How can millisecond pulsars transfer the accuracy of atomic time?

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Abstract

Atomic time scales like TAI and TT(BIPM) get their accuracy from primary frequency standards (presently Caesium fountains) which realize the SI second. The rotation period of some millisecond pulsars is so regular that they may provide information on the long term stability of atomic time scales. As atomic frequency standards continuously improve, atomic time progressively outperforms the rotation of pulsars. Nevertheless millisecond pulsars could be used as a flywheel to transfer the accuracy of newly developed standards to the past. We study the factors that may limit this transfer and estimate the accuracy that could be reached, with examples based on real pulsar data.

1. Introduction

The BIPM atomic time scales TAI and TT(BIPM) get their long-term stability and their accuracy from primary frequency standards (PFS) which realize the SI second. After the discovery of millisecond pulsars in the 1980s, it was realized that the regularity of their rotation may provide some information on the long term stability of atomic time scales. As atomic frequency standards continuously improve, atomic time progressively outperforms the rotation of pulsars. Nevertheless one application remains valid in all cases, in which millisecond pulsars would be used as a flywheel to transfer the accuracy of atomic time presently obtained from newly developed standards to the past [1]. In this paper we envision how to perform this transfer and estimate the achievable accuracy. In section 2, we recall the performances of atomic time and discuss in section 3 which pulsars would be best suited as a flywheel for the transfer. In section 4 we present the methods and their limitations based on some theoretical considerations and numerical examples.

2. Atomic time scales

Terrestrial Time TT is a coordinate time in the geocentric reference system defined by Resolutions of the International Astronomical Union. International Atomic Time TAI gets its stability from some 350 atomic clocks worldwide that generate a free atomic scale named EAL and its accuracy from a small number of primary frequency standards which frequency measurements are used to steer the EAL frequency. TAI is one realization of TT, following the relation TT(TAI) = TAI + 32.184 s. Because TAI is computed in "real-time" (every month) and has operational constraints, it is not optimal and the BIPM computes in deferred time another time scale TT(BIPM), which is based on a weighted average of the evaluations of TAI frequency by the PFS. The present procedure for computing TT(BIPM) is described in [2] and a yearly computation is performed each January, the latest available being TT(BIPM10) available at ftp://tai.bipm.org/TFG/TT(BIPM). Each version of TT(BIPM) is a new computation starting in 1993 and uses all PFS measurements until the end of the year of computation, e.g. until end 2010 for TT(BIPM10). Recent successive versions have negligible (few ns) differences except in their most recent year and all versions are strictly identical until 1993. However, a few significant changes have occurred over the last 25 years, the period of interest for pulsar analysis: Since TT(BIPM96), a correction for the blackbody frequency shift has been applied to all PFS evaluations, causing a systematic rate difference of order 1.7×10^{-14} with previous versions. Then a significant change in the computation procedure has occurred with TT(BIPM03) so that differences with earlier versions may be of order 100 ns.

Since about year 2000, Cs fountains have been operationally used in the formation of TAI and their accuracy is now in the low 10^{-16} in relative frequency so that the accuracy of atomic time is also at a similar

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level. This represents a gain of about two orders of magnitude since the discovery of millisecond pulsars in the 1980s. The accuracy and long-term stability of TAI and TT(BIPM) are estimated periodically [3], see Figure 1 for the estimated accuracy of TT(BIPM10) since 1993. In the years preceding 1993, it is estimated that the accuracy is of order $1x10^{-14}$ to $1.5x10^{-14}$, see e.g. [4]. On the other hand, since about 2007, the accuracy of TT(BIPM) is at or below $5x10^{-16}$. This is due to the ever increasing number of Cs fountain evaluations (some 300 since 1999, about 60 of them in 2010), and to the improved accuracy of each fountain evaluation. The long-term instability of TAI is estimated with respect to that of TT(BIPM) and is between $1x10^{-15}$ and $2x10^{-15}$ for averaging durations of a few years, a factor two or three worse than the value for TT(BIPM). In addition, systematic variations have been introduced in TAI, e.g. a rate change of order $2x10^{-14}$ between 1996 and 1998 to account for the blackbody frequency correction. For these reasons, TAI should not be used as a time reference for pulsar analysis. Similarly, time scales that are steered to TAI or UTC should not be used.

