of TAI at the BIPM as of January 2005. They contribute data each month from about 300 clocks. About 85% of the clocks are either commercial caesium clocks of the HP/Agilent 5071A type or active, auto-tuned hydrogen masers. Commercial caesium clocks with high performance tubes realize the atomic second with a relative frequency accuracy of 1×10^{-13}, almost one order of magnitude better than the standard model, and they have an excellent long term frequency stability. Active hydrogen masers also benefit from high frequency stabilities of the order of 10^{-15} over 1 day.

5.2.3. Free Atomic Time Scale (EAL), clock weighting and frequency prediction. To improve the stability of EAL, a weighting procedure is applied to the clocks. The algorithm treats data over a 30 day period, with measurements available every 5 days, the so-called standard dates (modified Julian dates ending in 4 or 9). The weight of a clock is considered as constant during the 30 day period of computation, and continuity with the previous period is assured by clock frequency prediction, a procedure that renders the scale insensitive to changes in the set of participating clocks. The algorithm is able to detect abnormal behaviour of clocks and disregard them, if necessary; this is done in an iterative process that starts with the weights obtained in the previous month and serves as an indicator of the behaviour of the clock in the month of computation. In the case of commercial caesium clocks, for averaging times around 30 days the predominant noise is random walk frequency modulation. All clocks in TAI are treated with this same frequency prediction model, but a revision appears to be necessary to take into account the increasing number of participating hydrogen masers, for which the predominant frequency noise is a linear drift (18% of the total number).

To avoid the possibility that very stable clocks indefinitely increase their weights and come to dominate the scale, a maximum relative weight is fixed for every period of calculation. Since January 2001, the maximum relative weight is fixed as a function of the number of participating clocks (N) as $\omega_{\max} = A/N$ (A is a constant equal to 2.5 at present), allowing a clock to reach the maximum weight when its variance computed from 12 consecutive 30 day samples is, at most, 5.8×10^{-15} [42].

The medium-term stability of EAL, expressed in terms of an Allan deviation, is estimated to be 0.6×10^{-15} for averaging times of 20 to 40 days. The frequency fluctuations of clocks that serve to characterize their weights are evaluated with respect to EAL.

5.2.4. Primary frequency standards. The accuracy of TAI is assured by the primary frequency standards developed in some laboratories reporting their frequency measurements to the BIPM. According to the directives of the CCTF, a report of a PFS should include the measurement of the frequency of the standard relative to that of a clock participating in TAI and a complete characterization of its uncertainty as published in a peer-reviewed journal. Five caesium fountains and two optically pumped caesium beam standards have contributed, more or less regularly, in the last 2 years to TAI with measurements over 10–30 day intervals. Two magnetically deflected caesium beam standards of the PTB (CS1 and CS2) are operated in a continuous manner and contribute permanently to both the accuracy of TAI and the stability of EAL as a clock. Table 3 gives the main characteristics of these primary frequency standards. In 2005, the definition of the second of the SI is realized, at best, by the primary frequency standards with an accuracy of the order of 10^{-15}.

Table 3. Primary frequency standards having contributed to TAI since January 2002. u_B is the Type B uncertainty as stated in the last report to the BIPM used for *Circular T*, expressed in 10^{-15}.

PFS	Type	u_B
BNM-SYRTE-FO2	Cs/Rb double fountain	0.7
BNM-SYRTE-FOM	Cs fountain	1.1
BNM-SYRTE-JPO	Optically pumped Cs beam	6.5
CRL-O1	Optically pumped Cs beam	5.5
IEN-CSF1	Cs fountain	1.0
NIST-F1	Cs fountain	0.3
PTB-CS1	Magnetically defl. Cs beam	8
PTB-CS2	Magnetically defl. Cs beam	12
PTB-CSF1	Cs fountain	0.9

Based on the frequency measurements of the PFS reported to the BIPM during a 12-month period, the fractional deviation, d, of the unitary scale interval of TAI from its theoretical value (the unitary scale interval of TT) is evaluated, together with its uncertainty. A filter is applied to the individual measurements which takes into account the correlation terms of successive measurements reported for the same standard and a model of the frequency instability of TAI [43].

In order to keep the unitary scale interval of TAI as close as possible to its definition (see section 4), a process called *frequency steering* has been implemented. It consists of applying a correction to the frequency of EAL when d exceeds a tolerance value, generally fixed at 2.5 times its uncertainty. These frequency corrections should be smaller than the frequency fluctuations of the time scale in order to preserve its long term stability. Over the period 1998–2004, frequency steering corrections of $\pm 1 \times 10^{-15}$ have been applied, when necessary, for intervals of 2 months at least. The values of d demonstrated that the unitary scale interval of TAI had significantly deviated from its definition and that the steering procedure was in need of revision. A different strategy for the frequency steering was adopted in July 2004. A frequency correction of variable magnitude, up to 0.7×10^{-15}, is applied for intervals of 1 month at least, if the value of d reach 2.5 times its uncertainty.

