EVALUATING THE ACCURACY OF TAI WITH PRIMARY FREQUENCY STANDARDS

G. Petit

BIPM, Pavillon de Breteuil, 92312 Sèvres Cedex – France- e-mail: gpetit @bipm.org

ABSTRACT

International Atomic Time TAI gets its stability from some 200 atomic clocks worldwide, which weighted average form the ensemble time scale EAL, and its accuracy from a small number of primary frequency standards (PFS) which frequency is compared to that of EAL, providing evaluations of the absolute TAI frequency. Based on recently updated procedures to estimate uncertainties of these evaluations, the uncertainties associated to the PFS evaluations and to the final accuracy of TAI are examined. A frequency drift of EAL is estimated as well as its influence on the accuracy estimation. New procedures for using PFS data are discussed.

INTRODUCTION

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. on 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 [1], 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 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 [2].

Since the end of the 1990s, a new generation of primary frequency standards has come into operation: In the atomic cesium fountains, the cesium atoms do not travel in a thermal beam but they are laser cooled and thrown as in a fountain. In these devices the systematic frequency shifts can be estimated with a relative uncertainty close to $1\text{x}10^{-15}$. So it is notable that, at the time of this writing, 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, $1\text{x}10^{-15}$ in fractional frequency. Improving the accuracy of TAI will require improvements in all three fields.

Since 1999, nine different primary frequency standards have provided evaluations of the TAI scale unit, including two Cs fountain clocks [3,4] for which all systematic frequency shifts have been estimated with a relative uncertainty close to $1\text{x}10^{-15}$. The algorithm [1] has been used to compare PFS evaluations over the past three years, relying on the stability of the underlying time scale EAL. As a result, the validity of the uncertainty associated to PFS evaluations is examined. A frequency drift of EAL is evaluated as well as its influence on the accuracy estimation. New procedures for using PFS data are discussed.

EVALUATION OF THE TAI SCALE UNIT

Because TAI is a coordinate time scale, the accuracy of TAI is usually expressed as the duration, *d*, of its scale unit in SI seconds. It is equal to the opposite of the TAI frequency, y_{TAI} , also noted f(TAI), which differs from f(EAL) by the (variable) frequency steering correction chosen by the BIPM. Primary frequency standards are usually compared during a given duration (period of evaluation) to one of the atomic clocks which are used in the formation of EAL. Some PFS are themselves such clocks in which case they are considered to be continuously evaluated and periods of evaluation are taken to be each computation interval of EAL, i.e. each month.

The uncertainty in one PFS evaluation is composed of three main components: the combined uncertainty originating from systematic effects, u_B, the uncertainty originating in the instability of the PFS for the duration of the interval of comparison, u_A, and the uncertainty in the link between the PFS and TAI (in fact EAL), $u_{link/TAI}$. To each PFS evaluation of the TAI frequency may then be associated an uncertainty which is estimated as the combined uncertainty of the values above. The set of such evaluations over the period mid-1998 to early 2002 may be found in Fig. 1. Because of varying conditions of operation, uncertainties of evaluation are typically all different and are not represented on Fig. 1 for clarity. Details may be found in the annual report of the BIPM [5] and a brief summary in Table 1, taken from BIPM annual report for 2001.

