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The Stability of Atomic Time Scales versus Millisecond Pulsars

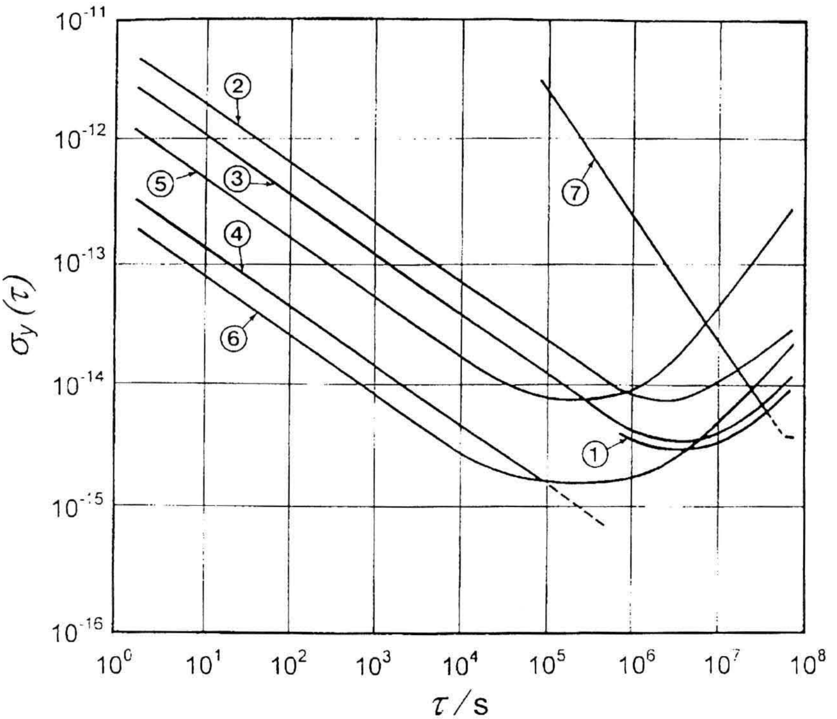
Abstract

Time scales based on an ensemble of atomic clocks realize the Earth's reference to date events. In recent years a number of technological advances have significantly improved the stability and accuracy of atomic time scales. These improvements are described and their impact on pulsar timing is analyzed. Reciprocally, the regularity of the period of rotation of millisecond pulsars can provide some information on the long-term stability of atomic time scales.

I Introduction

The frequency stability of a periodic phenomenon may be quantified by evaluating the relative changes in frequency within a given time interval. For this, a useful quantity is the Allan deviation (Allan 1987) which is denoted $\sigma_y(t)$ for an averaging time t. As an example, the fractional frequency stability of some of the clocks and time scales discussed in this paper is presented in Figure 1. Stability should be distinguished from accuracy, which is defined as the conformity of a value to its definition. Frequency accuracy is therefore only meaningful for a clock or a time scale when it explicitly aims at complying with a frequency implied by a conventional definition.

Soon after the discovery of the first millisecond pulsar in 1982, it was recognized that the periodicity of its pulses is extremely stable. As the pulses are sharp, their arrival could be timed to about one microsecond so it was possible, within a few years, to demonstrate that the stability of rotation of this millisecond pulsar rivals that of atomic clocks (Rawley et al. 1987): The relative frequency instability for averaging durations above one year is of order 10^{-14}. It is difficult, however, to interpret the instability of the timing data in terms of instability of the pulsar rotation itself because many other phenomena could contribute. Moreover, because many parameters of the pulsar systems are not known *a priori*, but have to be determined by measurement, pulsars cannot intrinsically define a time scale. These ideas have been developed by many authors (Blandford et al. 1984; Guinot & Petit 1991), but have sometimes been overlooked.



