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Rotation of the Earth and Time scales

E.F. Arias, B. Guinot, T.J. Quinn

Bureau International des Poids et Mesures

Introduction

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. This evolution is described in section 4. In spite of its success, borne out by 32 years of existence, the present system suffers increasingly from the inconvenience of *leap seconds*.

These notes bring together some astronomical elements that should be kept in mind in any proposed revision of the UTC system: the modern definition of UT1, its long term irregularities and the possibilities of prediction of the difference *UT1 – International Atomic Time* over 2 to 3 years.

A final section gives the personal views of the authors on a new system of time dissemination.

1. Universal Time UT1 and uniform time

Definitions

Historically, Universal Time is a form of solar time at the meridian of Greenwich, corrected for periodic terms. However, since the definition of the *fictitious mean Sun* by Newcomb in1896, it is conceptually an angle which is proportional to the Earth Rotation Angle (ERA) in space. This conceptual definition has been made explicit and rigorous by Recommendation B 1.8 of the International Astronomical Union in 2000. The linear relationship between ERA and Universal Time ensures that Universal Time remains in phase with solar time at the Greenwich meridian in the very long term; however, for complex astronomical reasons this cannot be achieved rigorously. Thus, Universal Time has a very small secular departure from the solar time.

The notation UT1, introduced in 1955, means that the rotation of the Earth is referred to the axis of rotation, moving both in space and in the Earth. For simplicity, we will extend this notation before 1955, when a number of small corrections of order of 10 ms, e.g. for polar motion, where not always applied. We recall also the use of UT2, which is a form of UT1, after removal of an annual component. The duration of 24 hours of UT1 in SI seconds (in the present definition) is usually called the *length of the day* (LOD).

Uniform time references

(a) Dynamical time references

Ephemeris Time (ET) is a uniform time based on the orbital motion of the Earth around the Sun. It was formally defined by the IAU in 1952 by considering as conventional an expression of the longitude of the Sun experimentally obtained by Newcomb. Ephemeris Time can be extended backwards using observations of planets, of the Moon and occultations. Quasi continuous values of *UT1 - ET* are available since 1667. As the precision of the most ancient data is too low for our purpose, we shall use here the series of annual averages starting in 1861 obtained by Morrison (1979). The stated uncertainty of these data ranges from 0.3 s in 1861, to about 0.05 s in 1942 (subsequent values are smoothed).

In the more distant past, from about 700 BC, isolated values of *UT1 – ET* can be deduced from ancient eclipses. On the other hand, palaeontology provides estimates of the LOD as far back as $4x10^8$ years. These are based on organism growth, especially corals, and on sedimentation, which reveal the number of days in the year and in the synodic month (lunar influence).

(b) Atomic Time

From the publications of the former Bureau International de l’Heure (BIH) one can extract a continuous scale of atomic time since the beginning of operation of the caesium standard at the National Physical Laboratory, UK, in July 1955. This scale became International Atomic Time (TAI) in 1971, an appellation that we shall use since 1955. The series of *UT1 – TAI* used here consists of values at 5-day intervals. From 1955 to 1975 the data are taken in the Bulletin Horaire and in the Annual Report of the BIH. From 1975 to 2003, series eopc02 of the International Earth Rotation and Reference Systems Service (IERS), available on the Web, are used. In all these data, TAI represents uniform time with negligible errors. The uncertainties of UT1 (type A uncertainties) decreased from a few milliseconds in 1955 to a few microseconds in 2003.

(c) The problem of units and origins

The expression of the longitude of the Sun by Newcomb was based on observations made mostly during the 19th century, dated in UT1. In consequence, the unit of time implied by that expression, called the *ephemeris second*, has a duration approximating that of the average of the second of UT1 during the 19th century. The ephemeris second became the SI unit of time in 1960. Soon after this it become recognised that atomic frequency standards could provide a much better realisation of the second, and the SI definition based on the caesium hyperfine transition was adopted in 1967. The defining value of the frequency was chosen to ensure as closely as possible the coincidence with the ephemeris second (Markowitz *et al.*, 1958). Thus the SI second, has approximately the duration of the UT1 second averaged over the 19th century.

