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REPORT ON CORRELATIONS IN FREQUENCY CHANGES AMONG THE CLOCKS CONTRIBUTING TO TAI

by

Patrizia TAVELLA and Claudine THOMAS

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Patrizia TAVELLA+
Istituto Elettrotecnico Nazionale Galileo Ferraris
Strada delle Cacce, 91
10135 Torino
Italy

and

Claudine THOMAS
Bureau International des Poids et Mesures
Pavillon de Breteuil
92312 Sèvres cedex
France

+ Guest worker at the BIPM from October to December 1989, in April and November 1990 and in March 1991.

ABSTRACT

The clocks which are entered in the computation of TAI, are supposed to be statistically independent. The fact that some may not be independent could lead to a degradation of the stability and accuracy of the time scale. The 11th session of the CCDS explicitly asked the BIPM to examine frequency data of the clocks to see if correlations may be observed. The answer is positive: it does happen that the frequencies of several clocks, in particular ones kept in the same laboratory, show a common pattern of variation. This may occur because the clocks react globally to an external event such as a change in environmental conditions. Two other effects may also provide a partial explanation of the observed correlations. These are that frequency data are necessarily expressed relative to TAI and that all clocks are seen through time comparisons which may be noisy.

RESUME

Les horloges qui sont utilisées pour le calcul du TAI, sont supposées être statistiquement indépendantes. Le fait que certaines d'entre elles ne le soient pas peut entraîner une dégradation de la stabilité et de l'exactitude de l'échelle de temps. La 11e session du CCDS demanda explicitement au BIPM d'étudier les données de fréquence des horloges pour savoir si l'on peut y détecter des corrélations. La réponse est positive: il s'avère que les fréquences de plusieurs horloges, en particulier appartenant à un même laboratoire, présentent des variations similaires. L'une des raisons en est que les horloges réagissent de la même manière à un phénomène extérieur tel qu'une modification de leur environnement. Deux autres effets peuvent aussi expliquer partiellement les corrélations observées. Il s'agit du fait que l'on ne dispose que de fréquences calculées par rapport à TAI et aussi du fait que les horloges sont observées par l'intermédiaire d'un moyen de comparaison horaire qui peut être bruité.

INTRODUCTION

International Atomic Time (TAI) is a coordinate time scale used as the world reference. It is a software clock obtained through the combination of the readings of a number of atomic clocks of different types, located in different parts of the world and connected in a network which allows the precise exchange of time data.

The algorithm which produces TAI operates in two steps: first, the computation of a free atomic time scale EAL (échelle atomique libre) optimized for long-term stability, second a steering of the EAL frequency by comparison with primary frequency standards, to ensure accuracy. Basically EAL is a weighted average of the readings of its contributing clocks which are supposed to run freely and to be statistically independent. The weight of each clock is assigned according to its long-term stability [1] [2] and is evaluated from the variations of its frequency relative to EAL, averaged over two-month intervals.

At present, the EAL relies on approximately 200 atomic clocks, commercial caesium clocks, primary frequency standards operating continuously as clocks and hydrogen masers which are maintained by about fifty national time laboratories or observatories. If an external event simultaneously influences the behaviour of a set of clocks, for example clocks belonging to one laboratory or belonging to different laboratories situated in the same area, it can create correlated variations in the clock frequencies. If such correlations are not recognized and treated in the weighted average, the stability and accuracy of both EAL and TAI are degraded.

Aware of this problem, the Comité Consultatif pour la Définition de la Seconde (19-20 April 1989) made the following Declaration:

"The Comité Consultatif pour la Definition de la Seconde,

considering that correlation among the frequency changes between contributing clocks can degrade the long-term stability and accuracy of TAI,

recommends

- that the BIPM studies and reports on correlation in frequency changes among the clocks contributing to TAI,

and

- that the BIPM acts with contributing laboratories towards improving statistical independence of the clocks."

The present report, already partly published in [3], refers to the first part of this declaration. The variations of the frequencies, relative to TAI, of the clocks maintained in continuous operation for a long enough period, have been systematically analysed for evidence of correlation by methods described in the first section. The analyses show strong and persistent correlations both in the data from clocks in individual laboratories and from clocks belonging to different laboratories. In the second section we give four typical examples of correlations arising from:

- seasonal variation of TAI,
- changes in the environmental conditions of the clocks, for example variations of temperature or humidity,
- the time links through which the clocks are observed,
- frequency drifts.

The third section is a systematic review of correlations appearing in the laboratories contributing to TAI and keeping at least 2 clocks for the period January 1987-June 1990. Detailed interpretation of the detected correlations often depends on more than one of the four different effects listed in section II.

I. Methods used to detect correlations among the clock frequencies

The frequency of clock H_i relative to TAI is written as:

$$B_i(t) = [\beta(t) - \beta_i(t)]/\beta(t) \qquad (1)$$

where $\beta(t)$ and $\beta_i(t)$ are the mean frequencies of TAI and of clock H_i over the interval of basic duration τ = 60 days ending at date t. Since the quantities $\beta(t)$ and $\beta_i(t)$ are individually inaccessible, only the normalized frequency departure $B_i(t)$ of clock H_i from TAI can be estimated. The variations of the quantity $B_i(t)$ thus include any frequency variations of TAI itself.

Correlations among the variations of the clock frequencies can be shown in different ways.
As a first approach, one can graph the frequencies $B_i(t)$ versus time for a given set of clocks H_i (i=1,2, ..., n) and compare their variations. In a statistical and more quantitative approach the quantities $B_i(t)$, obtained for clock H_i over a long period of continuous operation, are expressed as a time series $\mathbf{B}_i$. Correlation between clock H_i and clock H_j frequency variations is then given by the cross-correlation function $\mu_{ij}(k)$, at lag k, of the bivariate process ($\mathbf{B}_i$, $\mathbf{B}_j$) [4], defined as:

$$\mu_{ij}(k) = \frac{\overline{[(B_i(t) - \overline{B_i}).(B_j(t+k\tau) - \overline{B_j})]}}{\sigma_i.\sigma_j}, \qquad (2)$$

where $\overline{B_i}$ and σ_i are the mean value and the standard deviation computed over the frequencies contained in the time series $\mathbf{B}_i$.

In the following, values $\mu_{ij}(k)$ are estimated from series containing 10 to 20 values. A variation of 1 unit for k corresponds to a shift of two months for series $\mathbf{B}_j$. If the resulting $\mu_{ij}(k)$ are close to +1 or -1, the two clocks H_i and H_j are highly correlated or anticorrelated at lag k. If $|\mu_{ij}(k)|$ is close to zero, the two clocks H_i and H_j are uncorrelated. In most of the cases, k was chosen to be zero.

An alternative way to vizualise correlation between the frequencies of H_i and H_j relative to TAI consists in graphing $B_j(t)$ versus $B_i(t)$. The points obtained are no longer ordered in time sequence. The least squares regression line of B_j on B_i is written as:

$$B_{j\ r.l.} = s_j.B_i + c_j, \tag{3}$$

where c_j is a constant, and the least squares regression line of Bi on Bj is given by:

$$B_{i\ r.l.} = s_i.B_j + c_i, \tag{4}$$

where c_i is another constant.

It is easily shown [5] that s_i, s_j and $\mu_{ij}(0)$ have the same sign and are linked by the relation:

$$[\mu_{ij}(0)]^2 = s_i.s_j. \tag{5}$$

On the graph of B_j versus B_i, the regression lines defined by (3) and (4) have slopes s_j and $1/s_i$ and if $\mu_{ij}(0)$ is close to ±1, these lines are nearly superposed. If $\mu_{ij}(0)$ is close to zero, the regression lines lie close to, respectively, the horizontal and vertical axes.

All the above methods are used in the sections which follow.

<u>Note</u>: The weighting procedure used in EAL computation is optimized for long-term stability. The weight of clock H_i is computed as the inverse of the classical variance of its six last two-month frequencies relative to EAL. Very stable clocks then receive high weights which, nevertheless, cannot exceed an absolute upper limit. This upper limit corresponds to a maximum contribution of about 2%. The use of classical variance helps to the deweighting of clocks with high seasonal fluctuations or frequency drifts and then protects the resulting time scale against such systematic variations. In this report the relative weight of the clocks shown as example will be systematically indicated.

II. Typical examples of correlation

We present here some typical examples of correlation found in the frequency data of clocks contributing to TAI. They correspond to cases which are easily interpreted because a principal cause is evident.

II.1. Correlation due to TAI itself

Variations with time of the clock frequencies implicitly include the variations with time of the TAI frequency itself, especially its seasonal fluctuation. This seasonal fluctuation can then create an artificial correlation among clocks designed for very good long-term stability and particularly protected from environmental changes. This is the case for primary frequency standards and also some of the H-masers which contribute to TAI.

Figure 1.1 shows the frequencies of the two primary standards PTB CS1 and PTB CS2 relative to TAI since the beginning of PTB CS2 operation. Annual variations can be seen. They have common phase and amplitude, the peak-to-peak amplitude being about 4 ns/day (4,6 10^{-14}). As already pointed out [9], it is likely that this seasonal variation is due to TAI itself. The strong correlation observed between these two clocks, illustrated by $\mu_{ij}(0)$ = 0,72 and by the least squares regression lines of Figure 1.2, is therefore more apparent than actual.

The same pattern may be seen in data of two APL hydrogen-masers 42 13 and 42 14: Figure 2 shows that they are correlated by a drift and a seasonal variation with $\mu_{ij}(0)$ = 0,81. Taking into account the value of the peak-to-peak amplitude (4,7 10^{-14}) and the phase of the apparent seasonal variation, one may deduce that TAI is mainly responsible for the apparent correlation.

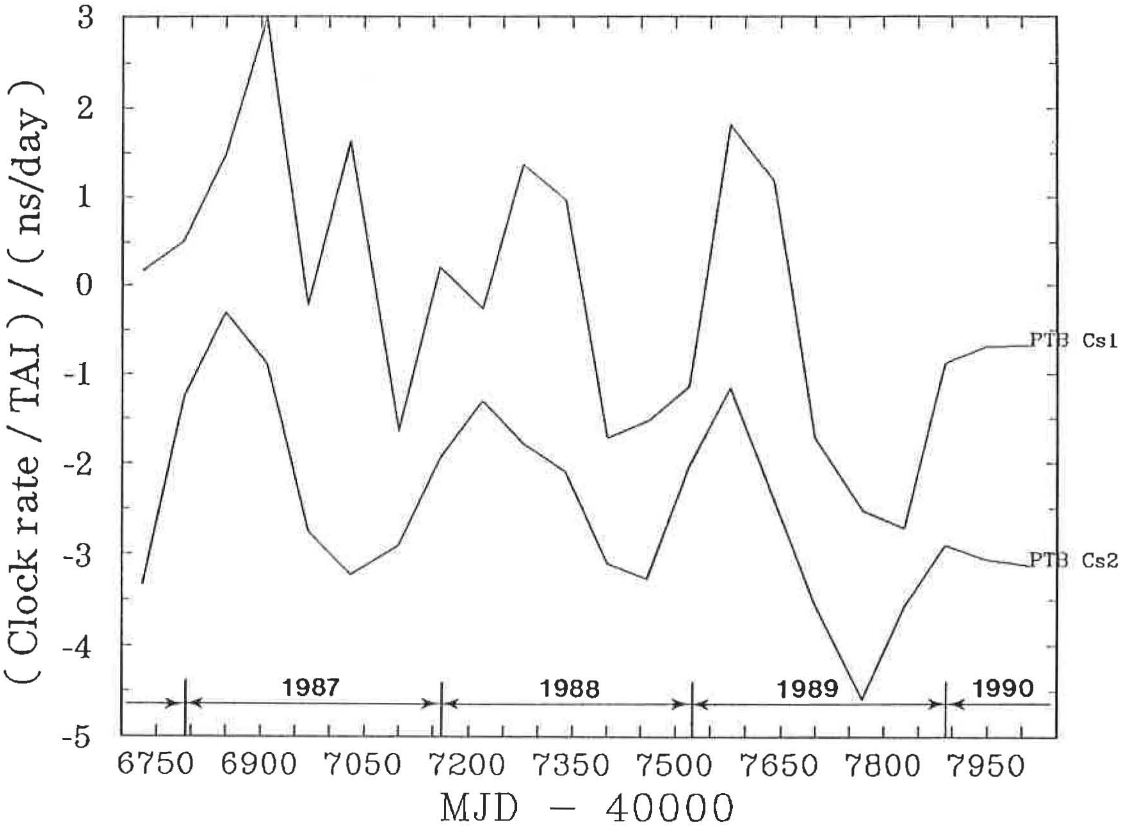
More striking is the case presented in Figure 3 which concerns three different clocks chosen from those with the best long-term stability. They are located in different parts of the world, in laboratories experiencing very different climatic conditions:

- PTB primary standard CS2, for Europe
- APL H-maser 42 13, for north America,
- AUS H-maser 44 2, for Australia.

These three clocks exhibit seasonal variations of almost the same amplitude and phase even although one is located in the southern hemisphere. We interpret this by supposing that what we see is mainly the seasonal variation of TAI itself. The cross-correlation coefficients obtained are:

- i=PTB CS2 j=AUS 44 2 $\mu_{ij}(0)$=0,80
- i=PTB CS2 j=APL 42 13 $\mu_{ij}(0)$=0,77
- i=AUS 44 2 j=APL 42 13 $\mu_{ij}(0)$=0,70,

so the correlation between these clock data is high. This is confirmed by Figure 4 which shows the regression lines of the AUS 44 2 and PTB CS2 frequencies against the APL 42 13 frequency. These straight lines, close to each



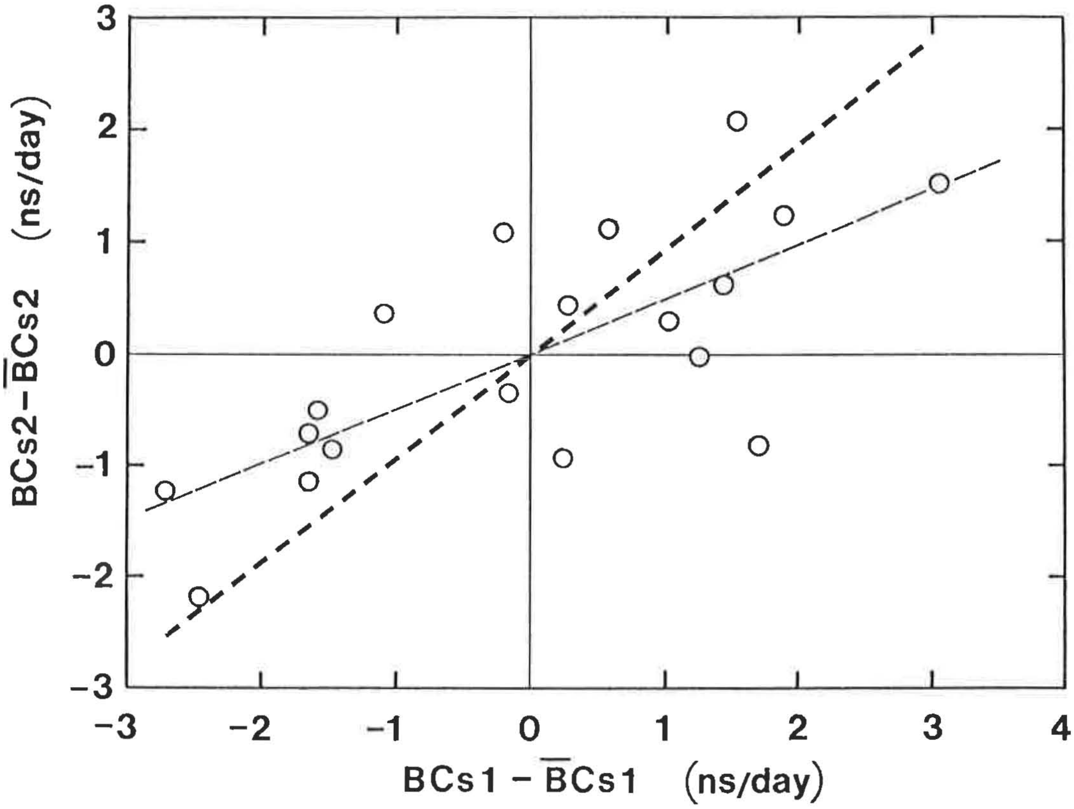


Fig. 1: Frequencies relative to TAI of the two primary standards PTB CS1 and PTB CS2 since October 1986:

1.1: variations with time,

1.2: frequency of PTB CS2 versus frequency of PTB CS1
(the frequency values are reduced to their averages)

- - - - - - - regression line with slope 1/si = 1/1,07 = 0,94

——————— regression line with slope sj = 0,49.

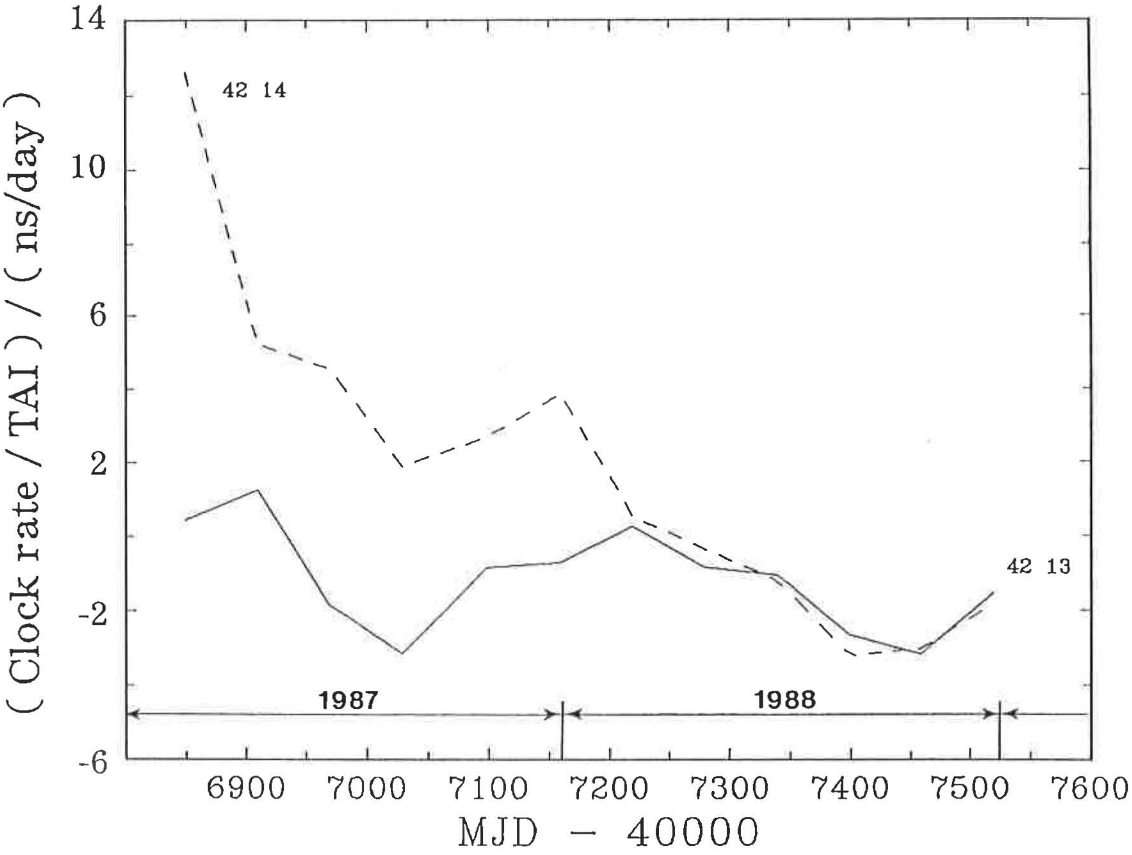


Fig. 2: Frequencies relative to TAI of the two H-masers APL 13 and APL 14 for a 20-month period. These H-masers were taken out of operation at the beginning of 1989 and reintroduced in TAI computation in 1990.

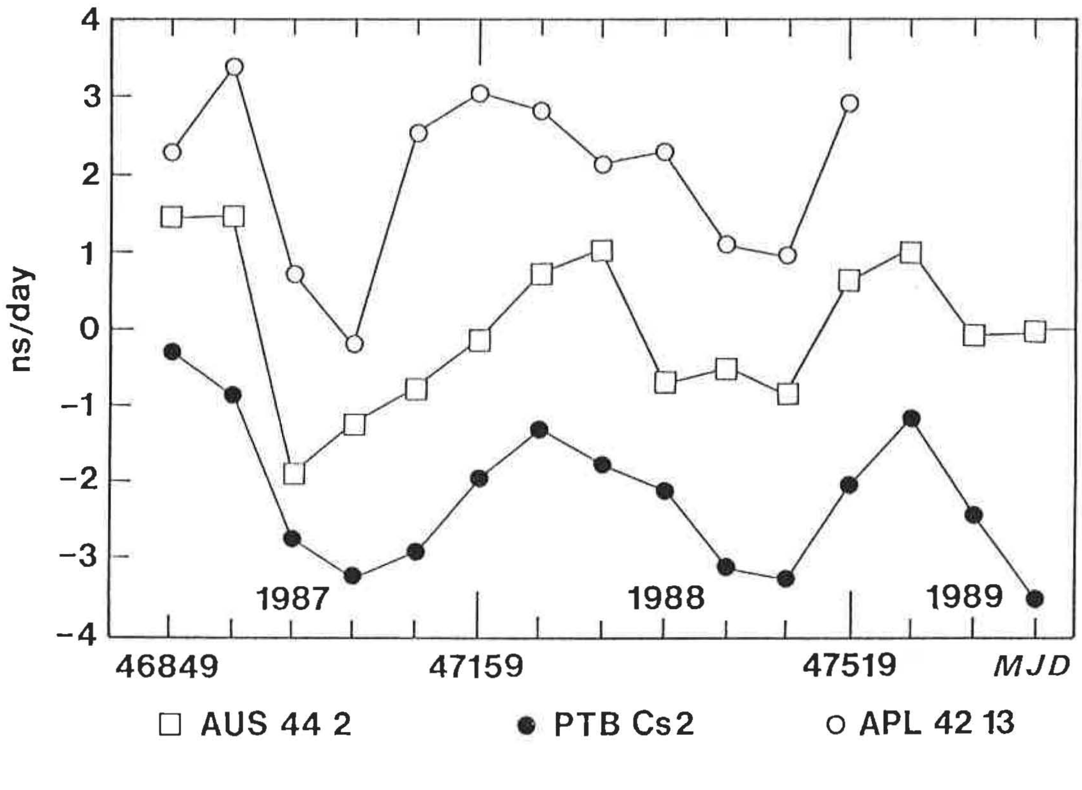


Fig. 3: Frequencies relative to TAI of APL H-maser 42 13, AUS H-maser 44 2 and PTB primary standard CS2. The H-maser values are globally shifted and the drifts removed.

other and close to the straight line of slope +1, attest to this high correlation.