Allan standard deviation (estimate of relative stability)
for TAI and various clocks

① TAI
② Commercial caesium clock
③ PTB CS2 primary caesium clock
④ BNM-LPTF caesium fountain
⑤ Passive hydrogen maser
⑥ Active hydrogen maser
⑦ Pulsar

Figure 1. Estimate of the relative stability, in terms of Allan standard deviation, $\sigma_y(t)$, for various clocks and time scales: 1=TAI, 2=commercial caesium clock, 3=PTB-CS2 primary standard, 4=LPTF-FO1 caesium fountain, 5=passive hydrogen maser, 6=active hydrogen maser, 7=pulsar (from Thomas 1996).

Since 1982 more than seventy millisecond pulsars have been discovered, thanks to a number of systematic radio surveys and this effort continues, as only a fraction of the sky and of the possible space of the defining parameters has been searched. Many of the pulsars discovered are candidates for precise timing and a number of them are regularly observed by many research groups. It is known that several phenomena may corrupt the timing data, among them errors in the atomic time scale used as reference, in the solar system ephemeris and in the model of interstellar propagation. It is interesting to note that errors in atomic time would produce similar effects for all pulsars and so correlation studies should reveal them. It has been proposed (Petit & Tavella 1996) to take advantage of the independence of the noise sources (other than atomic time) among pulsars to average them out in forming an ensemble pulsar time scale.

Clocks and time scales based on atomic transitions have been the basis of time keeping since 1955, and of the official definition of the second since 1967. Until very recently, their long term stability and accuracy was estimated to be about 2×10^{-14} and was challenged by the expected long term stability of the rotation of millisecond pulsars. In consequence it has sometimes been predicted that astronomy will once again take some part of the definition of time references. Recent achievements and expected improvements in clock technology and in the generation of atomic time scales now suggest that, in addition to providing the practical realization of time, atomic devices will remain the fundamental time reference in the foreseeable future. Millisecond pulsars could however provide some information on the long term instabilities in atomic time scales. They could also be used as a flywheel to transfer the accuracy of future atomic clocks back to present and past atomic time.

II Clocks and time scales

A clock is a physical device which realizes its proper time, while a time scale is a reference against which events may be dated. Nowadays, clocks based on atomic transitions are considered to be the most stable devices available and they form the basis of the atomic time scales to which time on Earth is referenced. Although a time scale can be realized by the output of a single clock, the best time scales are based on data from many atomic clocks linked as an ensemble. A time scale can be judged in terms of several properties, accuracy, stability, reliability, availability, all of which are of importance when choosing a reference time scale for the analysis of pulsar timing data.

In its Resolution A4 (IAU 1991) the International Astronomical Union defined relativistic systems of space-time coordinates. The time coordinate of the barycentric (solar system) and geocentric systems are denominated TCB (Barycentric Coordinate Time) and TCG (Geocentric Coordinate Time), respectively. Recommendation IV of Resolution A4 then defines Terrestrial Time TT as a geocentric coordinate time scale whose rate differs from that of TCG by a constant amount (difference of order

7×10^{-10}), so that the scale unit of TT agrees with the SI second on the geoid. Apart from a constant offset of 32.184 s introduced for historical reasons (Guinot 1995), International Atomic Time TAI is a realization of TT. Finally, the basis for all legal time references is provided by the Universal Time Coordinated, UTC, which differs from TAI by an exact number of seconds. The introduction of leap seconds is decided by the International Earth Rotation Service so as to keep UTC within 0.9 s of the scale UT1 which represents the rotation of the Earth.

The Time section of the Bureau International des Poids et Mesures is in charge of establishing and distributing International Atomic Time. The calculation of TAI (Thomas & Azoubib 1996) makes use of an intermediate free-running time scale, EAL, computed from the data of more than two hundred atomic clocks spread world-wide. EAL is then steered in frequency to produce TAI, so that its scale unit is in agreement with the SI second on the geoid as realized by several primary frequency standards. The properties of these two time scales are similar. Their stabilities are comparable (see estimates in the next section), although the steering process slightly degrades that of TAI. By definition, however, TAI is accurate while EAL is not. Finally they are very reliable, being based on more than 200 different clocks, and available with a delay of one month.

