UPPER LIMIT OF WEIGHTS IN TAI COMPUTATION

Claudine Thomas and Jacques Azoubib
Bureau International des Poids et Mesures
Pavillon de Breteuil
92312 Sèvres Cedex
France

Abstract

The international reference time scale TAI computed by the BIPM relies on a weighted average of data from a large number of atomic clocks. In it, the weight attributed to a given clock depends on its long-term stability. In this paper the TAI algorithm is used as the basis for a discussion of how to implement an upper limit of weight for clocks contributing to the ensemble time. This problem is approached through the comparison of two different techniques:

- *In one case, a maximum relative weight is fixed: no individual clock can contribute more than a given fraction to the resulting time scale. The weight of each clock is then adjusted according to the qualities of the whole set of contributing elements.*

- *In the other case, a parameter characteristic of frequency stability is chosen: no individual clock can appear more stable than the stated limit. This is equivalent to choosing an absolute limit of weight and attributing this to the most stable clocks independently of the other elements of the ensemble.*

The first technique is more robust than the second and automatically optimizes the stability of the resulting time scale, but leads to a more complicated computation. The second technique has been used in the TAI algorithm since the very beginning.

Careful analysis of tests on real clock data shows that improvement of the stability of the time scale requires revision from time to time of the fixed value chosen for the upper limit of absolute weight. In particular, we present results which confirm the decision of the CCDS Working Group on TAI to increase the absolute upper limit by a factor 2.5. We also show that the use of an upper relative contribution further helps to improve the stability and may be a useful step towards better use of the massive ensemble of HP 5071A clocks now contributing to TAI.

1 INTRODUCTION

The Bureau International des Poids et Mesures, BIPM, is responsible for the generation of worldwide reference time scales, among them International Atomic Time, TAI, and Coordinated Universal Time, UTC. The TAI relies basically on measurements taken from commercial atomic clocks and primary frequency standards maintained in national timing centers. Since 1977, the procedure used for combining these data has been carried out in two steps:

193

- The first step in the generation of TAI is the computation of the free atomic time scale, EAL (échelle atomique libre), obtained as a weighted average of a large number N of free-running and independent atomic clocks spread worldwide. The corresponding algorithm, ALGOS, is optimized for long-term stability and postprocesses measurements taken over a basic sample period of $T = 60$ d[1, 2, 3].

- In a second step, TAI is derived from EAL by frequency steering with the aim of maintaining the accuracy of its scale unit. The steering corrections, determined by comparing the EAL frequency with primary frequency standards, are of the same order of magnitude as the EAL instability[4, 5].

The relative weight ω_i attributed to a given clock H_i reflects its long-term stability. It uses clock measurements covering a full year and is designed to deweight both clocks which are highly sensitive to seasonal changes and hydrogen masers which show a large frequency drift. In practice, ω_i is proportional to the reciprocal of the individual classical variance $\sigma_i^2(6,T)$ computed from the frequencies of the clock, relative to EAL, estimated over the current 60-day interval and over the past five consecutive 60-day intervals. The ω_i are numbers between 0 and 1, often expressed as a percentage, which add to 1 over the full set of clocks. They are computed using a temporary value ω_{iTEMP} given by:

$$\omega_{iTEMP} = \frac{1}{\sigma_i^2(6,T)} \left[\sum_{i=1}^{N} \frac{1}{\sigma_i^2(6,T)} \right]^{-1} \tag{1}$$

The usual problem in such a design is that if one of the contributing clocks is much more stable than others it makes an ever more important relative contribution to the resulting time scale, and finally dominates it. Similarly, a small group may become dominant. This threatens the reliability of the time scale and leads to large instability if one of the high-weighted clocks fails. One of the theoretical solutions to this problem is to set an upper limit of weight. In practice there exist two different possibilities for implementing this limit: one can choose a minimum value σ_{MIN}^2 for the variance $\sigma_i^2(6,T)$ of any individual clock, or a maximum value ω_{MAX} for the relative contribution ω_i of any individual clock. These two solutions are not equivalent as shown in the following.

In ALGOS, the weight limit has always been chosen following the first of the possibilities described here. However, as the quality of the clocks contributing to EAL rapidly evolves, it is necessary to update the value chosen for the upper limit, and to examine alternatives.

2 UPPER LIMIT OF WEIGHTS IN THE PRESENT EAL COMPUTATION

In the present ALGOS configuration, the individual clock contribution is limited by setting a maximum individual stability, characterized by a minimum value, σ_{MIN}^2, of the classical variance computed from six consecutive 60-day frequencies of clock H_i, relative to EAL. This condition is written in the form:

$$\text{if } \sigma_i^2(6,T) \leq \sigma_{MIN}^2, \text{ then } \sigma_i^2(6,T) = \sigma_{MIN}^2 , \tag{2}$$

which means that some of the stability that could be brought to the resulting time scale by clocks for which $\sigma_i^2(6,T) \leq \sigma_{MIN}^2$ is given up for sake of reliability.

