A NEW REALIZATION OF TERRESTRIAL TIME

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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 (PFSs), whose 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 postprocessing, which is based on a weighted average of the evaluations of TAI frequency by the PFSs. 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-running 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) as a coordinate time of a geocentric reference system. 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 1st, 0 h TAI. The definition of TT was revised by the IAU in its Resolution B1.9 (2000), but the implicit difference is smaller than the uncertainty presently achieved in realizing TT. International Atomic Time TAI, the time scale established by the BIPM, is a realization of TT. 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 (PFSs) 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 a 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 conforms to its definition. 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]. 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 that 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 re-computation on a given time interval even if new data become available), it does not provide an optimal realization of TT. The BIPM, therefore, computes another realization TT (BIPM) in postprocessing **[3]**, which is based on a weighted average of the evaluations of TAI frequency by the PFSs. Several versions have been computed since the 1990s, the latest of which is TT (BIPM01) (see *ftp://62.161.69.5/pub/tai/ scale/*). Over the last 10 years, important improvement have been achieved (see Section 2) and, since 1999, 12 different primary frequency standards have provided evaluations of the TAI scale unit, 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 (see Section 3) and some of its applications are described in Section 4.

2. EVOLUTION OVER 10 YEARS: 1993-2003

We examine here the progress 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 effect on the long-term intervals (1 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 (hereafter designated by HP clocks) were introduced.

2.1 EAL STABILITY

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, over each of which we estimate a value of EAL stability, as listed in Table 1.

01/1993-04/1995: HP clocks appear, but the ensemble scale EAL does not discriminate well the best clocks. Some less stable clocks, thus, remain at the maximum weight, which decreases from about 1.4% to about 0.8% over the period, and EAL stability is not optimal.

05/1995-12/1997: HP clocks build up from 30% to about 60% of all clocks and most reach maximum weight, which decreases to 0.7% during the period. The ensemble mostly relies on them and EAL stability is greatly improved by the sheer number of good clocks.

01/1998-12/2000: The number of HP clocks only slightly increases and most reach maximum weight (0.7%). Only a slight improvement in EAL stability over this period.

01/2001 to present (Summer 2003): The number of HP clocks still slightly increases, but only the most stable reach maximum weight, which climbs to about 1% (typically 1.1% since July 2002). The improvement in EAL stability over this period is significant.

Table 1. Variance of EAL over each period, represented as the level of white frequency noise (WFN), flicker frequency noise (FFN) and random walk frequency noise (RWFN), with τ in days.

Period	WFN	FFN	RWFN
01/1993-04/1995	$100.\times10^{-30}/\tau$	1×10^{-30}	$9\times10^{-32} \times \tau$
05/1995-12/1997	$36.\times10^{-30}/\tau$	0.64×10^{-30}	$3.24\times10^{-32} \times \tau$
01/1998-12/2000	$36.\times10^{-30}/\tau$	0.36×10^{-30}	$2.56\times10^{-32} \times \tau$
01/2001-	$9.\times10^{-30}/\tau$	0.25×10^{-30}	$1\times10^{-32} \times \tau$

2.2 PRIMARY FREQUENCY STANDARDS

Much progress 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 blackbody 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). Then operational procedures have been defined to assign consistent uncertainties to measurements [2].

However, the most notable events have been the introduction of new types of primary standards: First, metrological evaluations of optically pumped PFSs were reported to the BIPM in 1995 and a few such instruments have been operational since that time. At about the same time, the first metrological evaluation of a Cs fountain was reported to the BIPM. Note, however, that such data have been regularly available only since the end of 1999 when several instruments became operational (see Table 2). A side effect has been the notable increase in the number of different PFSs available during a given year from about two in the early 1990s to about 10 presently.

Table 2 provides the main characteristics of the PFSs that have been reported in 2002 or 2003.