The time scales TAI and UTC are made available by providing, with a 5-day interval (10-day until December 1995), the difference between TAI and TA(k) and between UTC and UTC(k), where TA(k) and UTC(k) represent time scales maintained by laboratory k. At present there are 17 laboratories keeping a TA(k) and more than 45 keeping a UTC(k). These data are published in the monthly BIPM circular T and in the annual report of the BIPM time section. They are also available electronically (anonymous `ftp` on `145.238.2.2`, subdirectory TAI).

Because it is computed in near real time, TAI is subject to certain stability limitations. Each year, therefore, the BIPM Time section establishes another realization of TT, denoted TT(BIPMxx), which covers the period 1975.5 to 19xx.0 where xx are the last two digits of the year of computation. The computation of TT(BIPMxx) is based on a different algorithm (Guinot 1988), and makes use of all available data from all primary frequency standards. Each new realization is a complete recalculation differing from, and taking precedence over, the previous one for the common dates. It is provided in the form TT(BIPMxx)−TAI for the dates of publication of TAI.

The time scales to be used as a reference for the analysis of pulsar timing have already been reviewed by Guinot & Petit (1991). Their conclusions remain valid and suggest that the best choice is a deferred-time realization of TT such as TT(BIPMxx). It is also advisable to use the most recent version of TT(BIPM) as new data and upgrades of the algorithms are expected to improve the whole time scale. Alternately, a free-running atomic time scale, for example TA(PTB), may be used. Estimates of the stability of most TA(k) relative to TAI may be found in the annual report of the BIPM Time section. When using a TA(k), it is advisable to check with the organization

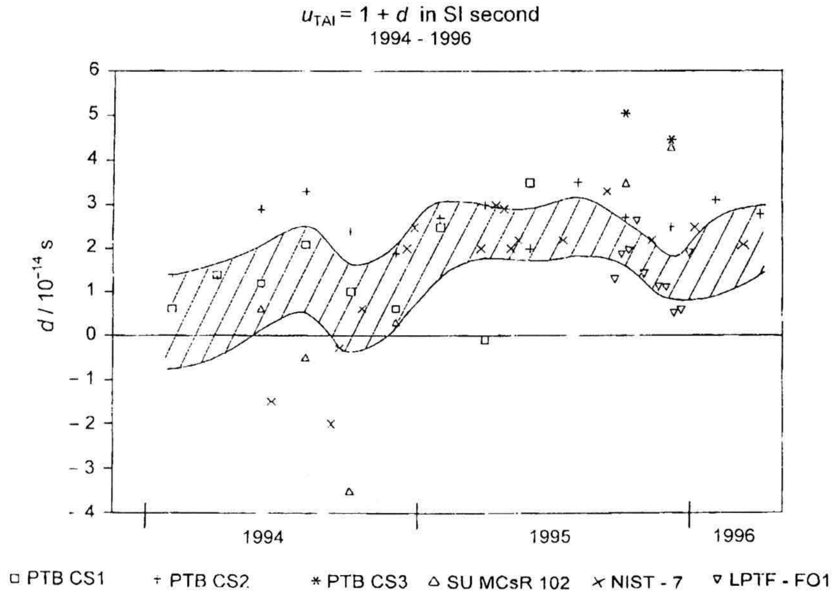


Figure 2. Departure d of the TAI scale unit from the SI second as produced by six primary frequency standards, and as computed by the BIPM (shaded area represents the one sigma confidence interval), over the period January 1994 to April 1996 (from Thomas 1996).

providing the time scale as changes may occur in the realization over the period considered. Steered time scales, and those available in real time, are less likely to match the stability requirements for the analysis of pulsar timing measurements.