The origin of the various atomic times (including TAI), was chosen by mutual agreement between laboratories (non official) so that they coincided with UT1 on 1958 January 1. Why on a UT1 date, instead of an ET date? The reason is that ET was available only years after the observations, and with an insufficient precision. Later, the value of *TAI – ET* was estimated to be 32,184 s and this value was adopted conventionally to define the relativistic coordinate times needed in astronomy and geodesy. All efforts to align ET and TAI have failed, astronomers and physicists being reluctant to change.

2. Irregularities of UT1

The uniformity of the rotation of the Earth had been questioned by some philosophers and astronomers since Kepler. But the irregularities of UT1 were proven and measured only during the first half of the 20th century when ET became available.

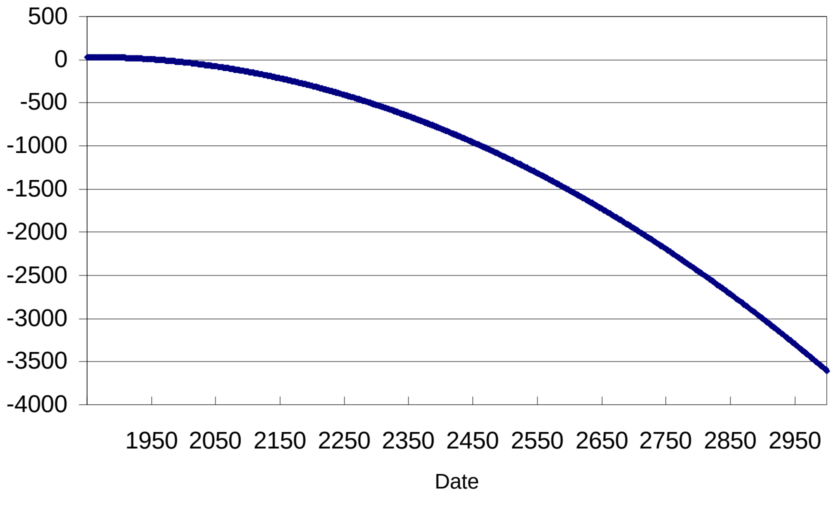
Secular deceleration of the Earth's rotation

Consideration of ancient eclipses and of palaeontology led to the conclusion that the rate of rotation of the Earth has always decreased. The rotational energy is mostly lost in oceanic tides, with a transfer to orbital energy of the Moon, the Earth-Moon distance increasing by 4 cm/year. The estimate of the deceleration is rather uncertain; the LOD increase lies between 1 and 2 milliseconds per century. A value close to 1.5 ms/century is nowadays generally accepted. The corresponding relative variation of the angular velocity is

$$\dot{w}/w = 4.0\times10^{-22}\ \mathrm{rad\ s}^{\ 2}.$$

Figure 1 shows the effect of the secular term of *UT1 – uniform time*, assuming that the rate is null in 1850. One observes that the difference would be of half an hour towards 2600 and one hour towards 3000.

Fig. 1. Secular term of *UT1-uniform time*, in seconds



Decade fluctuations

After removal of the secular term as above, figures 2 and 3 show what is left in *UTI – ET* and *UT1 –TAI*. Fluctuations in the range ± 10 s are observed. They are not periodic, they contribute noise in the domain of Fourier frequencies of 0.1 year^{-1} and less. These fluctuations are remarkably smooth, which open the possibility of a prediction of *UT1 – TAI* at the level of one second up to 2 or 3 years, as it will be seen later. A small part of these fluctuations is predictable: the effect of long term zonal tides, the only important term (here) having a period of 18.6 years and a semi-amplitude of 0.15 s. The rest of the fluctuations is attributed mostly to core/mantle coupling, although the mechanism is not entirely understood. It is not predictable for the time being. Non-predictable atmospheric and oceanographic effects also bring contributions.