Table 1 gives values of σ_{MIN} used to produce different time scales, published or analyzed for tests, with ALGOS: for example, since 2 May 1995, the value of σ_{MIN} has been set at 2 ns/d.

Period of Computation	Time scale	p_{MAX}	σ_{MIN}, (ns/d)	$\sigma_{yMIN}(T)$, 10^{-14}
1 Jan 88 – 2 May 95	EAL	1000	$\sqrt{10}$	2.11
2 May 95 – still valid	EAL	2500	2	1.34
Mar 92 – Jun 95	E5000	5000	$\sqrt{2}$	0.94
Mar 92 – Jun 95	E10000	10000	1	0.67

Table 1 Values of σ_{MIN} used to produce different time scales with ALGOS: EAL (published), and E5000 and E10000 (analyzed in this paper). The corresponding upper limit of weight, p_{MAX} is deduced from (8) and the minimum Allan deviation, $\sigma_{yMIN}(T)$, is related to σ_{MIN} through $\sigma_{yMIN}(T) = \sigma_{MIN}/\sqrt{3}$ assuming random walk frequency modulation of clocks over the averaging time $T = 60$ d[3]

An objective criterion to safeguard EAL against abrupt steps of clock frequencies is also required. For each clock H_i the average $\bar{y}_i$ and the variance $\sigma_i^2(5,T)$ of the frequencies y_i over the last five 60-day intervals, are first computed. Assuming a random walk frequency modulation, a six sample variance $s_i^2(6,T)$ is calculated using the two criteria:

$$s_i^2(6,T) = (6/5)\sigma_i^2(5,T), \text{ and} \tag{3}$$

$$\text{if } s_i^2(6,T) \leq \sigma_{MIN}^2, \text{ then } s_i^2(6,T) = \sigma_{MIN}^2. \tag{4}$$

Abnormal behavior of clock H_i is considered to occur if, over the interval of computation,

$$r_i = (y_i - \bar{y}_i)/s_i(6,T) > 3 . \tag{5}$$

In this case the weight of clock H_i is set to zero.

Equation (4) is a direct consequence of using the criterion of maximum stability expressed in (2). It has the effect that the weight of a clock which is more stable than the allowed maximum is not necessarily turned to zero even if it experiences a frequency step greater than $3s_i(6,T)$. Such a clock is given a "reserve of stability" which allows it to be maintained close to the upper weight even although its stability has degraded. The result is that the ratio in (5) is not independent of the choice of the value of σ_{MIN}.

Although an absolute value for σ_{MIN} is fixed over a number of years, the maximum contribution of any individual clock ω_{MAX} fluctuates with time according to the global quality of the whole

195

ensemble of clocks. This is shown in Figure 1 for the period January 1988 – April 1995 during which σ_{MIN} remained constant (see Table 1): ω_{MAX} has decreased since mid-1990 and has remained below 1% since mid-1993, following the massive input from the newly designed HP 5071A clocks which show outstanding long-term stability. The value of ω_{MAX} thus cannot be deduced uniquely from the value of σ_{MIN} and a better way to represent σ_{MIN} is to introduce an absolute weight p_i rather than a relative weight ω_i. There exists an infinity of choices for the definition of the absolute weight p_i, which allow p_i to be inversely proportional to $\sigma_i^2(6,T)$ and:

$$\omega_i = p_i \left[\sum_{i=1}^{N} p_i \right]^{-1} . \tag{6}$$

In practice, the weight p_i is computed in terms of a temporary value p_{iTEMP} according to:

$$p_{iTEMP} = \frac{10000}{\sigma_i^2(6,T)}, \text{ where } \sigma_i^2(6,T) \text{ is expressed in } (ns/d)^2. \tag{7}$$

It follows that there exists a maximum value for the absolute weight defined by:

$$p_{MAX} = \frac{10000}{\sigma_{MIN}^2}, \text{ where } \sigma_{MIN}^2 \text{ isexpressed in } (ns/d)^2. \tag{8}$$

For example, since 2 May 1995, the value of p_{MAX} has been fixed at 2500. For the 60 day interval of computation May–June 1995, 172 clocks contributed to TAI. Of these, 93 showed a stability better than the stated limit ($\sigma_{MIN} = 2$ ns/d) and thus received the maximum absolute weight p_{MAX}. Each of these clocks contributed a weight of 0.92% to the ensemble.

The absolute weight p_i of each clock H_i is deduced from (5), (7) and (8): it is zero, p_{iTEMP} or p_{MAX} independent of the other clocks of the ensemble. The set of relative weights ω_i is then obtained using (6).

