AN ALGORITHM FOR THE ITALIAN ATOMIC TIME SCALE

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Abstract

During the past twenty years, the time scale at the IEN has been realized by a commercial cesium clock, selected from an ensemble of five, whose rate has been continuously steered towards UTC to maintain a long term agreement within 3×10^{-13}.

A time scale algorithm, suitable for a small clock ensemble and capable of improving the medium and long term stability of the IEN time scale, has been recently designed taking care of reducing the effects of the seasonal variations and the sudden frequency anomalies of the single cesium clocks.

The new time scale, TA(IEN), is obtained as a weighted average of the clock ensemble computed once a day from the time comparisons between the local reference UTC(IEN) and the single clocks. It is foreseen to include in the computation also ten cesium clocks maintained in other Italian laboratories to further improve its reliability and its long term stability.

To implement this algorithm, a personal computer program in Quick Basic has been prepared and it has been tested at the IEN time and frequency laboratory.

The paper reports on the results obtained using this algorithm on the real clocks data relative to a period of about two years.

INTRODUCTION

The generation of an independent atomic time scale from an ensemble of clocks, used as a reference for the generation of a local UTC time scale, has been realized by several laboratories to obtain a more reliable and uniform time scale that, if needed, can be steered to UTC(BIPM) in order to synchronize within the limits recommended by the CCIR and by the CCDS. Moreover, a recent Recommendation - S5/1993 - of this last Committee, has suggested to the primary laboratories to coordinate with UTC(BIPM) within 100 ns.

The approach used in the generation of the UTC(IEN) time scale at the Istituto Elettrotecnico Nazionale (IEN), based on a single clock selected from the clock ensemble that allowed to maintain in the last years the Italian reference of time within ±1.2 s to UTC, will no longer be suitable to attain the new bounds of uncertainty.

The investigations performed in the past on the long term behaviour of the IEN time scale and on the six IEN cesium clocks, proved in fact that the effects of the frequency perturbations caused by the environmental conditions changes, the variations due to the electronics or to the human intervention, are seen as abrupt changes in the rate of the time scale that can easily exceed the uncertainty limits suggested by the international bodies. It was therefore decided to undertake the study of time scale algorithms to individuate a suitable procedure based, at the moment being, only on the IEN cesium clocks with plans to include in the near future also at least ten clocks maintained in other Italian laboratories.

In the sections that follows, some details will be given on the devised algorithm and on the computer program prepared for the automatic computation of the paper time scale.

The features of UTC(IEN) and of the first results of the paper time scale TA(IEN) will be discussed along with some considerations about the future activity at the IEN on this subject.

REALIZATION OF UTC(IEN)

Since 1970, the time scale of IEN, the primary metrological institute in Italy for the electrical quantities, has been realized by means of an ensemble of commercial cesium beam standards maintained in a temperature controlled room. According to its long term stability, a master clock has been selected from the ensemble, and its rate continuously adjusted by means of a phase microstepper to mantain a long term agreement within 3×10^{-13} with the international time scale UTC computed by the BIPM. UTC(IEN) has been maintained within ±1.2 s with this international reference and is the base of legal time in Italy. The IEN time scale is related to UTC by means of GPS syncronization method according to the "common view" measurements schedule coordinated by the BIPM.

The equipment used to realize the IEN time scale and to perform the clock intercomparisons is shown in Fig. 1; four cesiums are maintained in a room located at 10 m underground, with a strict temperature (±0.5 °C) and humidity (±10 %) control and other two cesiums are located in the Laboratory with a temperature control only within ±1 °C. The time comparisons are performed twice a day, at 00 and 12 UTC, with an uncertainty of 1 ns and stored in a data base.

The behaviour of UTC(IEN) versus UTC for the period January 1989 – September 1993, obtained from the time differences supplied by BIPM Circular T, is shown in Fig. 2 where the rate changes applied to the phase microstepper have also been marked. Two comments can be done about this graph: first, no change of the rate chosen in November 1991 to compensate for the master clock (IEN/Cs4) frequency departure has been necessary, up to now, to maintain UTC(IEN) in close agreement with UTC. This is a result of the new conditioning system of the clock room, performing also the humidity control, that was put in operation on February 1992 and has strongly reduced the seasonal effects previously observed on the cesium clocks. On the other hand, it can be noticed that at the end of January 1993 (MJD 49012), probably as a consequence of a failure in the humidity control system, there has been a sudden rate change of the master clock that recovered five days later and looks like a time step on the plot. Other abrupt rate changes of the master clock occured also in the past giving rise to serious reliability problems[1]. Fig. 3 shows the Allan deviation of the IEN time scale versus UTC for different observation times, computed over about 170 ten-day time differences.

GUIDELINE OF THE ENSEMBLE TIME ALGORITHM

After the first numerical experiments[1] and the following studies on time scales[2], an ensemble time algorithm has been recently proposed for the computation of the IEN paper clock.

