Rapport BIPM-98/2

BUREAU INTERNATIONAL DES POIDS ET MESURES

WEIGHTING FACTORS ATTRIBUTED TO MEASUREMENTS OF PRIMARY FREQUENCY STANDARDS IN ESTIMATING THE ACCURACY OF TAI

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Abstract

At its 2nd meeting, held in Long Beach, California, on 4 December 1997, the CCTF Working Group on the Expression of Uncertainties in Primary Frequency Standards requested from the BIPM Time Section information on the weighting factors attributed to measurements of primary frequency standards in the estimation of the accuracy of International Atomic Time, TAI. This report, drawn up in answer to this request, explains and interprets the values of the weights assigned to measurements of FO1 (the BNM-LPTF fountain), NIST-7 (the NIST optically pumped standard), and PTB CS2 (one of the classical PTB standards) in the estimates of the accuracy of TAI which cover the year 1997.

Résumé

Le Groupe de travail du CCTF sur l'expression des incertitudes des étalons primaires de fréquence s'est réuni pour la deuxième fois à Long Beach, en Californie, le 4 décembre 1997. Lors de cette réunion, le Groupe de travail a demandé à la Section du temps du BIPM de fournir des informations relatives aux poids attribués aux mesures provenant d'étalons primaires de fréquence, dans le calcul de l'estimation de l'exactitude du Temps atomique international TAI. Ce rapport, écrit en réponse à cette requête, explique et donne une interprétation des valeurs des poids attribués aux résultats de trois étalons primaires dans les estimations de l'exactitude de TAI calculées pour 1997. Ces trois étalons sont la fontaine du BNM-LPTF, FO1, l'étalon à pompage optique du NIST, NIST-7, et l'un des étalons classiques de la PTB, PTB CS2.

INTRODUCTION

By definition, the duration of the TAI scale unit, u, should be as close as possible to the SI second on the rotating geoid, u_0. The accuracy of International Atomic Time, TAI, may thus be described by the relative difference d, together with its uncertainty σ, between u and u_0:

$$d = \frac{u - u_0}{u_0}. \qquad (1)$$

The BIPM regularly receives measurements from a number of accurate primary frequency standards. Each individual frequency measurement, i, is corrected for all known corrections and delivers a realization, u_{0i}, of the SI second on the rotating geoid, valid over the calibration interval denoted I_{Ci} and defined by its length τ_{Ci} and its central date t_{Ci}. The comparison between the duration of the TAI scale interval with u_{0i}, over I_{Ci}, provides an estimation d_i of d, with an uncertainty, σ_i, equal, in most cases, to the type B uncertainty of the standard, σ_{Bi}, determined by the laboratory:

$$d_i = \frac{u - u_{0i}}{u_{0i}}. \qquad (2)$$

The BIPM thus has at its disposal a number of individual calibrations (d_i, σ_i) which are regularly published in *Circular T*.

The individual measurements can also be treated in a global way in order to deliver a more accurate value of d for any interval of estimation, I_E, defined by its length τ_E and its central date t_E (Note: I_E depends only upon the dates of computation of TAI and thus does not include the index i). This global treatment operates with preceding and following calibrations taking place over intervals I_{Ci} included or not in I_E, even partially overlapping with I_E, and for which $t_E - t_{Ci}$ may be positive or negative. It is thus necessary to transfer temporally, over $|t_E - t_{Ci}|$, the individual calibrations (d_i, σ_i). In the temporal transfer the values d_i are kept constant but the values σ_i are increased. The additional uncertainty is due to the instability, over $|t_E - t_{Ci}|$, of the continuous time scale which ensures the temporal transfer from calibration intervals to estimation intervals. It is thus important to chose the most stable of the time scales the BIPM produces as the transfer time scale. The free atomic time scale EAL plays this role. It follows that the basic measurements which are used are not d_i, related to TAI, but the equivalent related to EAL. In practice, laboratories provides frequency measurements, so the result of interest is the relative frequency departure of EAL with respect to the frequency, f_{0i}, produced in measurement i. This is referred to as b_i:

$$b_i = \frac{f - f_{0i}}{f_{0i}}, \qquad (3)$$

where f is the frequency of EAL over the interval of calibration I_{Ci}. The uncertainty of b_i is σ_i.

