# ATOMIC TIMESCALES AND PULSARS

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ABSTRACT. I review the atomic time scales generated by the BIPM, International Atomic Time TAI and the realization of Terrestrial Time TT(BIPM). TT(BIPM) is shown to be now accurate to within a few $10^{-16}$ in relative frequency and the performances of TAI and TT(BIPM) are compared. Millisecond pulsars have a very regular period of rotation and data from several pulsars may be used to realize an ensemble pulsar timescale. It is shown that a pulsar timescale may detect past instabilities in TAI. However TT(BIPM) is much more stable than TAI and should be used as a reference in pulsar analysis. Since the beginning of regular millisecond pulsar observations in the 1980s, primary standards and atomic time have gained one order of magnitude in accuracy every $\sim$ 12 years, and this trend should continue for some time.

## 1. BIPM ATOMIC TIMESCALES

Since decades, International Atomic Time TAI gets its stability from a large number of atomic clocks spread worldwide that generate the free atomic scale EAL and its accuracy from a small number of primary frequency standards (PFS) which frequency measurements are used to steer the EAL frequency: f(TAI) = f(EAL) + frequency steering, where the steering frequency is chosen so that the TAI scale unit is close to the SI second. Evolutions in the number and the type of clocks and primary standards and in the algorithms have progressively brought the 1-month stability of TAI in the low $10^{-16}$ and its frequency is known to the same level of accuracy.

The 1-month instability of EAL is estimated to be $3 \times 10^{-16}$ in 2012-2013 following the estimation technique presented in [1]. It had been noticed for many years that EAL had a systematic drift with respect to the primary standards, a situation which prompted to a change in the prediction algorithm: Since August 2011 a quadratic model is used for frequency prediction [2] and the secular drift has disappeared. A consequence is that, since end September 2012, no new steering is needed and TAI differs from EAL by a constant rate.

Complementary to the TAI computation which is performed "in real-time" every month, the BIPM also computes every year (or whenever needed) another 'post-processed' timescale, TT(BIPM) [3], which is based on all available PFS data. Each new version TT(BIPMxx) updates and replaces the previous one, the latest official realization being TT(BIPM13), released in January 2014.

## 2. PERFORMANCE OF ATOMIC TIME AND PRIMARY STANDARDS BETWEEN THE 1980S AND NOW

We cover the progress of atomic clocks and time scales since the beginning of regular observations of millisecond pulsars. We distinguish two main periods which are delimited by the arrival of Cs fountains in the end of the 1990s.

In the first part, from the 1980s to end 1990s, the stability of TAI has notably improved.

- End 1980s - early 1990s: TAI is obtained from 150-170 clocks, and instability at a level above $1 \times 10^{-14}$ is possible over several months to years; A major feature was then the introduction of a new type of commercial Cs clocks in 1993, providing a factor of 2-3 improvement in stability over previous clocks;
- At the end 1990s, TAI is obtained from more than 200 clocks, most of them of the new type, and its stability has improved to the level of a few parts in $10^{15}$ up to an averaging time of 1-2 years.

Concurrently, laboratory Cs standards (PFS) attain $1 \times 10^{-14}$ accuracy at the end of the 1980s / early 1990s: PTB Cs1 (accuracy $\sim 3 \times 10^{-14}$) was operated continuously over 1978-1995; PTB Cs2 (accuracy

$\sim 1.5\times10^{-14}$) started continuous operation in 1986; NIST7 (accuracy $\sim 1\times10^{-14}$) started (discontinuous operation) in 1995. Moreover, a few other standards are also available from other time laboratories (CRL, NRC, SU). This drove the development of the post-processed time scale TT(BIPM), first computed in 1988 as TT(BIPM87) and yearly after 1992. Its accuracy (or instability over a few years) is estimated at $\sim 1\times10^{-14}$ in the end 1980s-early 1990s and at $\sim 3\times10^{-15}$ in the end 1990s.

In the second part, since the end-1990s, frequency standards have dramatically improved:

- The first Cs fountain PFS was reported to the BIPM in 1995, and regular submissions of fountain data started in 1999 with the number of reported evaluations steadily increasing over the years. Since 2004, the Consultative Committee for Time and Frequency (CCTF) [4] has regularly recommended the development and report of primary and secondary standards. Since 2009, more than four fountain evaluations are reported each month on average and this number will continue to increase as several new Cs fountains are currently under development.
- In addition a Secondary Frequency Standard (SFS) based on the 87Rb transition was reported for the first time in 2012: SYRTE-FO2(Rb) has a stated uncertainty $u_B = 3.3\times10^{-16}$ [5] and 30 evaluations, going back to end 2009, have been reported as of October 2013. On the other hand, the US Naval Observatory started in December 2011 to report data from 4 Rb fountains operated as clocks (not as SFS).
- Finally a very large number of frequency standards based on a number of different atomic transitions are in development. Some claim performance in the $\sim 10^{-17}$ or $10^{-18}$. However they are not reporting to the BIPM yet.