III Recent and future progress in atomic time scales

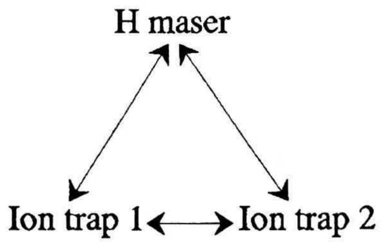
In the period 1993–1995 great progress has been made. As a result atomic time scales show improved stability for all averaging durations.

First, the general use of GPS time transfer has decreased the measurement noise of clock comparisons, so that the instabilities it introduces do not exceed 1–2 $\times 10^{-15}$ for an averaging duration of 10 days. The short and medium term stability (for an averaging duration ranging from 10 days to 160 days) has also improved due to a combination of factors: the introduction of many new commercial caesium clocks with improved stability; the development of cavity auto-tuned H-masers which are not subject to frequency drift; the use of better algorithms. As a result, it is estimated that the stability of EAL is about 2–3 $\times 10^{-15}$ for an averaging duration of 20 days to 80 days (Thomas 1996).

For long averaging durations (one year and over), the concepts of stability and accuracy are intricately linked. Progress arises from the operation of new primary frequency standards of unprecedented accuracy. At the LPTF in Paris (France) a caesium fountain, LPTF-FO1, has been under evaluation since the fall of 1995. Its stability is $\sigma_y(t) = 2 \times 10^{-13} t^{-1/2}$ for t up to 10000 s and its accuracy is estimated to be 3×10^{-15} (Clairon et al. 1995). The NIST-7, an optically pumped caesium beam standard developed at the NIST in Boulder (Colorado, USA), has been in regular operation since 1994. Its accuracy is estimated to be 1×10^{-14}, with improvements expected (Shirley et al. 1995). The PTB-CS3, a caesium beam standard developed at the PTB in Braunschweig (Germany), has an accuracy of 1.4×10^{-14} (Bauch et al. 1996) and began operation in 1996. In addition PTB- CS2, which has an accuracy of 1.5×10^{-14}, has been in regular operation since 1986. As a result, the uncertainty in the determination of the scale unit of TAI is below 1×10^{-14} for recent years (BIPM 1996). Figure 2 shows the departure of the scale unit of TAI from the SI second on the geoid over recent years, which presents a global shift of about 2×10^{-14}. This discrepancy results from the recent decision by the Consultative Committee for the Definition of the Second (CCDS 1996) to apply a correction for the black-body radiation frequency shift to the data of all primary frequency standards, and it will be progressively reduced. Similarly it is estimated that the long term stability and accuracy of the realization of TT computed by the BIPM since 1996 (TT(BIPMxx) with xx < 96) is also below 1×10^{-14} for recent years (1994 and later). In addition TT(BIPM96) incorporates the black-body correction so this realization of TT is consistent with the new decision of the CCDS.

The limitations of conventional caesium beam standards originate mainly from phase shifts in the Ramsey cavity where the atoms interact, from side effects of the magnetic fields used for state selection and detection of the atoms, and from the uncertainty in the velocity of the atoms in the beam. In addition, the high velocity of the atoms limits the intrinsic width of the Ramsey fringes. These difficulties are all overcome when low velocity atoms interact at the same place in a small cavity, and optical pumping is used for state selection and detection. For neutral caesium atoms, such conditions can be realized in a fountain or in zero gravity. They can also be realized for ions by confining them in an electromagnetic trap. Based on these techniques, a great number of frequency standards are being developed throughout the world.