After temporal transfer to the chosen interval I_E, calibrations b_i are combined to obtain b and σ valid over a given I_E. In this combination a weighting factor, ω_i, is assigned to measurement b_i:

$$b = \sum_{i=1}^{N} \omega_i b_i , \qquad (4)$$

with

$$\sum_{i=1}^{N} \omega_i = 1, \ \omega_i \geq 0. \qquad (5)$$

Here N is the number of individual measurements b_i.

Individual measurements are considered to be independent from one another.

The value d is deduced from the known relationship between the frequencies of EAL and TAI, b_S, over I_E:

$$d = b_S - b. \qquad (6)$$

The value of b_S is given by the sum of all frequency steering corrections applied from the beginning of TAI computation to I_E.

In practice, this global treatment is not an easy task because the time scale is affected by different types of noise according to the length of time involved, and because the system is not stationary since the time-scale stability improves with the passing of time. In addition, the combination of transferred calibrations given in (4) should be optimized in order to obtain the best global estimate (that with the smallest possible uncertainty). This problem was solved in 1977 by Azoubib, Granveaud and Guinot [1] (The question of temporal transfer is also treated in [2]). An expression of the uncertainty generated by the combination of transferred calibrations is given in [1] (page 89). This involves the weighting factors, ω_i, and a number of other parameters:

- the uncertainty σ_i of each measurement b_i,
- a model for the stability of the time scale EAL*,
- the length of individual calibration intervals τ_{Ci},
- the length of the estimation interval τ_E,
- the length of the time intervals $|t_E - t_{Ci}|$ separating the calibration intervals and the estimation interval.

By minimizing this uncertainty it is possible to determine the weighting factors ω_i and obtain a value for σ corresponding to the computed minimum. The weighting factors are then used in (4) and (6) to compute d.

The method described in [1] is applied at the BIPM and provides the regular estimations of d and σ which are published in successive issues of *Circular T* and of the *Annual Report of the BIPM Time Section*. The purpose of this report is to explain and interpret the values of the weighting factors, ω_i, attributed to individual measurements from primary frequency standards when estimating the accuracy of TAI in 1997.

* To estimate the accuracy of TAI in 1997, the model chosen to describe the stability of the time scale EAL included three noise types: white frequency modulation (WFM), flicker frequency modulation (FFM) and random walk frequency modulation (RWFM). In terms of Allan deviation, the chosen noise levels were: $\sigma_{y\mathrm{WFM}}(\tau = 1\ \mathrm{d}) = 1{,}4 \times 10^{-14}$, $\sigma_{y\mathrm{FFM}} = 4{,}5 \times 10^{-15}$, and $\sigma_{y\mathrm{RWFM}}\ (\tau = 1\ \mathrm{d}) = 0{,}4 \times 10^{-15}$. This model has been changed starting March 1998.

1. CONDITIONS OF THE ESTIMATION OF TAI ACCURACY IN 1997

The characteristics of the estimation intervals, I_E, used in the calculation of TAI accuracy over 1997, are shown in Table 1 (upper-right part of the Table, entitled 'Estimation'). They correspond to the successive two-month intervals used for the TAI computation and are identified with their central date t_E and their length τ_E. Also shown in this part of the table is the frequency of EAL with respect to TAI, b_S. As cumulative steering corrections were used to compensate for the 'black-body' step, b_S is not constant over 1997.

An important point to note is that this report is based on the results published in the *Annual Report of the BIPM Time Section*, volume 10, for 1997. When editing the *Annual Report of the BIPM Time Section*, volume 11, for 1998, the estimates of TAI accuracy will be recomputed taking into account measurements from primary standards which became available in 1998. This may lead to changes in the assigned weights, especially for the estimates covering the second half of 1997.

2. MEASUREMENTS FROM PRIMARY FREQUENCY STANDARDS

The BIPM regularly receives frequency measurements from a number of accurate primary frequency standards. In this report we constrain the set of measurements to those carried out after December 1995. They were provided by the BNM-LPTF caesium fountain FO1, the optically pumped caesium standard NIST-7 and the classical standard PTB CS2. The classical standard PTB CS3 also provided frequency measurements over this period, a matter which is discussed at the end of this Section.