Because of their excellent long-term stability, the clocks mentioned in this section have maximum relative weight (about 2%) in the TAI computation, even although their frequency data show correlations.

To conclude, the frequency variations observed here mainly represent the seasonal variation of TAI itself. Its peak-to-peak amplitude is of the order of 5 10^{-14} with a maximum at the end of the winter. In what follows, a larger amplitude or a different phase in the annual fluctuation of a clock frequency relative to TAI will be attributed to the clock itself rather than to TAI.

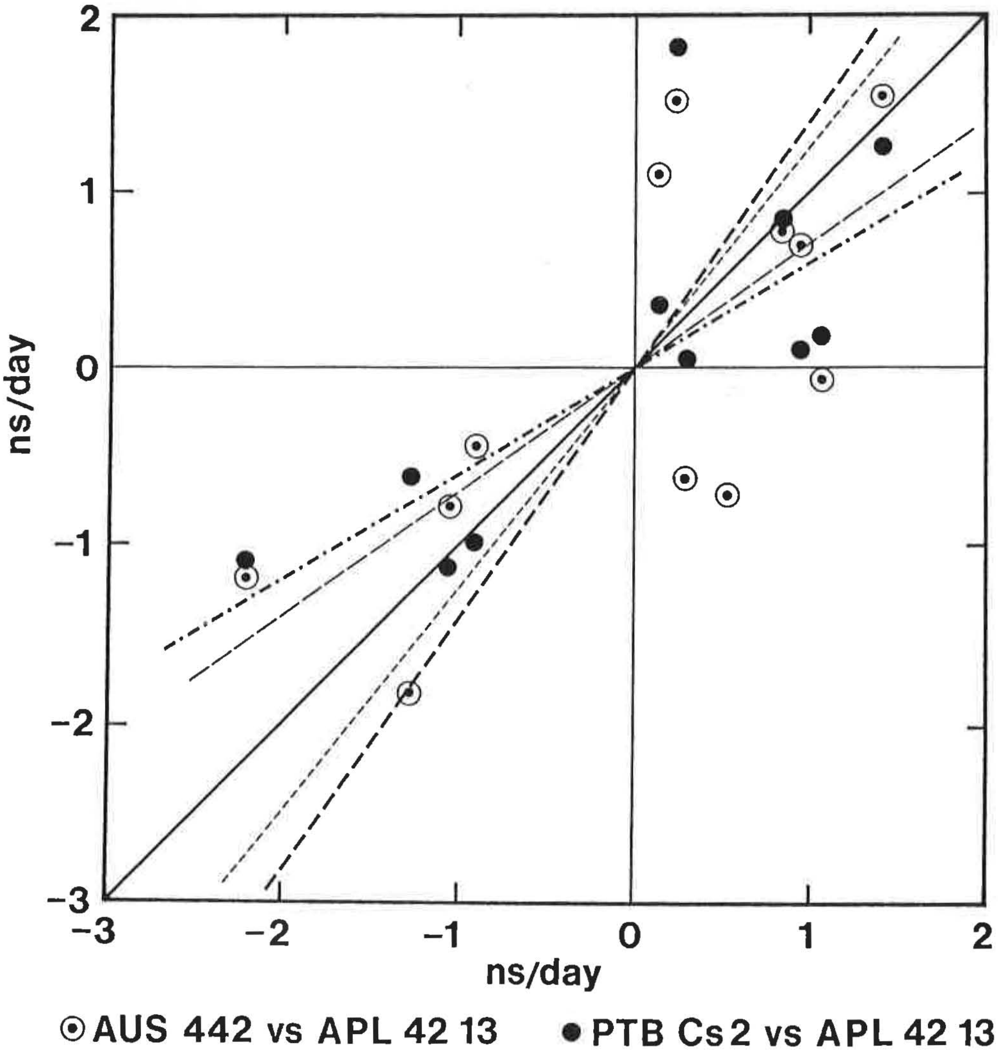


Fig. 4: Frequencies relative to TAI of APL H-maser 44 2 and PTB primary standard CS2 versus the frequency relative to TAI of APL H-maser 42 13 (the frequency values are reduced to their averages)
- - - - - - regression lines of AUS 44 2 versus APL 42 13,
-·-·-·-·-·- regression lines of PTB CS2 versus APL 42 13,
———————— straight line of slope +1.

II.2. Correlation due to changes in clocks environment

Commercial caesium clocks are more or less sensitive to changes of their environment, in particular to variations of temperature or humidity. Most timing centres keep their clocks in temperature-controlled rooms but relatively few use humidity-controlled rooms. Recently means have been found [6] to make clocks less sensitive to changes in their environment, but the application of such techniques had not been developed at the time of this study.

A typical example of frequency variations due to humidity changes is presented in Fig. 5. It concerns two commercial caesium clocks kept by the NAOM in Mizusawa (Japan). These clocks nearly present the same seasonal variation, with peak-to-peak amplitude of about 15ns/day ($1,7\ 10^{-13}$), which leads to a correlation in their frequency data ($\mu_{ij}(0) = 0,80$). This amplitude is much bigger than that observed for TAI. The relative humidity variation was recorded in this laboratory and reported to the BIPM for 1988 and 1989. It varied from 35% in winter to more than 70% at the end of summer, the temperature meanwhile being constant within 1°C. Figure 5 shows that the frequencies of these two clocks are highly correlated to the humidity conditions and then appear to be highly correlated among them. These clocks were entered in TAI computation for 1989 with relative weights of about 0,7%.

Another case is shown in Fig. 6. This concerns two commercial caesium clocks kept by the IEN in Turin (Italy). They present high seasonal variations with different peak-to-peak amplitudes (30ns/day and 45ns/day) and different phases: the humidity changes are thus experienced differently. The values of the cross-correlation function $\mu_{ij}(k)$ at different lags k are given in Fig. 7: a high correlation coefficient (negative in this case) appears when one B series is shifted by two months (k=1) showing a difference of about two months between the time constants of response of the two clocks. Between the maximum of anticorrelation (k=1 or k=7) and the maximum of correlation (k=4) there is an interval of six months as might be expected for a seasonal variation. In the TAI computation, these clocks had relative weights of about 1% and 0,15% in the period examined.

To conclude, environmental changes can induce large annual fluctuations in clock frequencies which, as a consequence, appear highly correlated. In the TAI computation, clock weights are chosen to be inversely proportional to the classical variance of six consecutive two-month frequency averages. So clocks with large annual fluctuations are deweighted and the induced correlations have reduced impact.

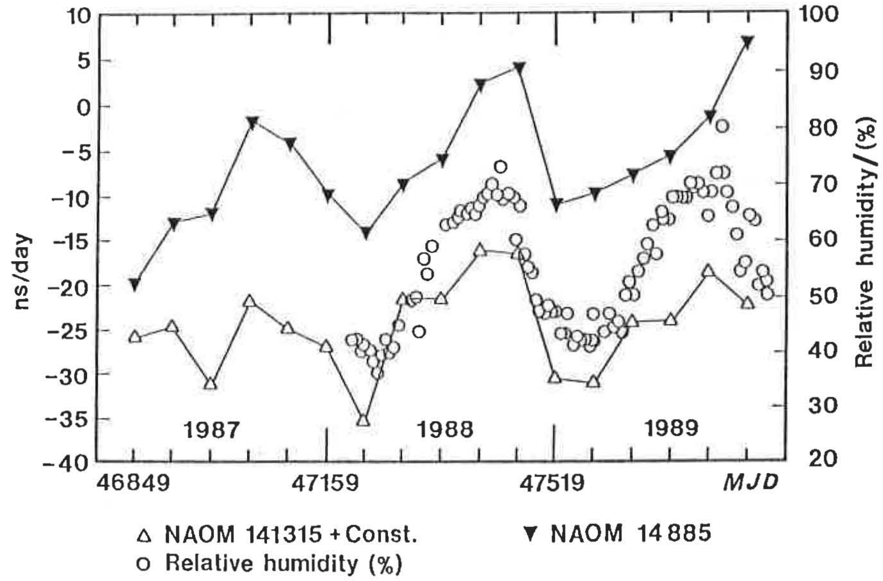


Fig. 5: Frequencies relative to TAI of NAOM 14 885 and NAOM 141315 and relative humidity in the room where they are kept.

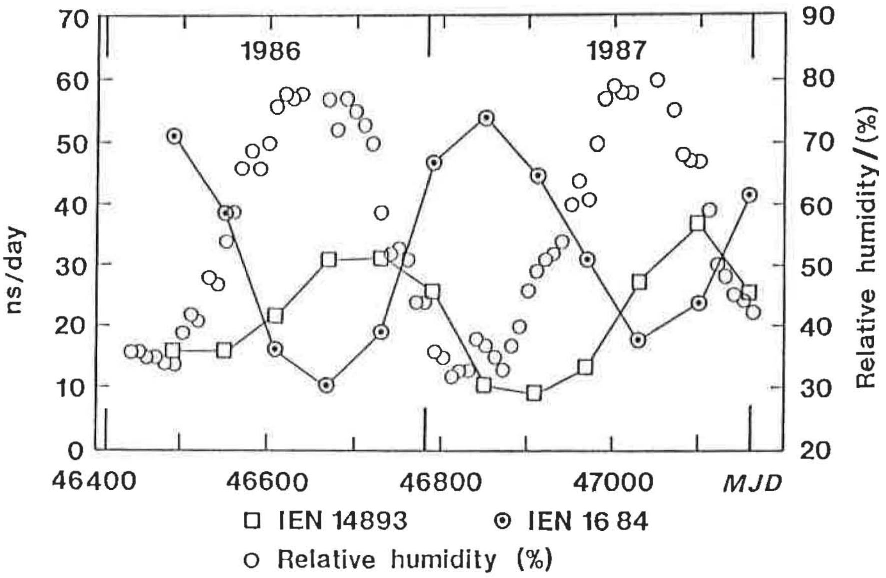


Fig. 6: Variation with time of the frequencies relative to TAI of IEN 14 893 and IEN 16 84 and relative humidity in the room where they are kept.

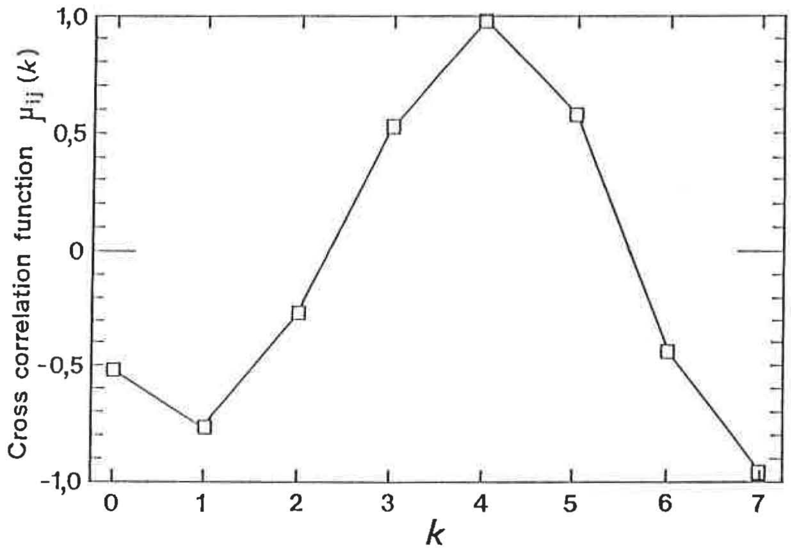


Fig. 7: Cross-correlation function $\mu ij(k)$ (as defined in Section I) versus lag k, for the two clocks IEN 14 893 and IEN 16 84.

II.3. Correlation attributed to time links

The most obvious case of correlation in the data presented here involves two Russian clocks, the two H-masers SU 381 and SU 382 (Fig. 8). These appear to be totally correlated during the period examined because they were seen through a very noisy Loran-C time-link which completely occults their long-term qualities. We obtain $\mu_{ij}(0)=0,999$. These two H-masers where intentionally weighted to zero in the TAI computation. They now contribute again thanks to an improved link performed via GLONASS satellites [7].

For this study, which considers only two-month averaged frequencies, noise due to GPS time comparisons is completely smoothed out and cannot induce correlations.

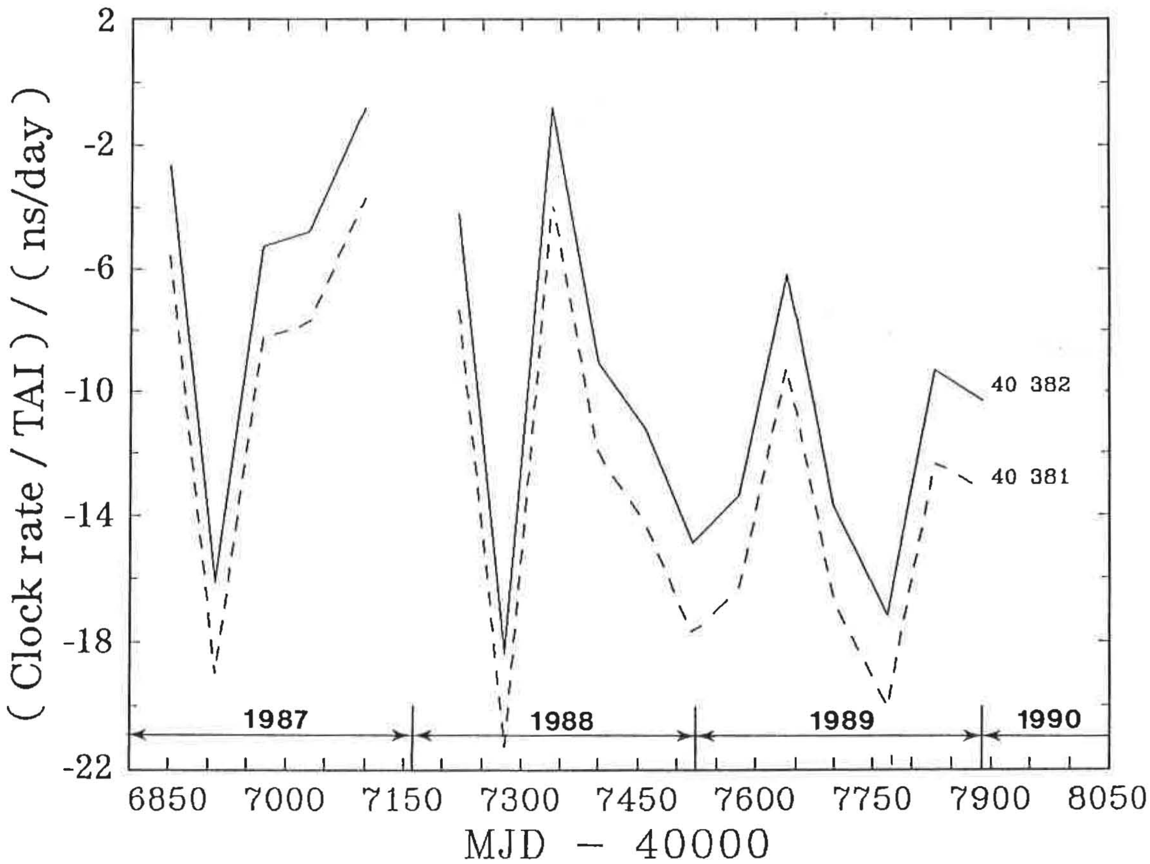


Fig. 8: Variation with time of the frequencies relative to TAI of SU H-masers 381 and 382 (the frequency values are shifted by 3ns/day for SU 382).

II.4. Correlation due to frequency drifts

A correlation between clock data can be observed when the principal variation of their two-month averaged frequencies is linear with time. A typical example of such drifts, which might be due to ageing, is given in Fig. 9 for two commercial clocks kept by the ORB. For this period the cross-correlation coefficient is $\mu_{ij}(0)$=0,82. If the drifts, estimated simply as slopes of linear fits on frequency data, are removed (Fig. 10), it drops to 0,22.

In TAI computations, a clock affected by a frequency drift is deweighted (the two clocks of the previous example had relative contributions of about 0,2%). The inverse variation of clock weights with classical frequency variances was chosen, in part, to protect TAI against such drifting [2], it also reduces the impact of such correlations.

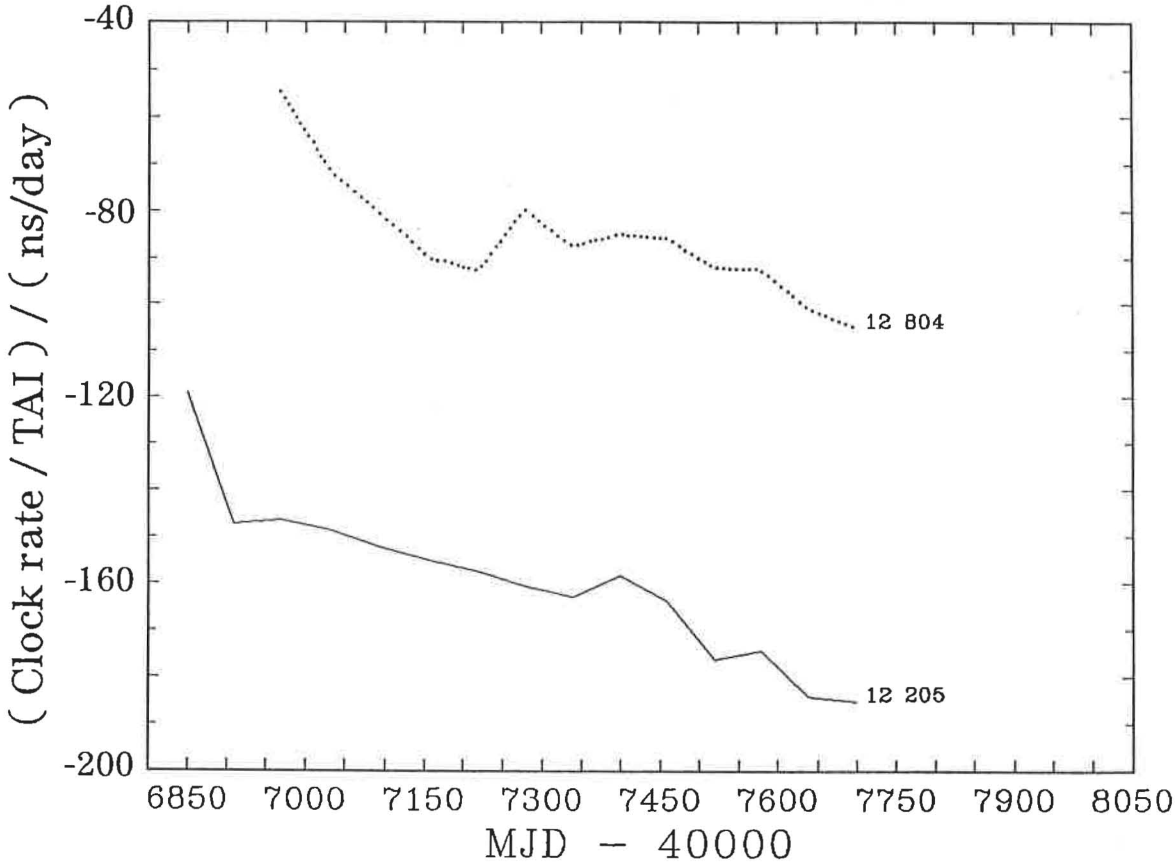


Fig. 9: Variation with time of the frequencies relative to TAI of ORB commercial caesium clocks 12 804 and 12 205. Their performance after MJD 47699 is ignored because both of them had a frequency step.

