A NEW REALIZATION OF TERRESTRIAL TIME

G. PETIT
Bureau International des Poids et Mesures
92312 Sèvres France
e-mail: gpetit@bipm.org

ABSTRACT. Terrestrial Time TT is a time coordinate in a geocentric reference system. It is realized through International Atomic Time TAI, which gets its stability from some 200 atomic clocks worldwide and its accuracy from a small number of primary frequency standards (PFS) which frequency measurements are used to steer the TAI frequency. Because TAI is computed in "real-time" and has operational constraints, it does not provide an optimal realization of TT. The BIPM therefore computes another realization TT(BIPM) in post-processing, which is based on a weighted average of the evaluations of TAI frequency by the PFS. The procedures to process PFS data have been recently updated and we consequently propose an updated computation of TT(BIPM). We use all recently available data from new Cs fountain PFS and a revised estimation of the stability of the free atomic time scale EAL on which TAI is based. The performance of the new realization of TT is discussed and is used to assess the accuracy of recent PFS measurements.

1. INTRODUCTION

Terrestrial Time TT was defined by Recommendation IV of Resolution A4 of the International Astronomical Union, adopted at its XXIst General Assembly (1991). The scale unit of TT is chosen to agree with the SI second on the rotating geoid and its origin is defined by the following relation to TAI : TT = TAI + 32.184 s on 1977 January 1^{st}, 0 h TAI. International Atomic Time TAI, the time scale established by the BIPM, is a realization of Terrestrial Time TT, i.e. a coordinate time of a geocentric reference system. TAI gets its stability from some 200 atomic clocks kept in some 50 laboratories worldwide and its accuracy from a small number of primary frequency standards (PFS) developed by a few metrology laboratories. The scale interval (unit) of TAI is based on the SI second, i.e. the period associated with an hyperfine transition of the cesium atom, as it is realized by these primary frequency standards. To be more specific, in the computation of TAI, a free-running time scale, EAL, is first established from a weighted average of some 200 atomic clocks, then the frequency of EAL is compared with that of the primary frequency standards using all available data processed with the algorithm presented in [Azoubib et al. 1977], and a frequency shift (frequency steering correction) is applied to EAL to ensure that the frequency of TAI is accurate. Changes to the steering correction are designed to ensure accuracy without degrading the long-term (several months) stability of TAI, and these changes are announced in advance in the BIPM monthly Circular T. Uncertainty in the frequency of TAI originates from uncertainties in the PFS evaluations and in the links between each PFS and TAI, and from instabilities in the time scale used to connect the PFS evaluations which are carried out at different times. Procedures to estimate these uncertainties and to report the results in BIPM publications have been updated in 2000 [Petit 1999]. It is notable that, at present time, the three sources of uncertainty in TAI (time scale instabilities, uncertainties in PFS frequency and in frequency transfer techniques) contribute each at a level which is close to, or slightly below, 1×10^{-15} in fractional frequency.

Because TAI is computed in "real-time" every month and has operational constraints (e.g. no correction for a mistake discovered many days after the publication), it does not provide an optimal realization of TT. The BIPM therefore computes another realization TT(BIPM) in post-processing [Guinot 1988], which is based on a weighted average of the evaluations of TAI frequency by the PFS. Several versions have been computed in the 1990s, the latest of which is TT(BIPM99) (see ftp://62.161.69.5/pub/tai/scale/). Over the last ten years important improvements have been achieved (see section 2) and, since 1999, twelve different primary frequency standards have provided evaluations of the TAI frequency, including five Cs fountain clocks for which all systematic frequency shifts have been estimated with a relative uncertainty close to 1×10^{-15}. Therefore a new realization of TT(BIPM) has been computed and some of its applications are described in section 3.

2. EVOLUTION OVER 10 YEARS: 1993-2003

We examine here the progresses realized over the last decade, mainly in what concerns the stability of the ensemble time scale EAL and the accuracy of TAI. Substantial improvements have also taken place in time transfer but these have little effects on the long-term intervals (one month and above) in which we are interested here. We choose to consider a period starting around 1993, when the first commercial clocks of a new generation were introduced.