Two are the main features of the clocks involved: they are all commercial cesium clocks – only one of the last generation – and till recently they showed a quite important seasonal frequency fluctuation due to the humidity variations in the clock room[3].

Two are also the aims of the ensemble time: improve the reliability and reduce the long term instability at one month of the Italian time scale UTC(IEN). Since UTC(IEN) has to be accessible in real time and it is foreseen to utilize also the measurements data of clocks kept in other Italian laboratories, the computation is a real time daily procedure on the internal clocks, that will be delayed of one week to permit the collection of the data of the other laboratories.

The computation algorithm starts from the weighted average of a clock reading and follows the same steps of the main ensemble algorithm nowadays in use[2]. The ensemble time TA(t) is defined as the weighted average of clock readings $h_i(t)$ as:

$$TA(t) = \frac{\sum p_i(t)[h_i - h\prime_i]}{\sum p_i(t)} \tag{1}$$

where $h\prime_i(t)$ is a time correction useful to avoid time and frequency jumps when clocks enter or exit the ensemble and when the weights are changed and $p_i(t)$ is the weight assigned to the clock.

Clock weights are defined as inversely proportional to the one–month instability of each clock. Due to the presence of seasonal noise, the one–month instability is evaluated by the “classical” variance of twelve samples of mean monthly frequencies. Each mean monthly frequency is estimated by a linear fit on the time deviations of each clock with reference to the ensemble time. The choice of the classical variance and of the twelve samples is due to the aim of reducing the possible seasonal noise. If this problem, as it is the case now for the internal clocks, is overcome by a better control of the clock room environment, the weight evaluation could be based on a recursive – maybe filtered – variance estimation.

Though from the theoretical point of view it is not necessary, the practice has shown the importance of an upper limit of weight, particularly in this case of a very small ensemble of clocks, to avoid the predominance of any one of them. Such an upper limit has been fixed to 50 %. Since the instability of each clock is estimated against the ensemble time scale to which the same clock contributed, a correction is introduced[4] to unbias this estimation.

A possible check of the evaluation of each clock instability could be performed by decoupling the noise contribution of each individual clock from the comparison measurements by means of a suitable N-cornered hat technique[5,6].

The other fundamental point of time scale algorithms are the time and frequency corrections to avoid the instabilities due to the entering and removal of clocks or to the variations of the weight values. To this aim it is necessary[2] to predict the frequency of each clock from day to day. By observing that the involved clocks show a minimal instability over an integration period of about ten days, it has been chosen to predict the frequency of each clock for the next day as equal to the mean daily value of its frequency evaluated over the previous ten days. The prediction step has also the duty of abnormal behaviour detection. In fact, if the predicted frequency results to be very different, more than 3σ ($\tau = 1\ d$) from the computed one, the clock is temporary left outside the ensemble time with weight equal to zero.

Much more care is necessary to avoid problems and to automatically face the possible anomalies occurring in the use of real clocks. Some of these necessary checks will be described in the next section. For example, a new entering of a clock, calls for an observation period permitting to evaluate its instability and hence its weight. In our case, a new clock entering the ensemble is observed for three months, receiving a weight equal to zero and from the fourth to the twelfth month, its annual instability is extrapolated from the variance of the mean monthly frequency samples at disposal and assuming random walk frequency noise as predominant. After one year of continuous operation, the weight determination automatically follows the procedure described above.

COMPUTER PROGRAM OUTLINE

To implement the time scale algorithm in the IEN automatic data acquisition system, a program in Quick Basic language has been prepared on a Personal Computer and it has been tested on the data of the IEN clock ensemble. Due to the complexity of the program, it has been divided in subroutines to simplify any modification it should be necessary to meet further developments of the algorithm. The program performs all the operations required to generate the paper time scale as the acquisition of the clock data, the daily computation of the mean time scale and the supply of the results in different forms. All the procedure is performed automatically and the human intervention is required only at the end of the process in case of anomalies. The program flow chart is shown in Fig. 4.

The first operation performed is to get the measured time differences from the data acquisition archive, to check for the number of clocks in operation and to report about any modification occured in the ensemble. Moreover the program checks for data anomalies or discontinuities on the available clocks. The standard chosen to detect the clock deviations from the expected rates is to verify if the difference between the actual time difference of a clock against UTC(IEN) and its predicted value, exceeds 3σ ($\tau = 1d$). The prediction is obtained by adding to the previous value its mean daily rate evaluated over the last ten days. The standard deviation, used as a threshold, is evaluated at least over a three month period up to a maximum of one year.

Due to the limited number of clocks presently available, to detect anomalies it has been necessary to use as a reference UTC(IEN) instead of the computed time scale TA(IEN), as usually done, because of the insufficient indipendence of this scale from the contributing clocks. Of course special care must be taken to recognize the master clock anomalies.

Afterwards, the weight of each clock is computed, as inversely proportional to the variance of its past twelve monthly frequencies, on the second day of each month and kept constant for the whole month.