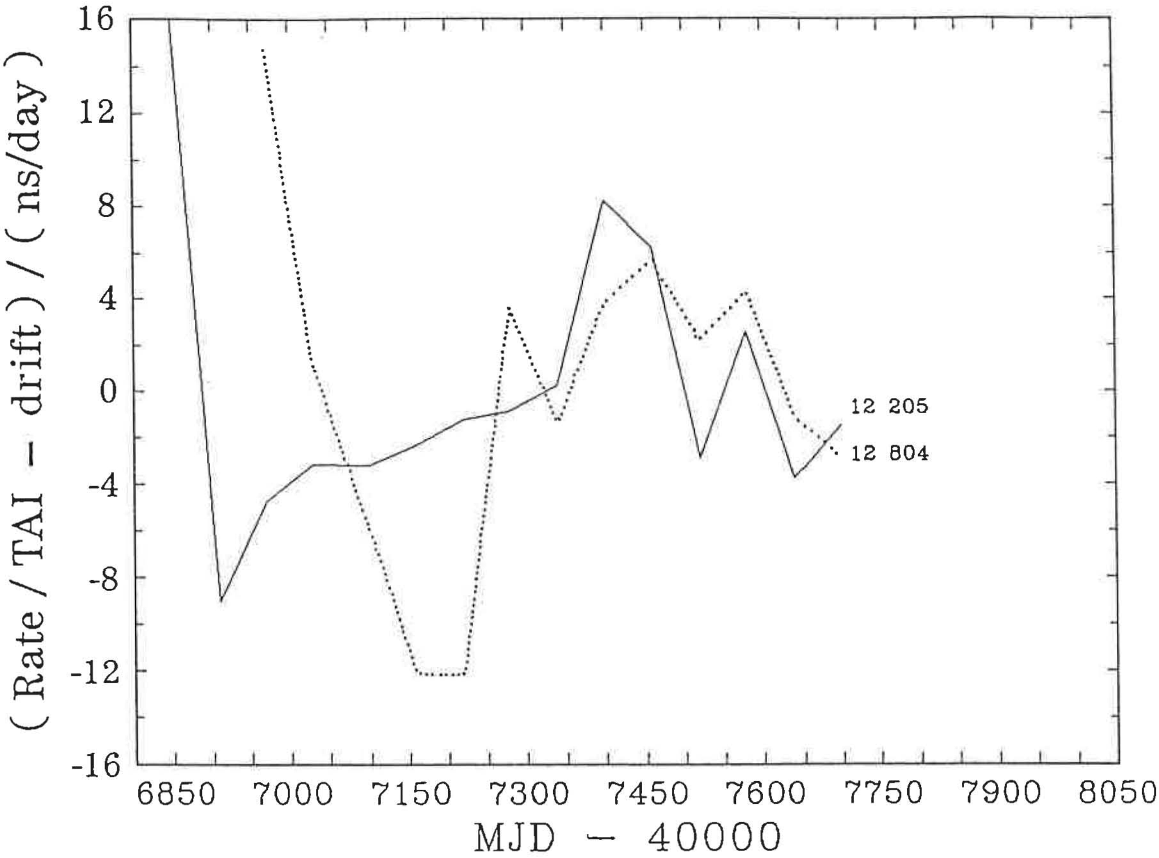


Fig. 10: Variation with time of the frequencies relative to TAI of ORB commercial caesium clocks 12 804 and 12 205 after drifts removing (respectively: -0,057ns/day^2 and -0,045ns/day^2).

III. Systematic research of correlations between clock frequency changes

Following is a catologue of the laboratories (in alphabetical order) which contributed to TAI from January 1987 (MJD 46849) to April 1990 (MJD 48009) and which maintained at least two clocks over an acceptably long operating period. Correlations occurring among clock frequency data are noted and an interpretation is given where possible. The relative contributions to TAI of the clocks involved are listed.

For each laboratory a graph showing the variation with time of the two-month averaged frequencies relative to TAI of the clocks is shown (Fig. n.a). Correlations are decribed by graphs (Fig. n.b,c...) which represent the frequencies, in their reduced form or with drifts removed, and by the calculated cross-correlation coefficients.

APL: APPLIED PHYSICAL LABORATORY, Laurel, Maryland, USA
(see Fig. 11.a, Fig. 11.b and also Section II.1).

The APL clock set stopped contributing to TAI on MJD 47519 (December 1988) and was reintroduced at mid-1990. This set mainly comprises H-masers which present long-term drifts.

For the period MJD 46849 to MJD 47519, one obtains:

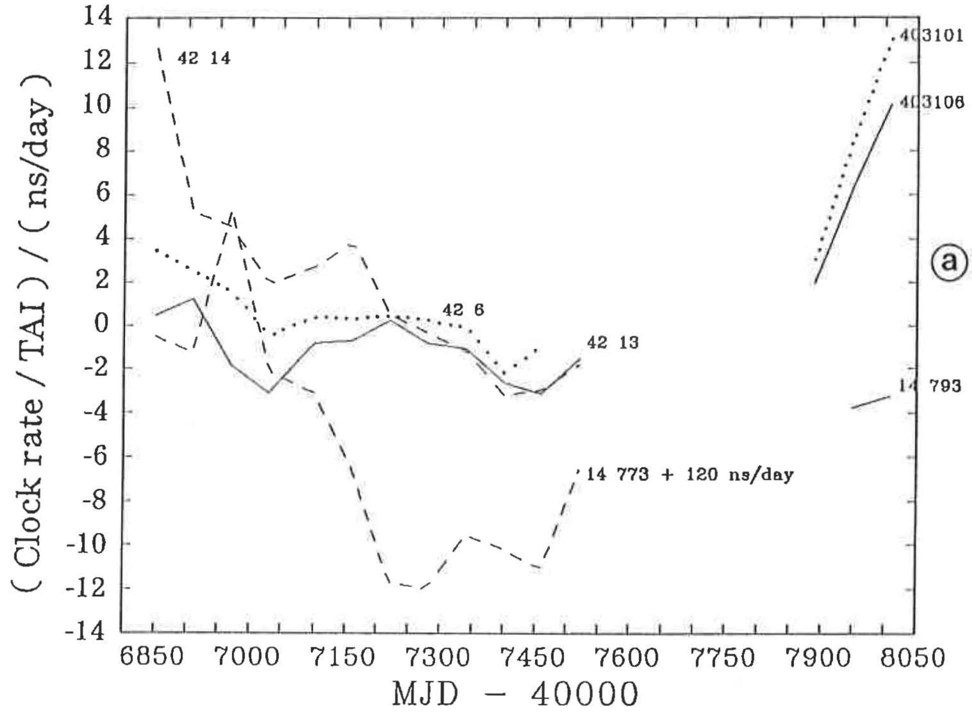
i = 42 6 j = 42 13 $\mu_{ij}(0)$ = 0,75
i = 42 6 j = 42 14 $\mu_{ij}(0)$ = 0,90
i = 42 13 j = 42 14 $\mu_{ij}(0)$ = 0,59.

When the drifts are removed, H-masers 42 6, 42 14 and 42 13 present very similar annual fluctuations due mainly to the injection of TAI annual fluctuation. We find:

i = 42 6 j = 42 13 $\mu_{ij}(0)$ = 0,70
i = 42 6 j = 42 14 $\mu_{ij}(0)$ = 0,60
i = 42 13 j = 42 14 $\mu_{ij}(0)$ = 0,37.

The values of $\mu_{ij}(0)$ thus decrease through suppression of the correlation due to the drifts. It is noticeable that the frequency relative to TAI of H-maser 42 6 closely follows that of H-maser 42 13.

These three H-masers were assigned the maximum relative contribution to TAI throughout the period of study (about 2,2%).



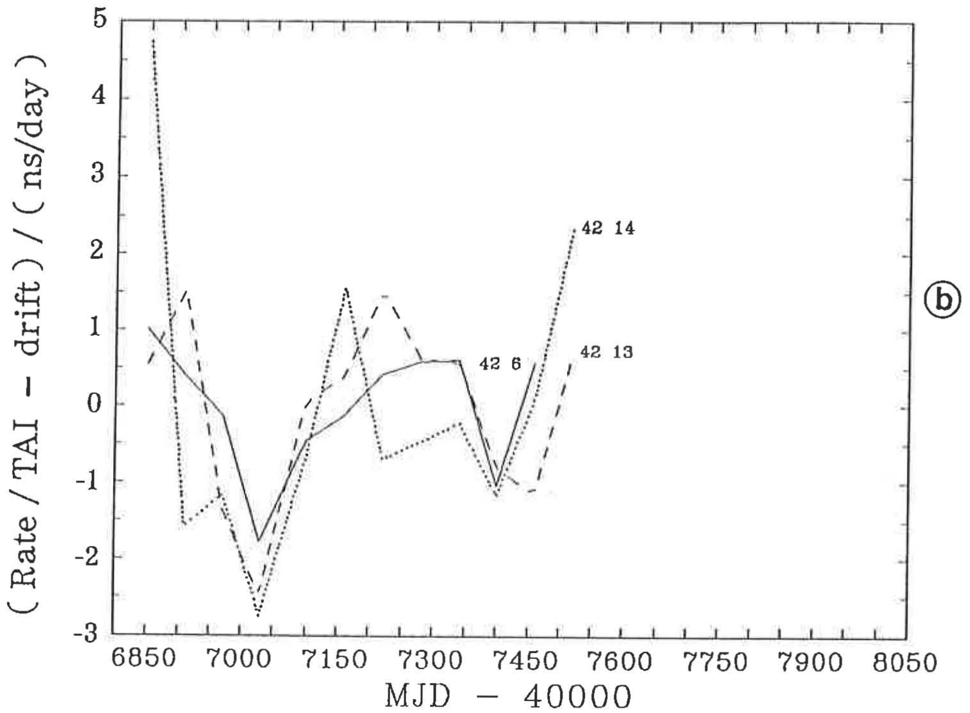


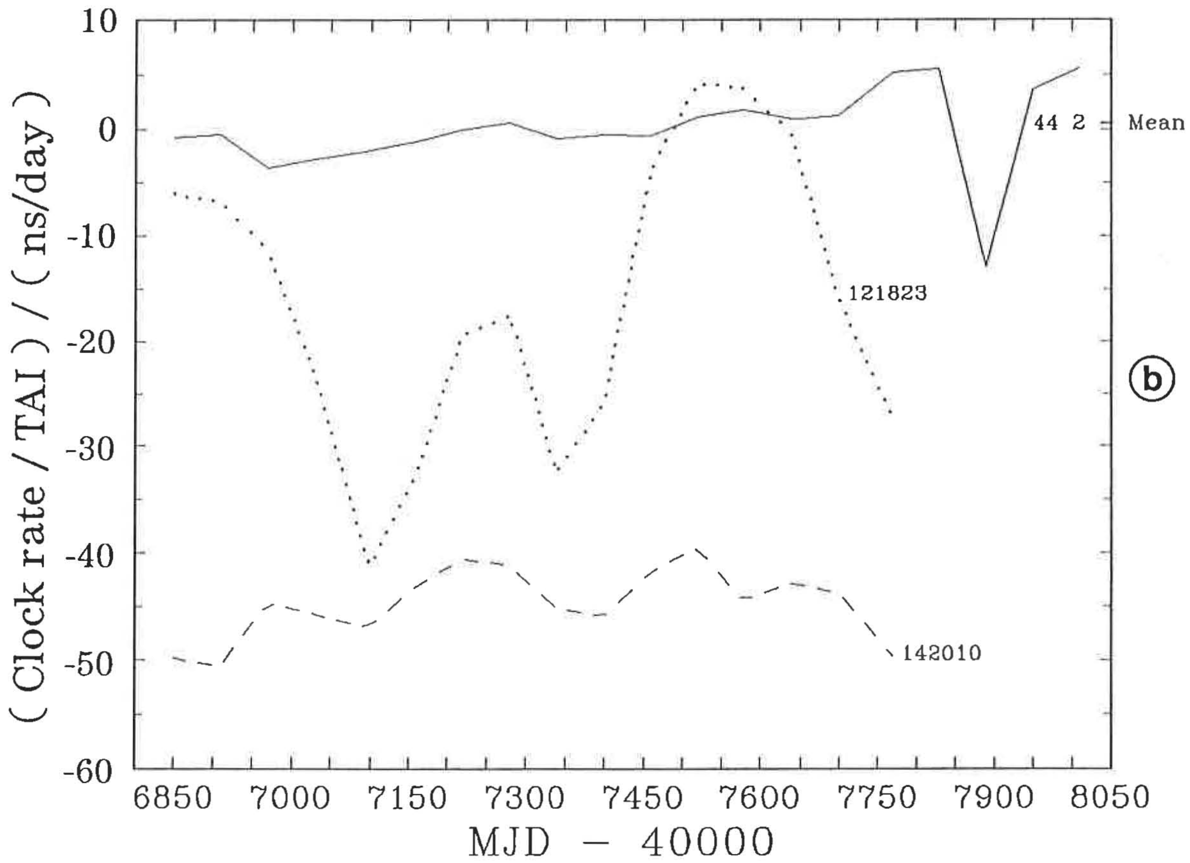
Fig. 11: Frequencies relative to TAI of APL clocks;
11.a: general overview,
11.b: 3 H-masers 42 6, 42 13 and 42 14 with drifts removed (resp. -0,007ns/day^2, -0,003ns/day^2 and -0.018ns/day^2).

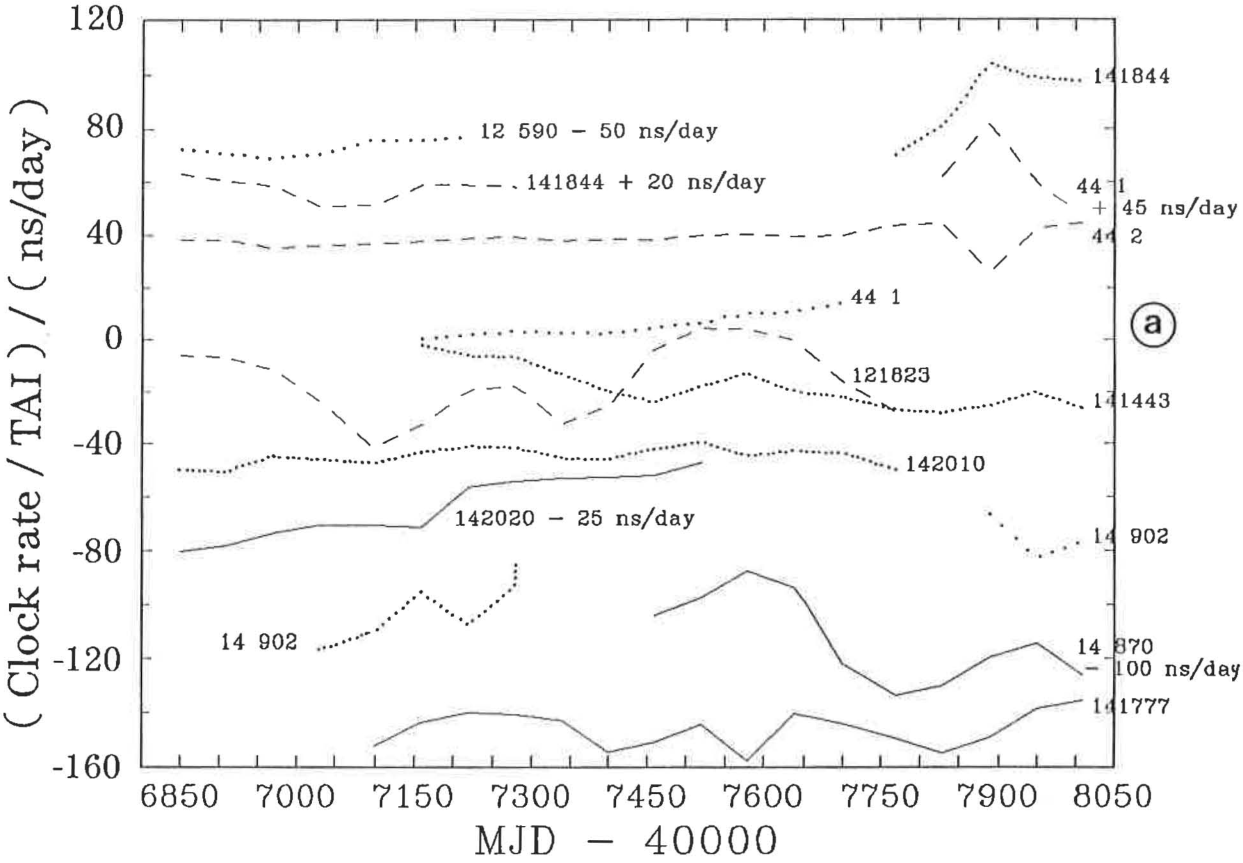
AUS: CONSORTIUM OF AUSTRALIAN LABORATORIES, Canberra, Australia
(see Fig. 12.a, Fig. 12.b, Fig.12.c and also Section II.1).

The AUS clock set contains several H-masers, in particular H-maser 44 2 already quoted in Section II.1, and commercial caesium clocks. In Fig. 12.a, no variation involving the complete set of clocks is observed, as might be the case if there were a global reaction to some environmental change. The correlation between six of AUS clocks having a long period of operation gives:

i = 121823 j = 44 2 $\mu_{ij}(0)$ = 0,20
i = 121823 j = 142010 $\mu_{ij}(0)$ = 0,24
i = 44 2 j = 142010 $\mu_{ij}(0)$ = 0,02
i = 141777 j = 44 2 $\mu_{ij}(0)$ = 0,12
i = 141777 j = 141443 $\mu_{ij}(0)$ = 0,25
i = 44 2 j = 141443 $\mu_{ij}(0)$ =-0,13.

These results provide no evidence of correlation. Apparently the clocks are independent and they have been introduced in TAI computation according to their individual qualities.





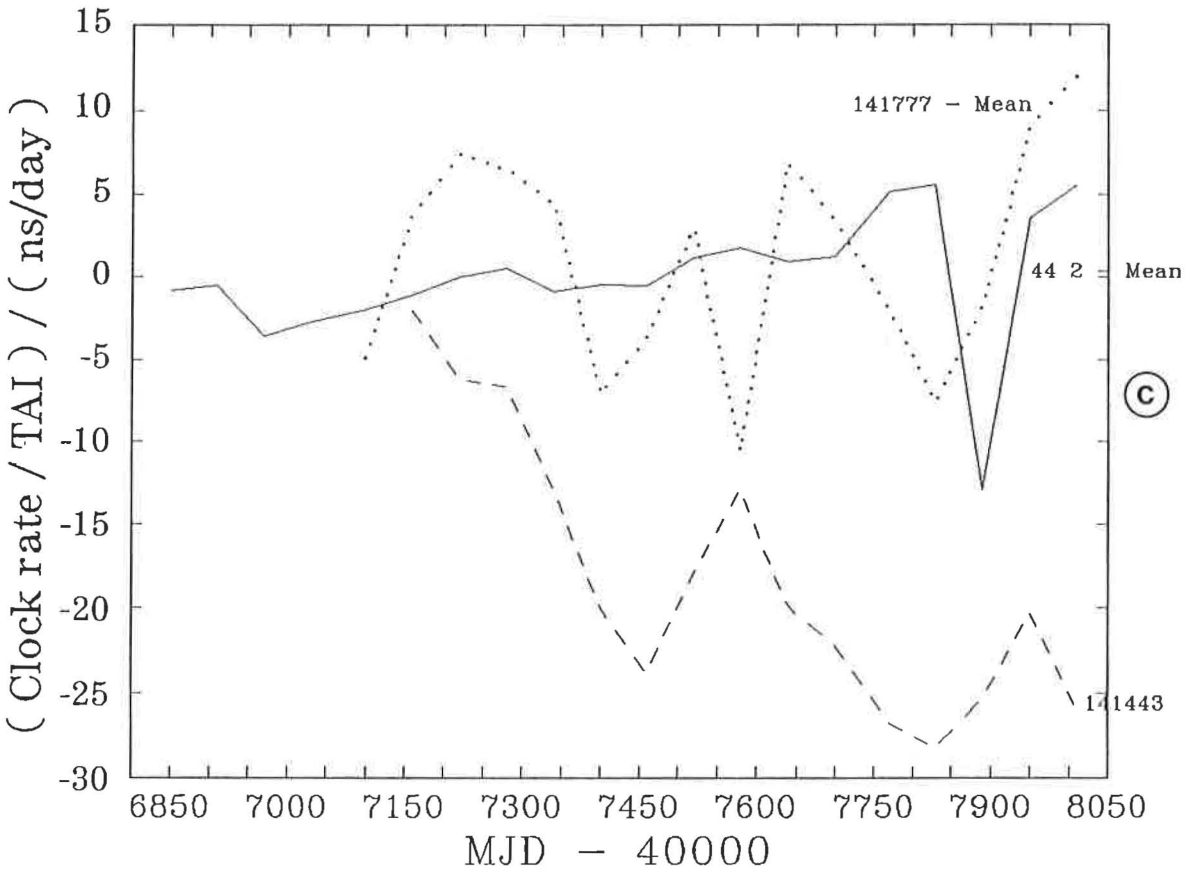


Fig. 12: Frequencies relative to TAI of AUS clocks;
12.a: general overview,
12.b: caesium clocks 121813 and 142010 compared to H-maser 44 2,
12.c: caesium clocks 141777 and 141443 compared to H-maser 44 2.

CH: CONSORTIUM OF SWISS LABORATORIES, Bern, Switzerland (Fig. 13).

Twenty two Swiss clocks of commercial type appeared in TAI for the period under study. Only the six of them which operated for the longest period are examined here. The clocks are kept at three different sites in Switzerland but a clear correlation by site does not appear, as confirmed by:

i = 21 194 j = 16 64 $\mu_{ij}(0)$ =-0,17
i = 16 77 j = 12 863 $\mu_{ij}(0)$ = 0,01
i = 21 243 j = 21 179 $\mu_{ij}(0)$ = 0,21.

However the frequency relative to TAI of four of the clocks clearly presents an annual variation, these particular clocks probably being more sensitive to global changes of humidity. This induces an apparent correlation as confirmed in particular by:

i = 12 863 j = 16 64 $\mu_{ij}(0)$ = 0,54
i = 12 863 j = 21 243 $\mu_{ij}(0)$ = 0,63.