Improvements in the stability of EAL have mainly resulted from two sources: the improvement of the clocks themselves and the changes in the weighting scheme that were introduced to better take advantage of the quality of the clocks in the ensemble average. There were three main changes in the decade: From 05/1995, the variance below which the maximum weight is attributed to a clock was decreased. From 01/1998, the maximum weight of a clock was set to a fixed value (0.7%). From 01/2001, the maximum weight was set to 2/N, where N is the number of weighted clocks (typically 220), then it was set to 2.5/N from 07/2002. We therefore distinguish four periods to describe the stability of EAL, each of them representing an improvement over the previous one (see Petit 2003).

Many progresses in primary frequency standards and some change in the treatment of their data have occurred over the decade: First, following Recommendation S2 (1996) of the CCDS, a frequency correction for the black-body radiation shift has been applied to all primary frequency standard results. The main effect is a global change in the frequency of TT which has been taken into account since TT(BIPM96). However the most notable events have been the introduction of new types of primary standards: First optically pumped PFS in 1995, then Cs fountains. The first fountain data were reported in 1995 but such data have been regularly available only since the end of 1999. A side effect has been the notable increase in the number of different PFS available during a given year: from about two per year in the early 1990s, the number increased to nearly 10 per year in the 2000s.

3. THE NEW REALIZATION TT(BIPM2003) AND SOME APPLICATIONS

Basic features of the new procedure for computing TT(BIPM) are the following:

*All PFS measurements reported back to 1992 have had their associated uncertainty values updated in accordance to the new procedure [Petit 1999].

*The frequency of EAL with respect to the PFS is then estimated for each month since 1993 with the usual procedure [Azoubib et al. 1977] but with new estimations for the stability model of EAL as mentioned in Section 2. This best estimate represents f(EAL-TT).

*The series of monthly values f(EAL-TT) is slightly smoothed (low pass filter with a cutting frequency around 2 yr^{-1}) so as to include possible yearly signatures in the smoothed frequencies (EAL-TT). It is estimated that yearly signatures are most likely due to EAL rather than to the primary standards, so this procedure mostly removes these signatures from TT.

*The smoothed frequencies are interpolated and integrated with a 5-day step since MJD 48984 (28 Dec 1992), at which epoch continuity is ensured with TT(BIPM99). This forms TT(BIPM2003) which is available at ftp://62.161.69.5/pub/tai/scale/.

[TT(BIPM99)-TT(BIPM2003)] remains in the range [-40ns,+25ns] until August 1997. Then the difference gets larger and reaches -170 ns in February 1999. This may be partly due to the influence of the new primary standards introduced in 1999 that were not available for the computation of TT(BIPM99) but affect TT(BIPM2003) already during the end of 1998. Figure 1a shows the difference between TAI and TT(BIPM2003) over 1993-2003. Two main periods may be distinguished, when the frequency of TAI is notably too low: In the first period, 1993-1998, this results from the decision in 1995 to correct the PFS frequencies for the Blackbody frequency shift, automatically shifting the TAI frequency by about -2×10^{-14} , a step which took about 3 years to recover by continuously steering its frequency by 1×10^{-15} every two months. In the second period, about since end 1999, this is due to other causes: when Cs fountains started to contribute significantly, it was observed that their estimation of TAI frequency was somewhat lower than the estimation given by other PFSs. Although this was recognized quite early, the present steering policy has so far failed to bring the TAI frequency close to that of the PFSs probably because a systematic frequency drift in EAL, of unknown origin, adds its effect to counter the frequency steering corrections. The net result is a nearly systematic frequency difference between TAI and TT(BIPM2003) which integrates to some 4 microseconds over 10 years.