FiG. 2. *UT1-TE* corrected for secular variation, in seconds

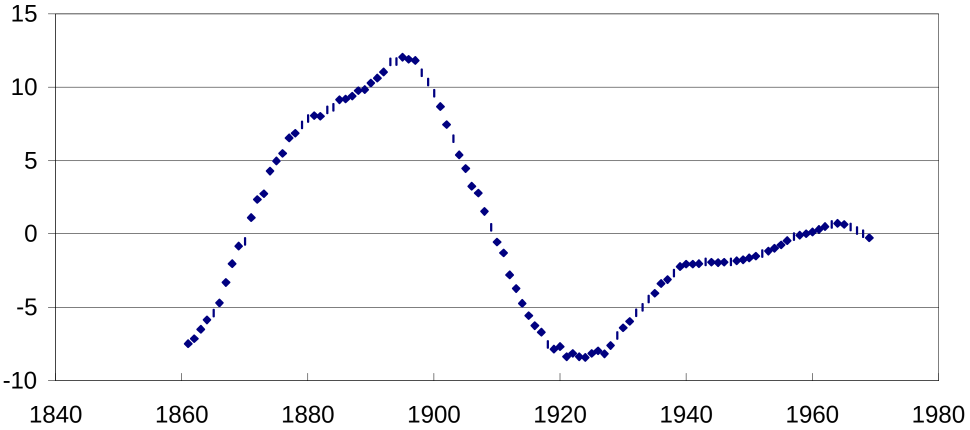
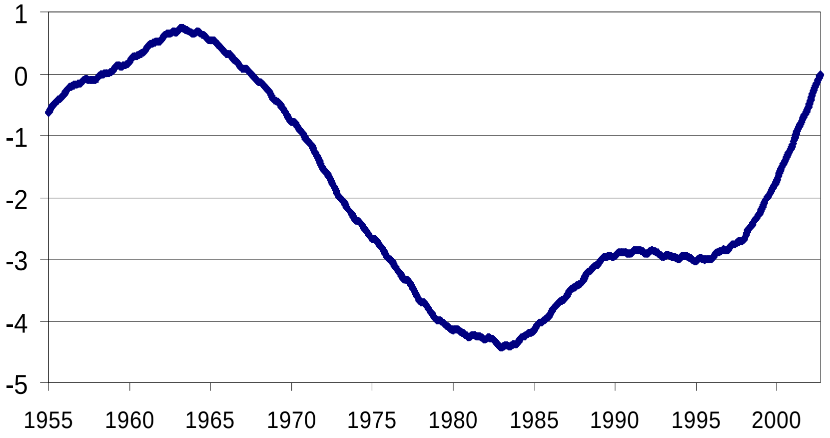


Fig. 3. *UT1-TAI* corrected for secular variation, in seconds



Short term fluctuations

An annual component is hardly visible on figure 3. It has a total amplitude of 60 ms about 90% of which can be removed by a fixed conventional formula in order to obtain UT2. Its cause lies in the atmospheric motions which also contribute noise in shorter term with amplitudes of a few milliseconds. When needed, the effect of the atmosphere on UT1 can be removed using measurements of its angular momentum and of the repartition of its mass. A known contribution of short-term zonal tides (semi amplitude of 2 ms) can be removed also. These fluctuations have little influence for the question at hand, the definition of UTC, and no corrections were applied in our work.

3. Prediction of UT1 – TAI over 2 to 3 years

We have made an empirical linear prediction of *UT1 - TAI* over 2 years for a date *d* by using the mean observed rate between dates *d* – 3 years and *d* – 2 years. The calculation is repeated every 5 days. Figure 4 shows the observed prediction error for the period 1955-2003. Its maximum and minimum are 0.6 s and – 0.5 s.

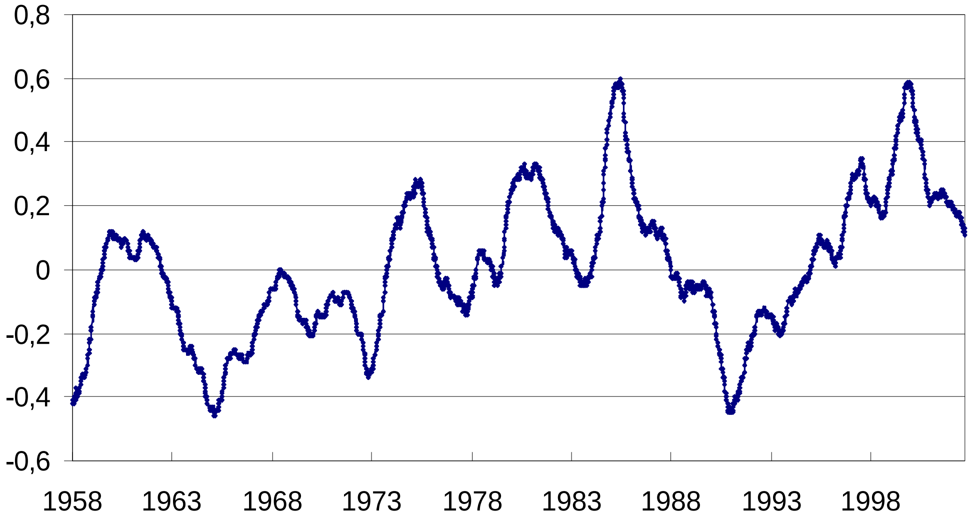


Fig. 4. Two-year prediction of *UT1-TAI* (observed - predicted) in seconds

Extending the prediction over an additional year, i.e. over 3 years, one obtains the prediction error shown by figure 5, which reaches 1 s.