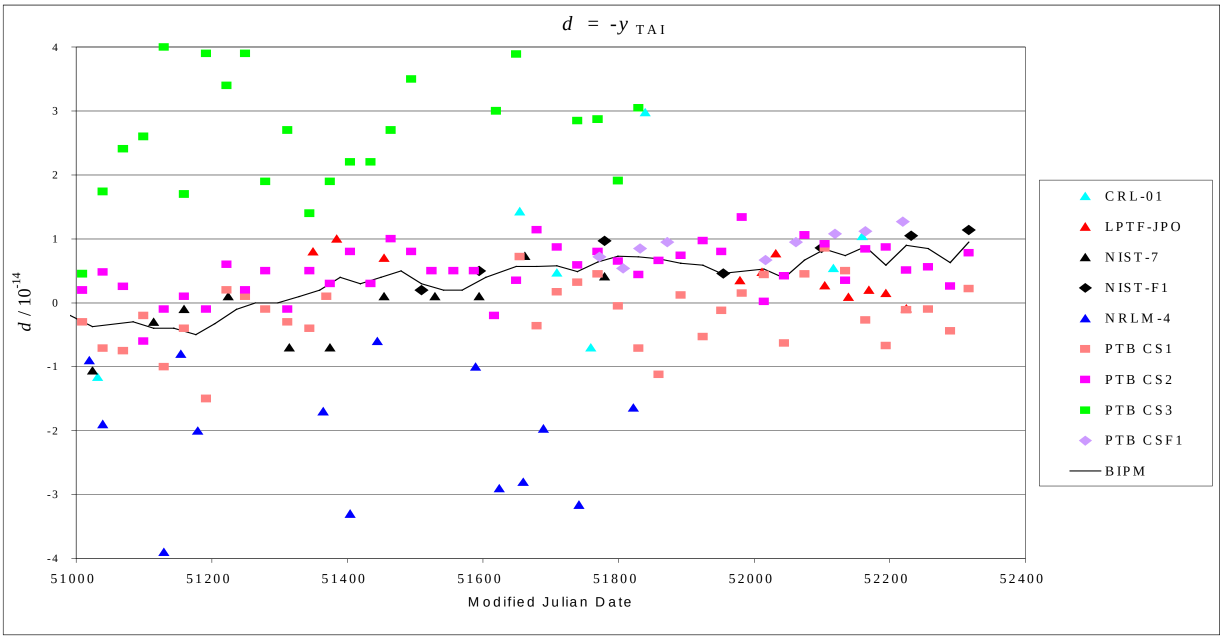

Fig. 1: Evaluation of the scale unit of TAI, *d*, since mid-1998 through various primary frequency standards (symbols) and through the BIPM estimation procedure (solid line)

Primary Standard	Typical standard uncertainty u_B	Operation	Comparison with	Typical duration of comparison
CRL-O1	4×10^{-15}	Discontinuous	UTC(CRL)	10 or 15 d
LPTF-JPO	6×10^{-15}	Discontinuous	H maser	15 to 30 d
NIST-F1	1×10^{-15}	Discontinuous	H maser	30 to 45 d
PTB CS1	8×10^{-15}	Continuous	TAI	30 d
PTB CS2	12×10^{-15}	Continuous	TAI	30 d
PTB CSF1	1×10^{-15}	Discontinuous	H maser	15 or 20 d

Table 1: Principal characteristics of primary frequency standards reported in 2001

Using all PFS evaluations of the EAL frequency, the BIPM computes an estimate of the EAL frequency over an estimation interval (typically one month) as a weighted average of all evaluations taken (typically one year) before and after the estimation interval and using EAL as a flywheel for the evaluations carried out at before and after. The complete algorithm is described in [1]. In its present use, the basic hypothesis of this algorithm are the following:

1. The reference time scale (EAL) has a known instability and no systematics
2. All PFS evaluations are independent
3. The instabilities of the PFS are independent of that of the reference time scale.

These monthly BIPM estimates of the TAI scale unit are shown on Figure 1 (solid line).

Among the hypothesis stated above, at least two may be challenged: First, as has been suspected for a long time, it is now quite clear that EAL has a systematic frequency drift. Second, different evaluations carried out by the same PFS should not, in general, be considered to be completely independent.

INFLUENCE OF A FREQUENCY DRIFT OF EAL

It has been long suspected that a systematic frequency drift is present in EAL. Because past values of the estimation of f(EAL) are not always readily available, the easiest way to evidence this fact over the very long term is to plot f(EAL)-f(TAI), i.e. the values of frequency steering correction applied by the BIPM (see Fig. 2). It is cautioned that, for various reasons, these values are only very approximate values of the measurements of f(EAL) with primary frequency standards but they do give the general tendency which is close to a decrease of 8×10^{-14} over 13 years. Note that values and uncertainties of f(TAI) may reach several parts in 10^{14} in the first reported years and that, in addition to the presumed frequency drift, an independent cause for a frequency bias between EAL and TAI was the introduction in 1996 of a correction to the PFS data for the blackbody frequency shift, for an average amount close to 2×10^{-14} which had to be compensated for in the steering correction between 1996 and 1999. Over the period 1999-2002, f(EAL) was estimated in an homogeneous manner following the procedure described above, using all available PFS evaluations as independent data. The results are shown in Fig. 3 and are very consistent with a frequency drift of f(EAL) of about -0.5×10^{-14} per year.