At this point , the average time scale TA(IEN) is computed according to the selected algorithm, and the program checks the archive to verify if there is any advice of a man–made time or frequency step. If so, the program corrects one year backwards for the specified step all the previous data of the clock to eliminate such discontinuities. This is instrumental for a reliable prediction of the clock rates and to detect any abnormal rate change. If an anomaly is detected, the program sets the weight of the clock to zero and starts again the time scale computation.

In the next step, the date is checked, and if found coincident with the first day of the month, the mean monthly frequency of each clock against TA(IEN) is computed. These data are stored and used for the weighting of the clocks.

The procedure is now completed and the results are stored, displayed or printed and plotted together with a warning if any anomaly has occurred. At this step, it is still possible for an operator to introduce missing data and ask for a recomputation.

In details, the data supplied daily by the program are: the time differences between UTC(IEN) and TA(IEN), between each clock and TA(IEN), the relative weights of the clocks and their mean monthly frequency departures.

EXPERIMENTAL RESULTS

To evaluate the long term instability of the atomic time scale TA(IEN), computed with four cesium clocks for the period January 1992 – September 1993, the time differences for the standard dates versus UTC time scale have been computed and compared with those relative to UTC(IEN). The results are shown in Fig. 5 with a constant and a slope (-96 ns/d) removed in the case of TA(IEN). The Allan deviations of both IEN time scales versus UTC have been computed for the same period and for different sampling times, using 630 days of data and the results are represented in Fig. 6. The medium term instability, of the two time scales – from 1 to 8 days – has been evaluated over the last six months versus an HP cesium 5071A/opt. 001 (IEN/Cs8) and it has been found comparable showing that the ensemble algorithm optimized for the long term stability, does not waste, in any case, the medium term. Fig. 7 shows the Allan deviation of each clock contributing to TA(IEN) and the scale itself, computed over 630 days of data, and Fig. 8 reports their relative weights assigned by the algorithm.

If one compares the behaviour of the UTC(IEN) time scale from MJD 48622 to 48987 with the relative humidity swing in the clock room also reported in Fig. 5, and ranging from about 30 % to 70 %, can still find a relationship between the humidity changes and the time scale variations. This effect disappeared after April 1993 (MJD 49105) when the humidity control had been improved. TA(IEN) behaviour instead is not sensibly affected by the environmental effects, but its rate changes strongly depend on the relative weight of the contributing clocks due to their limited number (see Fig. 8). Also the peak–to–peak excursion of TA(IEN) is more restricted, 0.4 s, than that found on UTC(IEN) amounting to 1.3 s.

Concerning the long term frequency instability of the two time scales reported in Fig. 6, the Allan deviation for $\tau > 10d$ of TA(IEN) is always better. The same consideration can be done if one compares the Allan deviation of TA(IEN) with that of each clock contributing to this time scale (Fig. 7), with the exception of IEN/Cs8 that joined the clock ensemble only during the last four months.

As far as reliability is concerned, it can be seen that the abrupt rate change of the master clock occurred on MJD 49012 is well smoothed in TA(IEN). The anomalies detection procedure has individuated the frequency jump and set the weight of the master clock (IEN/Cs4) to zero. The ensemble time is anyway quite insensitive to the abrupt removal of one of the clocks.

FUTURE DEVELOPMENTS

From the experience gained in the experimental phase of the IEN ensemble time scale algorithm, it is foreseen to further improve the following features. As the control of the temperature and humidity of the IEN clock room has been improved, reducing any seasonal effect, the weighting procedure can be modified in order to shorten the observation time, now set at 12 months, allowing to insert also clocks available for short periods and increasing the number of clocks used in the mean scale computation.

To improve the reliability, additional effort will be done for what concerns the automatic detection of the clock anomalies, that now requires sometimes the human intervention; this feature is very important if the time scale computation has to be performed automatically.

A next step will consist in generating the UTC(IEN) time scale from TA(IEN), updating the amount of the microstepper correction according to the evaluation of the selected master clock rate against TA(IEN). In this way, a better long term stability and reliability of UTC(IEN) will be insured.

On the other hand, to improve the short term stability, the possibility of using a flywheel oscillator such as a good crystal or a maser is under study.

Further improvements in the ensemble time scale TA(IEN) can be obtained when also the data of other ten cesium clocks maintained in four Italian institutions are entered in the ensemble by means of the GPS synchronization link. This will require the implementation of a filter on the GPS results, to smooth the medium term noise added by this synchronization link.

The increase from 5 to 15 in the number of the clocks used to compute the Italian atomic time scale, will reduce its sensitivity to the introduction or removal of clocks from the ensemble and also to the variation of the relative weights attributed to the single clocks, leading to a gain as regards its reliability and long term stability.

CONCLUSIONS

To improve the long term stability and reliability of the UTC(IEN) time scale, an ensemble time algorithm has been devised, optimized for one–month stability and designed to smooth out the seasonal noise.

A PC program, written in Quick Basic, has been prepared to automatize the computation and it is operating in the IEN Time and Frequency Laboratory, supplying once a day, the time differences between each clock and the ensemble time scale. These data will be used to increase the reliability of the IEN reference time scale.