It is not an easy task to fix the value of σ_{MIN}: to make the system reliable a sufficient number of clocks should reach the limit, but some discrimination should be exercised, even among the best clocks. The choice is thus empirical and should evolve with time as the global quality of data improves. For example, faced with the massive input to the EAL computation of data from the very stable HP 5071A units, the CCDS Working Group on TAI decided to increase p_{MAX} a factor of 2.5, a decision which was applied on 2 May 1995[6]. The distribution of the absolute weights attributed through ALGOS is illustrated in Figure 2 for the two consecutive 60 day intervals March–April 1995 and May–June 1995. In each histogram four sets of clocks are distinguished:

- clocks with null weight resulting from abnormal behavior,

- clocks with a small weight, less than 20% of p_{MAX}, but not null,

- clocks with a non-negligible weight, less than p_{MAX} but greater than 20% of p_{MAX}, and

- clocks at p_{MAX}.

The agreed increase in p_{MAX} took place between the two 60 day intervals under study, although the clocks themselves were nearly unchanged. The figure shows that the increase of p_{MAX} helps to equilibrate the distribution of weights: very stable clocks experience stronger discrimination, the detection of abnormal behavior operates more often and intermediate weights are attributed to a larger amount of clocks. All these features improve the stability of the resulting time scale.

The choice of the value of σ_{MIN} should also reflect the physical characteristics of the contributing clocks. The Allan deviations $\sigma_{yMIN}(T = 60$ d) corresponding to the different values of σ_{MIN} which have been used or tested are given in Table 1. The value of $\sigma_{yMIN}(T)$ corresponding to $p_{MAX} = 2500$ is small for most of the cesium clocks which are not HP 5071A units: these may not be stable enough to reach the maximum weight. This is not the case for the HP 5071A units. In Figure 3 values of $\sigma_{yMIN}(T)$ are compared with Allan deviations for the least stable HP 5071A unit to contribute to EAL. It may be seen that this particular clock can hardly reach $p_{MAX} = 5000$ and cannot reach $p_{MAX} = 10000$. Most HP 5071A clocks present a flicker floor at 6×10^{-15} for averaging times ranging from 20 d to 40 d; to discriminate between the best units thus calls for values of p_{MAX} larger than 10000 or for an alternative way of choosing the upper limit.

3 ALTERNATIVE CHOICE FOR THE UPPER LIMIT OF WEIGHTS IN EAL COMPUTATION

Another way to limit individual clock contributions is to choose a value of ω_{MAX}, expressed as a fraction (percentage or number between 0 and 1). In this case no criterion exists for individual clock stability and the weight computation requires a two-step iterative procedure:

- A first set of iterations starts from (1). In each, a cut is made at ω_{MAX} and the temporary weights are normalized. Several iterations are necessary because each normalization increases the temporary weight of those clocks which have not reached ω_{MAX} and may thus lead to another cut. This first set of iterations is convergent: it ends when no more cuts are necessary. It follows that there exists one particular clock which is the last to reach ω_{MAX} in the iteration process. This clock is the least stable at ω_{MAX} and the variance characteristic of its stability $\sigma_i^2(6, T)$ is the minimum allowed in the ensemble of clocks at ω_{MAX}. It thus plays the role of σ_{MIN}^2 defined in 2. The criterion for detection of abnormal behavior can thus operate according to (5). This process affects a number of clocks taken from the whole set with either $\omega_{iTEMP} = \omega_{MAX}$ or $\omega_{iTEMP} < \omega_{MAX}$[3].

- A second set of iterations should then be run to normalize the data and cut off the new temporary relative weights obtained after detection of abnormal behavior. This second set of iterations is also convergent: it delivers a set of normalized relative weights making it possible to compute the weighted average.

The important feature of this process is that it does not independently assign a weight to each clock. Rather the set of clocks is treated globally. Another way to consider this point is to note that the value of σ_{MIN}, the minimum stability required to reach the upper relative weight, is not fixed as in the case of the current ALGOS. It is free to fluctuate: if the global stability of the clocks is improving, the value of σ_{MIN} decreases and the criterion of reaching ω_{MAX} becomes more difficult to satisfy. There is thus an automatic discrimination among the best clocks which improves the stability of the time scale. In the case of the current ALGOS this must be done "by hand", through a change of p_{MAX}.

The choice of the value of ω_{MAX} is empirical, as was the choice of σ_{MIN} in the current ALGOS. If we had to implement this new choice for EAL computation at a given date, the most reasonable solution for the choice of ω_{MAX} would be that giving the best continuity. This could be realized by setting ω_{MAX} to the value it would have had over the current 60 day interval if the computation had been done with the current ALGOS.

4 TESTS ON REAL DATA

In this section five different time scales are compared. They are all computed by running the algorithm ALGOS over real clock data, but differ in the way of implementing the upper limit of weight and in its value. They are:

- EAL with p_{MAX} = 1000 over the period March 1992 – April 1995,

- E2500 with p_{MAX} = 2500 over the period March 1992 – June 1995,

- E5000 with p_{MAX} = 5000 over the period March 1992 – June 1995,

- E10000 with p_{MAX} = 10000 over the period March 1992 – June 1995,

- ER with p_{MAX} = 1.37% over the period January 1993 – June 1995.