6. Dissemination of the time scales

6.1. *BIPM Circular T and Annual report of the time section.*

The time scales TAI and UTC are disseminated every month by *Circular T* [44]. Access to UTC is provided in the form of differences [UTC − UTC(k)], making at the same time the local approximations UTC(k) traceable to UTC; starting in January 2005, their uncertainties are also published [45]. The use of an integral number of seconds of [TAI − UTC] leads to TAI.

The values of the frequency corrections on TAI and their intervals of validity are regularly reported. This information is needed for the laboratories to steer the frequency of their UTC(k) to UTC.

Circular T provides wide access to the best realization of the second through the estimation of the fractional deviation, d, of the scale interval of TAI with respect to its theoretical value based on the SI second, calculated as explained above. The values of d for the individual contributions of PFS are also published, giving access to the second as realized by each of the primary standards.

Access to GPS time with an uncertainty of a few nanoseconds and to GLONASS time with an uncertainty of a few tens of nanoseconds is provided via their differences with respect to TAI and UTC.

Within *Circular T*, the time links used for the calculation of 1 month, with their respective Type A and Type B uncertainties, are detailed, accompanied by information about the technique used in the calibration of the time transfer equipment or link.

The ftp server of the BIPM time section gives access to clock data and time transfer files provided by the participating laboratories, as well as the rates and weights for clocks in TAI in each month of calculation. This information is particularly useful for laboratories in the study of their clock's behaviour.

Results for a complete year are published in the *Annual Report of the BIPM Time Section* [46], together with information about the laboratories' equipment, time signals and time dissemination services, as reported by the laboratories to the BIPM.

Data used for the calculation of TAI, *Circular T*, some tables of the *Annual Report* and all relevant results and information are available on the ftp server of the BIPM time section (www.bipm.org).

6.2. GPS time

GPS satellites disseminate a common time scale designated as *GPS time*. It is the system time for GPS. The GPS time was set to UTC on 6 January 1980, and since then it has not been adjusted to UTC by leap seconds. Therefore [TAI − GPS time] = 19 s + C, where C is a small quantity which is at the most 1 µs, and in practice of the order of 10 ns. GPS time is the result of clock combination steered to the realization of UTC(USNO) (modulo 1 s), from which it cannot differ by more than 1 µs; the exact difference is contained in the GPS navigation message. UTC(USNO) represents UTC at the level of a few nanoseconds, and its dissemination via GPS gives the widest access to a real-time approximation of TAI and UTC.

7. Conclusion

> *I heard once from a learned man, that the motions of the sun, moon, and stars, constituted time, and I assented not. For why should not the motions of all bodies rather be times? Or, if the lights of heaven should cease, and a potter's wheel run round, should there be no time by which we might measure those whirlings, and say, that either it moved with equal pauses, or if it turned sometimes slower, otherwhiles quicker, that some rounds were longer, other shorter? Or, while we were saying this, should we not also be speaking in time? Or, should there in our words be some syllables short, others long, but because those sounded in a shorter time, these in a longer? God, grant to men to see in a small thing notices common to things great and small. The stars and lights of heaven, are also for signs, and for seasons, and for years, and for days; they are; yet neither should I say, that the going round of that wooden wheel was a day, nor yet he, that it was therefore no time.* (Saint-Augustine)

Since immemorial time the motion of celestial bodies measured time. But, some 16 centuries after Saint-Augustine, it is not the potter's wheel which replaced the motion of celestial bodies to measure time, it is an atomic transition. This mutation, towards 1960, raised many discussions among scientists and a large interest in the general public, with frequent articles in newspapers, sometimes provocative. However, this mutation is not yet complete. We have now a pure atomic time scale, the TAI, and a hybrid system, the Coordinated Universal Time (UTC), which is not really a time scale since it is stepped by amounts of 1 s in order to follow the irregular rotation of Earth. The UTC is a compromise which gives easy access to TAI with full accuracy and a sufficient approximation to the familiar solar time. It contributed greatly to the acceptance of atomic time by the public.

Atomic time-keeping is at the basis of a multitude of scientific and technical applications, but is now often ignored. This is the fate of metrology. However, in the case of time, the situation is aggravated by the fact that time is easily available with full accuracy, at no cost.... For this reason, it appears especially important to stress that international atomic time-keeping is an example of efficient worldwide cooperation, under the coordination of the BIH and later of the BIPM. At the basis of the enterprise are the time laboratories which develop, maintain and operate, in a continuous and permanent effort, complex instrumentation. Especially at the beginnings, the simple requirement of communicating data to the coordinating office was time-consuming and costly. The community is greatly indebted to the heads and staffs of these laboratories for their support and their expertise.

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