The same method applied to the annual values of *UT1 – ET* suffers from the uncertainties of ET, as it can be seen on figure 6. Nevertheless, the prediction error over two years does not exceed 2.2 s.

Fig. 5. Three-year prediction of *UT1-TAI* (observed - predicted) in seconds

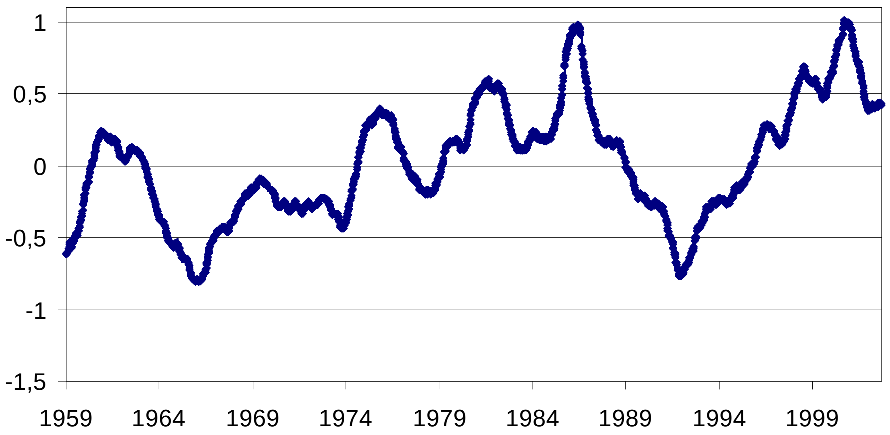
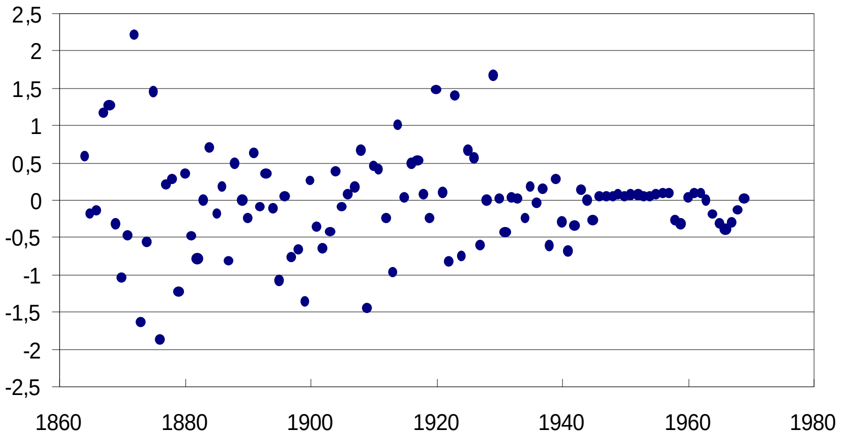


Fig. 6. Two-year prediction of *UT1-TE* (observed - predicted) in seconds



4. Time signal emissions. The history of UTC

The pre-UTC era

When the first international radio time signals were transmitted, in about 1910, the intent was to disseminate Greenwich mean time or Greenwich mean sidereal time for the needs of navigation and geodesy. However, large discrepancies, exceeding one second, were observed and many new problems appeared: incoherent star positions, instrumental errors, longitude errors, poor knowledge on the propagation, etc. This led to the creation of a coordinating agency, the BIH, which began to operate unofficially in 1911 at the Paris Observatory and got its official statutes, as a service of the International Astronomical Union, in 1919.

We shall only recall here how the time centres and the BIH operated just before the existence of caesium clocks, say in 1954.