The EAL is the free atomic time scale which was effectively the first step in the calculation of the published TAI over the period March 1992 – April 1995, just before the implementation of p_{MAX} = 2500 on 2 May 1995. For E2500, E5000 and E10000, the value of p_{MAX} is simply increased. The ER scale is computed using a maximum relative contribution, as explained in Section 3. The period of computation is chosen to cover the two years in which large numbers of HP 5071A clocks entered the TAI ensemble. The value of p_{MAX} is held constant throughout the period of computation, its value being 1.37%, the value of the maximum relative weight assigned to clocks in the EAL computation, with p_{MAX} = 1000, in the 60 day interval January–February 1993. The ER and the EAL are thus very close to one another over this particular interval.

Figure 4 shows the comparative variation with time of the number of clocks reaching the maximum weight for the five time scales under study. Four different 60 day intervals are chosen, March – April 1992, 1993, 1994 and 1995, and three clock types are distinguished: hydrogen masers, HP 5071A clocks and other cesium clocks. It follows that:

198

- The number of HP 5071A clocks reaching the maximum weight increases with time for the five time scales under study.

- Nearly all HP 5071A clocks are weighted at the maximum absolute weight p_{MAX}, independent of the value of p_{MAX}, as soon they enter the ensemble.

- Increasing the value of p_{MAX} yields a decrease in the number of highly weighted hydrogen masers and cesium clocks which are not of the HP 5071A type.

- The time scale ER which was initiated in January – February 1993 is very close to EAL for its first 60 day intervals of computation so, for each clock type, the number of clocks at the upper weight is identical for EAL and ER for the period March – April 1993.

- The use of a constant value of ω_{MAX} in ER produces a discrimination with time among hydrogen masers and those cesium clocks which are not of the HP 5071A type, similar to that obtained by increasing p_{MAX}. However, it also discriminates among the HP 5071A clocks, only maintaining the best of them at ω_{MAX}. The discrimination is more important than in the case of E10000 for which the value of p_{MAX} was already multiplied by a factor 10 relative to the value of p_{MAX} used in the published EAL.

It follows that increasing p_{MAX} or fixing ω_{MAX} makes the algorithm more sensitive to the frequency drift of hydrogen masers and to the instability of cesium clocks which are not of the HP 5071A design. In addition, the use of a constant ω_{MAX} provides some discrimination among HP 5071A units as they progressively enter the ensemble.

It is difficult to set an objective criterion to test the reliability of the time scale. Intuitively, reliability is ensured if a sufficient fraction of the total number of clocks reaches the upper limit of weight and if this fraction does not vary too much. The fraction is given in Table 2 for the four 60-day intervals already chosen for Figure 4. The time scale ER appears to be the most reliable among the five under test:

- The fraction of clocks at the upper limit of weight increased rapidly with time for the four time scales which use an absolute upper limit, while it remains nearly constant at a value close to 25% when a relative upper limit is used.

- Less than 12% of the clocks reached the upper weight during the first eighteen months of computation of E5000 and E10000, so these two time scales are not sufficiently reliable.

- May 1995 was a good time to increase the value of p_{MAX} in EAL by a factor 2.5. Indeed as more than half of the clocks were at upper limit of weight, a stronger discrimination was necessary.

Interval	EAL	E2500	E5000	E10000	ER
Mar–Apr 92	18.3%	9.1%	5.1%	4.6%	
Mar–Apr 93	23.5%	12.9%	7.8%	5.1%	22.6%
Mar–Apr 94	40.3%	32.1%	28.0%	24.4%	25.8%
Mar–Apr 95	52.1%	43.1%	38.0%	32.4%	28.2%

Table 2 Ratio of the number of clocks at upper weight to the total number of clocks (expressed as a percentage) for the computation of five different time scales.

Figure 5 shows the variation with time of the relative weight of a clock reaching p_{MAX} for the four values of p_{MAX} under study. The limit $\omega_{MAX} = 1.37\%$ is also indicated. The individual maximum relative weight varies much more with time for $p_{MAX} = 10000$ than for smaller values. A convergence may be seen for the three last 60 day intervals, from November – December 1994 to March – April 1995, towards values between 0.7% and 1.2% for all values of p_{MAX}. These are too small relative to the value of 1.37% for ω_{MAX} which delivered the most reliable time scale in the period under study.

Values of the Allan deviation $\sigma_y(\tau)$ have been computed by application of the N-cornered hat technique to data obtained in comparisons between EAL, or E2500, or E5000, or E10000, or ER and five of the best independent time scales in the world maintained at the NIST (Boulder, Colorado, USA), the VNIIFTRI (Moscow, Russia), the USNO (Washington DC, USA), the PTB and the LPTF (Paris, France). They are given in Table 3, and shown graphically in Figure 6 for EAL, E2500 and ER.