Further improvements in the LPTF's fountain and the development of a second device capable of operating either as a fountain on Earth or as a low velocity beam in zero gravity should make attainable an accuracy of 1×10^{-16} (Clairon et al. 1995). Linear Hg+ ion traps are being developed at the JPL in Pasadena (California, USA). Measurements of their stability give $\sigma_y(t) = 7 \times 10^{-14} t^{-1/2}$ for t up to 10000 s and $\sigma_y(t)$ remains below 10^{-15} for t up to 10 days (Tjoelker et al. 1995). Linear Yb+ ion traps are being developed at the CSIRO in Sydney (Australia) (Fisk et al. 1996). Recent measurements give $\sigma_y(t) = 5 \times 10^{-14} t^{-1/2}$ for t up to 20000 s (Figure 3). Such developments promise that the medium term stability of atomic time scales will



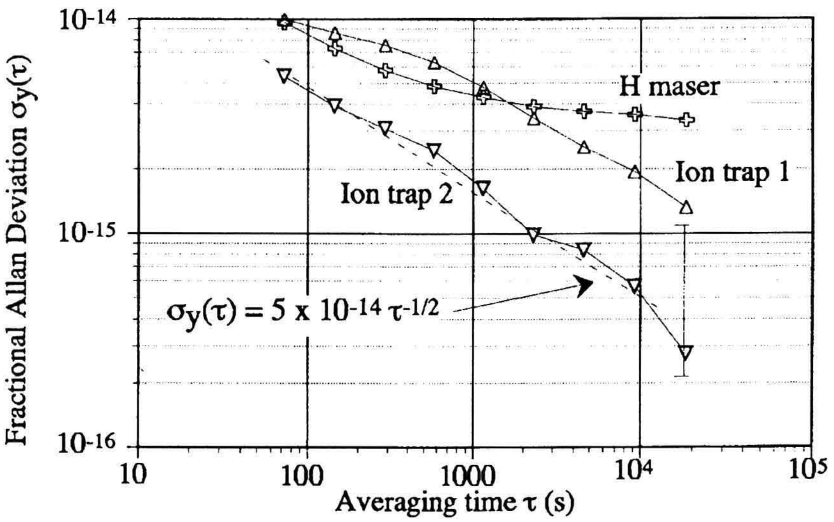


Figure 3. Estimate of the relative stability, in terms of Allan standard deviation $\sigma_y(t)$ determined by a "three- cornered hat" analysis, for two Yb+ ion traps and a hydrogen maser used to compare them (courtesy of P. Fisk and M. Lawn, CSIRO).

approach 10^{-16} in coming years. Similar long term stability is expected from the new frequency standards, but it will take some time for this to be acknowledged.

IV Pulsars and time scales

The application of pulsar measurements to time scales can be viewed from three different perspectives (Petit & Tavella 1996). In the first, the rotation of the pulsar itself is the source of a dynamical time scale PT (Pulsar Time) which can be read by counting the pulses received by a radio telescope. In the second, pulsar timing is an access to Ephemeris Time, the dynamical time resulting from the orbital motion of the Earth,