From the experimental results obtained, it turns out that a weighted average of clock readings meets our targets, provided that some checks on clock data are performed and all the information on human interventions are given.

Future plans include:

- the use of other atomic clocks maintained in other Italian laboratories referred to IEN by means of a GPS sychronization link;
- improvements in the algorithm as far as prediction, filtering and instability estimation techniques are concerned;
- the hardware realization of the ensemble time scale.

REFERENCES

[1] F. Cordara, V. Pettiti, P. Tavella, *"Status report and future trends of the IEN time scale"*, Proc. 3rd International Time Scale Algorithm Symposium, Torino – Italy, pp. 9–26, 1988.

[2] P. Tavella, C. Thomas, *"Comparative study of time scale algorithms"*, Metrologia 28, pp. 57–63, 1991.

[3] E. Bava, F. Cordara, V. Pettiti, P. Tavella, *"Analysis of the seasonal effects on cesium clocks to improve the long term stability of time scale"*, Proc. 19th PTTI, Redondo Beach - (CA) USA, pp. 185–202, 1987.

[4] P. Tavella , S. Azoubib, C. Thomas, *"Study of the clock ensemble correlation in ALGOS using real data"*, Proc. 5th European Frequency and Time Forum, Besancon – France, pp.435–441, 1991.

[5] A. Premoli, P. Tavella, *"A revisited 3-cornered hat method for estimating frequency standard instability"*, IEEE Trans. Instr. Meas. vol. 42, n. 1, pp 113–130, February 1993.

[6] P. Tavella, A. Premoli, *"Estimating the instabilities of N clocks by measuring differences of their readings"*, To appear on Metrologia, November 1993.

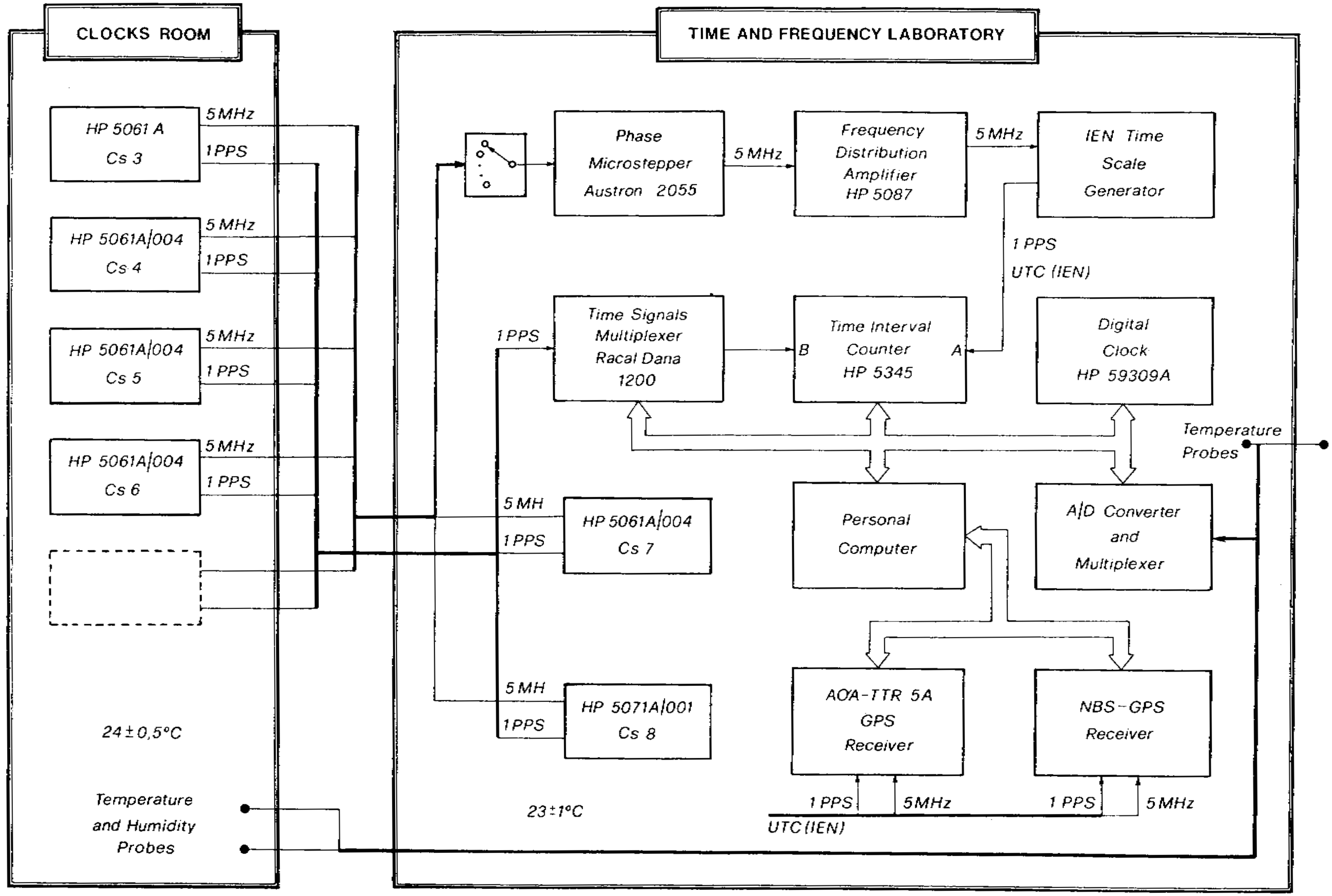

Fig. 1 - Block diagram of the equipment used to generate and compare UTC(IEN).