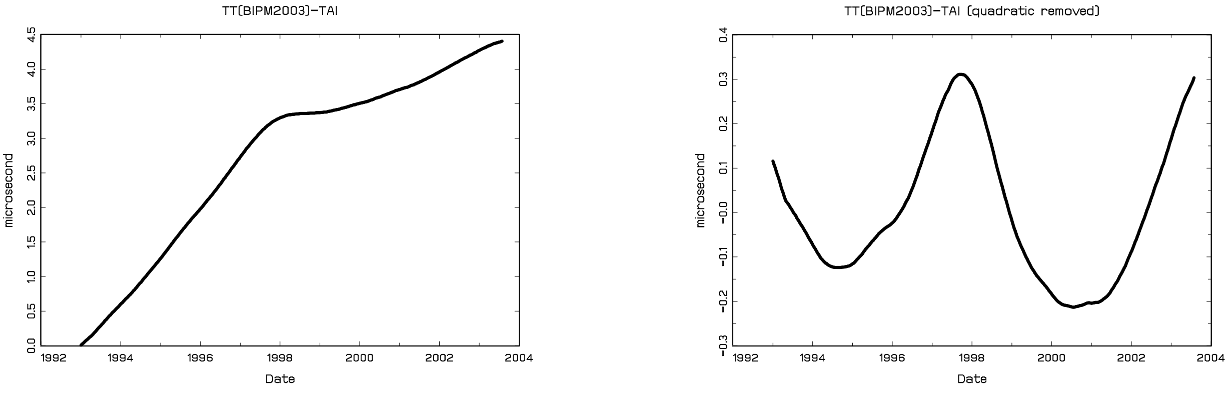

Figure 1: a: Difference between TT(BIPM2003) and TAI (with an offset removed) b: Difference in pulsar timing of using TT(BIPM2003) or TAI as a reference

The most demanding application of a time scale on the long term is the analysis of long series of measurements of the time of arrival of radio pulses from millisecond pulsars [Petit and Tavella

1996]. In such an analysis, several physical parameters of the pulsar are obtained by adjusting a model to the data, assuming that long-term systematic effects from both the reference time scale and the series of measurements do not contaminate this estimation. It is useful to try to estimate in what respect time scales like TAI or TT(BIPM) may differ for this purpose. Because the pulsar rotation period and its derivative are always obtained by adjustment, all comparisons between different time scales must be done after removing the best-fit quadratic between them. Such an adjustment over a period of 10 years yields quasi-periodic differences between the two scales, with apparent period of a few years and amplitude of several hundred ns (Figure 1b). This compares to a timing noise that may be as low as a few hundred ns in the best cases, so this effect is not negligible in principle. However, the timing noise and some other long term effects are generally larger than this for most pulsars. Nevertheless it is always advised to use a post-processed time scale like the new TT(BIPM2003) for pulsar analysis, rather than a real-time scale such as TAI, GPS time or a local atomic time scale realized by a single time laboratory

Another important application of TT(BIPM2003) is to serve as a frequency reference to compare Cs fountain data. Half a dozen Cs fountains from four different laboratories have contributed to the estimation of EAL frequency over the past years. However they operate intermittently and it is generally not possible to directly compare them because their operation is not simultaneous. Then the most convenient way to intercompare them is to use a common reference which is as accurate and stable as possible. TT(BIPM2003) may serve this purpose and the results of such comparisons will be presented in a subsequent paper [Petit 2003].

4. CONCLUSIONS

We compute a post-processed time scale, TT(BIPM2003), basing its stability on EAL and its accuracy on all available PFS measurements. Presently the three sources of uncertainty (time scale instabilities, uncertainties in PFS frequency and in frequency transfer techniques) each contribute at a level which is close to, or slightly below, 1×10^{-15} in fractional frequency so that the uncertainty in the frequency of TT(BIPM2003) is close to 1×10^{-15}. This time scale is considered the best realization of Terrestrial Time and is therefore most suited as a reference for the analysis of pulsar data. It also allows a better comparison of the different PFS measurements that are presently sparse and rarely simultaneous.

It is expected that the accuracy of PFS will progress rapidly in the coming years. Progresses in time scale formation and in time transfer techniques should accompany the progresses in primary frequency standard technology to bring the accuracy of TT(BIPM) and the uncertainty on the TAI frequency well below 1×10^{-15} in the near future.

5. REFERENCES

Azoubib J., Granveaud M., Guinot B., *Metrologia* 13, 87, 1977.

Guinot B., *Astron. Astrophys.*, 192, pp. 370–373, 1988.

Petit G., *Proc.* 31^{st} *PTTI*, pp. 297–304, 1999.

Petit G., *Proc. 35th PTTI*, 2003, to be published.

Petit G., Tavella P., *Astron. Astrophys.*, 308, pp. 290–298, 1996.