	$\sigma_y(\tau)$				
	$\tau = 10$ d	$\tau = 20$ d	$\tau = 40$ d	$\tau = 80$ d	$\tau = 160$ d
EAL[1]	4.0×10^{-15}	3.4×10^{-15}	3.1×10^{-15}	3.7×10^{-15}	4.6×10^{-15}
E2500[2]	3.7×10^{-15}	2.8×10^{-15}	2.5×10^{-15}	3.1×10^{-15}	3.9×10^{-15}
E5000[2]	3.7×10^{-15}	2.7×10^{-15}	2.3×10^{-15}	3.1×10^{-15}	4.4×10^{-15}
E10000[2]	3.4×10^{-15}	2.5×10^{-15}	2.1×10^{-15}	3.1×10^{-15}	4.8×10^{-15}
ER[3]	2.8×10^{-15}	2.0×10^{-15}	2.0×10^{-15}	2.6×10^{-15}	

Table 3 Values of the Allan deviation $\sigma_y(\tau)$ computed for five time scales under study by application of the N-cornered hat technique, using data covering the periods: [1]January 1993 – April 1995, [2]January 1993 – June 1995, [3]July 1993 – June 1995.

The time scale ER is obviously the most stable, with a flicker floor of 2 parts in 10^{15}. In addition, one can clearly see typical frequency noise: white frequency noise for τ between 10 d and 20 d and random walk frequency modulation for τ between 40 d and 80 d. Unfortunately, not enough data are available to allow a safe estimation of the stability of ER at longer averaging times.

The time scale E2500 shows better stability than EAL for all averaging times. It was thus justified to increase p_{MAX} from 1000 to 2500 in May 1995.

The noise characteristics of EAL and E2500 are not as pure as those for ER, probably due to residual systematic effects. In particular, Table 3 shows that the $\sigma_y(\tau)$ values obtained for

200

E2500, E5000 and E10000 with $\tau = 80$ d are identical: a limit of about 3.1×10^{-15} seems to have been reached. This suggests the presence of a 'bump' of the type which characterizes a seasonal frequency dependence, an effect which was not apparent in EAL but is revealed by increasing p_{MAX}. Notice also that this seasonal effect decreases for ER with $\sigma_y(\tau = 80$ d$) = 2.6 \times 10^{-15}$.

5 CONCLUSIONS

From the beginning, an absolute upper limit of weight has been set in computation of the free atomic time scale EAL. This has the effect that the stability of the most stable clocks is artificially degraded, their characteristic frequency variances being limited to a minimum value. This technique is very simple to put in operation since the weight attributed to a given clock reflects its own behavior independent of the other participating clocks. However, from time to time it is necessary to adapt the value chosen for the minimum variance to match the global quality of the clock ensemble. After tests carried out at the BIPM on real clock data covering the last few years, the CCDS Working Group on TAI decided in March 1995 to reduce the minimum variance by a factor 2.5, an action implemented in the EAL computation on 2 May 1995. This change helps to improve the stability of the resulting time scale by discriminating among participating hydrogen masers and those commercial cesium clocks which are not newly designed HP 5071A units.

More generally, an upper limit of weight could be set for the maximum relative contribution from any one clock. The corresponding weighting procedure is more complicated, since the weight of each clock should be adjusted according to the quality of the whole set of contributing elements, but it gives very encouraging results. With the progressive entrance of very stable clocks, such as the HP 5071A units, fixing an upper limit of relative weight removes from the highest weight category some of those with the weakest stability. This technique is robust and automatically leads to a time scale more stable than the equivalent one computed with a maximum absolute weight. Tests carried out on real clock data covering 1993, 1994, and the beginning of 1995 largely confirm this result, showing a flicker floor level of the resulting time scale at the level of 2 parts in 10^{15} and a reduction of all systematic effects. These results suggest that the stability of the international reference time scale TAI could be improved by setting an upper relative contribution for individual contributing clocks.

REFERENCES

[1] P. Tavella, and C. Thomas 1991, *"Comparative study of time scale algorithms,"* Metrologia, **28**, 57-63.

[2] C. Thomas, P. Wolf, and P. Tavella 1994, Time scales, Monograph BIPM 94/1, 52 pages.

[3] C. Thomas, and J. Azoubib 1995, *"TAI computation: study of an alternative choice for implementing an upper limit of clock weights,"* Metrologia, in press.

[4] J. Azoubib, M. Granveaud, and B. Guinot 1977, *"Estimation of the scale unit duration of time scales,"* Metrologia, **13**, 87-93.

[5] *"Differences between the normalized frequencies of EAL and TAI,"* 1994, Annual Report of the BIPM Time Section, 7, Table 5, p. 35.