A fully equipped time service had astronomical instrument(s), clocks (pendulum clocks, diapasons, and the first quartz clocks), time signal receivers and a system to monitor time signals emissions. The aim was to extrapolate the values of *UT1- master clock* on the basis of astronomical observations made by the service (subject to meteorology). This required smoothing, usually visual, and a good sense of prediction. Each time service operated almost independently.

At that time the BIH received from all the participating time services a huge amount of time signal reception times and astronomical determinations of UT1, referred to local master clocks. The processing of these data was leading to a "definitive time", i.e. *UT1 – emission time*, of the various time signals. A *Bulletin Horaire*, published every two months, provided *UT1 –emission time* of about 250 emissions for each day. These results were available about one year after the tabulated dates. They showed departures of time signals with respect to UT1 usually in the range ± 50 ms, sometimes reaching ± 0.1 s.

Birth of UTC

The principle of UTC was born from a decision of the National Bureau of Standards (NBS) in 1956. The NBS began to base the time signal emissions WWV on a master clock maintained at a constant frequency with the help of atomic frequency standards. The frequency was adjusted to the rate of UT1 by the use of a frequency offset but, this being done, the frequency offset was not changed. When UT1 departed from the readings of the master clock, an adjustment in time was made in time steps of 20 ms. We emphasize the radical change from a conceptual point of view, since a time offset with respect to UT1 was deliberately accepted. For this reason this system did not at first receive unanimous approval, to say the least!

In 1958, the frequency offset for WWV was referred to the value of the frequency of the caesium transition now in use. The adopted offset of 100×10^{-10} was kept until the end of 1959. Numerous time steps of 20 ms had to be made.

During the year 1960, the advantages of the new system began to be recognised and the US Naval Observatory, the Royal Greenwich Observatory, the Naval Research Laboratory (USA), the National Physical Laboratory (UK) all began to use it. An international frequency offset of 150×10^{-10} was adopted by mutual agreement, which cancelled provisionally the need for time steps. The time signal emissions were also synchronized, as far as possible. In September 1960, the International Union of Radio Science (URSI) issued a recommendation that the BIH be in charge of choosing the frequency offset to be adopted internationally after consulting the time laboratories; the offset should be modified only at the end of a year. Later the BIH also coordinated the time steps.

From 1961 until the end of 1970, the system of UTC was operated with frequency offsets and time steps. At the beginning, small frequency changes were applied, in order to avoid frequent time steps. However, many time signals had second pulses obtained by dividing the carrier frequency by a fixed number so that the carrier frequency was also offset. This frequency was used by important systems, especially in radio communications. To avoid difficulties, the tendency was to maintain an unchanged frequency offset at the cost of more frequent and/or larger time steps.

In 1963, the International Radio Consultative Committee (CCIR, a committee of the International Telecommunication Union) recommended that the time signals be maintained within ± 100 ms from UT2 by steps of multiples of 50 ms. Only one 50 ms step occurred, the following ones being of 100 ms, their date of occurrence being chosen by the BIH. The UTC system, thus established, operated until the end of 1970.

Figure 7 summarizes the UTC frequency offsets; figure 8 shows the evolution of UTC time steps.

In parallel to the UTC system, the CCIR admitted the possibility of time signal emissions without frequency offset, with steps of 200 ms: the Stepped Atomic Time, SAT. Only two emissions adopted the SAT, in Germany and in USA, from 1967 to 1972.

Precise definition of UTC

In 1964, the BIH began to publish two series of results at five-day intervals:

(a) *UT2 – A3*, A3 being its own atomic time scale, which became TAI, for the studies of the Earth's rotation,

(b) *UT2 – UTC*, with monthly values of the departure *E = UTC –Signal emitted*, the values of *E* being slowly variable.

However, until the end of 1964, there was no formal definition of UTC. The BIH considered UTC as an average of the emission time of coordinated signals. The new mode of dissemination of results was mainly a way to reduce the volume of data and also a way to favour a better coordination by encouraging a reduction of the values of *E*.

In 1965, the BIH took the decision to define UTC by a mathematical relation with A3 based on the agreed frequency offsets, without a time step in UTC at the changeover. Most of the users did not notice this change. It was nevertheless the origin of the firm link between UTC and TAI.

The present definition of UTC

With the development of time/frequency systems, the inconvenience of the frequency offset of UTC was growing. The idea of abandoning the offset, which led to the experimental SAT, was in many people's minds. But the time steps of SAT were too frequent and steps of one second appeared as a reasonable solution.

