

Long term stability of atomic time scales

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Abstract. We review the stability and accuracy achieved by the reference atomic time scales TAI and TT(BIPM). We show that they presently are in the low 10^{-16} in relative value, based on the performance of primary standards, of the ensemble time scale and of the time transfer techniques. We consider how the 1×10^{-16} value could be reached or superseded and which are the present limitations to attain this goal.

Keywords. time, reference systems

1. Introduction

International Atomic Time TAI gets its stability from some 400 atomic clocks worldwide that generate the free atomic scale EAL, and its accuracy from about ten primary frequency standards (PFS) that are used to steer the EAL frequency. Terrestrial Time is a coordinate time in the geocentric reference system defined by the International Astronomical Union. TAI provides one realization of TT but it is not optimal because of operational constraints. The BIPM therefore computes in deferred time another realization, TT(BIPM), which is based on a weighted average of the evaluations of the TAI frequency by the PFS. A new version is computed each January, the latest available being TT(BIPM11), available at [ftp://tai.bipm.org/TFG/TT\(BIPM\)](ftp://tai.bipm.org/TFG/TT(BIPM)).

We review the stability and accuracy achieved by the reference atomic time scales TAI and TT(BIPM). We show that they presently are at the level of a few 10^{-16} in relative value, based on the performance of primary standards, of the ensemble time scale and of the time transfer techniques. We consider how the 1×10^{-16} value could be reached or superseded and which are the present limitations to attain this goal.

2. Achieving low- 10^{-16} accuracy

The stability of atomic time scales, the PFS accuracy and the capabilities of frequency transfer all achieve a performance in the low 10^{-16} in relative frequency stability.

The stability and accuracy of the BIPM time scales has been studied in (Petit, G., 2007, *Proc. 21st EFTF conference*, 391–394). The 1-month stability of all scales is that of EAL, at $3 - 4 \times 10^{-16}$ and slightly improves with the number of participating clocks. Using TT(BIPM11) as a reference shows that the drift affecting EAL in past years has disappeared since a change of algorithm effective in August 2011. It is expected that this will improve the long-term (6 months and above) stability of TAI to well below 1×10^{-15} but this needs to be ascertained in future studies. The estimated accuracy of TT(BIPM) over recent years is at 3×10^{-16} or below (Petit, G., Panfilo, G., 2012, *IEEE Tans. IM*, accepted). This is due to the ever increasing number of Cs fountain evaluations, about 50 every year since 2008, and to the improved accuracy of each evaluation.

The time transfer techniques presently most used in TAI are dual frequency Global

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Positioning System (GPS) phase and code measurements in a mode called precise point positioning (PPP), and two-way time transfer (TW) using telecommunication satellites. A combination of these two techniques can provide best performance at all averaging times (Jiang, Z., Petit, G., 2009, *Metrologia*, 46-3, 305–314), reaching the low 10^{-16} at 30 day averaging. They are used for many TAI time links so that the contribution of frequency transfer to the instability of TAI is estimated to be in the low 10^{-16} .

3. Reaching 1×10^{-16} and beyond

From numerous recent publications, see e.g. in parts II, IV and V of (Maleki L. (ed.), 2009, *Proc 7th Symp. Freq. Standards and Metrology*, World Scientific, 308–313), it is clear that some frequency standards have reached a level where all systematic effects may be estimated with an uncertainty at 1×10^{-16} or below. Their accuracy budget is thus better than that of the Cs transition providing the definition of the SI second. Some of these transitions have been recognized as secondary representations of the second (SFS) by the Consultative Committee for Time and Frequency (CCTF). As of 2009, this list includes the hyperfine transition of ^{87}Rb and optical transitions of Sr, Hg^+ , Sr^+ and Yb^+ , and three of these transitions state total uncertainties in the low 10^{-15} , a value dominated by the uncertainty in the realization of the SI second itself. This list is expected to expand with time and the reported uncertainties of the transition frequencies should correspondingly decrease. The first update of this list will happen at the September 2012 meeting of the CCTF.

Submitting formal evaluations to the BIPM for the best SFS would allow providing information on these SFS to the community in an homogeneous and complete manner. It also ensures that all available evaluations for a given secondary transition can be compared to the PFS in a consistent manner by the BIPM, so as to allow an optimal determination of the reference value of the transition frequency. Eventually, SFS evaluations could also contribute, through the reference value of the transition frequency, to estimate the accuracy of TAI and to generate TT(BIPM). In January 2012, the first evaluations of an SFS have been transmitted to the BIPM. It concerns the ^{87}Rb transition realized in the dual atom fountain SYRTE-FO2 at the LNE-SYRTE (Guéna J. *et al.*, 2010, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, 57 (3), pp. 647–653).

The techniques presently used for time transfer may progress, but they will still limit the performance of time scales, specially for short and moderate averaging times (typically up to one month). Several new techniques have emerged that should be able to provide frequency transfer uncertainty in the low 10^{-17} and possibly below. Some are based on microwave or optical links to a low Earth orbit payload and should provide global coverage provided a stable clock is available in the space payload. Another technique transfers a stable laser frequency over a standard fiber link and provides even better performance in frequency transfer, although presently limited in spatial extension.

4. Conclusions

We have shown that the present performance of the reference atomic time scales TAI and TT(BIPM) is in the low 10^{-16} in stability and accuracy. New frequency standards already promise that the performance of 1×10^{-16} and below is possible but a better reliability and wider availability of these are needed for use in time scale formation. Improving the techniques for time and frequency transfer is also an important issue. Ultimately, a new approach to the problem of elaborating an ensemble time scale may be needed.