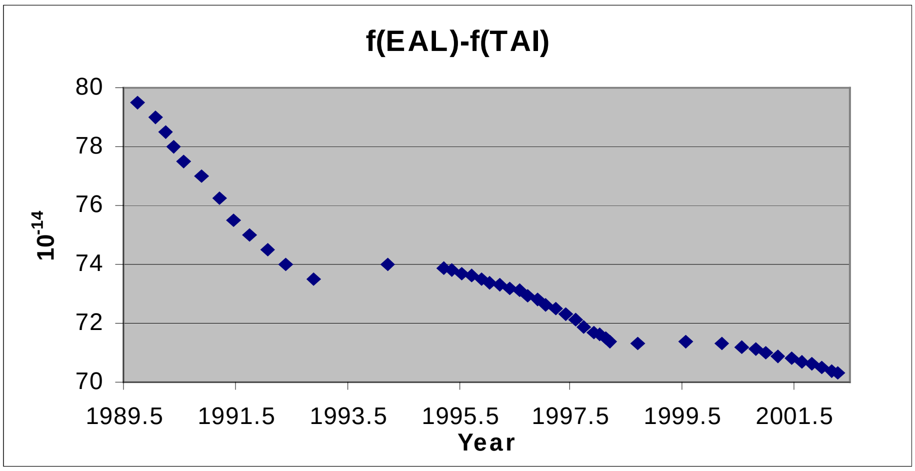

Fig. 2: Frequency steering f(EAL)-f(TAI) over 13 years.

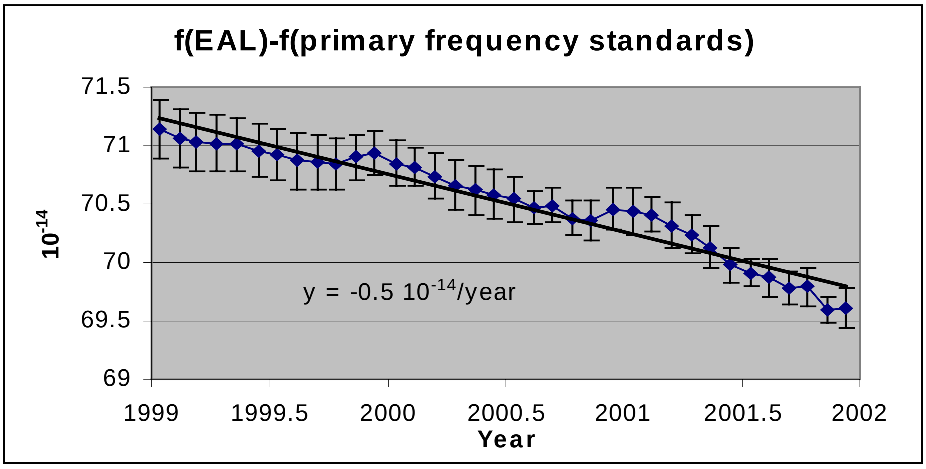

Fig. 3: Values of f(EAL) from the BIPM estimation procedure. The average frequency drift is also shown.

Such a drift should be taken into account when estimating f(EAL). One can evaluate that, in unfavorable cases where the time distribution of PFS evaluations is very unsymmetrical around the estimation interval (e.g. all very accurate measurements are before the estimation interval) the estimation of f(EAL) could be biased by 1×10^{-15}, i.e. half its present formal uncertainty. Because it is expected that PFS will soon report uncertainties in the 10^{-16} level, this is not to be neglected.

INFLUENCE OF CORRELATIONS BETWEEN PFS EVALUATIONS

Inclusion of the correlations between different evaluations of the same primary frequency standard has been considered in [1]. It has, however, not been used so far in the estimation of f(EAL). Tests are being conducted on the influence of these correlations. The estimation of f(EAL) may be biased by more than 1×10^{-15} and the resulting estimated standard uncertainty on f(EAL) is larger, as expected from the theory of estimation. Conclusions will be presented to the Consultative Committee on Time and Frequency in 2003.

CONCLUSIONS

It is proposed that the frequency drift of EAL could be taken into account both in expressing the difference between EAL and TAI (using a linear model instead of a constant frequency) and in using primary frequency standards data to estimate the accuracy of TAI. Proper use of the correlations between different evaluations of a given primary standards could also yield a more accurate estimate of the TAI frequency and of its uncertainty. Progresses in time transfer techniques (e.g. use of a denser set of two way satellite time transfer measurement or of dual-frequency phase and code measurements of the signals of GPS or other navigation satellite systems) should accompany the progresses in primary frequency standard technology to bring the uncertainty of the TAI frequency below 1×10^{-15} in the near future.

REFERENCES

[1] Azoubib J., Granveaud M., Guinot B., *Metrologia* 13, 87, 1977.
[2] Petit G., *Proc. 31st PTTI*, 297-304, 1999.
[3] Weyers S. et al., *Metrologia* 38-4, 343, 2001
[4] Jefferts S.R. et al., *Metrologia*, submitted.
[5] Annual report of the BIPM time section Vol. 13, 2000; data also available on ftp://62.161.69.5/pub/tai