3. TT (BIPM2003): A NEW REALIZATION OF TT

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 [2].
- The frequency of EAL with respect to the PFSs is then estimated for each month since 1993 with the usual procedure [1], but with new estimations for the stability model of EAL as reported in Table 1. This best estimate represents f (EAL-TT).
- The series of monthly values f (EAL-TT) is smoothed (low pass filter with a cutting frequency around 2 yr^{-1}), so as to let possible yearly signatures subsist in the smoothed series f (EAL-TT)$_S$. It is estimated that yearly signatures are most likely due to EAL rather than to the PFSs, so that this procedure removes most of 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 previous realizations. This forms TT (BIPM2003), which is available at *ftp://62.161.69.5/pub/tai/scale/* in the file ttbipm.03.

Table 2. Principal characteristics of primary frequency standards reported in 2002-2003. Second column indicates Type (beam or fountain) and type of selection (Magnetic or Optical).

Primary Standard	Type/ Selection	Typical Type B Std. Uncertainty	Operation	Comparison with	Operation Period	Typical Comparison
CRL-O1	Beam /Opt.	4×10^{-15}	Discontinuous	UTC (CRL)	1998->2002	10 d
IEN CSF1	Fountain	2×10^{-15}	Discontinuous	H maser	2003->....	10 d
NIST7	Beam /Opt.	$X\times10^{-15}$	Discontinuous	H-maser	1995->2000	30 d
NIST-F1	Fountain	1×10^{-15}	Discontinuous	H maser	1999->....	30 d
PTB CS1	Beam /Mag.	8×10^{-15}	Continuous	TAI	1998->....	30 d
PTB CS2	Beam /Mag.	12×10^{-15}	Continuous	TAI	1993->....	30 d
PTB CSF1	Fountain	1×10^{-15}	Discontinuous	H maser	2000->....	15 to 30 d
SYRTE-JPO	Beam /Opt.	8×10^{-15}	Discontinuous	H maser	1999->....	30 d
SYRTE-FO2	Fountain	1×10^{-15}	Discontinuous	H maser	2002->....	5 to 15 d
SYRTE-FOM	Fountain	1×10^{-15}	Discontinuous	H maser	2002->....	30 d

Figure 1 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 the TAI 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 failed to bring the TAI frequency close to that of the PFSs, probably because of 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 µs over 10 years. The standard uncertainty of the frequency of TT (BIPM2003) decreases from $6\text{-}7\times10^{-15}$ in 1993-1994 to about 1.5×10^{-15} in 2002-2003.

4. EXAMPLES OF APPLICATION OF TT (BIPM2003)

4.1 DIFFERENCE IN PULSAR TIMING ANALYSIS OF USING TAI VS. TT (BIPM2003)

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 **[4]**. 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, thus, useful to estimate in what respect time scales like TAI or TT (BIPM2003) 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 2). This compares to a timing noise that may be as low as a few hundred ns in the best cases, so it is not negligible. In addition, such an effect could be larger for a longer analysis (in principle, 20 years of data are available for the first discovered millisecond pulsars). In practice, however, the timing noise and some other long-term effects are generally larger than this level for most pulsars. Nevertheless, it is always advised to use a postprocessed time scale like the new TT (BIPM2003) for pulsar analysis, rather than a scale available in real time, such as TAI, GPS time, or a local atomic time scale realized by a single time laboratory.

4.2 COMPARISON OF CS FOUNTAIN DATA TO TT (BIPM2003)

Half a dozen Cs fountains from four different laboratories have contributed to the estimation of EAL frequency over the past years. Direct comparison of two fountains operating simultaneously is sometimes possible and is optimal in reducing the uncertainty brought by the comparison method **[5]**. However, Cs fountains are generally operated intermittently and it is rarely possible to directly compare them, because their operation is not simultaneous. The most convenient way to intercompare them is then to use a common reference that is as accurate and stable as possible. Here, TT (BIPM2003) has been used as a reference to express the frequency of the best PFS reported to the BIPM in the past years. Figure 3 shows all values of the difference f (PFS) – f (TT (BIPM2003)) for nine different standards, including five Cs fountains. For clarity, the uncertainty values are not reported in Figure 3, but Figure 4 shows the values f (PFS) – f (TT (BIPM2003)) normalized by the total uncertainty of the frequency comparison (as computed and published by the BIPM). It may be seen that, for some recent PFS measurements, the frequency difference with TT (BIPM2003) is somewhat larger than its uncertainty and varies significantly from one measurement to the next. The source of this effect is under study. Possible causes are: systematic effects due to the reference clock (for those PFSs that have significant dead time in their operation); undetected systematic or slowly varying effects in time transfer techniques; or undetected variations of the PFS frequency itself.