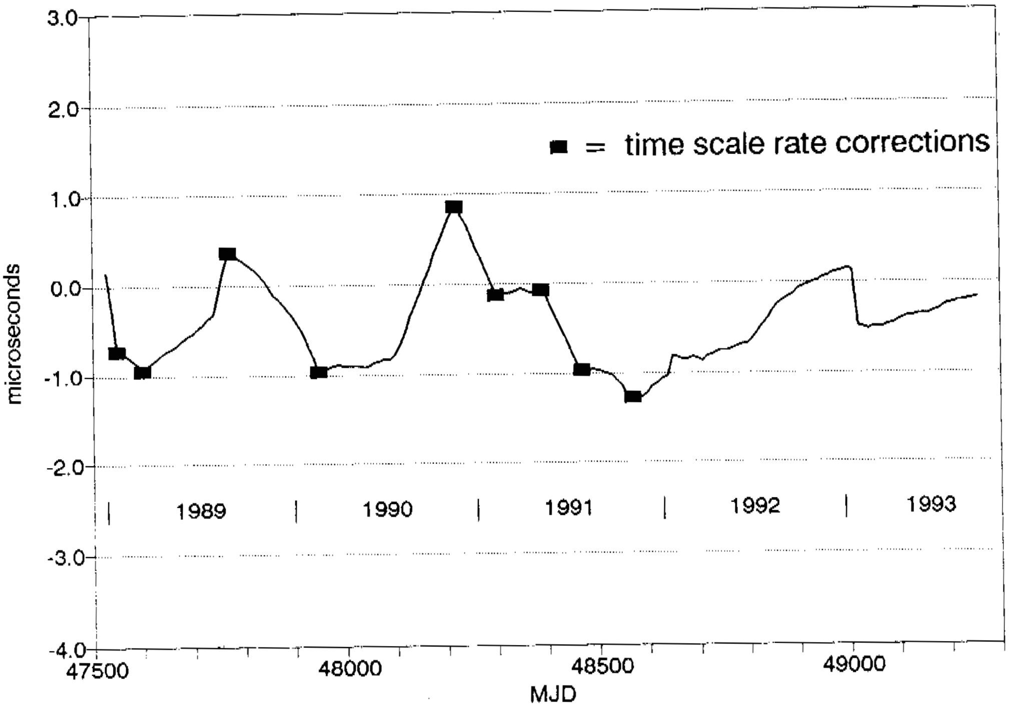

Fig. 2 - UTC(IEN) vs. UTC from January 1989 to September 1993.