The characteristics of the measurements provided by the primary frequency standards FO1, NIST-7 and PTB CS2 are given in Table 1 (lower-left part of the Table, entitled 'Measurements'). Each calibration interval is identified by its central date, t_{Ci}, and its length, τ_{Ci}. The values of b_i and σ_{Bi} are also reported for each measurement i. As already noted, the global uncertainty σ_i of b_i is usually very close to σ_{Bi}. However, in some cases, it may be necessary to take into account other uncertainty components. These arise from:

- the instability (type A uncertainty, σ_{Ai}, also reported in Table 1) of the primary frequency standard over I_{Ci},
- the frequency comparison between the primary standard and the local oscillator inside the laboratory, usually a hydrogen maser, and
- the link between the laboratory and the global GPS network used for TAI computation.

In practice, the design of the algorithm used at the BIPM is such that only two components of uncertainty can be introduced for each measurement: σ_{Ai} and σ_{Bi}. The parts of uncertainty coming from the local oscillator and from the outside link are estimated by the BIPM and added (in a quadratic way) to σ_{Ai}. The σ_{Bi} values are those indicated by the laboratory operating the primary standard.

The measurements quoted in Table 1 can be described as follows:

- The measurements provided by the FO1 can be split in two groups. Three measurements were taken in May 1996 (around 50215). For each, the length of the calibration interval was 5 days, and the type B uncertainty was 0.3×10^{-14} (value given by the BNM-LPTF). The fourth measurement covers 30 days centred on 50769 (November 1997). The value of

σ_{Bi} given by the BNM-LPTF for this measurement is 0.22 x 10^{-14}*. The FO1 did not work continuously over these periods of calibration. Rather, it produced a number of frequency measurements relative to the internal BNM-LPTF hydrogen maser, often averaged over about 10 hours. The possible instability of the hydrogen maser between successive measurements and the link between the BNM-LPTF and the outside global network (especially for 5 day measurements) is taken into account in the σ_{Ai} values.

- Six NIST-7 measurements have been available since the end of 1995. The calibration intervals are 5 day or 10 day duration, and match the time intervals between TAI updates (MJD ending in 4 and 9). The six measurements are spaced at nearly equal intervals from December 1995 to December 1997, and the type B uncertainties given by the NIST range from 0.5 x 10^{-14} to 1.0 x 10^{-14}. The type A uncertainty is given by the NIST, an additional component takes into account the link between the NIST and the outside global network.
- Since PTB CS2 operates continuously, the calibration intervals are strictly the estimation intervals of TAI accuracy. The type B uncertainty of the standard is usually 1.5 x 10^{-14}, except for the measurement centred on MJD 50659 (July-August 1997) for which the type B uncertainty is 2.7 x 10^{-14}. These type B uncertainty values were provided by the PTB. The BIPM estimates the type A uncertainty for each measurement: it has been temporarily increased over the second half of 1997.

The primary standard PTB CS3 has a type B uncertainty of 1.4 x 10^{-14} and has produced measurements covering the same calibration intervals as PTB CS2. Unfortunately, large frequency steps were observed in PTB CS3 data in September 1996 (about 3 × 10^{-14}) and March 1997 (about 1.5 × 10^{-14}), so its type A uncertainty is much larger than its type B uncertainty over the period under study. It follows that the weighting factors assigned to individual PTB CS3 measurements when estimating the accuracy of TAI are very small (less that 0.5%). For this reason Table 1 does not refer to measurements from PTB CS3. It is important to note that future improvements in the stability of PTB CS3 would allow it to gain weight when estimating the accuracy of TAI.

3. WEIGHTING FACTORS

The weighting factors, ω_i, assigned to individual measurements, *i*, are given in Table 1, in the form of relative weights expressed in percent (referred to as weights in the following). Since the weights attributed to PTB CS3 measurements are not reported:

- the sum of the weights (along one column) is less than 100%,
- the equation:

$$d = b_S - \sum_i \omega_i b_i \qquad (7)$$

applied to data from Table 1, does not give exactly the same values of *d* than those published in the *Annual Report of the BIPM Time Section* for 1997 (Table 7 of volume 10, p. 37).

3.1 Weights of PTB CS2 measurements

The weights attributed to the twelve measurements of PTB CS2 retained for this study are reported in Figure 1. They can be identified by their central dates reported on the X axis. In

* The algorithm used for estimation of TAI accuracy until 1997 could not accept uncertainty values with digits corresponding to parts in 10^{16}, so the value introduced was 0.3 x 10^{-14}. This has been corrected starting March 1998.