However, it was strongly opposed by some parties who felt that the departure of the disseminated time from UT1 should not exceed 0.1 s. One of the arguments was that 0.1 s is the threshold of human discrimination in time. But why to refer to UT1? At the epoch of these discussions, at the end of the 1960's, astronomical navigation was the rule. For that purpose, UT1 must be available in real time. But an error of 0.1 s on UT1 results in a maximum error (at the equator, in longitude) of 0,025 nautical mile (46 metres). The observation with the sextant at sea and the evaluation of the refraction lead to errors of 1 to 2 miles. Other uses of

UT1 in real time either require a low precision of a few seconds (visibility of celestial bodies, sunrise, etc.), or require the best possible precision and rely on short term predicted values (for example, space navigation).

The definition of the form of UTC that is in use at present was given by the CCIR in 1970. The new UTC was introduced on 1972 January 1, after a time step of -0.107 7580 s so that the difference *UTC – TAI* be an integer. Recommendation 460-1 (1974) of the CCIR, raised the maximum departure of UTC from UT1 from 0.7 s to 0.9 s and opened the way to introducing a leap second at the end of any month instead of at the end of June or December only. An audible code was defined, which gave *DUT1 = UT1 – UTC* to the nearest 0.1 s. In 1975, the Conférence Générale des Poids et Mesures, considered that the use of UTC was “parfaitement recommendable”.

The UTC system functioned with no particular difficulties. Only once had leap seconds to be introduced at a 6-month interval (July 1972, January 1973). From 1973 to 1980, a leap second appeared at the beginning of each year, then their frequency decreased. The audible code for *DUT1* was abandoned by a few time signal emissions.

5. A suggestion for a new dissemination of time

We come now to a section of this report where the authors express their own personal views on the future of timing. It must be quite clear, that these are not the “official” opinion of the BIPM, the organisation to which they belong or are affiliated.

The UTC system is, at present, a good compromise.

However, we observe that the leap seconds are becoming increasingly inconvenient:

- there is a growing need for a continuous dating system, e.g. in telecommunications, banking, positioning systems;
- the file giving the information on *UTC – TAI* increases indefinitely, and has to be updated at irregular intervals, with the risk of omissions and errors;
- 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" may be a cause of difficulty;
- the frequency of occurrence of positive leap seconds will increase, although slowly, in the long term (figure 9); but decade fluctuations of the Earth rotation may well lead in the near future to two leap seconds per year;
- the existence of both UTC and TAI favours the proliferation of time scales, something we wish to avoid; for example the system time of satellite positioning systems is TAI - 19 s for GPS, UTC for GLONASS, and TAI for Galileo.

These remarks lead us to formulate the following suggestions:

(a) we should move towards the adoption of a world-wide, continuous time scale, or at least a continuous one during several centuries;
(b) this should be made in a single change, not by successive improvements;
(c) the delay between the decision of adopting a new time scale and the date of its application should be long enough to allow all users to be prepared for the change;
(d) in the meantime, the existing UTC definition should be kept as it is (by adding a leap second when necessary).

We propose two possible ways for the implementation of these suggestions:

Proposal I:

(a) the worldwide time scale should be TAI (it could be renamed International Time (TI), since we should not refer to a particular technique);
(b) this would require a step of an integer number of seconds at the changeover from UTC to TAI (at the moment it would be 32 s);
(c) legal times would be based on TAI by correction of an integer number of hours left at the discretion of the various States (at present the Time zones system is not followed in many countries).

Proposal II

(a) TAI should be preserved as it is;
(b) no more leap seconds would be added to UTC thus its difference from TAI would be frozen at its value at the moment of application; instead, a leap hour will be added when necessary sometime in the far distant future;
(c) legal times would continue to be based on the newly defined UTC.

Note: While proposal I fully satisfies the condition of continuity, proposal II does not, but the first leap hour should not occur before about the year 2600.

Access to UT1

The dissemination of data depending on UT1 is and will remain essential. The critical case is that of annual ephemerides for astronomical navigation (sea, air), for public use (sunrise, sunset, visibility of stars, planets, etc.) which require a precision of order of 1 second. Note that this is hardly different from that which was required of Harrison to gain the longitude prize. These ephemerides should be based on a prediction of *UT1 – TAI* and expressed directly with TAI (proposal I) or UTC (proposal II) as time argument. Using the two-year prediction as discussed in section 3, this leaves one full year for the preparation and distribution of the ephemerides. Such a modification is totally transparent for the user. 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 ephemerides.