On the other hand, industrial clocks have not very much changed but TAI has been based on more clocks with the years: about 200 in 2000, about 300 in 2005, more than 400 in recent years. In addition, the algorithm has been improved several times: new weighting schemes in 2001 and 2003; use of clock drift in the frequency prediction (2011); new weighting scheme (2014). The 1-month instability of TAI is estimated at $\sim 3\times10^{-16}$ in 2012-2013 and should somewhat improve with the recent changes. Its long-term (years) instability may reach $1-2\times10^{-15}$ until 2011, but should now remain well below $1\times10^{-15}$ since the recent changes in the algorithm.

A new version of TT(BIPM) has been computed each year since 1999 and monthly estimates have been made available since 2009. Its accuracy / long-term instability was $6\times10^{-15}$ in 1993-1994, reached $1\times10^{-15}$ in the early 2000s with the arrival of Cs fountains and is now about $2-3\times10^{-16}$ since 2011.

## 3. LONG TERM COMPARISON OF TAI VS. TT(BIPM)

Figure 1 displays the comparison (in rate) of TAI and TT(BIPM12) over the period 1985-2013. We note the following:

- Before 1993, large instabilities are seen, of amplitude several $10^{-14}$. This is probably due to the sensitivity of TAI clocks and time transfer techniques to the environment. After 1993, the stability improves with the introduction of new commercial clocks and of GPS time links.
- 1996-1998: An intentional frequency change of $\sim 2\times10^{-14}$ was introduced in TAI over the course of two years to account for the new practical realization of the second: as decided by the CCTF in 1996 [4], a frequency correction for the black-body frequency shift, which is typically of order $2\times10^{-14}$ for Cs standards operated at room-temperature, must be applied to all frequency standards.
- 1999-2012: The behavior is more or less “random walk”, but remains bounded by the steering of TAI. The instability is of order $1-2\times10^{-15}$ @ years.
- 2013 onwards (not shown): The EAL drift has been removed and no steering is needed; we still expect a bounded Random walk behavior for TAI-TT(BIPM), but with a much reduced amplitude, well below $1\times10^{-15}$.

As a summary, it is natural that, over any period, TAI is not as accurate / stable as TT(BIPM). Therefore the most recent realization of TT(BIPM) should be used for any analysis that is post-processed and demands stability or accuracy over long periods, as is the case for pulsar timing.

## 4. WHAT PULSARS MAY SAY ON TAI / TT(BIPM)

As indicated above, the difference in rate between TAI and TT(BIPM) over nearly three decades shows quite significant features, of amplitude much larger than the uncertainty in the frequency of TT(BIPM)

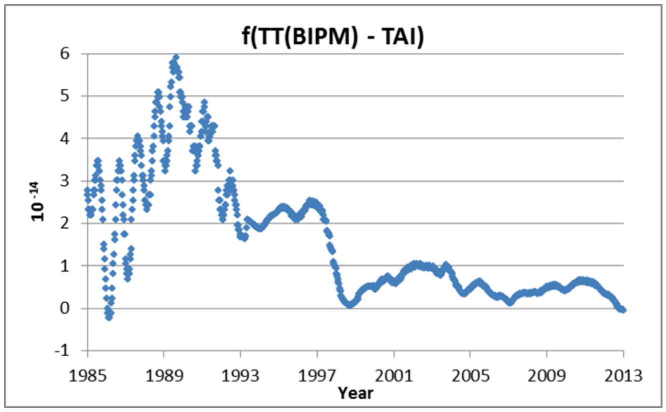


Figure 1: Difference in rate of TT(BIPM) and TAI; see text for details.

at the same epoch. Indeed, at any time, we estimate the uncertainty of TT(BIPM) to be the best achievable for an atomic timescale. If the rotation rate of a pulsar is more regular that TAI, we anticipate that an analysis of pulsar timing data that encompasses a long period could discriminate between TAI and TT(BIPM). The evidence would be that the pulsar timing data fit better a model of the pulsar parameters when TT(BIPM) is used as a reference than when TAI is the reference. Because programs of pulsar observation generally cannot cover such long periods without interruptions or other events that perturb the continuity, it has been proposed to generate ensemble pulsar time [6, 7]. Similarly to what is done for atomic time, an ensemble pulsar time ensures continuity and provides a better performance than any single participating pulsar.