The mean relative contribution to TAI of the Swiss clocks affected by annual variations was of order 0,4%.

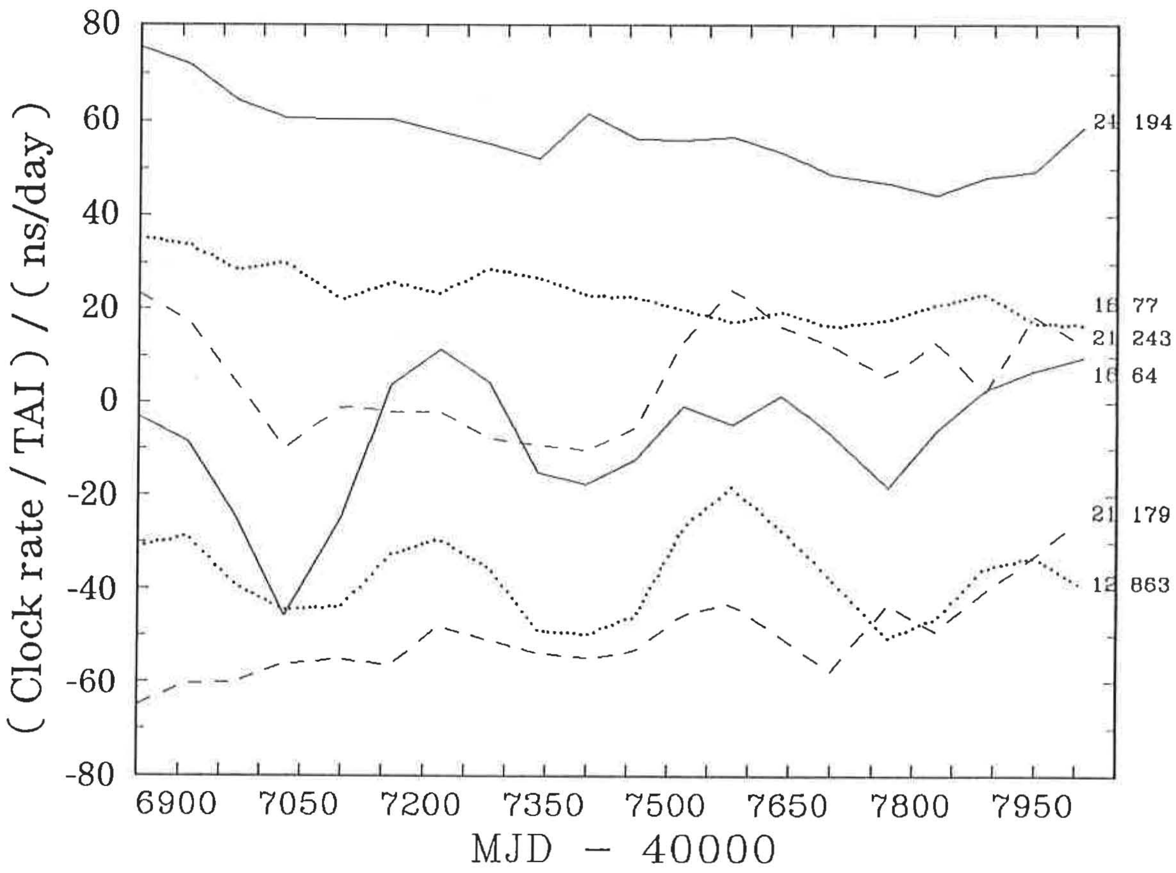


Fig.13: Frequencies relative to TAI of six CH clocks (all of them are of commercial type). Clocks kept by the same swiss laboratory are represented by the same line type.

CRL: COMMUNICATIONS RESEARCH LABORATORY, Tokyo, Japan (Figs. 14.a and 14.b).

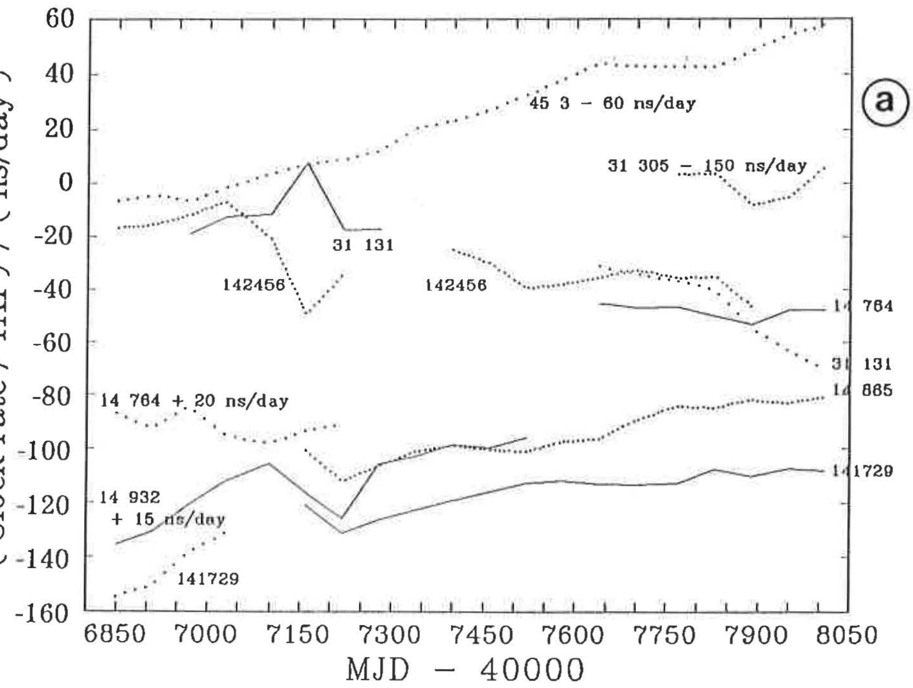
No annual variation involving the whole set of clocks (8 commercial caesium clocks and the H-maser 45 3) may be seen. However, one can observe a case of 'fugitive correlation': at about MJD 47150, nearly all the clocks, but one (31 131), presents a frequency step in the same sense. It is also noticeable that H-maser 45 3 is not affected. Most probably the effect is due to some sudden environmental change in the laboratory which was particularly felt by commercial clocks, and was corrected soon after.
Cross-correlation coefficients have been computed for two of the commercial clocks and H-maser 45 3:

i = 14 865 j = 141729 $\mu_{ij}(0)$ = 0,87
i = 14 865 j = 45 3 $\mu_{ij}(0)$ = 0,88
i = 141729 j = 45 3 $\mu_{ij}(0)$ = 0,91.

They correspond to high correlations.
On removing the drifts of these clocks (Fig. 14.b), the cross-correlation coefficients drop to:

i = 14 865 j = 141729 $\mu_{ij}(0)$ = 0,22
i = 14 865 j = 45 3 $\mu_{ij}(0)$ =-0,36
i = 141729 j = 45 3 $\mu_{ij}(0)$ = 0,43

giving the evidence of correlations which are mainly attributed to the natural drift of the clocks.
These three clocks were highly weighted in the TAI computation, often reaching the maximum relative contribution of about 2%.



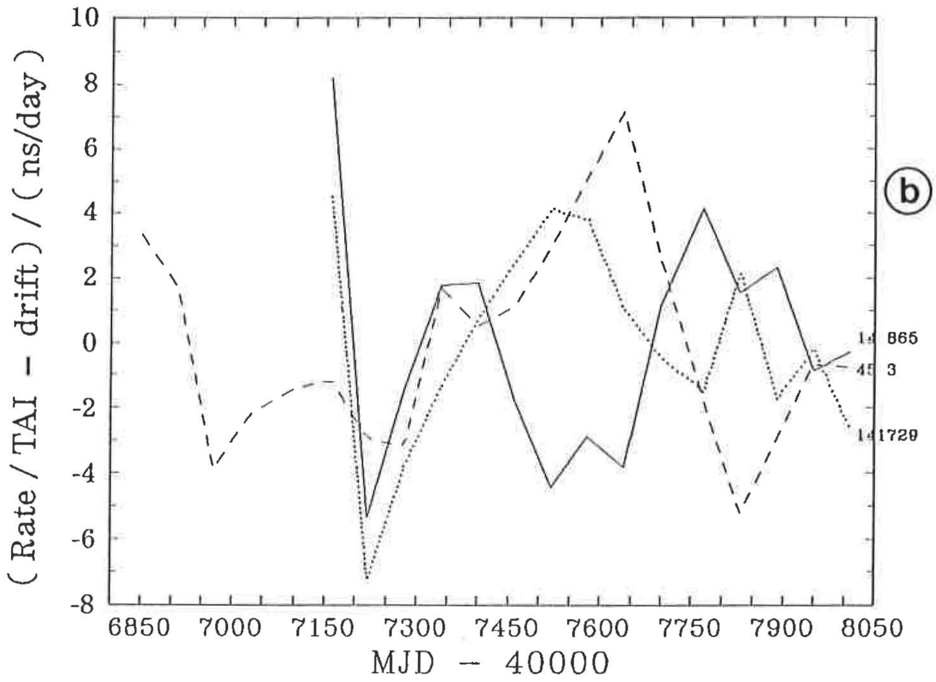


Fig. 14: Frequencies relative to TAI of CRL clocks;
14.a: general overview,
14.b: caesium clocks 14 865 and 141729 compared to H-maser 45 3 (removed drifts resp. 0,034ns/day^2, 0,023ns/day^2 and 0,059ns/day^2).

CSAO: SHAANXI ASTRONOMICAL OBSERVATORY, Lintong, P. R. China (Fig. 15.a and Fig. 15.b).

Five commercial CSAO clocks contributed to the TAI computation, two of them having operated for the whole period under study and one for more than two years. Both large annual variations and drifts can be observed. This induces a high correlation confirmed by:

$i = 121648 \; j = 121646 \quad \mu_{ij}(0) = 0{,}86.$

This correlation is even clearer when drifts are removed (Fig. 15.b), the frequencies of these two clocks being affected of variations of the same sign and magnitude for nearly every two-month interval of the period under study. The mean relative contribution to TAI of these two clocks was about 0,2%.

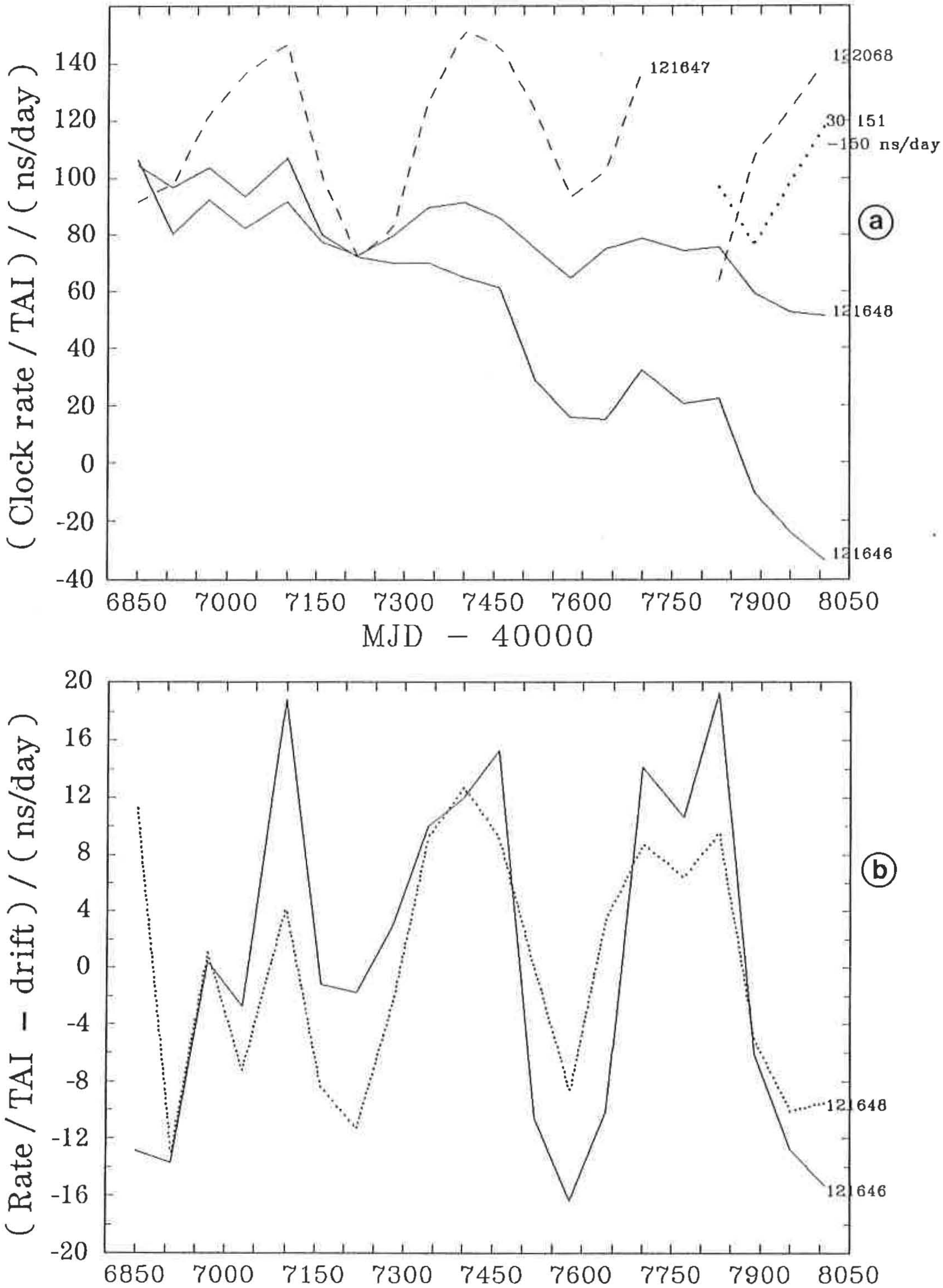
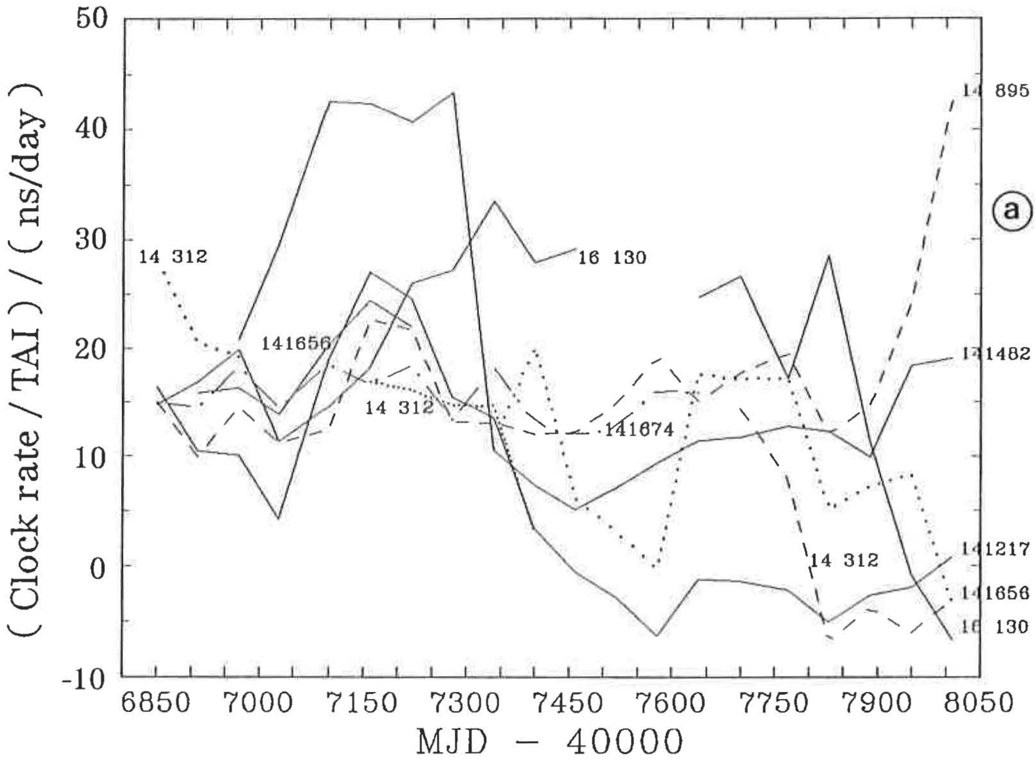


Fig. 15: Frequencies relative to TAI of CSAO clocks;
15.a: general overview,
15.b: two commercial caesium clocks 121648 and 121646 (removed drift resp. $-0{,}029 ns/day^2$ and $-0{,}120 ns/day^2$).

FTZ: FERNMELDETECHNISCHES ZENTRALAMT, Darmstadt, Germany (Fig. 16.a and 16.b).

Seven commercial caesium clocks contributed to the TAI computation. No global variation of their frequencies can be seen other than annual variations for the first half of the period under study. Three clocks operated continuously for more than three years. Until mid-1988, these were highly correlated in their annual variations and had low relative contributions to TAI (about 0,2%). Subsequently they were globally more stable and reached the maximum relative weight (about 2%) in 1989. A high correlation can be observed in the data of two of them (Fig. 16.b), this is confirmed by:

i = 141482 j = 141217 $\mu_{ij}(0)$ = 0,83.



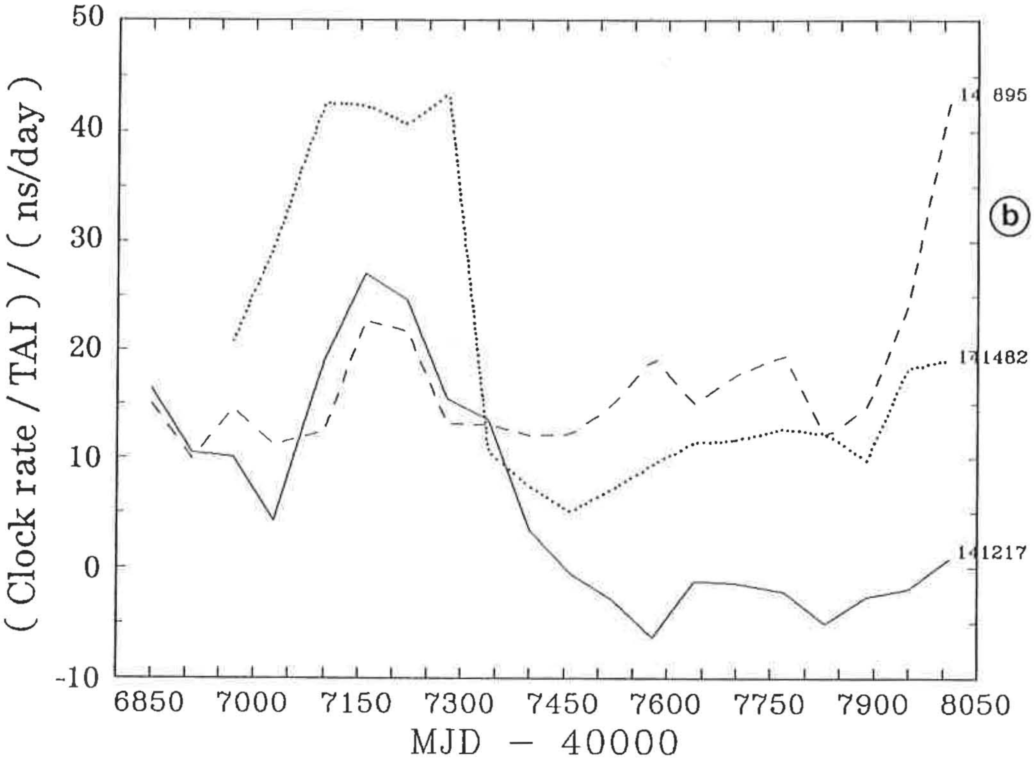


Fig. 16: Frequencies relative to TAI of FTZ clocks;
16.a: general overview,
16.b: three commercial caesium clocks 14 895, 141482 and 141217.

IEN: ISTITUTO ELETTROTECNICO NAZIONALE GALILEO FERRARIS, Torino, Italy (Figs. 17 and 6 and 7 of Section II.2).

The discussion of Section II.2 has already pointed out a particular interesting example of correlation apparently caused by humidity changes. Figure 17 shows the behaviour of the IEN clocks for a more recent period: a large seasonal fluctuation can be observed for the commercial caesium clock 141230.