The other needs of UT1 would be satisfied as they are presently, by dissemination of *UT1 – TAI* (proposal I) or *UT1 – UTC* (proposal II), 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.

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Figure 7. UTC frequency offsets

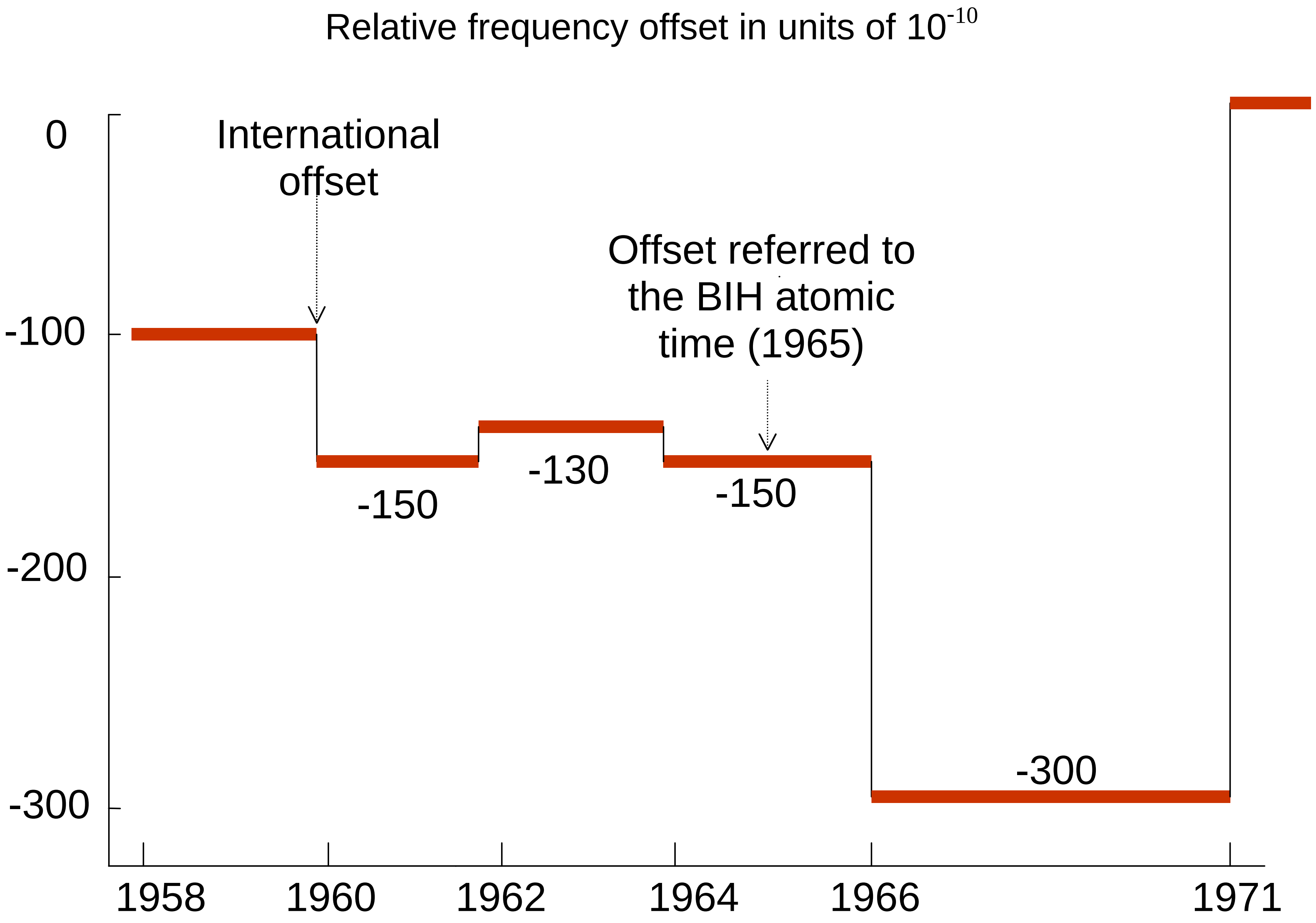

Figure 8. Evolution of UTC time steps