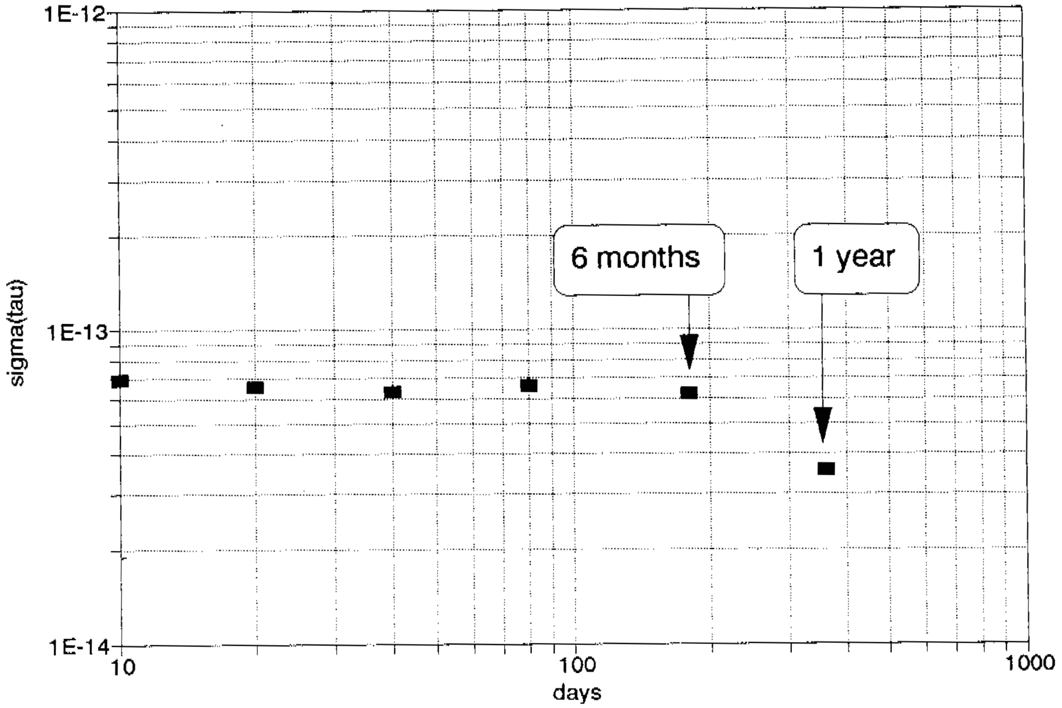

Fig. 3 - Allan deviation of UTC(IEN) vs. UTC (January 1989 - September 1993).

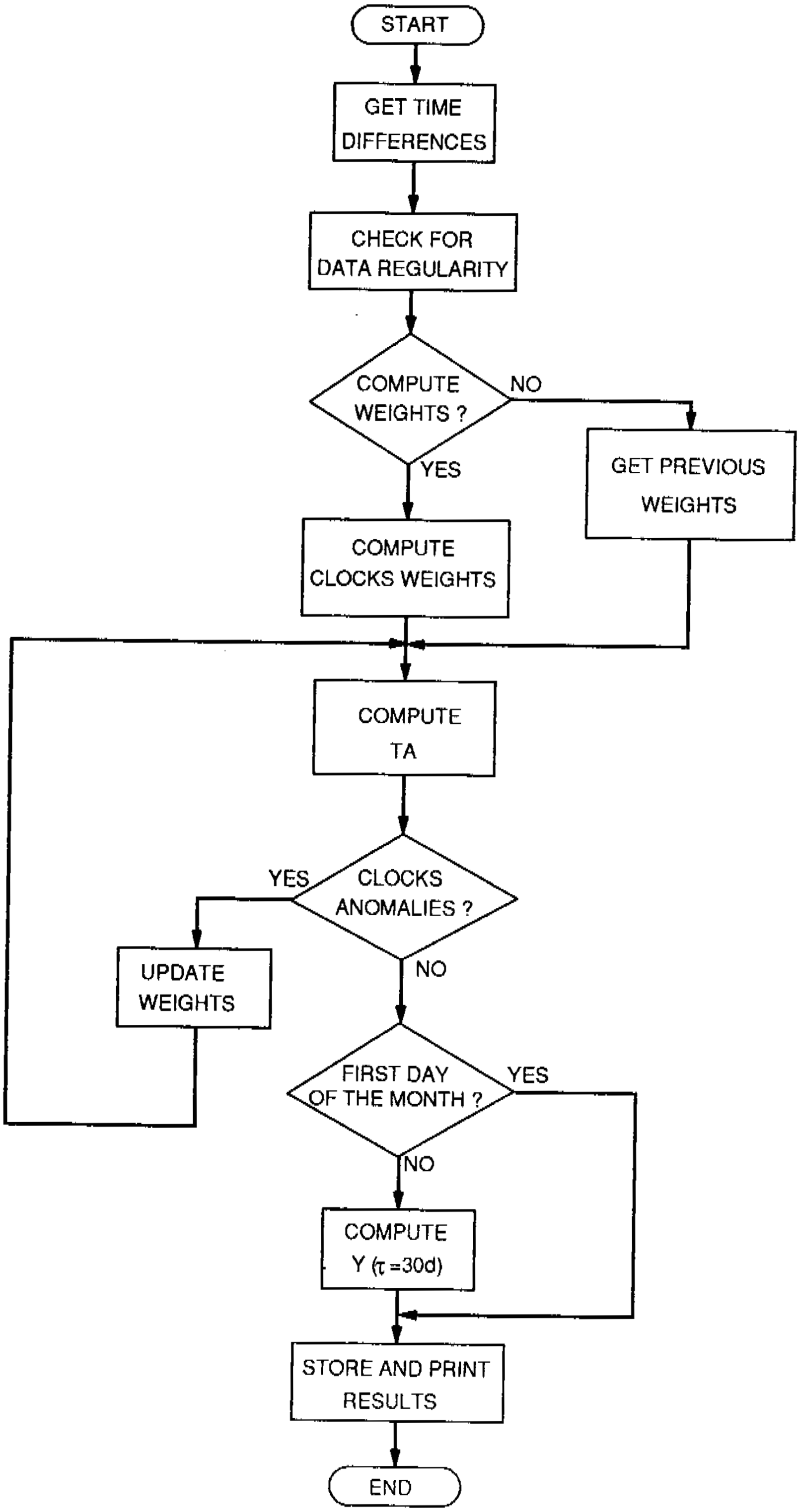

Fig. 4 - Program flowchart.