[6] G. Petit 1995, *"Report on the discussions and decisions of the meeting of the CCDS Working Group on TAI,"* 7 pages.
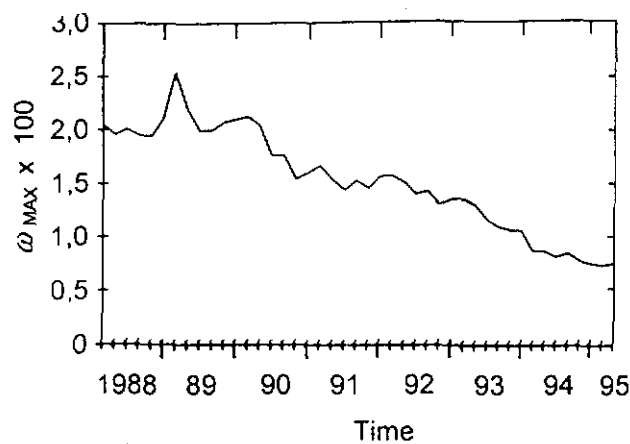
Figure 1: Variation with time of the maximum relative contribution ω_{MAX} of an individual clock in EAL computation for the period January 1988 - April 1995 (σ_{MIN} = 2 ns / d).
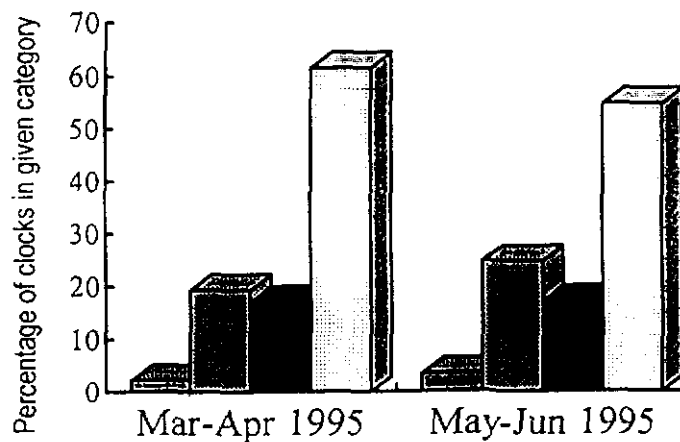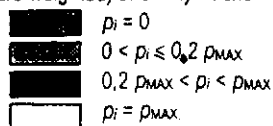

Figure 2: Histograms showing the distribution of clocks assigned a weight p_i for two consecutive 60 day intervals of 1995: March - April 1995 (p_{MAX} = 1000, 181 clocks are weighted) and May - June 1995 (p_{MAX} = 2500, 170 clocks are weighted).
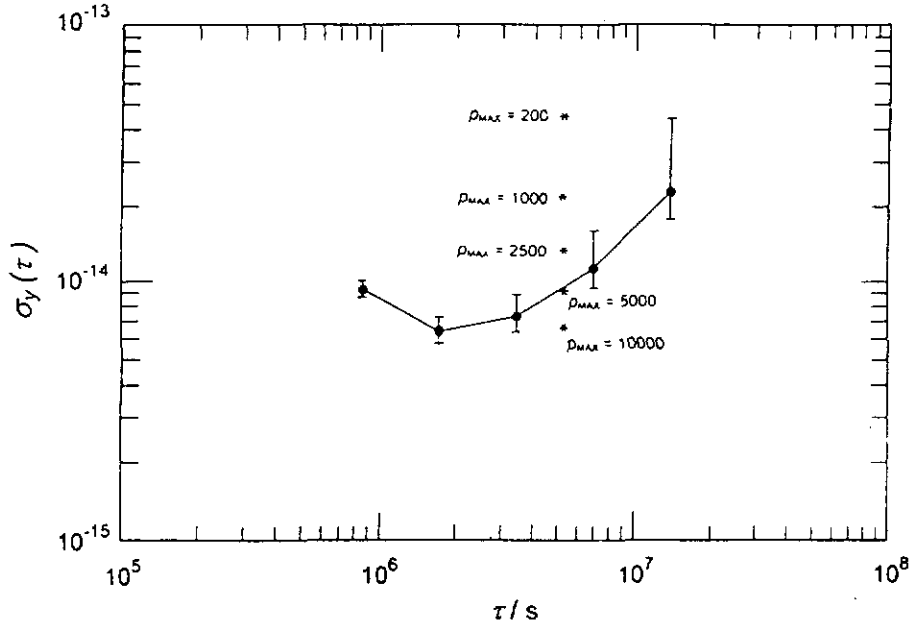
- ▮ $p_i = 0$
- ▨ $0 < p_i \leq 0{,}2 \, p_{MAX}$
- ▮ $0{,}2 \, p_{MAX} < p_i < p_{MAX}$
- ☐ $p_i = p_{MAX}$