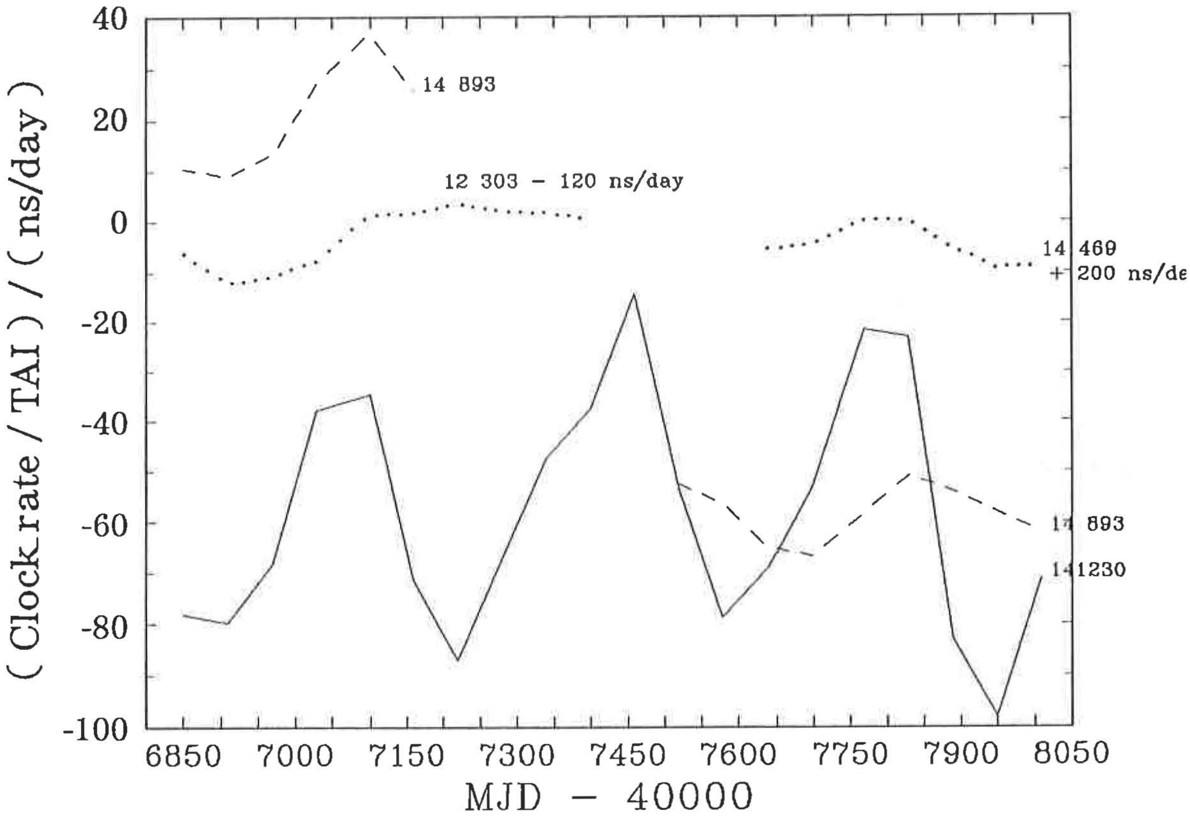


Fig. 17: Frequencies relative to TAI of IEN clocks.

IFAG: INSTITUT FÜR ANGEWANDTE GEODÄSIE, Wettzell, Germany (Fig. 18.a and 18.b).

Six commercial caesium clocks contributed to the TAI computation for the period under study, some of them showing drifts and seasonal fluctuations. As in the case of the IEN clock set (Section II.2), it is especially interesting to study the cross-correlation function $\mu_{ij}(k)$ for two the clocks:

i = 16 138 j = 16 274 $\mu_{ij}(0) = 0{,}31$.

When drifts are removed (Fig. 18.b), $\mu_{ij}(k)$ varies as:

i = 16 138 j = 16 274 $\mu_{ij}(0) = -0{,}57$
i = 16 138 j = 16 274 $\mu_{ij}(1) = 0{,}13$
i = 16 138 j = 16 274 $\mu_{ij}(2) = 0{,}74$
i = 16 138 j = 16 274 $\mu_{ij}(3) = 0{,}52$
i = 16 138 j = 16 274 $\mu_{ij}(4) = -0{,}24$

where the time series $B_{16\ 274}$ is two-month shifted towards left for a variation of k by 1 unit. These two clocks are thus correlated in their drifts, but are anticorrelated in their seasonal variations which have opposite phase (Fig. 18.b).

Clocks 16 138 and 16 274 contributed to TAI respectively by about 0,05% and 0,4% during 1989.

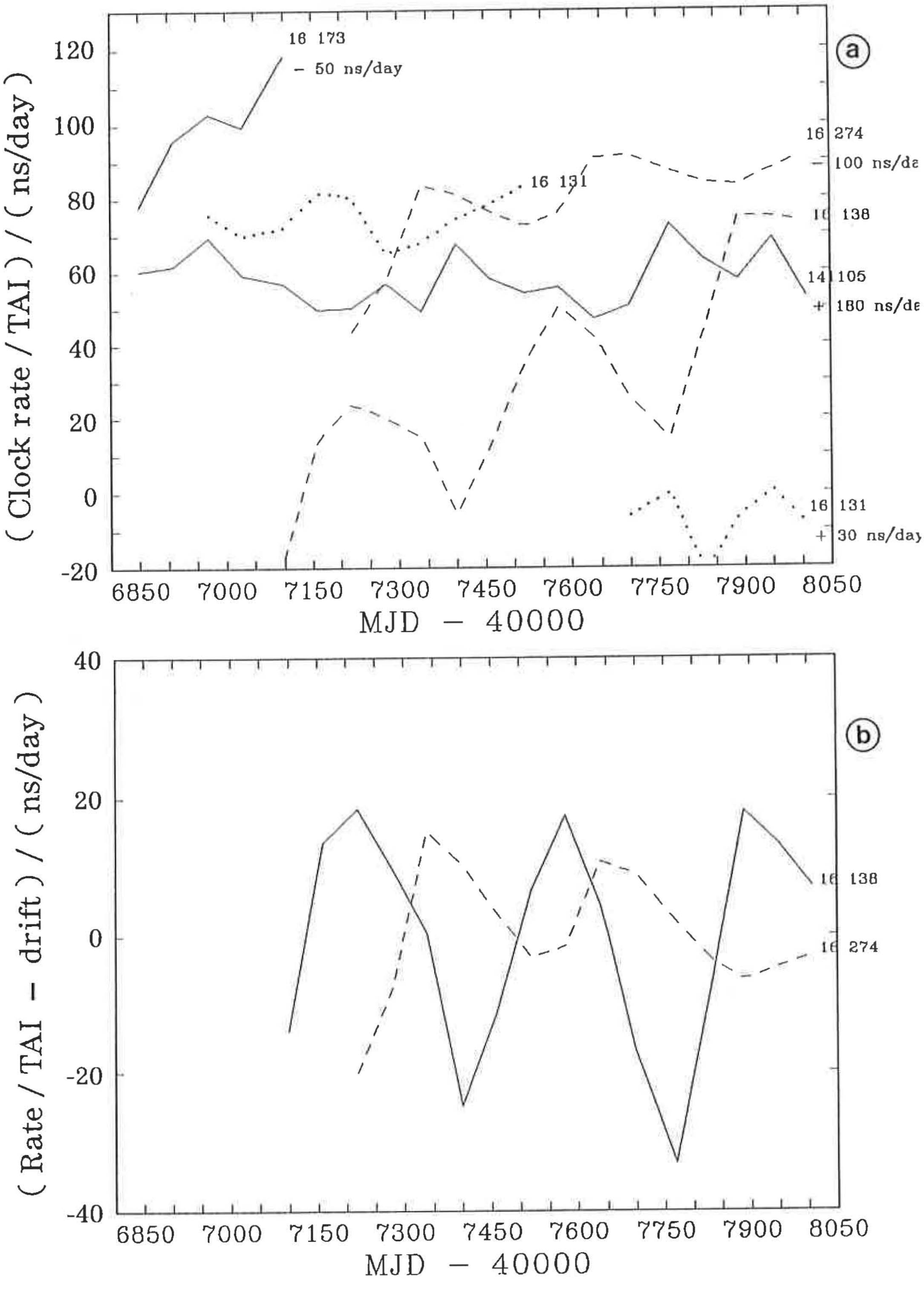


Fig. 18: Frequencies relative to TAI of IFAG clocks;
18.a: general overview,
18.b: two commercial caesium clocks 16 138 and 16 274 (removed drift resp. 0,076ns/day^2 and 0,039ns/day^2).

KSRI: KOREA STANDARDS RESEARCH INSTITUTE, Taejon, Rep. of Korea (Fig. 19).

Five commercial caesium KSRI clocks contributed to the TAI computation, only one of them being in continuous operation for the whole period under study. It is thus inappropriate to search for correlations. This particular clock was assigned low weight, often close to zero, because it showed large frequency steps.

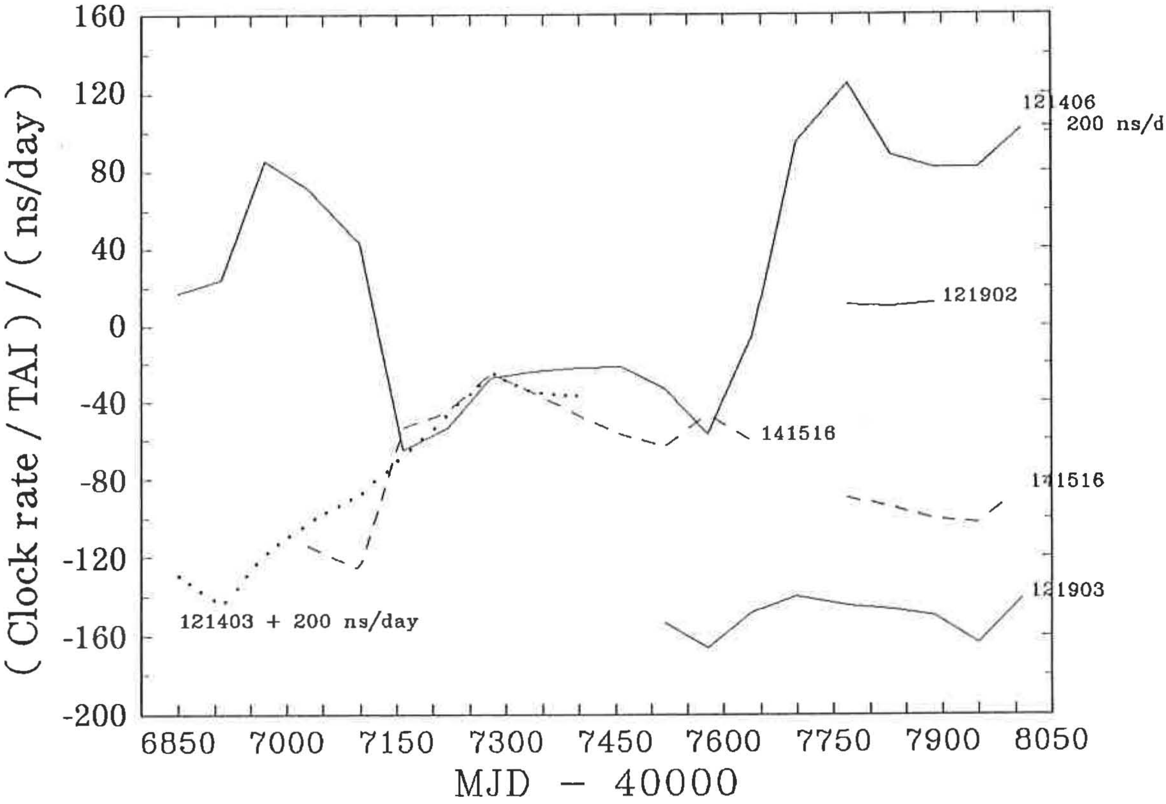


Fig. 19: Frequencies relative to TAI of KSRI clocks, general overview.

NAOM: NATIONAL ASTRONOMICAL OBSERVATORY, Mizusawa, Japan (Fig. 5 of Section II.2 and Fig. 20).

Besides clocks 14 885 and 141315, the frequency variations of which have already been analysed in Section II.2, three other commercial caesium NAOM clocks participated in the TAI computation but for shorter periods. Figure 20 adds the seasonal variations of clocks 14 885 and 141315 for 1990, which are not represented in Fig. 5. Throughout the period under study, these two clocks were highly correlated with $\mu_{ij}(0)$ equal to 0,75.

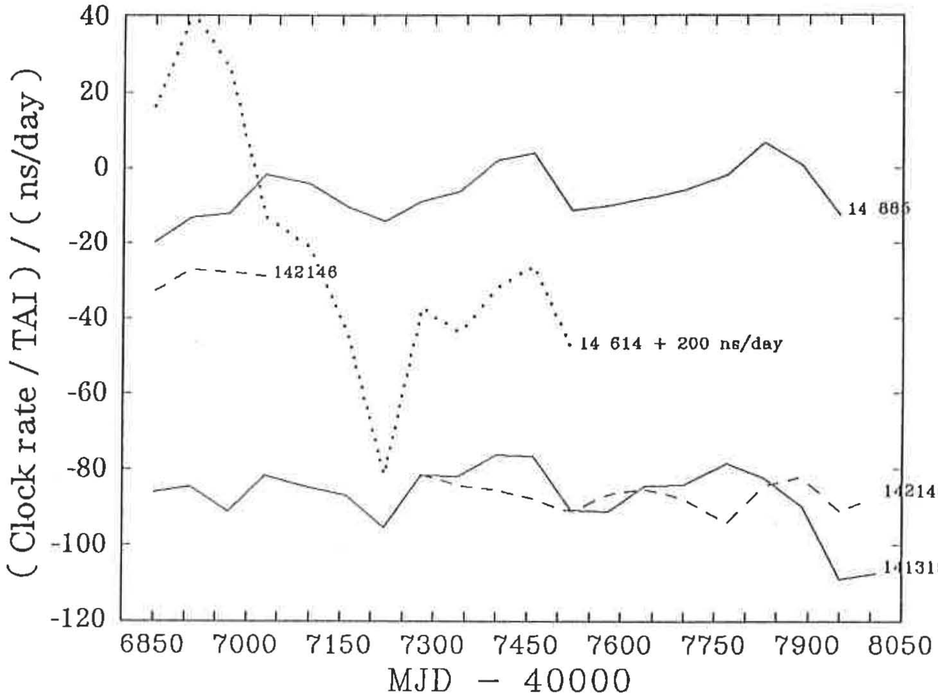


Fig. 20: Frequencies relative to TAI of NAOM clocks, general overview (Clock 11 176 is not shown).

NIM: NATIONAL INSTITUTE OF METROLOGY, Beijing, P. R. China (Fig. 21).

The NIM commercial caesium clocks were affected by large frequency steps, partly due to noisy time links, which deweighted them and did not allow the study of persistent correlations. Nevertheless, one can observe here a case of fugitive correlation, around MJD 47300, corresponding perhaps to a common reaction by clocks 121633 and 121640 to some external event.

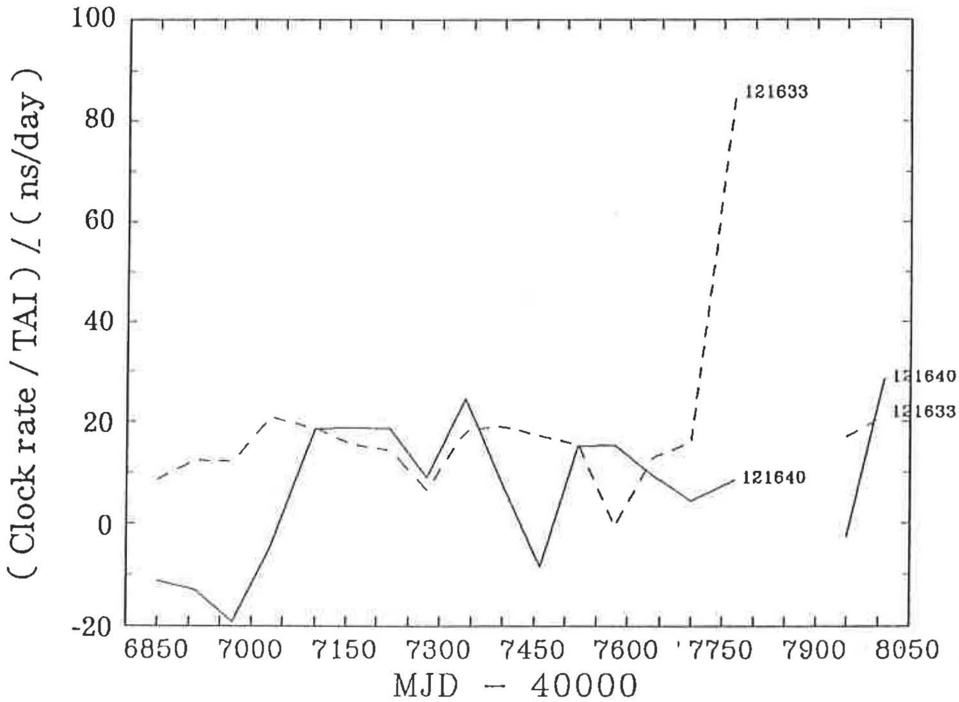


Fig. 21: Frequencies relative to TAI of NIM clocks, general overview (Clock 121615 is not shown).

NIST: NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, Boulder, Colorado, USA (Fig. 22.a, Fig. 22.b and Fig. 22.c).

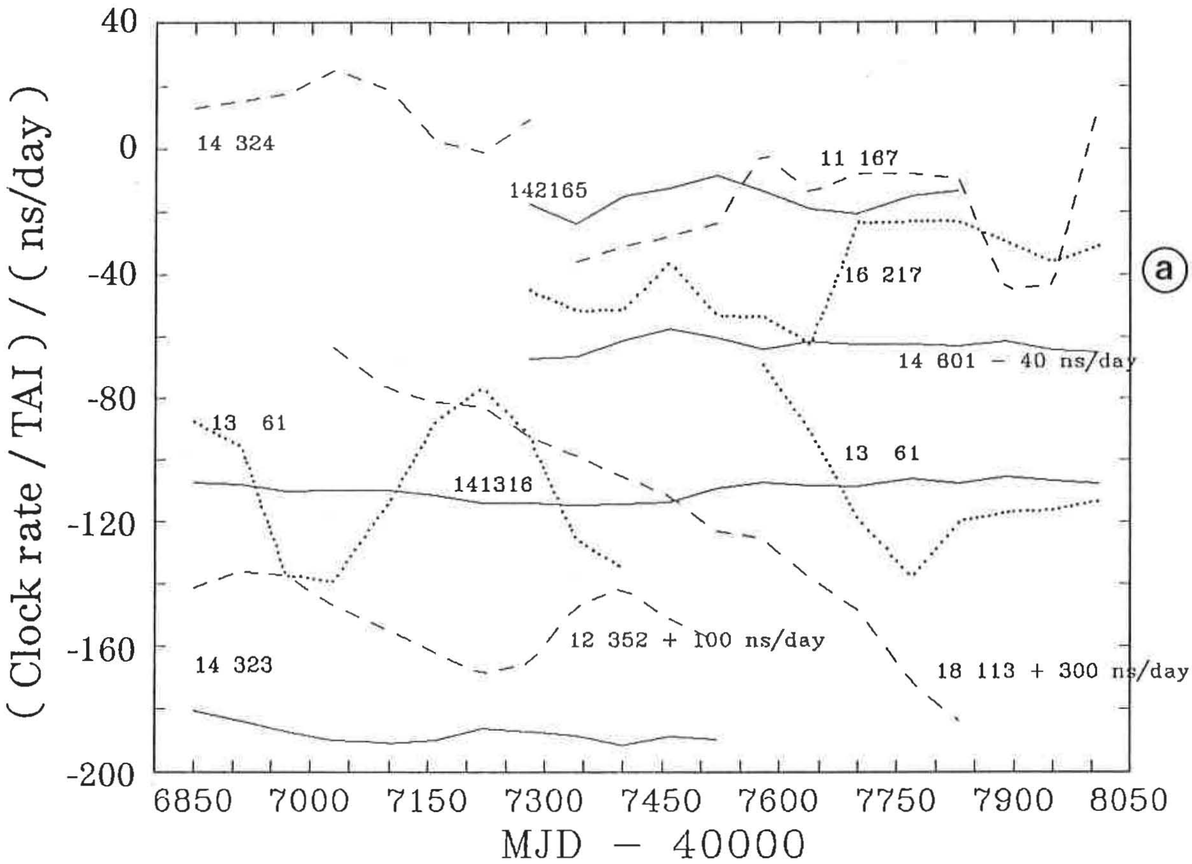
About ten commercial caesium NIST clocks have contributed to TAI. One of them, clock 141316, was in continuous operation for the four years considered here and always received the maximum weight. The period under study may usefully be divided into two parts which correspond to different patterns of the clock behaviour. During the first part, 1987-1988, the clocks presented clear seasonal variations (Fig. 22.b) which correlated or anticorrelated them:

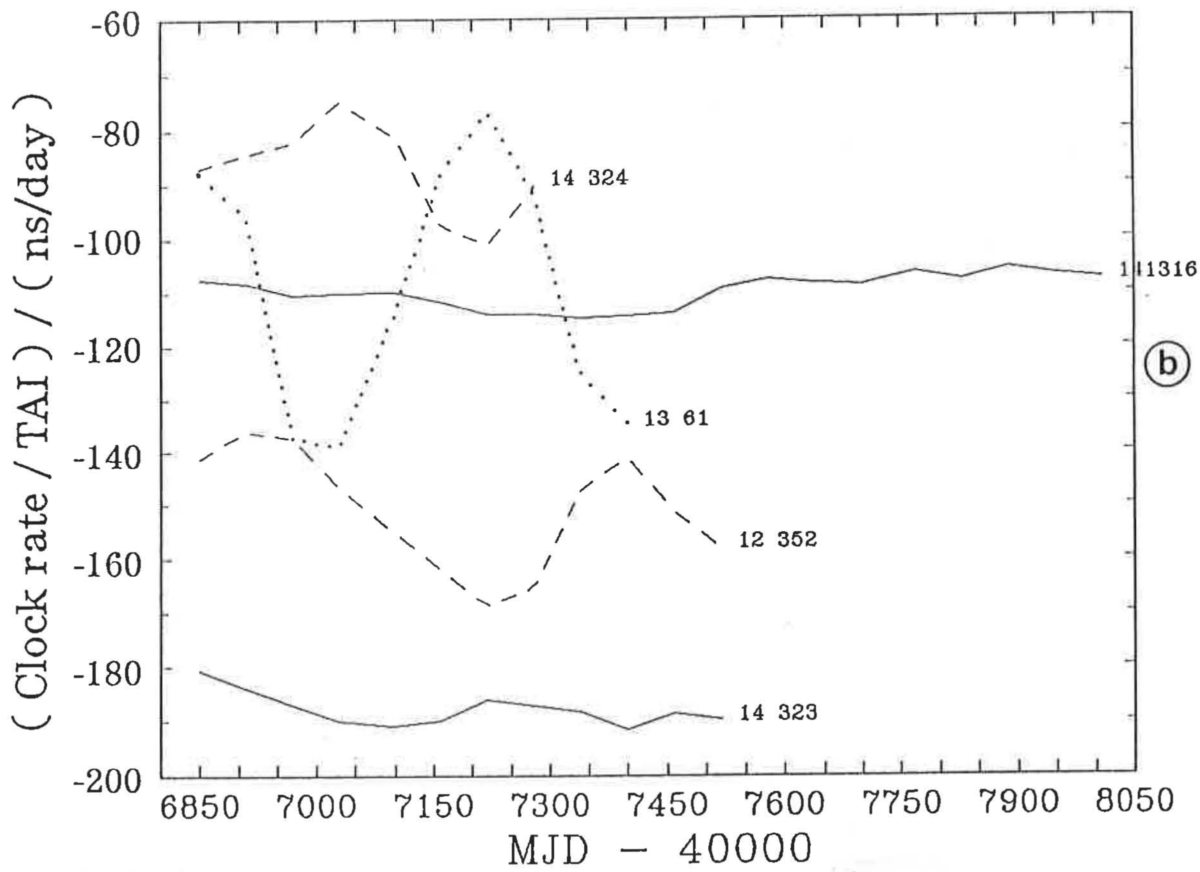
i = 12 352 j = 14 324 $\mu_{ij}(0) = 0,61$

i = 12 352 j = 13 61 $\mu_{ij}(1) =-0,57$.