Figure 1, six curves have been drawn, each joining the weights of individual measurements in one estimate of the accuracy of TAI carried out over 1997.

Figure 1 shows that, in general, the individual measurement carried out during the chosen estimation interval, receives the highest weight. This is apparent for instance in the red, pink or yellow curves, and is reinforced in the special case of PTB CS2 for which the calibration and estimation intervals match the same temporal grid. There is one exception: the PTB CS2 measurement carried over July-August 1997 (central date MJD 50659) is not assigned the highest weight in the green curve related to the estimation over the same interval. This has its origin in the poor quality of this particular measurement, which is characterized by a high uncertainty.

The highest weight assigned to any individual PTB CS2 measurement is about 20% and is strongly dependent on the availability of measurements from other primary standards with central dates lying inside the estimation interval.

Although PTB CS2 is not the most accurate primary standard to report data to the BIPM, the total weight of its measurements taken in 1996 and 1997 amounts to 57% in the estimation for January-February 1997 (which can be regarded as definitive). This shows that the regularity of PTB CS2 measurements compensates for its lack of accuracy. This is a very important point: safe estimation of the accuracy of TAI needs numerous and regular measurements.

3.2 Weights of NIST-7 measurements

Figure 2 is similar to Figure 1 for the six NIST-7 measurements which cover the period December 1995 to November 1997. Figure 2 is more difficult to interpret because the calibration and estimation intervals do not coincide. In addition, the lengths of the calibration intervals and the uncertainty of measurements vary from one measurement to another. However, Figure 2 can be described as follows:

- There exists one NIST-7 measurement (centred on MJD 50444) which lies entirely within the estimation interval January-February 1997 (red curve). For that particular estimate, this measurement is assigned its highest weight, 17.2%.
- No NIST-7 measurements lie within the estimate interval March-April 1997 (pink curve), but two measurements (centred on MJD 50444 and 50624) lie close to it, one on each side. For that particular estimate, they are assigned weights of 7.9% and 9.4%.
- One NIST-7 measurement (centred on MJD 50624) lies entirely within the estimation interval May-June 1997 (yellow curve). It was obtained at the end of June so it is close to the border with the following estimation interval. For the estimation covering May-June 1997, it is assigned its highest weight, 22.2%. This is also the highest weight assigned to any individual NIST-7 measurement in 1997. The reason is the high quality of the standard for that particular measurement, since it is characterized by a smaller uncertainty than other measurements in 1997.
- No NIST-7 measurements lie within the estimation interval July-August 1997 (green curve), but the measurement centred on MJD 50624 is very close to it. For that particular estimation, it is assigned a weight of 19.5%.
- A single NIST-7 measurement (centred on MJD 50744) lies within the estimation interval September-October 1997 (blue curve). It was obtained at the end of October, so lies at the border with the following estimation interval. For the estimation covering September-October 1997, it is assigned its highest weight, 14.3%. This value is smaller than the values (22.2% and 19.5%) assigned to earlier NIST-7 measurements which lie within the

interval of estimation, the reason being that FO1, a standard more accurate than NIST-7, provided measurements in November 1997.

- No NIST-7 measurements exist within the estimation interval November-December 1997 (black curve), but the measurement centred on MJD 50744 is very close. For that particular estimation, this measurement is assigned a weight of 5.4%, a relatively small value because FO1 provided one measurement in November 1997.

Figure 2 confirms the conclusions already suggested by Figure 1; individual measurements carried out over calibration intervals lying entirely within the chosen estimation interval, are assigned their highest weight for this estimate. The values of the weights depend strongly on the availability of measurements from other primary standards with central dates which lie within the estimation interval, and on the quality of the measurement itself.

In 1997, the NIST-7 measurements were not numerous but, because they were equally spread all over the year, they had a non-negligible impact on each of the six estimates of the accuracy of TAI made over this year.

3.3 Weights of FO1 measurements

Only one FO1 measurement was reported in 1997. It is entirely included inside the estimation interval November-December 1997 and thus has a high weight in this estimation, 73.9%. This value is very large with respect to the others quoted in this report because FO1 is more accurate than the other standards.