Figure 3. Curve characterizing the stability of the least stable HP 5071A unit contributing to EAL. The values of the Allan deviation $\sigma_{yMDV}(T = 60 \text{ d})$ corresponding to the minimum stability necessary for reaching ρ_{MAX} = 200, 1000, 2500, 5000, and 10000 are also indicated (see also the 5th column of Table 1).
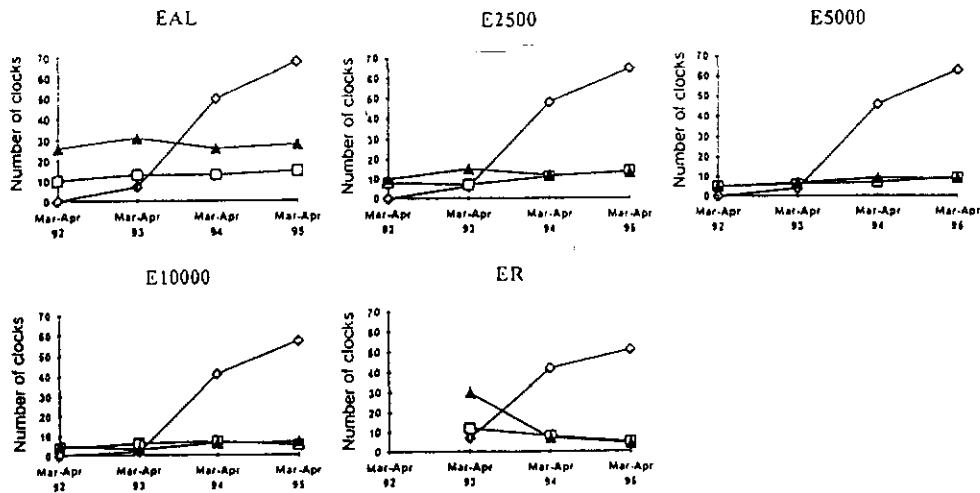

Figure 4: Variation with time of the number of clocks reaching the upper limit of weight in the computation of five different time scales: EAL, E2500, E5000, E10000 and ER.

Three different types of clocks are distinguished: HP 5071A (◇), hydrogen masers (□) and other caesium clocks (▲).
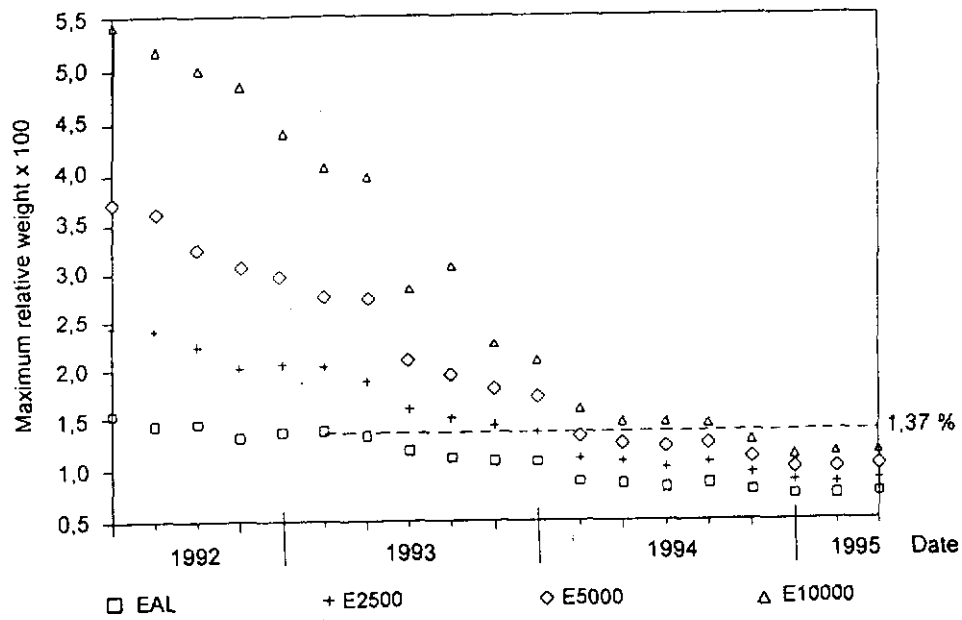
Figure 5. Maximum relative weight reached by individual clocks in the computation of the time scales EAL, E2500, E5000 and E10000 over the period March-April 1992 to March - April 1995. The upper limit of relative weight $\omega_{MAX} = 1,37\%$ used for computation of the time scale ER is indicated in the figure.
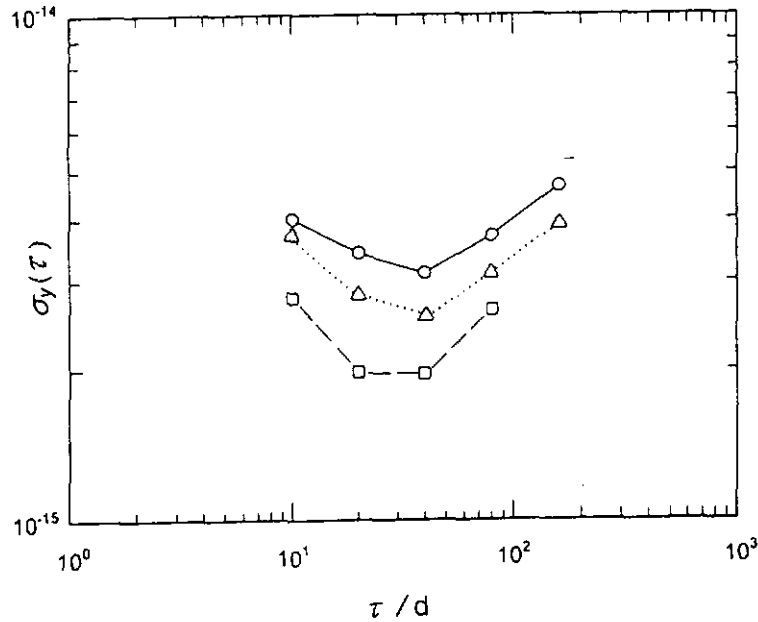