These clocks then stopped operating and were replaced by others, in particular by clocks 142165 and 14 601, which show smaller frequency variations (Fig. 22.c). This led to increasing relative contributions from NIST clocks. No correlation can be detected for this second part of the study. A possible explanation is the improvement of environmental conditions with the installation of humidity-controlled room for the clocks.

During the years 1988-1989, some of the NIST clocks reported to the BIPM operated under De Marchi's conditions [5]. Unfortunately we have at our disposal only two or three two-month samples of continuous operation and this is not enough to demonstrate the gain in long-term stability and the reduced sensitivity to external change.





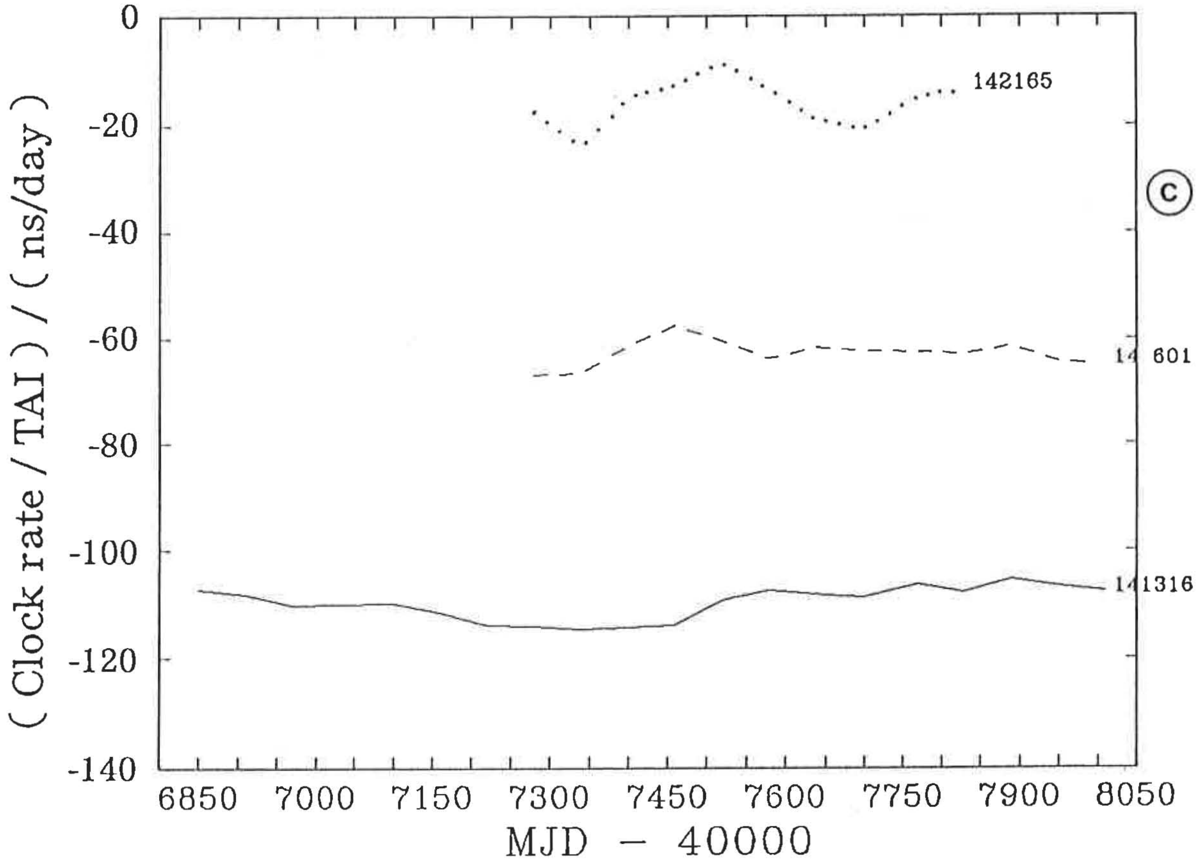


Fig. 22: Frequencies relative to TAI of NIST clocks;
22.a: general overview,
22.b: four commercial caesium clocks, having operated in 1987 and 1988, compared to clock 141316,
22.c: two commercial caesium clocks, having operated in 1989 and 1990, compared to clock 141316
(the scale is identical for Fig. 22.b and Fig. 22.c).

NPL: NATIONAL PHYSICAL LABORATORY, Teddington, United Kingdom (Fig. 23.a and Fig. 23.b).

Among the NPL commercial caesium clocks only three were in continuous operation throughout most of the period under study. The frequencies relative to TAI of two of them, clocks 12 316 and 141334, show drifts of opposite sign which induce a high correlation:

i = 12 316 j = 141334 $\mu_{ij}(0)$ =-0,90.

When drifts are removed (Fig. 23.b), the correlation between them drops:

i = 12 316 j = 141334 $\mu_{ij}(0)$ =-0,12.

No clear seasonal fluctuation can be observed.

Because of their frequency drifts these clocks were not highly weighted (mean relative contribution of about 0,10%) in the TAI computation.

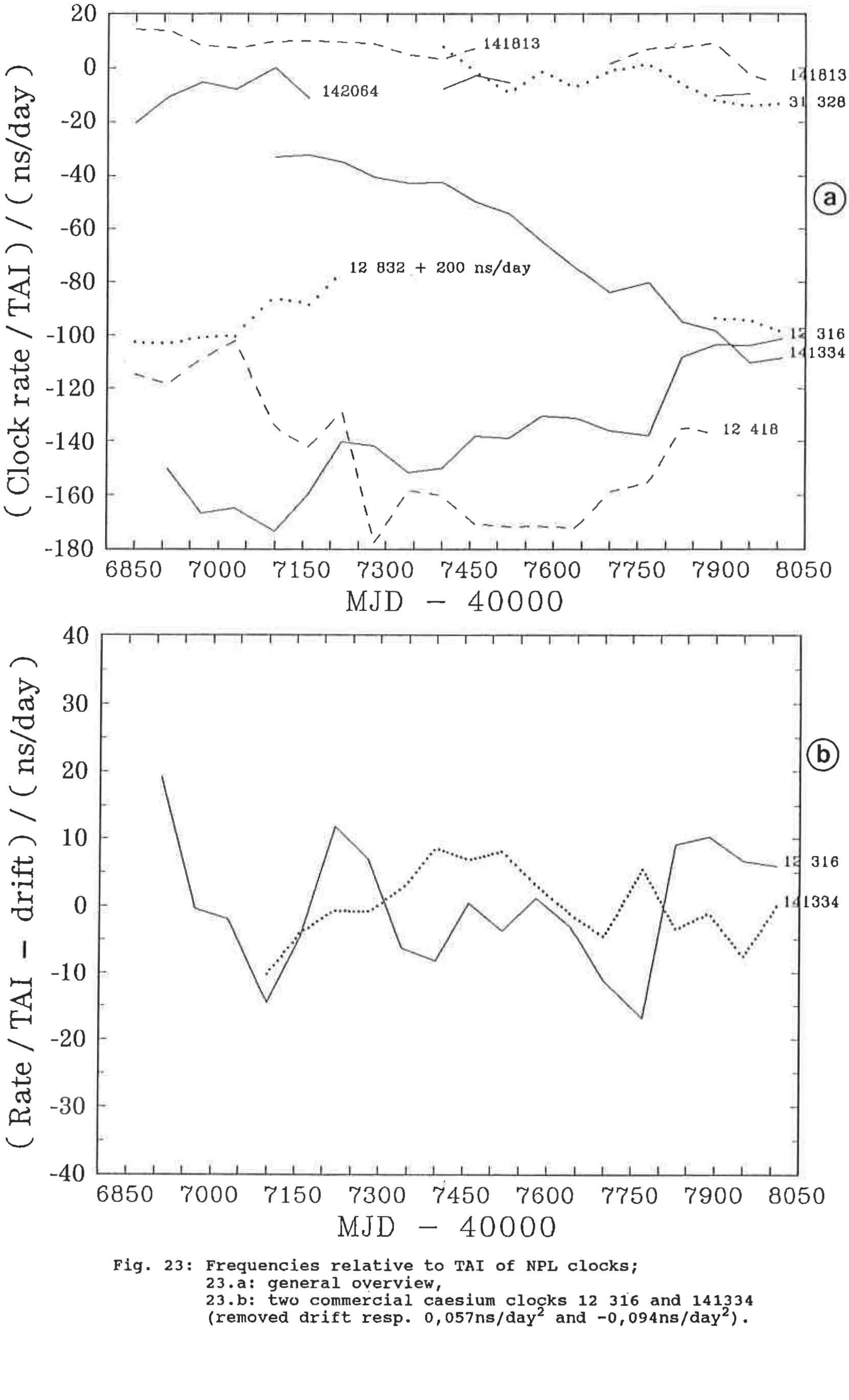


Fig. 23: Frequencies relative to TAI of NPL clocks;
23.a: general overview,
23.b: two commercial caesium clocks 12 316 and 141334 (removed drift resp. 0,057ns/day^2 and -0,094ns/day^2).

NRC: NATIONAL RESEARCH COUNCIL OF CANADA, Ottawa, Canada (Fig. 24.a and Fig. 24.b).

The NRC operated four primary frequency standards (NRC Cs5, NRC 61, 62 and 63) and a commercial caesium clock: of these clocks NRC 62 contributed for only a short while during the period under study. The frequencies relative to TAI of the NRC primary standards have large steps which figure annual variations. These correlate the three clocks:

i = Cs5 j = 61 $\mu_{ij}(0) = 0{,}70$
i = Cs5 j = 63 $\mu_{ij}(0) = 0{,}56$
i = 61 j = 63 $\mu_{ij}(0) = 0{,}58$.

For these four years, the frequencies of the NRC primary standards presented small negative drifts by comparison with TAI. When drifts are removed (Fig. 24.b), correlations among NRC Cs5, 61 and 63 are more apparent. The relative contributions to TAI of the NRC primary standards were about 0,2%.

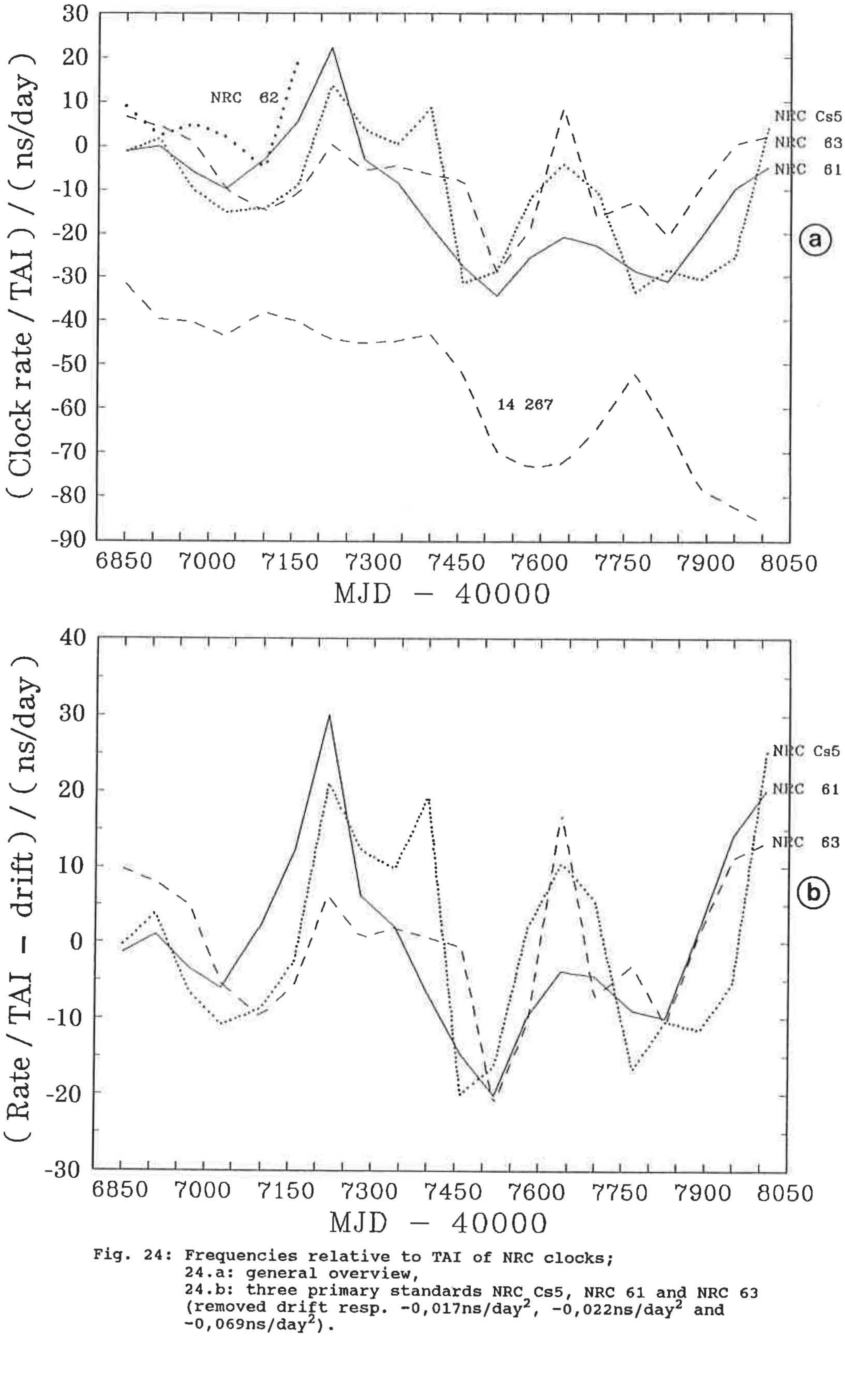
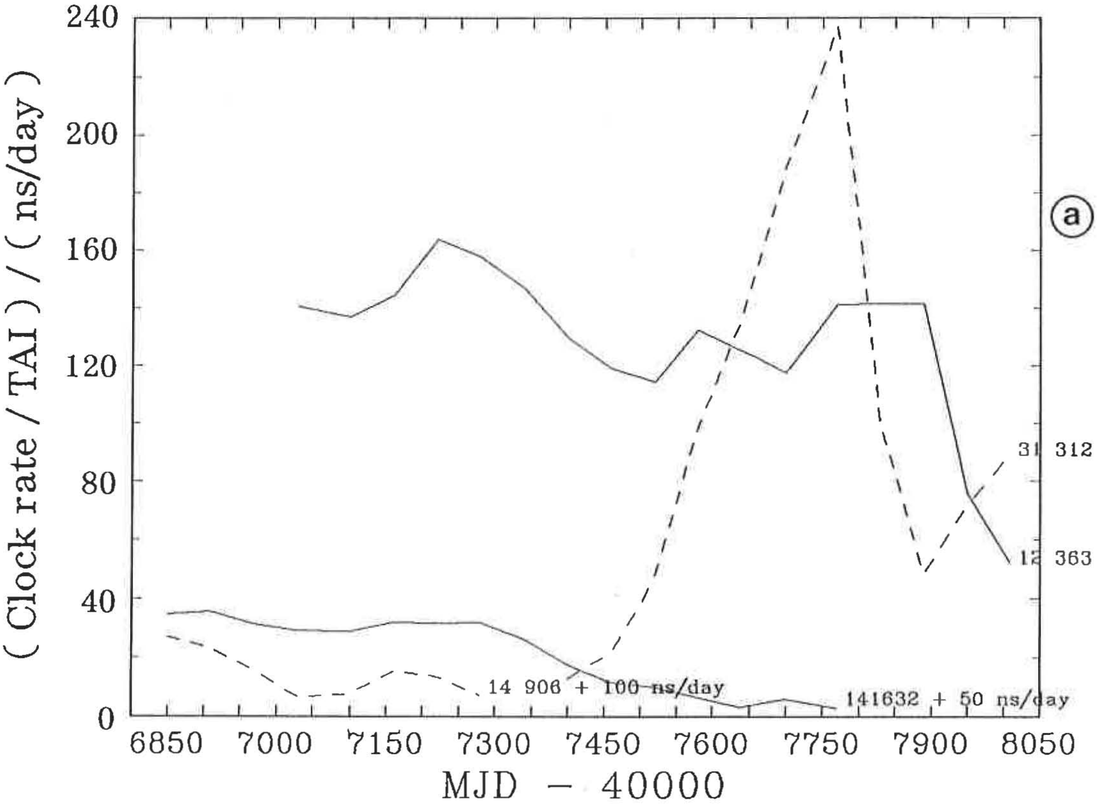


Fig. 24: Frequencies relative to TAI of NRC clocks;
24.a: general overview,
24.b: three primary standards NRC Cs5, NRC 61 and NRC 63 (removed drift resp. $-0{,}017 ns/day^2$, $-0{,}022 ns/day^2$ and $-0{,}069 ns/day^2$).

NRLM: NATIONAL RESEARCH LABORATORY OF METROLOGY, Tsukuba, Japan (Fig. 25.a and Fig. 25.b).

Four commercial caesium clocks kept by the NRLM contributed to TAI. Two of them show very large frequency steps in 1989-1990 which reduced their weights to zero. Annual fluctuations can be seen for three of the clocks operating in 1987-1988 (Fig. 25.b). These induced correlations (a computation of cross-correlation coefficients is not safe here, the period of simultaneous operation of these three clocks being too short).



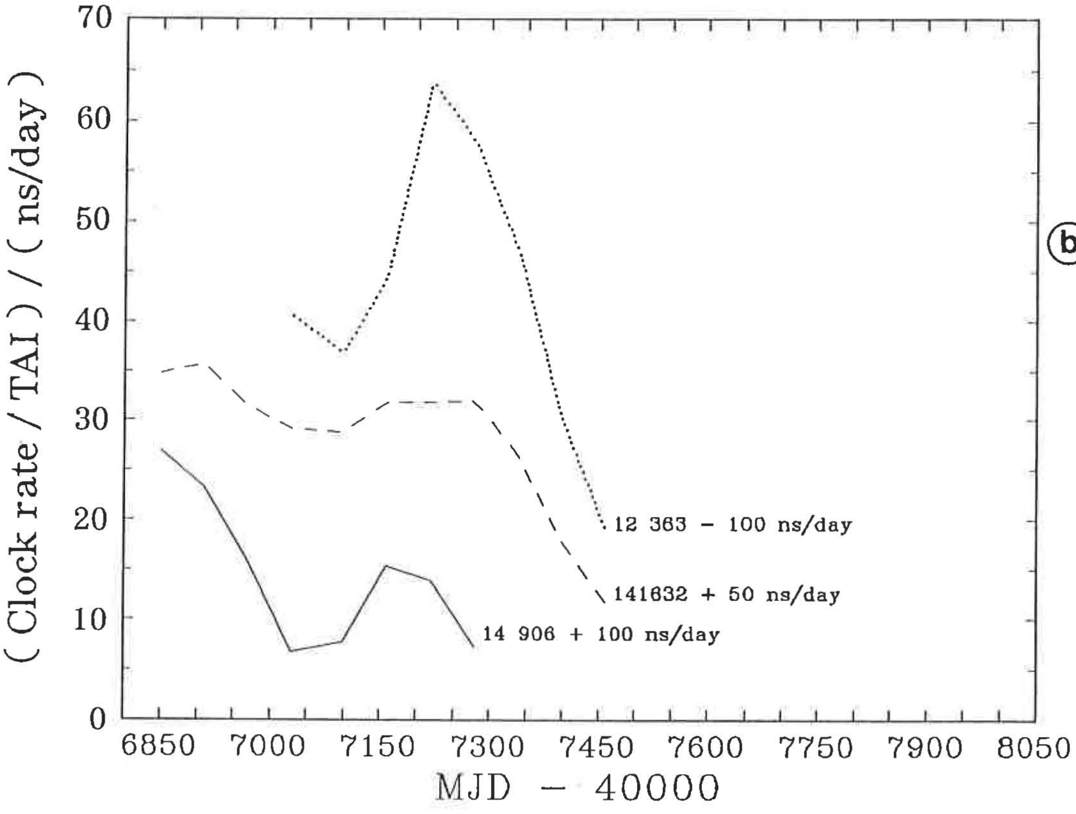


Fig. 25: Frequencies relative to TAI of NRLM clocks;
25.a: general overview,
25.b: three commercial caesium clocks 12 363, 141632 and 14 906.