Recently, Hobbs et al. (2012) [8] have used about 18 years of observations of 19 pulsars to solve for a "pulsar-based timescale" that they name TT(PPTA11). When using TAI as a reference, they show (see Figure 2) that TT(PPTA11) - TAI has very significant features and that these features are similar to those seen in TT(BIPM) - TAI after a quadratic adjustment. This is an evidence that TT(PPTA11) can reveal the main long-term instability in TAI over the studied period, which is due to the 1996-1998 TAI frequency change. As can be seen in Figure 2 and as concluded by Hobbs et al. (2012), there

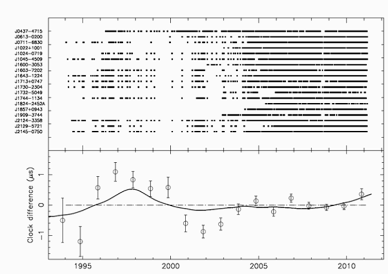


**Figure 6.** The top panel shows the sampling for the 19 pulsars in our sample. The lower panel shows the difference between TT(BIPM11) and TT(TAI) as the solid line. The data points indicate the difference between TT(PPTA11) and TT(TAI).

Figure 2: Reproduced from Figure 6 of Hobbs et al. (2012); cf. Hobbs 2014, this Volume page 117

still remain "marginal discrepancies between 1995 and 2003" between TT(PPTA11) and TT(BIPM11). These correspond in Figure 2 to the difference between the data points and the solid line.

To allow better comparison between TT(PPTA11), available as time data once a year, and TT(BIPM), available as frequency data, the data points for TT(PPTA11)-TAI in Figure 2 have been differentiated and the resulting yearly frequency points are reported in Figure 3, with the corresponding uncertainties obtained from Figure 2. One can see that the yearly points for TT(PPTA11) indeed show discrepancies with TT(BIPM11) but the values of the discrepancies as well as the uncertainties on f(TT(PPTA11)) are much larger than the estimated uncertainties of TT(BIPM11). Because there are correlations in both series (the yearly TT(PPTA11) points and the monthly TT(BIPM11) points), it is not obvious to draw firm conclusions. Nevertheless there is about one order of magnitude difference in the uncertainties of the two series so the discrepancies between TT(PPTA11) and TT(BIPM11) are more likely to be due to TT(PPTA11) than to TT(BIPM11). If the uncertainty in the pulsar based time scale can be reduced, e.g. by solving for fewer points for the pulsar time scale or with more data from more stable and continuously observed pulsars, a similar analysis could provide uncertainties in the pulsar-based time scale quite close to the TT(BIPM) uncertainties over the 1990s. This would be a valuable source of information on atomic time before the Cs fountains.

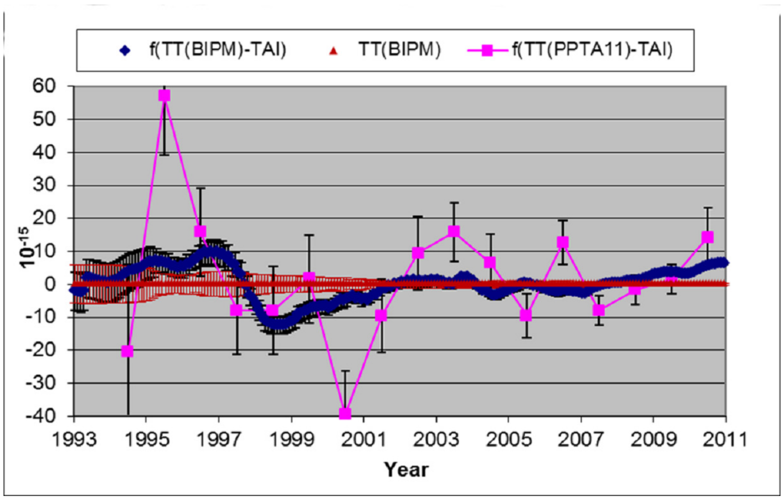


Figure 3: Frequency of TT(BIPM)-TAI (linear removed, dark blue) and estimated frequency uncertainty of TT(BIPM) (red), shown as monthly values. The frequency of TT(PPTA11)-TAI obtained by differencing the data points in Figure 2, is shown as yearly values (magenta).

## 5. CONCLUSIONS

Atomic timescales have gained one order of magnitude in long-term stability and accuracy every $\sim$ 12 years, and this trend should continue for some time. Present realizations of a pulsar-based timescale show frequency uncertainties that are significantly higher than those of atomic timescales. Future pulsar observations may overcome most limitations of the present pulsar data sets however it is not clear if these improvements will match those of the atomic timescales. Nevertheless a pulsar timescale may be used as a flywheel to transfer the accuracy of atomic time between epochs. In all cases, it is recommended that the latest realization of TT(BIPM) be used as a time reference for pulsar analysis.

## 6. REFERENCES

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