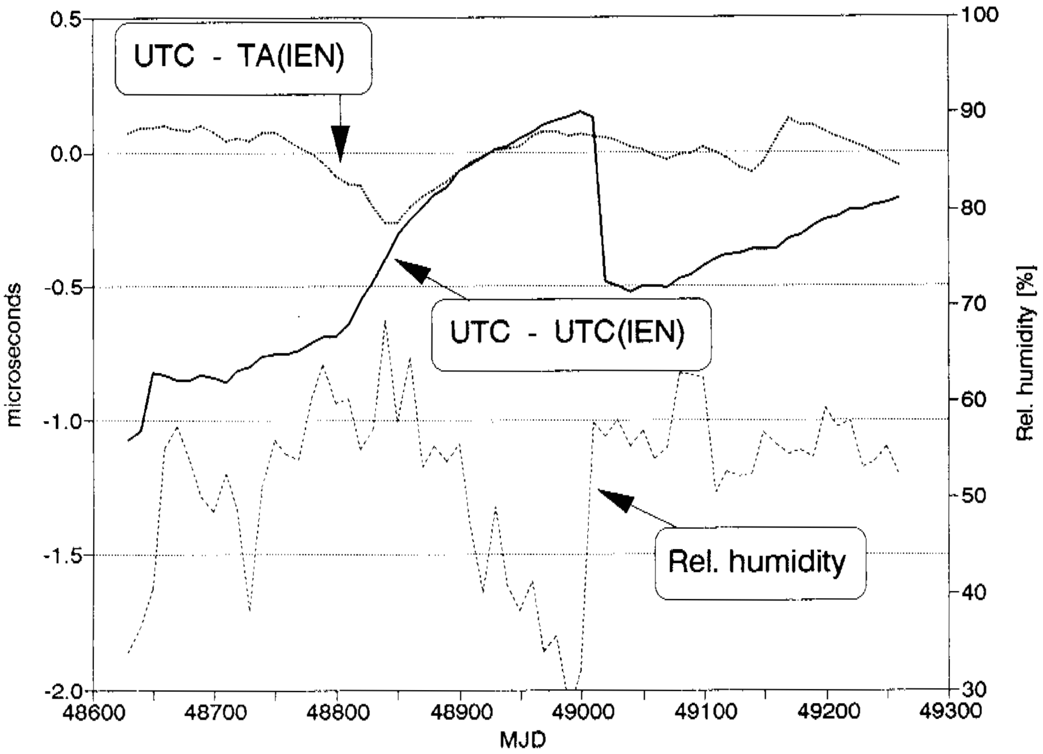

Fig. 5 - UTC(IEN), TA(IEN) and relative humidity behaviour.