5. CONCLUSIONS

We compute a postprocessed 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 that is at, 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 intended to provide our best realization of

Terrestrial Time. It is, therefore, most suited as a reference for the analysis of millisecond pulsar data. It also allows one to compare the measurements of primary frequency standards that are presently sparse and rarely simultaneous. It is expected that the accuracy of PFS will progress rapidly in the coming years. Progress in time scale formation and in time transfer techniques should accompany the progress in primary frequency standard technology to bring the accuracy of TT (BIPM) and the uncertainty on the TAI frequency below 1×10^{-15} in the near future.

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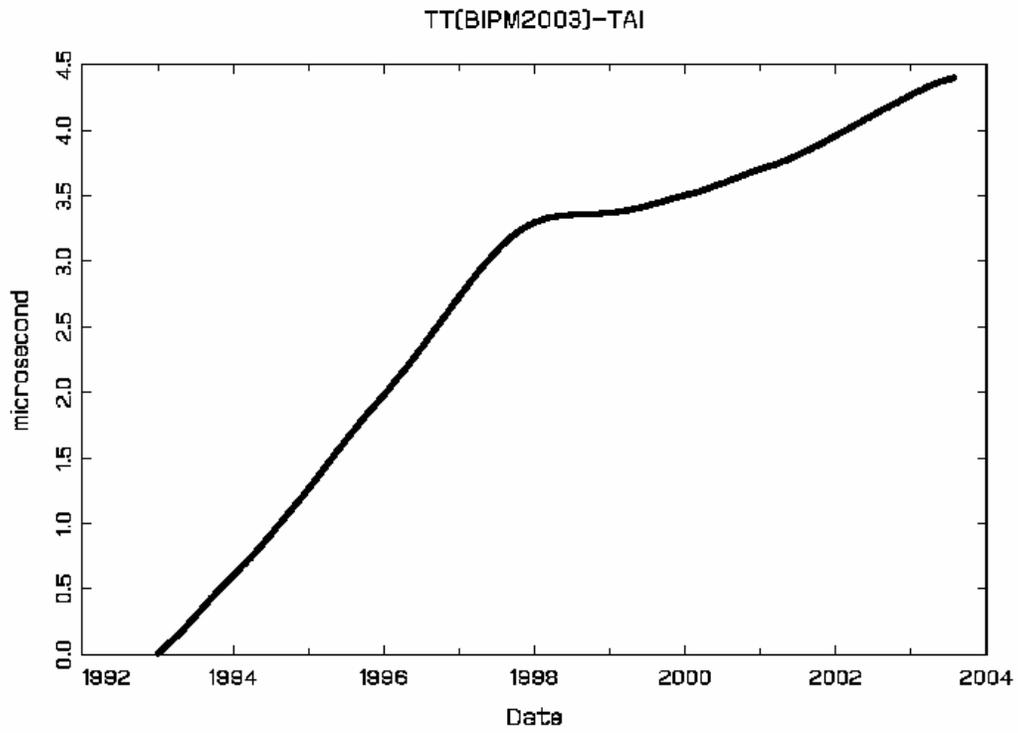
Figure 1. Difference between TT (BIPM2003) and TAI over 1993-2003 (with an offset removed).
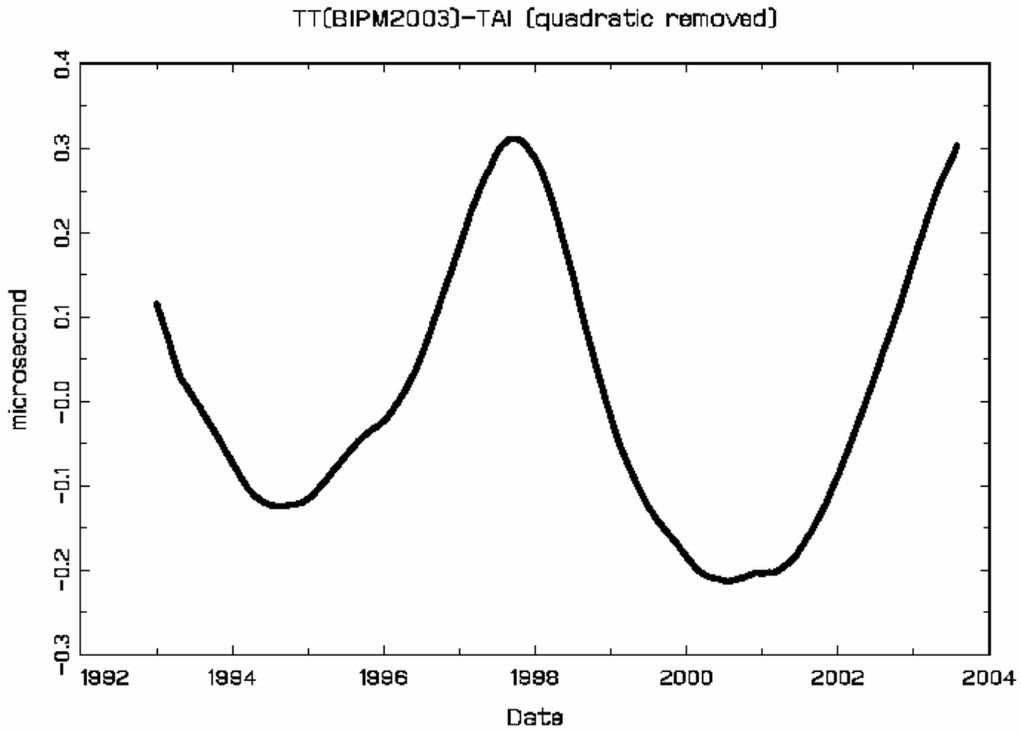
Figure 2. Effect on pulsar analysis of using TT (BIPM2003) or TAI as a reference.
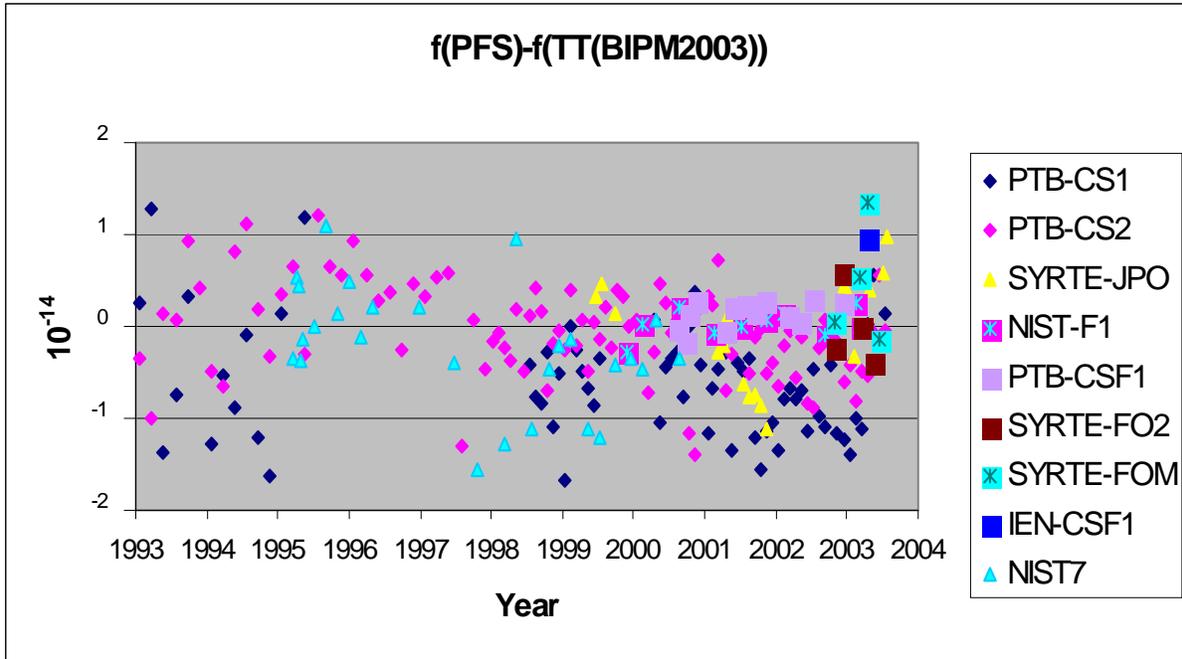
Figure 3. f (PFS – TT (BIPM2003)) for all measurement of nine primary frequency standards over 1993-2003.