Figure 3 shows the variation of the weight of the November FO1 measurement in the six estimations of the accuracy of TAI which took place in 1997 (red curve): this weight exceeds 5.7% throughout the year. This means that this particular measurement has an influence on the estimation of the accuracy of TAI for more than one year in arrears and will have a significant influence for another year, unless additional measurements become available from FO1 or another ultra-accurate standard in the course of 1998.

The two curves added to Figure 3 represent the weights in successive estimations of TAI accuracy of two particular measurements: the NIST-7 measurement centred on 50624 (blue curve) and the PTB CS2 measurement covering March-April 1997 (green curve). As already noted, the highest weight for each measurement is obtained when the calibration interval lies within the estimation interval; the weights depend strongly on the uncertainty of the measurement itself and on the presence of other measurements. In general, there is no simple relationship between σ_i and ω_i.

4. RESULTS OF THE ESTIMATION OF TAI ACCURACY IN 1997

The values of d and σ characterizing the estimates of TAI accuracy in 1997 are included in Table 1 (upper-right part of the Table).

In 1997, the smallest value of σ, which corresponds to the most accurate determination of the departure of the TAI scale interval from the SI second on the rotating geoid, is obtained for the interval November-December, for which a measurement from FO1 is available. The estimate thus relies mainly on the measurement from FO1 which is assigned a weight of 73.9%. The value of σ, 0.5 x 10^{-14}, is only slightly larger than the uncertainty of the FO1 measurement. The value obtained for d, 1.0 x 10^{-14}, is directly deduced from the measurement

b_i, 70.7 x 10^{-14}, corresponding to the FO1 measurement, taking into account the value of b_S in November-December 1997, 71.7 x 10^{-14}. The same simple relation applies for the estimate covering September-October 1997, in which the weight of the same FO1 measurement is also very high, 39.4%.

In general, values of d and σ decrease throughout 1997, indicating that TAI is progressively more accurate: the departure of its scale unit from the SI second on the rotating geoid is smaller because steering corrections were applied and is better known because FO1 data became available at the end of the year.

5. CONCLUSIONS

The determination of the weighting factors assigned to measurements of primary frequency standards in the estimation of the accuracy of TAI is complex and results from a global treatment involving the uncertainty of each measurement, a model for the stability of EAL, the length of calibration and estimation intervals, and the length of the time interval separating the calibration intervals and the estimation intervals. The highest weights, however, are always attributed to measurements from the most accurate standards, and to the data for which the calibration intervals lie within the chosen estimation interval.

The knowledge of the accuracy of TAI depends critically on the accuracy of the measurements made available to the BIPM. A single measurement of extremely high accuracy is of great help for its determination, but less accurate measurements presented in a regular series are also very valuable and are strongly to be encouraged.

The accuracy of TAI is estimated by the BIPM over successive two-month intervals corresponding to the bimesters January-February, March-April, etc. The 'real-time' estimates published in *Circular T* are never definitive because the optimal values are always subject to change in the light of subsequent additional measurements. The uncertainty values published in *Circular T* are thus conservative (1.0 x 10^{-14} in 1997). Refined estimates are given in successive volumes of the *Annual Report of the BIPM Time Section*. The uncertainties published in these volumes are smaller because we take advantage of data post-processing. The same post-processed treatment can be applied for any estimation interval different from the usual bimesters, on simple request to the BIPM Time Section. An example of application may be the determination of the absolute frequency of a very stable cold-ion standard [3].

References

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[2] Douglas R.J., Boulanger J.-S, Cundy S., Gagné M.-C., Cazemier W., Hoger B., Pelletier R., Bernard J., Madej A.A., Marmet L., Siemsen K., Whitford B.G., *Proc. 28th PTTI*, 1996, 65-74.

[3] Berkeland D.J., Miller J.D., Bergquist J.C., Itano W.M., Wineland D.J., *Phys. Rev. Let.*, 1998, **80**, 10, 2089-2092.