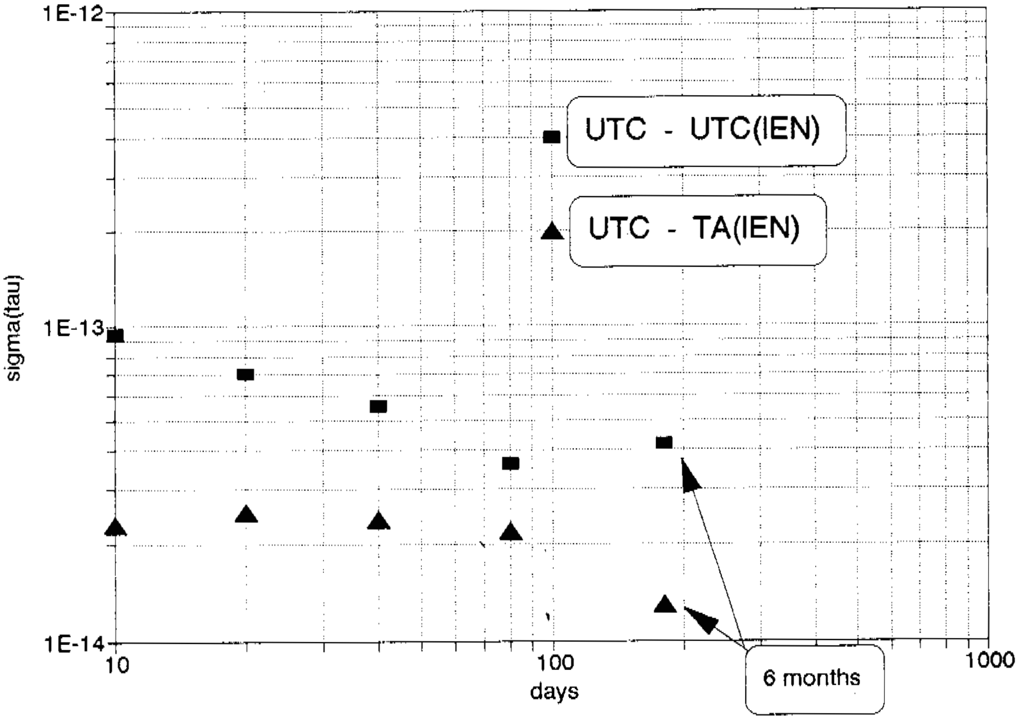

Fig. 6 - Allan deviation of UTC(IEN) and TA(IEN) vs. UTC (Jan. 1992 - Sep. 1993

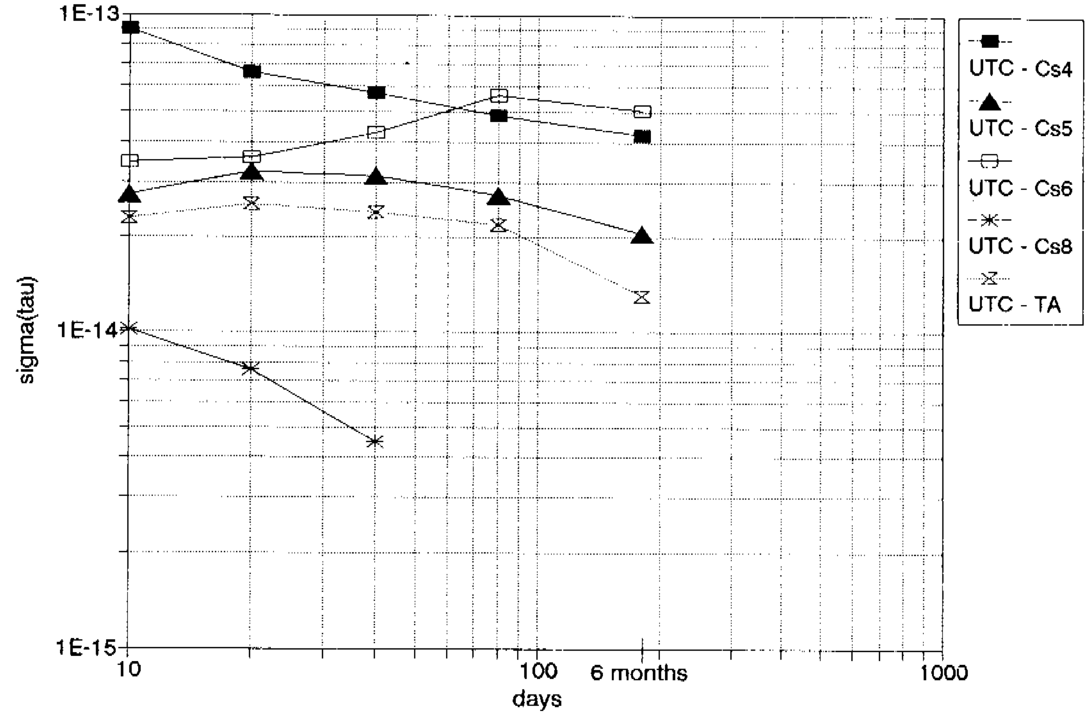

Fig. 7 - Allan deviation of the IEN clocks and TA(IEN) vs. UTC.

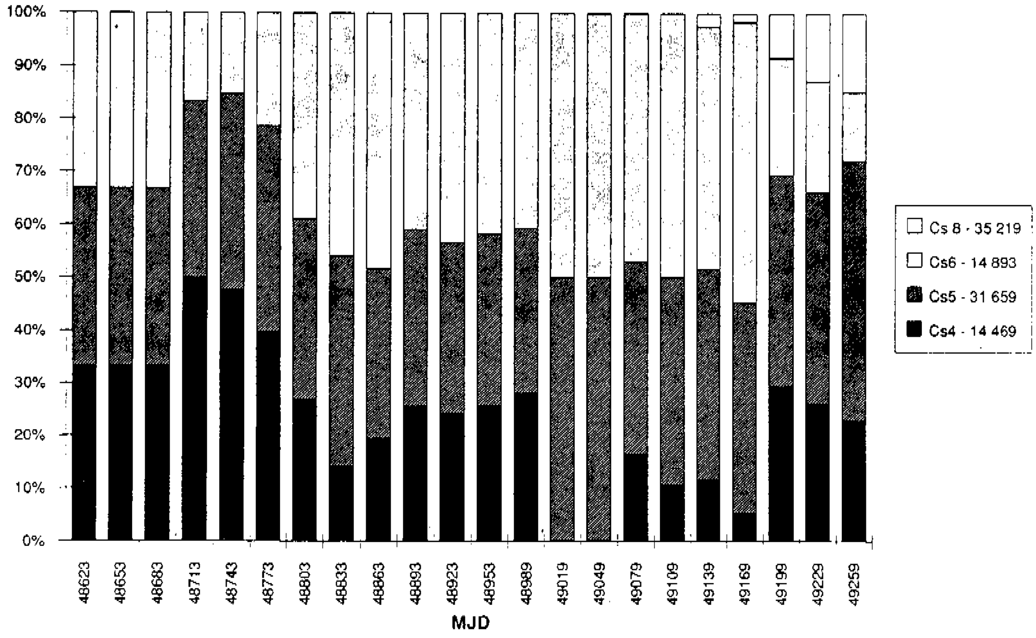

Fig. 8 - Relative weights of the clocks used in the TA(IEN) time scale.