OP: OBSERVATOIRE DE PARIS, Paris, France (Fig. 26.a and Fig. 26.b).

A number of commercial caesium clocks (more than 20), kept by several French laboratories and in particular by the LPTF (Laboratoire Primaire du Temps et des Fréquences, Paris), operated under the acronym 'OP'. The overview of Figure 26.a shows the general trend of frequency variation in the French clocks: with the passage of time, there are smaller seasonal fluctuations and fewer frequency steps. During 1990 the OP clock set presented a higher stability and an increasing relative contribution to TAI. This can be explained by the effort put into reducing the sensitivity of the clocks to variations of humidity [7] and by the improvement in French time transfers which are now performed via GPS.
The frequencies relative to TAI of the four clocks having the longest period of continuous operation are shown in Figure 26.b. There is no evidence for annual fluctuations, except for clock 14 134, and no evidence for high or persistent correlations.

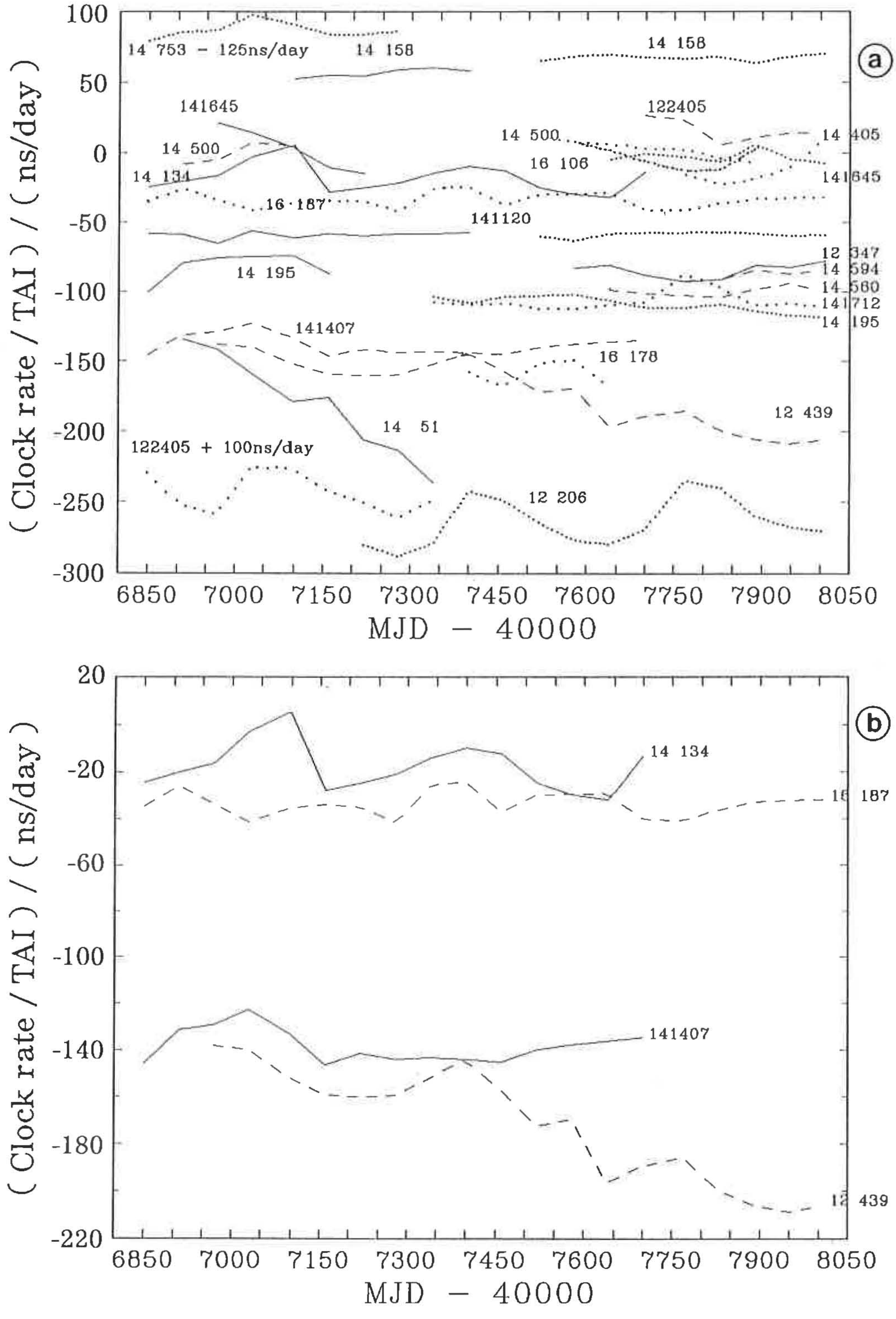


Fig. 26: Frequencies relative to TAI of OP clocks;
26.a: general overview,
26.b: four commercial caesium clocks 14 134, 16 187, 141407 and 12 439.

ORB: OBSERVATOIRE ROYAL DE BELGIQUE, Bruxelles, Belgium (see Section II.4).

PKNM: POLSKI KOMITET NORMALIZACJI MIAR I JAKOSCI, Warszawa, Poland (Fig. 27).

Four commercial caesium PKNM clocks contributed to TAI during the period under study. They had large frequency steps which deweighted them (mean relative contribution of order 0,03%) and masked possible seasonal variations. No evidence for correlation is available.

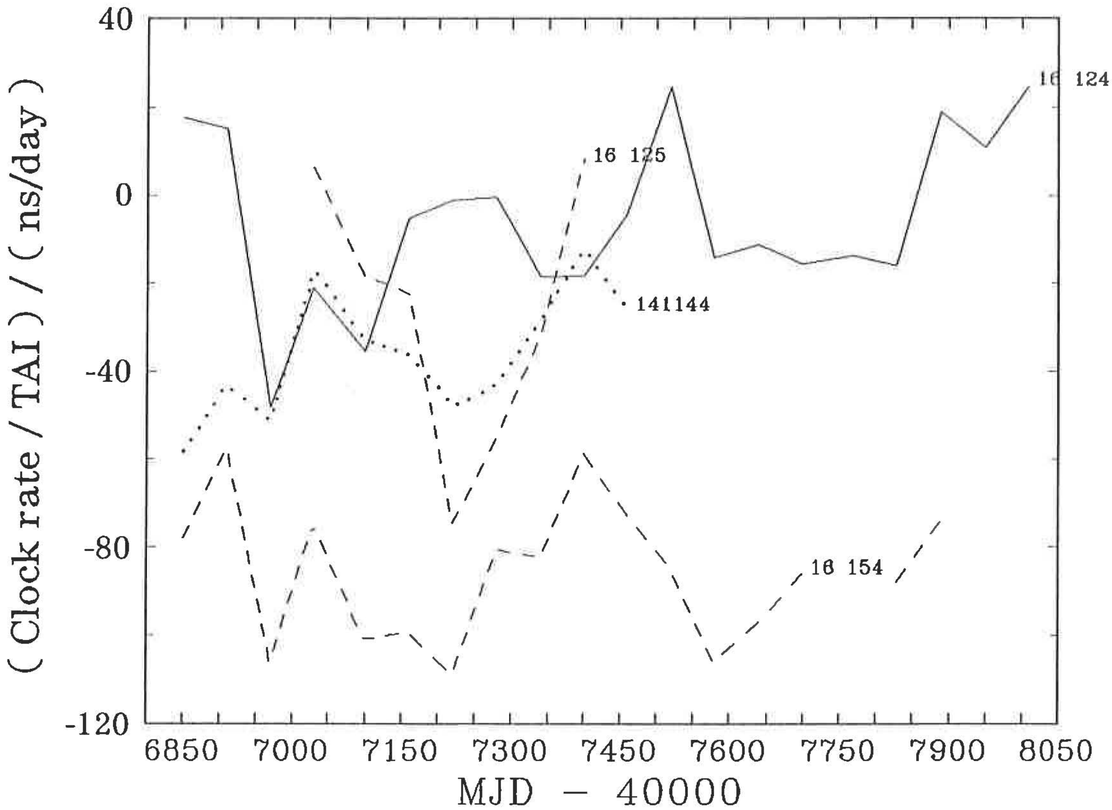


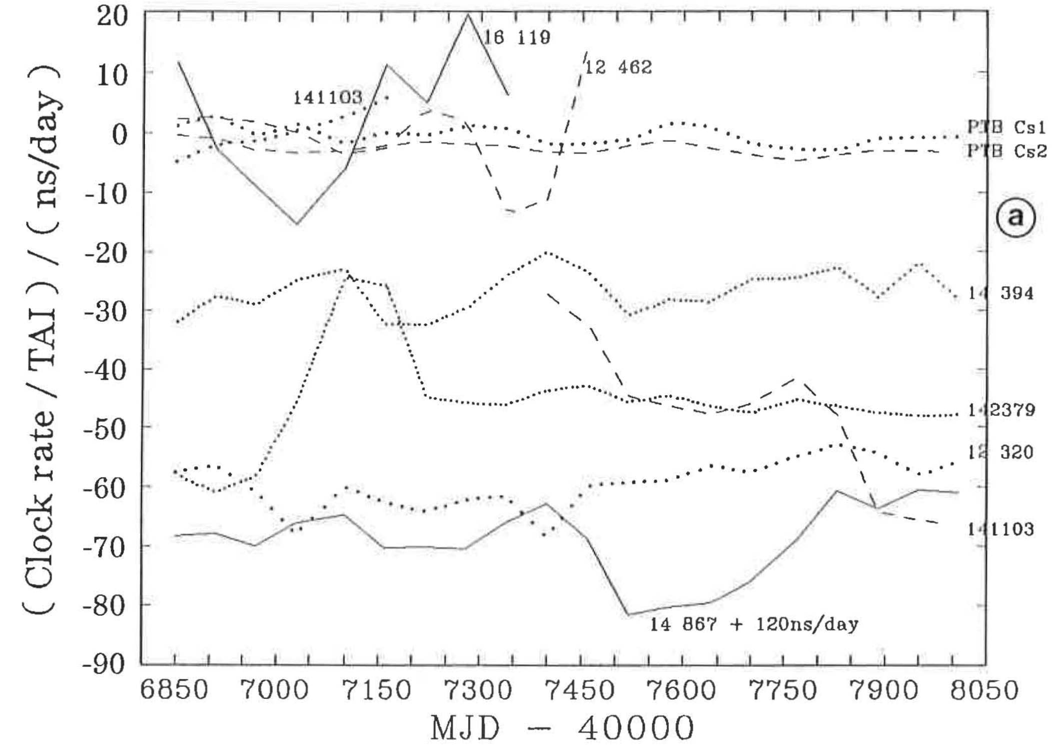
Fig. 27: Frequencies relative to TAI of PKNM clocks.

PTB: PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, Braunschweig, Germany (Figs. 1.1, 1.2 of Section II.1, 28.a and 28.b).

The PTB operates two primary standards CS1 and CS2 and several commercial caesium clocks, four of which were active throughout the period under study. An apparent correlation exists between the variations of the frequencies relative to TAI of the two primary standards, as shown in Section II.1. This is probably due to the seasonal fluctuation of TAI. Some of the commercial PTB clocks also show a seasonal fluctuation, especially in 1987-1988. This may be seen in the data for clock 14 394 (Fig. 28.b): the amplitude peak-to-peak (about 10ns/day) is larger than those for CS1 and CS2 and is opposite in phase. This confirms that annual variations of the primary standards originate in TAI whereas that observed for 14 394 is more probably due to its reaction to environmental changes (humidity variations). Though these annual variations have different causes, the clock data appear to be correlated:

i = Cs2 j = 14 394 $\mu_{ij}(0)$ =-0,66.

Clock 14 394 was entered in the TAI computation with a mean relative weight of about 1,6%.



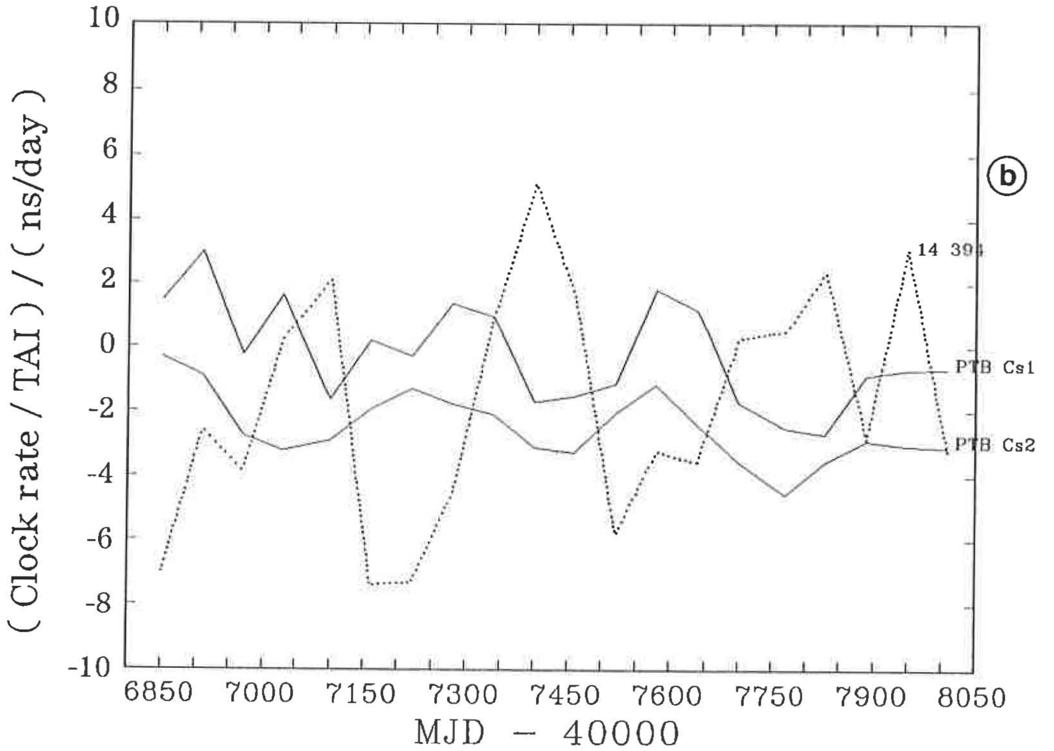


Fig. 28: Frequencies relative to TAI of PTB clocks;
28.a: general overview,
28.b: the two primary standards PTB CS1 and PTB CS2 and one commercial caesium clock.

ROA: REAL INSTITUTO Y OBSERVATORIO DE LA ARMADA, San Fernando, Spain (Fig. 29).

Of all the ROA participating clocks to TAI, just three operated throughout the period under study. They showed drifts of both signs and, for one of them (clock 16 121), an annual fluctuation can be observed. The cross-correlation coefficients are:

i = 141569 j = 16 121 $\mu_{ij}(0) = 0{,}52$
i = 141569 j = 16 177 $\mu_{ij}(0) = -0{,}86$
i = 16 121 j = 16 177 $\mu_{ij}(0) = -0{,}65$

and when drifts are removed:

i = 141569 j = 16 121 $\mu_{ij}(0) = -0{,}37$
i = 141569 j = 16 177 $\mu_{ij}(0) = -0{,}54$
i = 16 121 j = 16 177 $\mu_{ij}(0) < 0{,}01$.

This figures that the clocks are correlated or anticorrelated by their drifts relative to TAI.
The mean relative contributions to TAI of these clocks in 1989 were 0,5% for clock 141569, 0,4% for clock 16 121 and 0,1% for clock 16 177.

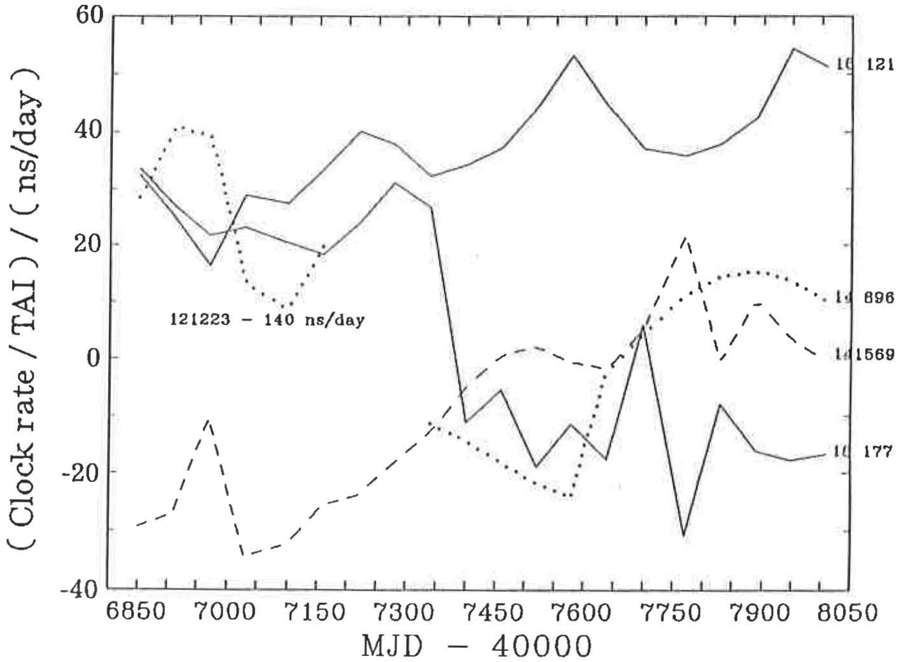


Fig. 29: Frequencies relative to TAI of ROA clocks.

SO: SHANGHAI OBSERVATORY, Shanghai, P.R. China (Fig. 30).

Three commercial caesium SO clocks contributed to TAI for the whole period under study. They were affected by drifts and one of them, clock 14 574, showed large frequency steps which deweighted it (mean relative contribution of about 0,06%). A correlation exists between clocks 16 180 and 12 997, with $\mu_{ij}(0) = 0{,}60$, mainly due to their drifts (respectively 0.045ns/day^2 and 0.031ns/day^2). Their mean relative weights were respectively 0,7% and 0,05%.

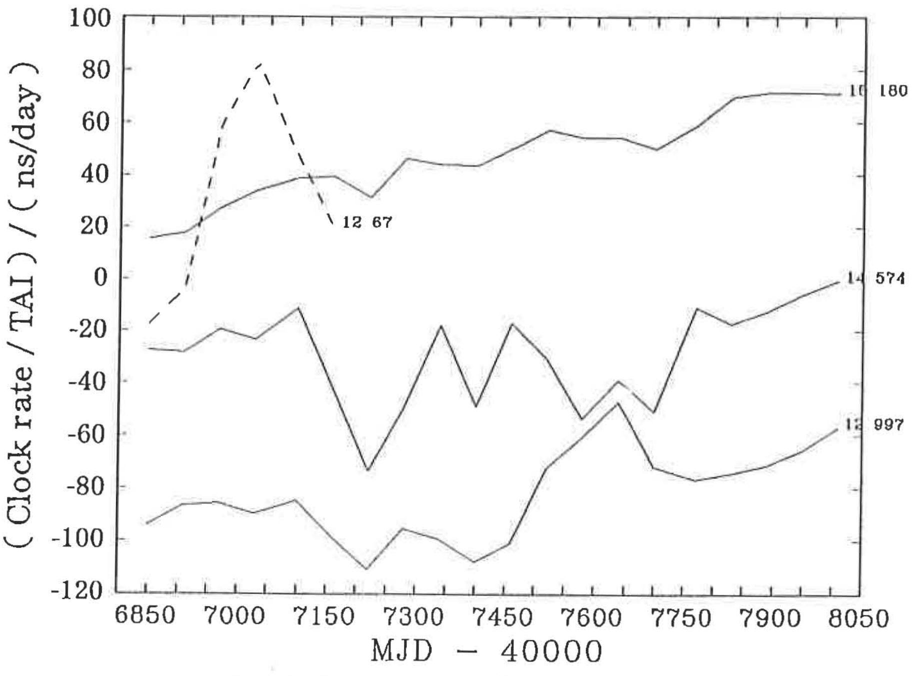


Fig. 30: Frequencies relative to TAI of SO clocks.

STA: SWEDISH TELECOMMUNICATIONS ADMINISTRATION, Stockholm, Sweden (Fig. 31).

Two STA commercial caesium clocks operated for the whole period under study, a third stopped in August 1988 and was reintroduced in 1989. There is no evidence of seasonal variation except for clock 14 900 and no evidence of correlation among the STA clocks. During 1990, clock 14 900 had a low relative weight (0,14%) while clocks 16 137 and 141376 showed a good long-term stability and contributed respectively for 1,5% and 1,6%.