Table 1. Weighting factors

Weights, expressed in percent, assigned to measurements of primary frequency standards in the estimation of the accuracy of TAI for 1997:

- The intervals of estimation, I_E, are specified by their central dates, t_E, and their lengths, τ_E.
- The intervals of calibration, I_{Ci}, are specified by their central dates, t_{Ci}, and their lengths, τ_{Ci}.
- The quantity b_S is the relative departure of the frequency of EAL from the frequency of TAI over I_E (sum of the steering corrections applied until t_E).
- The quantity b_i is the relative departure of the frequency of EAL from the frequency of a primary frequency standard measured over I_{Ci}.
- The quantity σ_{Bi} is the type B uncertainty (1 σ) of the primary frequency standard as declared by the laboratory for measurement over I_{Ci}.
- The quantity σ_{Ai} is the type A uncertainty (1 σ) of the primary frequency standard over I_{Ci}, with eventual additional components due to the internal link between the standard and the local oscillator, and the outside link between the laboratory and the global GPS network used in TAI computation.
- The quantity ω_i is the weight, expressed in percent, assigned to measurement over I_{Ci}.
- The quantity d is the relative departure of the TAI scale unit from the SI second on the rotating geoid, as published in the *Annual Report of the BIPM Time Section* for 1997.
- The quantity σ is the uncertainty (1 σ) on the d value, as published in the *Annual Report of the BIPM Time Section* for 1997.

Colors are identical to those of Figures 1 and 2. They highlight those measurements, and the assigned weights, which are entirely included in one of the estimation intervals of 1997.

Table 1.
Weighting factors

						Estimation					
				Interval I_E		**Jan-Feb 97**	**Mar-Apr 97**	**May-Jun 97**	**Jul-Aug 97**	**Sep-Oct 97**	**Nov-Dec 97**
				Cent. date t_E	MJD	50474	50534	50596,5	50659	50719	50779
				Length τ_E	/ d	60	60	65	60	60	60
				b_S	/ 10^{-14}	72.65	72.5	72.3	72.1	71.9	71.7
				d	/ 10^{-14}	2.6	2.4	2.1	1.7	1.2	1.0
				σ	/ 10^{-14}	0.7	0.8	0.7	0.8	0.7	0.5
Measurements											
Standard	Cent. date t_{Ci} MJD	Length τ_{Ci} / d	σ_{Ai} / 10^{-14}	σ_{Bi} / 10^{-14}	b_i / 10^{-14}	ω_i / %					
FO1	50211,5	5	0.5	0.3	70.1	1.8	1.4	1.1	0	0	0
FO1	50216,6	5	0.5	0.3	70.9	1.4	1.1	0.9	0	0	0
FO1	50221,5	5	0.5	0.3	71.4	1.3	1.1	0.9	0	0	0
FO1	**50769**	30	0.3	0.3	70.7	5.7	9.2	13.3	25.2	39.4	**73.9**
NIST-7	50081,5	5	0.4	1.0	70.9	0.5	0	0	0	0	0
NIST-7	50146,5	5	0.4	1.0	71.2	0.7	1.0	0	0	0	0
NIST-7	50204	10	1.0	0.5	70.7	0.9	0.8	0.7	0	0	0
NIST-7	**50444**	10	0.9	1.0	70.0	**17.2**	7.9	4.3	3.0	1.8	0.9
NIST-7	50624	10	1.0	0.7	70.6	5.2	9.4	22.2	19.5	8.2	2.6
NIST-7	**50744**	10	1.0	1.0	72.2	1.2	2.0	2.9	5.9	**14.3**	5.4
PTB CS2	50109	60	0.6	1.5	70.3	0.5	0	0	0	0	0
PTB CS2	50169	60	0.6	1.5	70.5	0.6	0.6	0	0	0	0
PTB CS2	50231,5	65	0.6	1.5	70.6	1.0	0.8	0.6	0	0	0
PTB CS2	50294	60	0.6	1.5	70.2	3.0	2.1	1.3	1.8	0	0
PTB CS2	50354	60	0.6	1.5	70.7	5.2	3.5	2.1	1.9	1.5	0
PTB CS2	50414	60	0.6	1.5	69.9	9.0	5.3	3.0	2.3	1.5	0.8
PTB CS2	**50474**	60	0.6	1.5	69.9	**19.4**	10.7	5.3	3.4	2.0	0.9
PTB CS2	**50534**	60	0.6	1.5	69.7	10.7	**21.7**	10.5	5.8	3.1	1.2
PTB CS2	50596,5	65	0.6	1.5	69.7	5.2	10.5	18.5	9.8	4.7	1.6
PTB CS2	50659	60	2.0	2.7	71.7	0.7	1.3	2.2	**5.2**	2.4	0.6
PTB CS2	**50719**	60	1.0	1.5	70.5	1.4	2.4	3.7	8.2	**13.7**	3.2
PTB CS2	**50779**	60	1.0	1.5	71.2	0.5	0.8	1.2	2.2	3.2	**7.1**

Figure 1. Weights of PTB CS2 measurements taken from January 1996 to December 1997 in the successive estimations of TAI accuracy carried out in 1997.