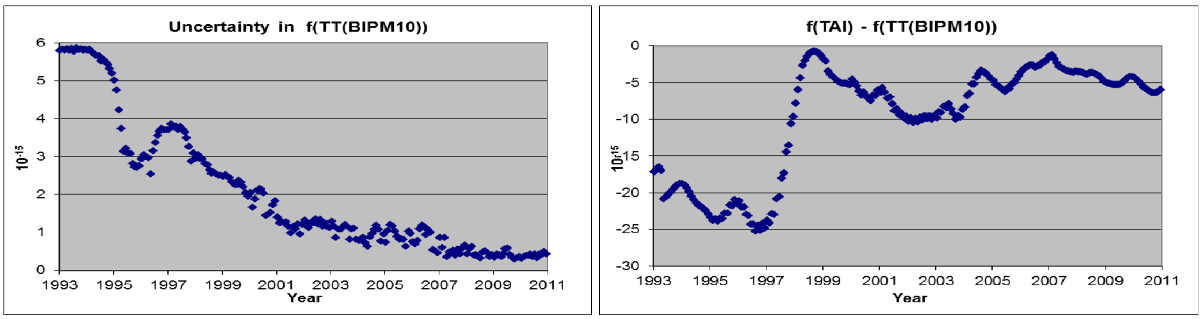

Figure 1: Fractional frequency accuracy of TT(BIPM) (left) and rate difference between TAI and TT(BIPM) (right) over the period 1993-2010.

3. Pulsars for long term stability

Millisecond pulsar data analysis is based on series of Times of Arrival (ToAs), more or less regularly spaced, of the pulsar signal. A special instrumentation is usually devoted to remove the interstellar dispersion, fold the data according to the current rotational period of the pulsar and provide the ToAs. The measured ToAs are compared to 'calculated ToAs' given a set of parameters for the pulsar (period and its derivative, position and proper motion, sometimes five or more orbital parameters in case of a binary system). Some or all parameters may be adjusted to the ToAs using a fitting procedure, e.g. with the tempo2 code [5], that minimizes in the least-squares sense, the residuals between measured and calculated ToAs. Assuming perfect pulsars, perfect measurements and a perfect knowledge of the parameters of the model, residuals would be due to the instability of the reference time scale.

In the real world, we only expect to infer some information on the long term stability of the reference time scale from such analysis. For best results, pulsars should be selected as fulfilling the following criteria: They should have a low timing noise e.g. the standard uncertainty of one ToA observation should be lower than 1 µs, preferably close to 0.1 µs, so as to ensure that the long-term behaviour (for averaging durations of a few years) is not driven by the measurement noise. And they should have been discovered and regularly observed since the early 1990s and should present no obvious sign of systematic behaviour or long-term instability over the whole observing period. Here “obvious” means any systematic effect significantly larger than can be expected from the reference time scale. An analysis of historical publications based on an initial list of 20 pulsars regularly observed at Nancay in the 2000s [6] provides the following candidates:

- J1713+0747: P = 4.57 ms; Recent measurement noise < 0.3 µs; observed since 1992 [7]
- J1744-1134: P= 4.07 ms; Recent measurement. noise < 0.3 µs; observed since 1994 [8]
- J1857+0943: P= 5.36 ms; Recent measurement noise < 1 µs; observed since 1986 [9]
- J2145-0750: P= 16.05 ms; Recent measurement noise < 1 µs; observed since 1993 [10]

Additional candidate pulsars may be found, when searching on the basis of the present measurement noise and of the observed stability. However none seems to have reports of observations in the early 1990s.

4. The pulsar flywheel : methods and limitations

We envision two methods for obtaining information on the reference time scale, under the general assumption that the pulsar long term stability is better than the effects we expect to detect.

In the first method, we assume that the complete set of ToA observations is available and we analyse the data set using the TEMPO2 software [5]. In order to characterize possible changes in the reference time scale, it would be needed to model the expected changes and introduce the relevant parameters in the adjustment. This has not been attempted so far but, as a workaround, it is possible to solve for different sets of timing parameters for the pulsar, thus in effect modifying the rate of the reference time scale over an interval or a set of intervals.

In the second method we split the data set into subsets that are analysed separately using the same procedures and we compare the pulsar period and period derivative resulting from the analysis to infer information on the reference time scale: As much as the pulsar parameters can be expected to be the same, differences in the two sets may be attributed to the reference time scale. The second method has the advantage that it is not necessary to obtain the ToAs for the data sets as long as the analysis results have been published in the literature and the physical model is the same for all data sets. In practice, it is adequate to obtain a model for an "ancient" dataset in the literature and to adopt the same physical model to process a "recent" ToA data set which is available.