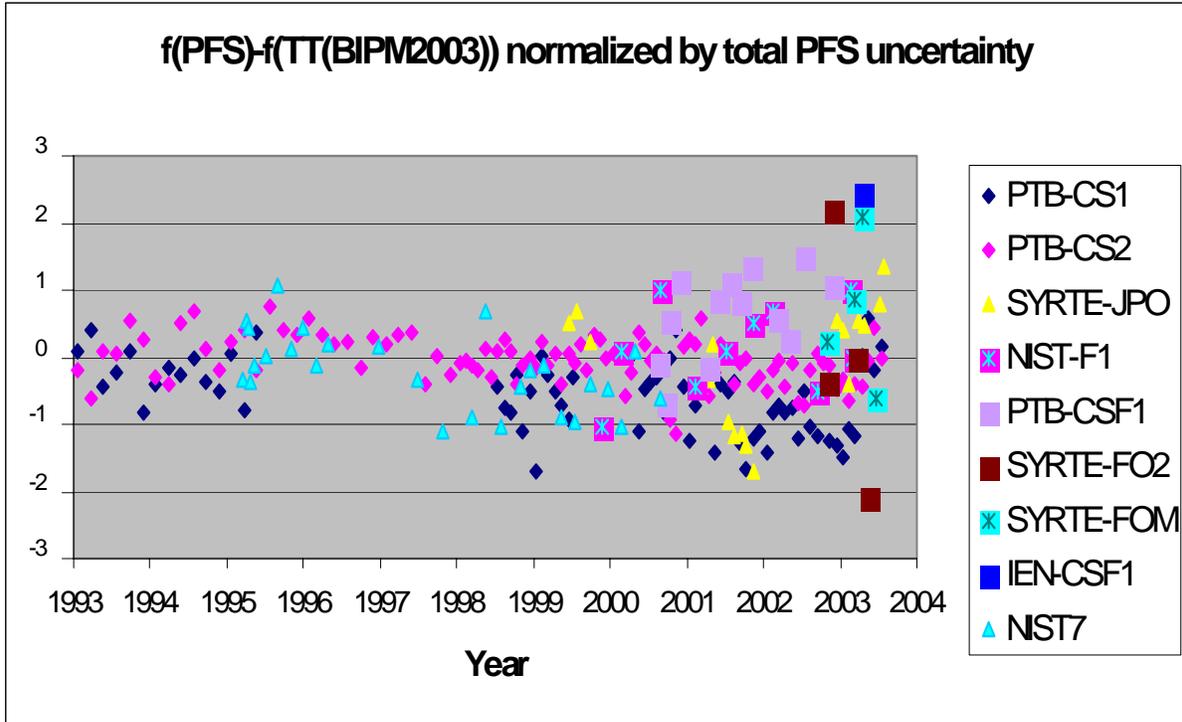Figure 4. f (PFS – TT (BIPM2003)) normalized: data of Figure 3 divided by their total standard uncertainty.

QUESTIONS AND ANSWERS

DEMETRIOS MATSAKIS (U.S. Naval Observatory): I just wondering if the time series is going to be available on your anonymous Web site. Or how are you going to distribute it?

ZHIHENG JIANG (for GERARD PETIT; Bureau International des Poids et Mesures): It will probably be published somewhere, no problem.