The continuous lines do not correspond to calculated curves; they are simple visual aids.

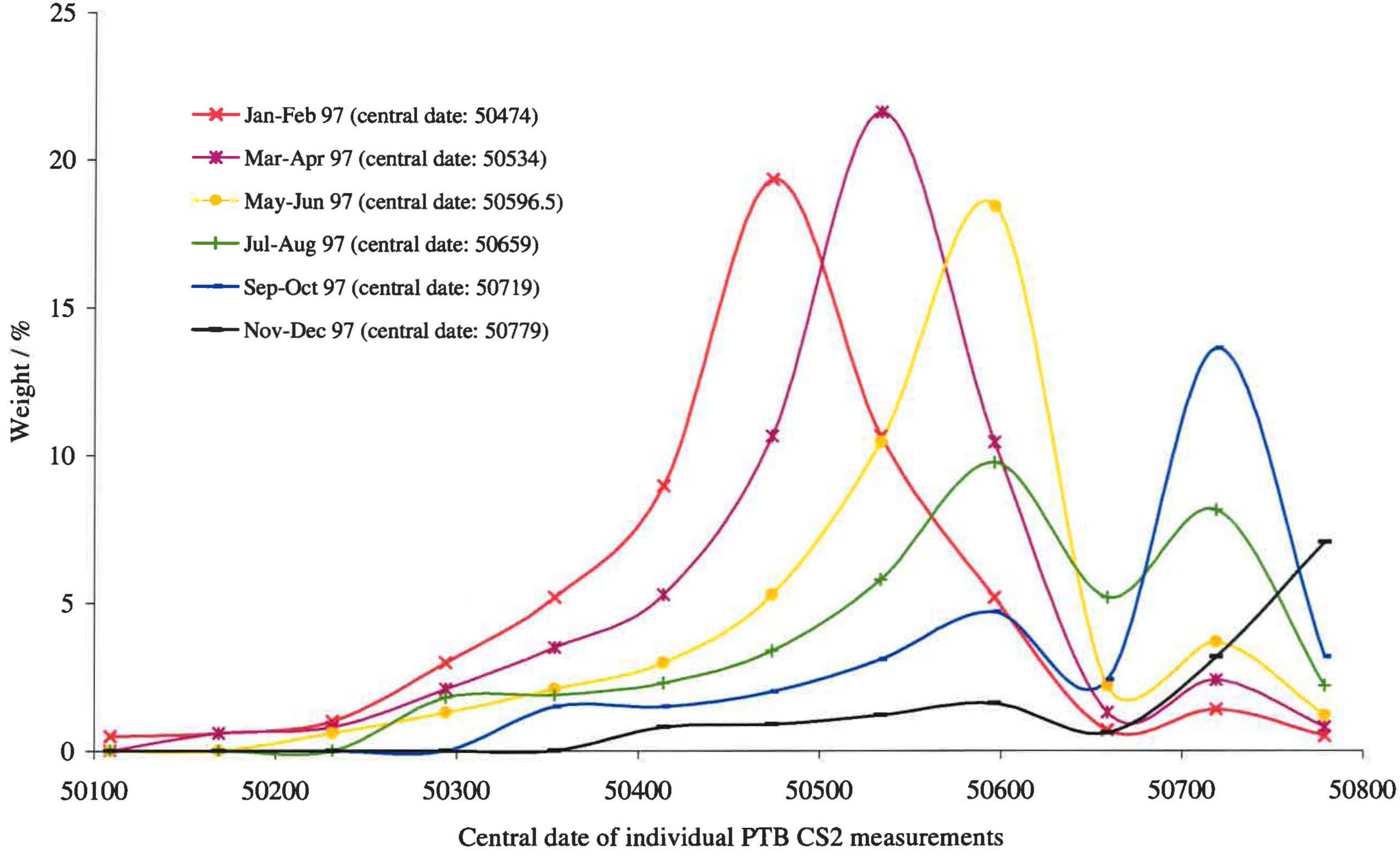

Figure 2. Weights of NIST-7 measurements taken from December 1995 to November 1997 in the successive estimations of TAI accuracy carried out in 1997.
The continuous lines do no correspond to calculated curves; they are simple visual aids.