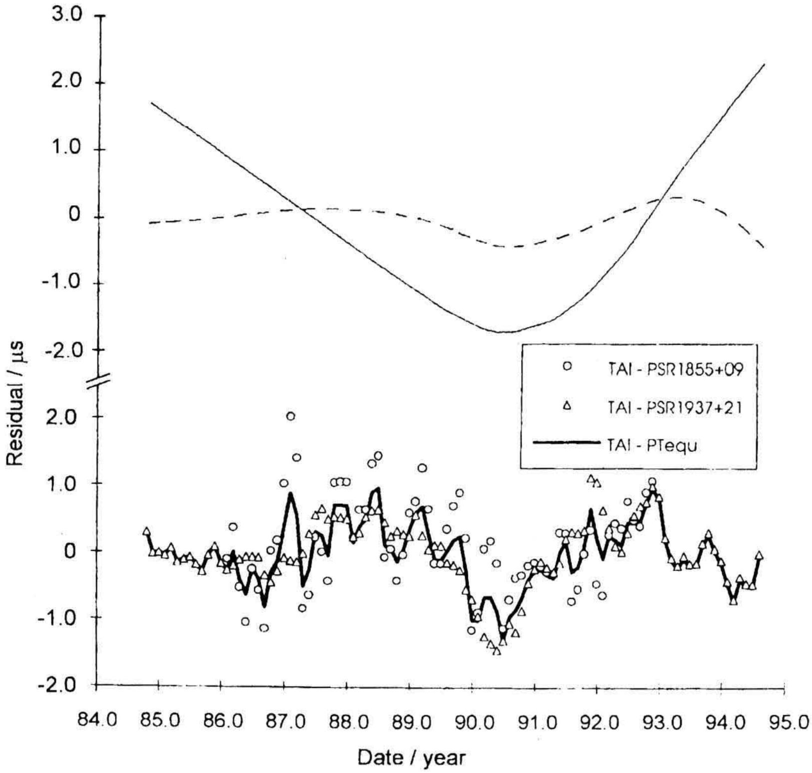


Figure 4. TAI-PT$_i$ for pulsars B1937+21, after removal of a cubic term (triangles), and B1855+09 (circles), and for an equal weight average PT$_{equ}$ (solid line). The effect that the frequency steering corrections applied to TAI would have on an ideal time scale is also shown on the same scale before (soild light curve) and after (dashed curve) the adjustment of a cubic term (Petit & Tavella 1996).

with a reading uncertainty of a few milliseconds. This is a considerable improvement over classical measurements of Ephemeris Time. In the third, pulsar timing provides access to the orbital motion of a pulsar in a binary system, which is described by a dynamical time parameter BPT (Binary Pulsar Time). For no averaging duration are the time scales generated in the last two applications expected to be as stable as atomic time, but the comparison of BPT with atomic time provides exciting perspectives for cosmology, gravitation and the dynamics of our galaxy (Taylor 1992).

A millisecond pulsar has the potential to provide a time scale whose long-term stability compares favorably with current atomic time. Using data from many pulsars, it is possible to derive an average pulsar time scale which is better than a scale derived from individual pulsar data and may have a stability better than atomic time. This improvement holds for averaging times well above one year but still much smaller than the total period of observation. A simple algorithm which realizes such a scale is described by Petit & Tavella (1996), along with a tentative application to real data. This paper shows that data from pulsars B1937+21 and B1855+09 seem to indicate some instability in TAI for the period 1989–1992 when repeated frequency steerings were applied (Figure 4).

Further studies can produce only limited improvements because very few pulsars with low timing noise have been observed regularly, and because the time span of the observations never exceeds ten years. Among the presently known pulsars, B1937+21 has low timing noise, but demonstrates long-term instability of unknown origin. For B1855+09, no low frequency noise can clearly be identified on the available 8-year data span (Kaspi et al. 1994). Of the more recently discovered pulsars, J1713+0747 seems very promising because the timing noise is low (Camilo et al. 1994). Other candidates include B1257+12 (Wolszczan 1994), although the presence of companions of planetary mass implies multi-parameter adjustment, B1534+12 (Wolszczan 1991), J2019+2425 and J2322+2057 (Nice & Taylor 1995), and J2317+1439 (Camilo et al. 1993). Observations of these pulsars began in the period 1990 to 1992, so observations covering 10 years will be completed at the beginning of the coming century, at which point the computation of an ensemble pulsar time should be reconsidered.

V Conclusions

Atomic time scales have provided the best time reference with which to date events since their introduction in the late 1950s. Since 1980, their long term stability and accuracy have been 2–3 $\times 10^{-14}$, but since 1994–1995 progress has pushed these values to below 1×10^{-14}. Ongoing technical developments suggest that future atomic clocks may achieve stability and accuracy of about 10^{-16} in the near future.

The rotation rate of millisecond pulsars is the most regular astronomical phenomenon known and can provide a time scale that rivals current atomic time in stability. Presently, few pulsars with suitable properties have been observed for long enough to provide a scale that outperforms atomic time. Current programmes of observation should provide enough data in the early 2000s to establish an ensemble pulsar time scale from five to eight individual series. This would be helpful in assessing whether the long term stability of atomic time scales has indeed been a few parts in 10^{15} since 1994–1995, as appears to be the case from present analyses.

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