Figure 6: Variation with the averaging time τ of the Allan standard deviation $\sigma_y(\tau)$ computed by application of the N-cornered hat technique on the data of time comparisons between EAL, or E2500, or ER, and 5 of the best independent time scales of the world. The data involved covers the periods January 1993 - June 1995 for EAL and E2500, and July 1993 - June 1995 for ER.

205

Questions and Answers

DR. GERNOT WINKLER (USNO, RETIRED): I remember that the original argument in favor of maximizing of setting a limit to the maximum weight has been the concern, that that time scale should not become dependent on a few very good performers. So it was a question of reliability and robustness. I think that's a very important point.

On the other hand, if you increase relative weight or go, as you said, with your ER scale and you still have about 25 percent of your clocks reaching that upper limit, that seems to be an entirely acceptable compromise. Do you agree?

CLAUDINE THOMAS (BIPM): Yes, I completely agree.

SERGEY V. ERMOLIN (HEWLETT-PACKARD CO.): My question is about the lower limit of stability. Why do you set a lower limit and artificially bring in the poorer performance clock to this lower limit to include it into the scale?

CLAUDINE THOMAS (BIPM): I'm not sure what you mean.

SERGEY V. ERMOLIN (HEWLETT-PACKARD CO.): Well, if I understood it correctly, you set a lower limit of stability, which was about, I think, 10 nanoseconds per day; and then you saved the clock below 10 nanoseconds per day. You still made it 10 nanoseconds per day. It seems to me that for you to include this inferior clock, you artificially bring the stability of the clock up. Why do you do it?

CLAUDINE THOMAS (BIPM): We do that because it is absolutely necessary to do that; because, if one clock was much more stable than others, it would, during time, when time is passing, completely dominate the time scale. That's what we cannot accept; because, if this clock fails, we would have a time step in our time scale.

Of course, we are losing stability for some very, very good clocks. It is a compromise, you know. We must improve the stability, so use the best clocks. But, on the other side, we must not have only one or a very small ensemble of clocks completely dominating the time scale. It is not possible because of availability. So it's a compromise.

SERGEY V. ERMOLIN (HEWLETT-PACKARD CO.): Yes, I understand it. I'm not sure I stated my question right. You also have clocks with bad performance which, on your report, you assign a higher stability.

CLAUDINE THOMAS (BIPM): You mean clocks with bad performance?

SERGEY V. ERMOLIN (HEWLETT-PACKARD CO.): Yes.

CLAUDINE THOMAS (BIPM): Which was reaching the limit, you mean?

SERGEY V. ERMOLIN (HEWLETT-PACKARD CO.): Yes, a lower unit.

CLAUDINE THOMAS (BIPM): I'm not sure I understand. Well, what I showed, this clock was maybe a bad clock for this kind of clock. But it's already a very good clock, it was below 10^{-14}.

ALBERT KIRK (JPL): Do you only consider measured performance data? Or do you also

use as an input reported discontinuities on these clocks, that are reported to you from around the world?

CLAUDINE THOMAS (BIPM): Do you mean if we are only using real clock data?

ALBERT KIRK (JPL): I mean, suppose somebody makes a small frequency adjustment of a few parts in 10^{14}.

CLAUDINE THOMAS (BIPM): We take these things into account - - -

ALBERT KIRK (JPL): If they are reported only.

CLAUDINE THOMAS (BIPM): If they are reported. We are asking people to report such operation. And if we see something which has not been reported, we ask people if they did something on their clock. So we try to monitor all these things the best we can, of course.