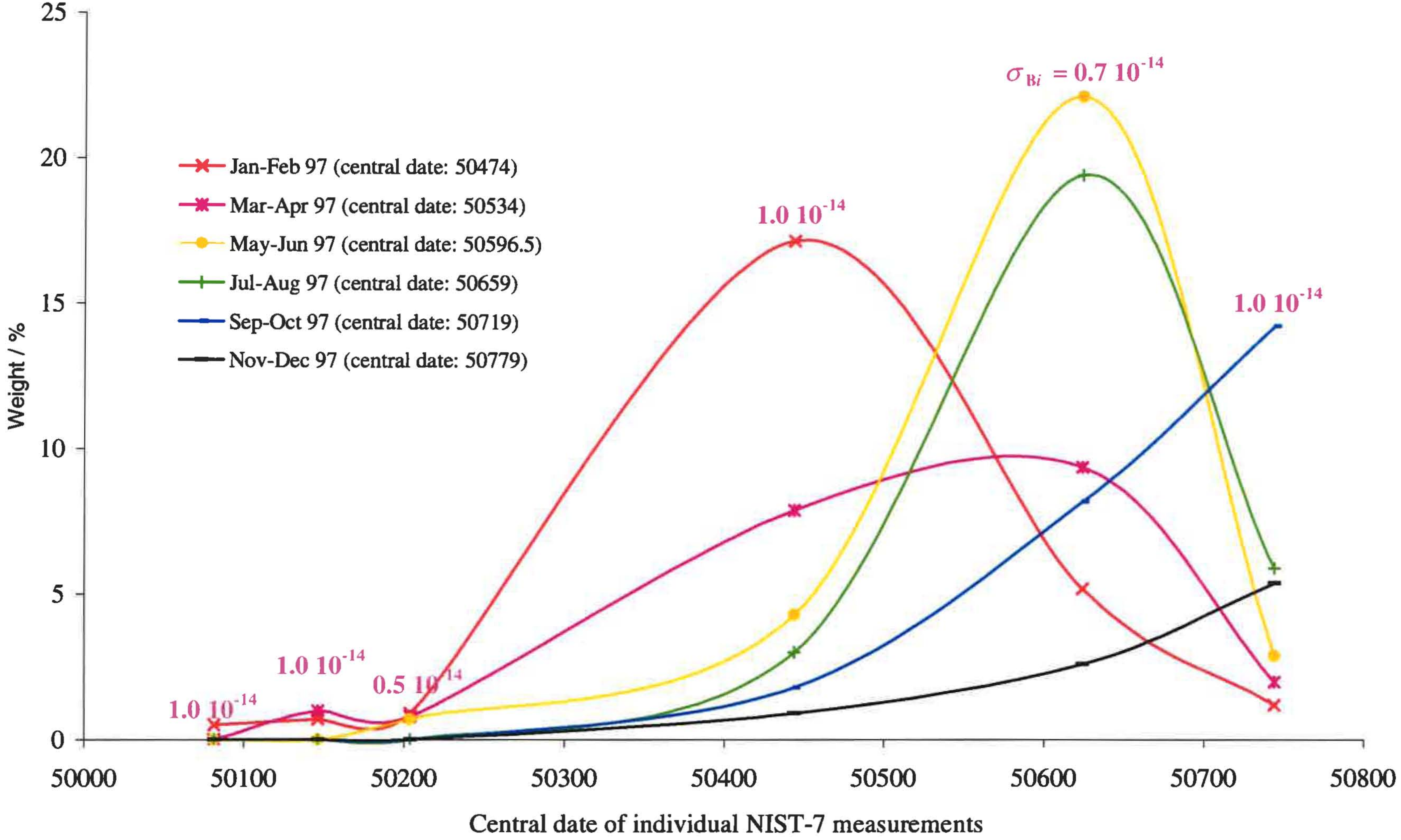

Figure 3. Weights in successive estimations of TAI accuracy carried out in 1997 of three individual measurements.

The continuous lines do not correspond to calculated curves; they are simple visual aids.