4.1 Limiting factors: a theoretical approach

In the following, we consider several factors that may cause systematic effects in the pulsar timing parameters (here considered as the rotation period and its derivative) and estimate the possible magnitude of such systematic effects from a theoretical approach. As we shall see, some factors can be present in both methods while some of them are mostly influent in the second method (comparison of models).

As a prerequisite, it is necessary that the reference time scale is the most recent version of TT(BIPM) available at the time of the analysis, or covering the whole interval of analysis. This is to avoid contamination of the results by known defects in TAI (see section 2). The other factors that have been identified as possible contributors of systematic effects are the following:

- The time coordinate used to express the period (in method 2). The period is reported either as a TDB-compatible value or a TCB-compatible value, where TCB and TDB are two possible coordinate times in the (solar system) barycentric celestial reference system. While it is straightforward to transform between the two, some uncertainty arises from the formulas used in the analysis. This uncertainty is expected to be in the 10^{-16} to 10^{-17} region (See a discussion of the transformation formulas between geocentric and barycentric time coordinates in Chapter 10 of [11]), thus should not be significant.
- The solar system ephemerides used have two important effects: directly as the value of the observed period depends on the relative motion of the pulsar and the solar system barycentre; indirectly through the correlations between position parameters and the period and its derivative. These correlations obviously decrease when the total duration increases thus this effect should be lower in method 1. Intrinsic differences between ephemerides have been studied by the teams providing them. Under the hypothesis that each new version of the ephemerides provides a better realization, [12] provides an account of the accuracy of DE200, which was the standard until the provision of DE405 in 1997, then DE421 in 2008. It should be noted that ephemerides realized with similar ensembles of observations and providing comparable relative planetary motions may significantly differ in the position and motion of the solar system barycentre, see [13].
- The delay due to the interstellar medium is characterized by the Dispersion Measure (DM). The variation of DM with time, if not properly accounted for, will cause an apparent change in the pulsar period P_0 following $\Delta P_0 / P_0 \approx -0.6\times10^{-14} \times (DM' / 10^{-4}yr^{-1}) (\nu /1.4GHz)^{-2}$. Variations of DM with time have been the subject of several studies, e.g. [14] estimates DM variations for 20 pulsars over a 2-3 year data span. For the pulsars mentioned in section 3, except for J1857+0943, the DM variation and its statistical uncertainty are found to be well below $1x10^{-4}yr^{-1}$, yielding an apparent change in the period well below 1×10^{-14}. These results must be taken with caution because the time span is much lower than the one envisioned in our analysis (15-20 years).

Overall, it is estimated that an uncertainty of order $1x10^{-14}$ may be reached when comparing the pulsar periods determined over two widely different intervals however it seems unlikely that a much better accuracy may be reached: Even though it is possible to gather all existing data sets and to process them with improved ephemerides as they become available, unknown variations in DM should limit the achievable uncertainty

4.2 A practical test

In the list of candidates of section 3, we have selected two pulsars for which high quality timing observations have been taken at the Nançay radio-observatory over 2004-2009 and for which the above methods may be applied: For J1857+0943, a set of ToAs from 1986.0 to 1993.0 is in the public domain [9] and a second set of timing data from Nançay, although with larger ToA uncertainty, is available for the period 1999.0-2002.0. For J1713+0747, a complete model based on ToAs for the period 1992.6-2004.4 and referred to TT(BIPM03) and DE405 has been published [7]. Preliminary results for J1713+0747 indicate that the apparent pulsar period obtained from the different data sets differ by about 1×10^{-14} in relative value. The significance of this result and the implications for the reference time scale are under study.

5.Conclusion

We present a simple approach in which the stability of the pulsar rotation period over long observation intervals is used to infer information on the long term stability of the reference atomic time scale and to transfer to the past the accuracy achieved by atomic time in recent years. We study the possible performance of the proposed methods. In the future, in contrast to this simple approach, it is planned that a global analysis of tens of pulsars observed for decades will search for the signature of cosmic gravitational waves along with other long term signatures of various origins, including the reference time scale. However this global dataset has started only over recent years, when the instability of atomic time is expected to be lower than other sources and should still improve in the coming years. It is not clear if pulsars will be able to tell us more about atomic time.

6.References

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