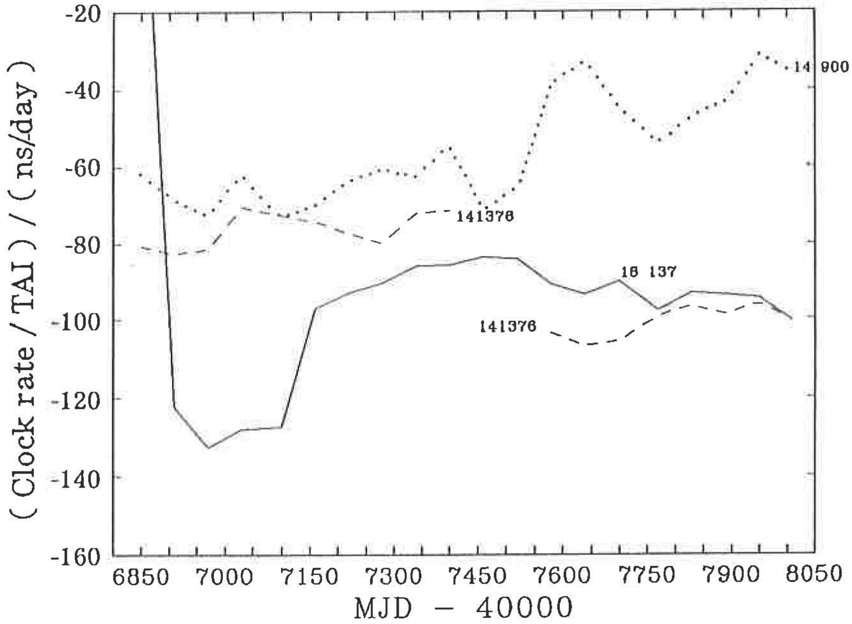


Fig. 31: Frequencies relative to TAI of STA clocks.

SU: VNIIFTRI, Moskva, URSS (see Section II.3).

TAO: TOKYO ASTRONOMICAL OBSERVATORY, Tokyo, Japan (Fig. 32).

In the general overview concerning the TAO clock set (Fig. 32) no clear annual fluctuation can be detected. This may be linked to the fact that the TAO clocks have, since several years, been kept in a temperature- and humidity- controlled room. There is no evidence of correlation.

Two commercial caesium clocks, 142494 and 141075, operated troughout the period under study showing excellent long-term stability. They contributed to TAI with the maximum relative weight (about 2,2% in 1989). It is noticeable that their frequencies relative to TAI nearly show no variation with time, specifically they do not allow observation of the TAI annual fluctuation. One can imagine that they have an individual seasonal variation with a small enough amplitude and an appropriate phase so that TAI seasonal variation is effectively cancelled.

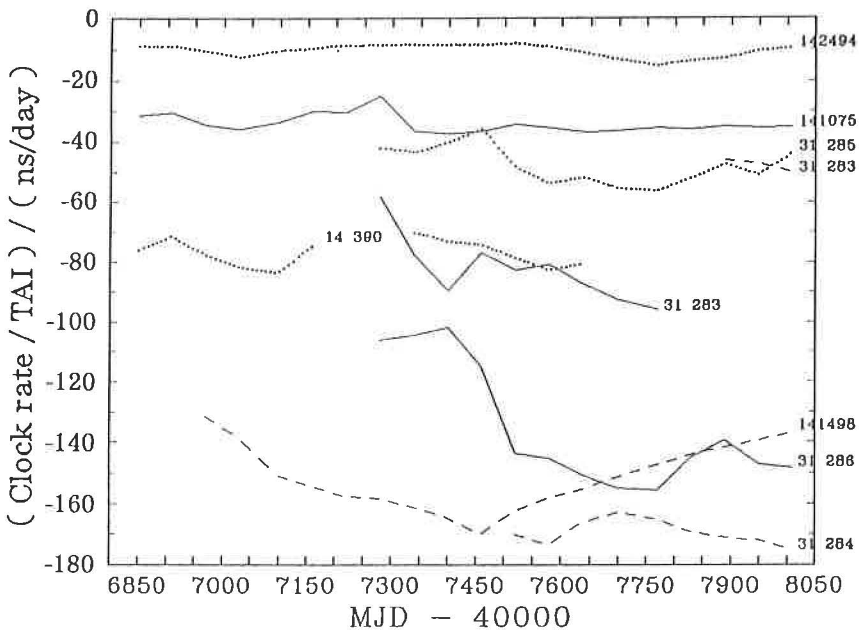
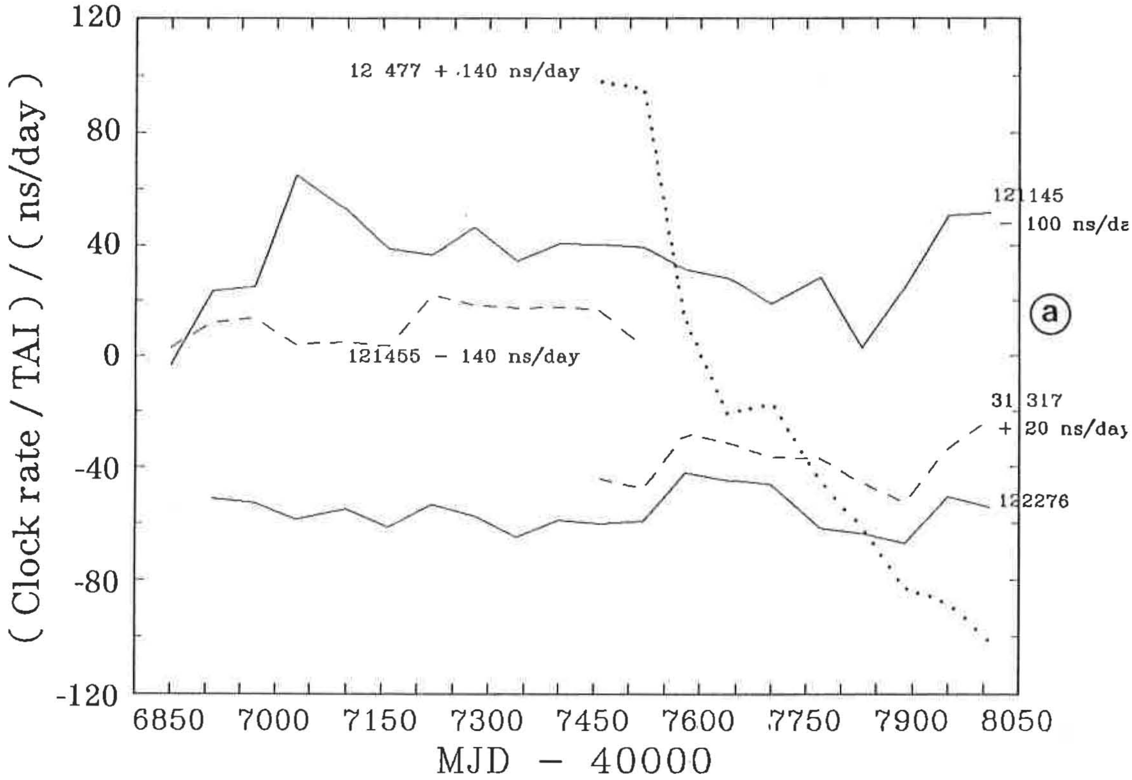


Fig. 32: Frequencies relative to TAI of TAO clocks.

TL: TELECOMMUNICATION LABORATORIES, Chung-Li, Taiwan, China (Fig. 33.a and Fig. 33.b).

Five TL commercial caesium clocks contributed to TAI. Two of them, clock 121145 and 122276, operated continuously throughout the period of study. These two showed annual fluctuations and frequency steps, partly due to noisy time links, which deweighted them: their mean relative contributions were of about 0,3% for 1989.
A correlation, with $\mu_{ij}(0)$ = 0,75, is observed for clock 31 317 and 122276 (see Fig. 33.b).



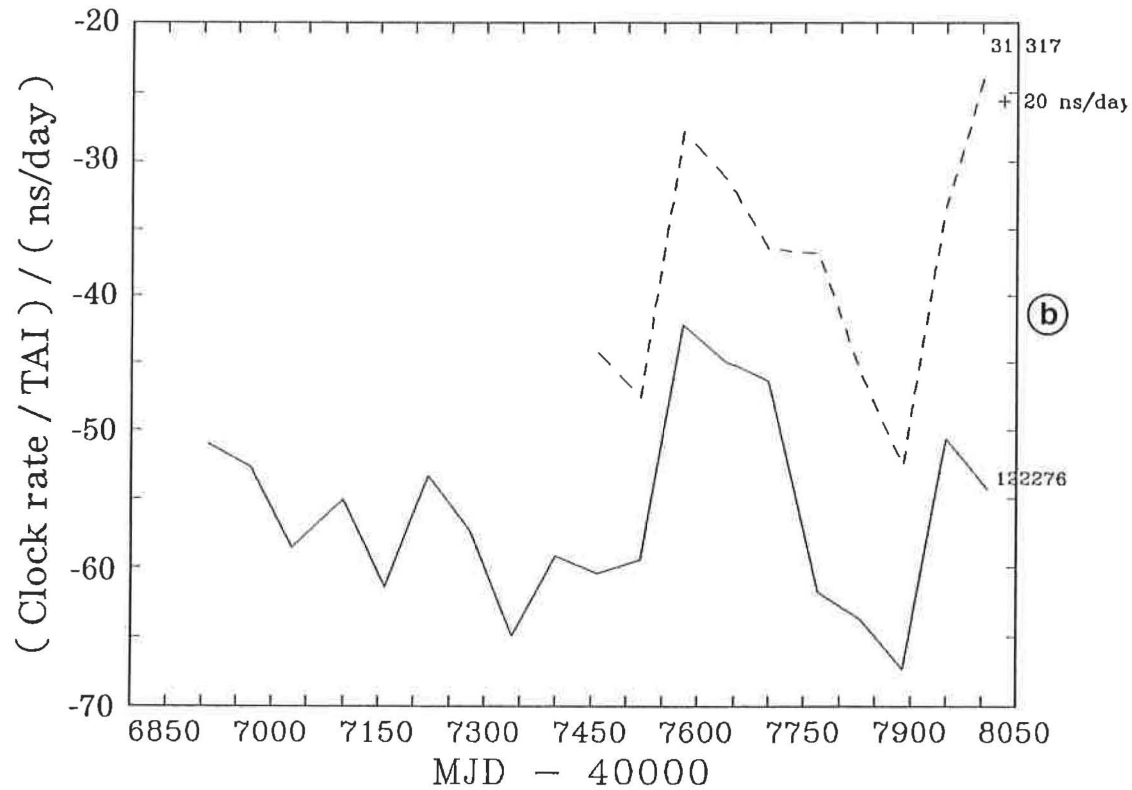
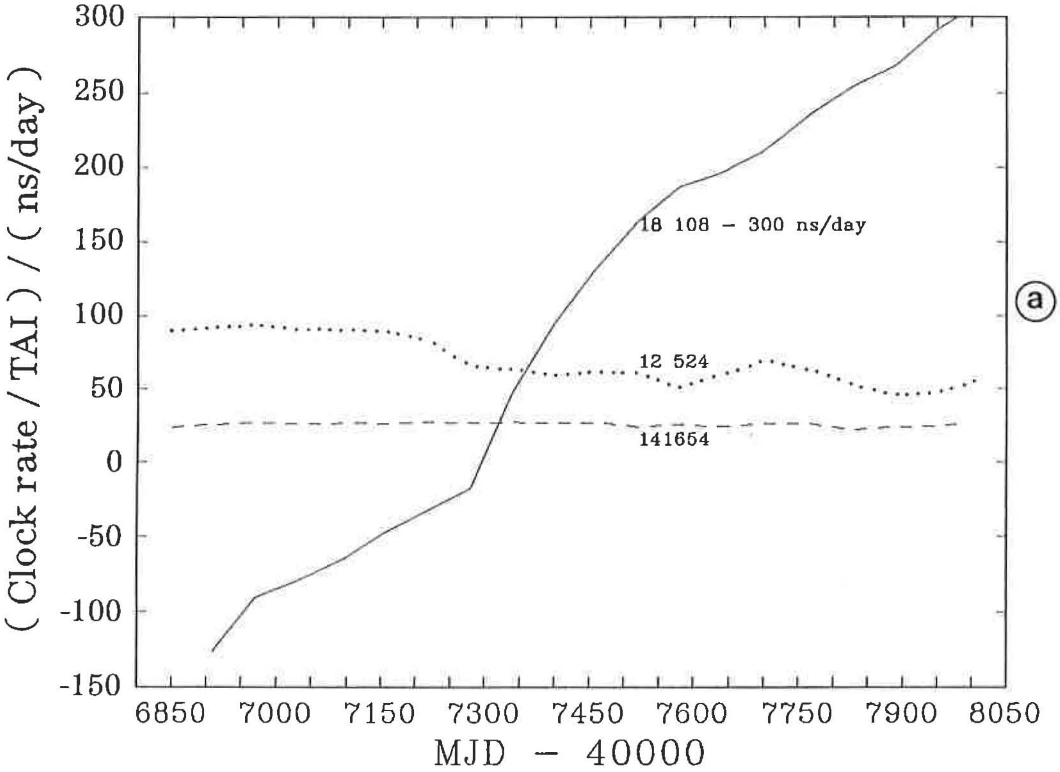


Fig. 33: Frequencies relative to TAI of TL clocks;
33.a: general overview,
33.b: two commercial caesium clocks 122276 and 31 317.

TUG: TECHNISCHE UNIVERSITÄT GRAZ, Graz, Austria (Fig. 34.a and Fig. 34.b).

Three TUG commercial caesium clocks contributed to TAI, each of them having a long continuous operation which covered the whole period under study. One of them, clock 18 108, shows a large drift of about 0,42ns/day^2. The frequencies relative to TAI of the two other clocks are reproduced in Figure 34.b with a larger scale. Commercial clock 141654 has a particularly good long-term stability and contributed to TAI with the maximum relative weight for some years. This clock is kept in a temperature-controlled room but no other particular precautions are taken. So that this clock, which is rather insensitive to environmental changes, may naturally satisfy De Marchi's conditions [5]. Clock 12 524 is much more noisy and contributed to TAI for 0.6% in 1989.



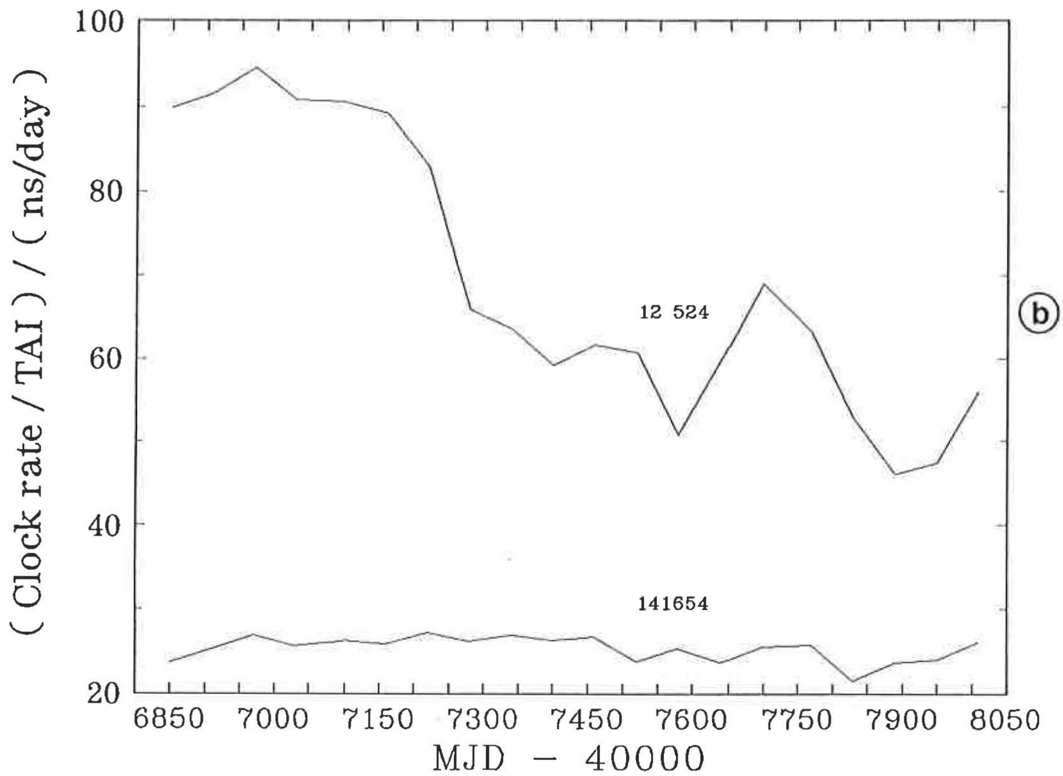


Fig. 34: Frequencies relative to TAI of TUG clocks;
34.a: general overview,
34.b: two commercial caesium clocks 12 524 and 141654.

USNO: UNITED STATES NAVAL OBSERVATORY, Washington D.C.,USA.

Several tens of USNO clocks participated in the TAI computation. These included commercial caesium clocks and H-masers over different periods of operation.
The USNO gives the opportunity to study a very interesting case of what one might call 'fugitive correlation': it involves the whole USNO clock set and appears only during a short period (November 1989) as if a local and brief event had influenced the global behaviour of the clocks. Table 1 shows the variations of the frequencies, between consecutive 60-day intervals, for the complete clock set kept by USNO, for the year 1989. The reported quantities are:

$$\delta B_i(t) = B_i(t) - B_i(t-\tau) \qquad (6)$$

where τ = 60 days and where $B_i(t)$ is defined in (1) of Section I.
It may be seen that 21 clocks of the 30 clocks entered in the TAI computation have decreasing frequencies between September-October 1989 and November-December 1989 (last column of Table 1). Such a global variation did not occur before in 1989.
At the bottom of Table 1 is reported the relative weight of the complete USNO clock ensemble in TAI computation for the two-month period ending at date t, defined as:

$$\Omega(t) = \Sigma\ w_i(t), \qquad (7)$$

where $w_i(t)$ is the relative weight of clock i on the two-month period ending at date t and where Σ operates on the USNO clock ensemble.
The frequency variation given to TAI by the USNO ensemble is written as:

$$\delta B(t) = \Sigma\ w_i(t).\delta B_i(t) \qquad (8)$$

and is also reported in Table 1.
The quantity $\Omega(t)$ increased during year 1989 because the number of clocks increased and because the frequency variations we are studying here were probably too small to deweight to any significant extent the clocks involved. The resulting frequency variation $\delta B(t)$ is much larger in absolute value and is of opposite sign to that observed earlier. This fugitive correlation, probably due to a short and sharp environmental change, degraded both the stability of the local atomic time scale computed by the USNO and the stability of TAI.

Clock	$\delta B_i(47639)$	$\delta B_i(47699)$	$\delta B_i(47769)$	$\delta B_i(47829)$	$\delta B_i(47889)$
142482	5.25	2.73	21.87	18.50	-15.53
142483	0.91	4.64	7.27	2.42	-1.98
142485	-10.84	26.04	-3.04	-11.21	-27.10
141117	3.46	16.26	-6.47	-4.41	-17.38
142314	3.25	2.17	17.47	-13.79	16.64
142486	4.92	3.57	-26.25	3.69	7.97
14 116	8.87	2.39	15.96	-17.47	-1.53
14 583	8.18	19.00	-60.93	14.80	30.05
142312	15.28	-6.41	-19.15	12.68	0.73
40 23	4.95	-31.83	-6.92	123.31	-42.27
141819	3.17	11.85	2.95	-3.52	-14.31
14 787	17.06	12.72	-4.41	-0.50	-24.55
43 8	4.01	13.18	30.28	-64.46	44.88
142481	24.45	5.82	3.11	3.70	-3.75
31 339	-6.90	-2.57	10.43	19.90	-14.63
141028	-43.91	-25.99	-40.44	45.06	21.09
141362	10.79	-6.27	7.53	0.31	-7.59
141605	4.08	7.35	2.86	2.41	-7.43
311034	-7.24	1.14	2.14	4.64	-4.23
31 335	-5.29	-15.93	10.29	2.56	-2.45
40 22	49.01	-25.17	-17.82	-13.77	-14.94
141255	3.96	-1.07	-0.70	2.80	0.12
14 656	-4.51	-0.05	4.89	1.72	2.22
141710	4.65	-3.52	-2.33	6.19	-7.49
142488	18.41	-4.71	-1.15	2.49	-8.12
141305	6.62	-6.32	-4.15	2.67	-1.24
141846		4.09	3.04	3.72	-4.75
40 1			-7.08	6.27	-35.37
141094					-8.70
141343					9.42
$\Omega(t)$	8%	12%	13%	13%	16%
$\delta B(t)$	0.26	0.14	0.21	0.33	-0.59

Table 1: Variation between two consecutive two-month intervals of the frequencies relative to TAI of USNO clocks for 1989.

$\delta B_i(t)$, $\Omega(t)$ and $\delta B(t)$ are defined in (6), (7) and (8).
$\delta B_i(t)$ and $\delta B(t)$ are expressed in ns/day.
Dates t, expressed in MJD in the table, correspond to:

MJD 47639	1989 April 23
MJD 47699	1989 June 22
MJD 47769	1989 August 31
MJD 47829	1989 October 30
MJD 47889	1989 December 29.

VSL: VAN SWINDEN LABORATORIUM, Delft, Nederland (Fig. 35).

Five VSL commercial caesium clocks contributed to the TAI computation, some of them with discontinuous operation. A number of large drifts are present so no clear seasonal variation can be detected. The comments made on the TUG commercial clock 141654 (see above) apply also to one VSL commercial clock, 141034, which shows high stability and contributes to TAI with maximum weight. This again might be a case of natural De Marchi's conditions [5].

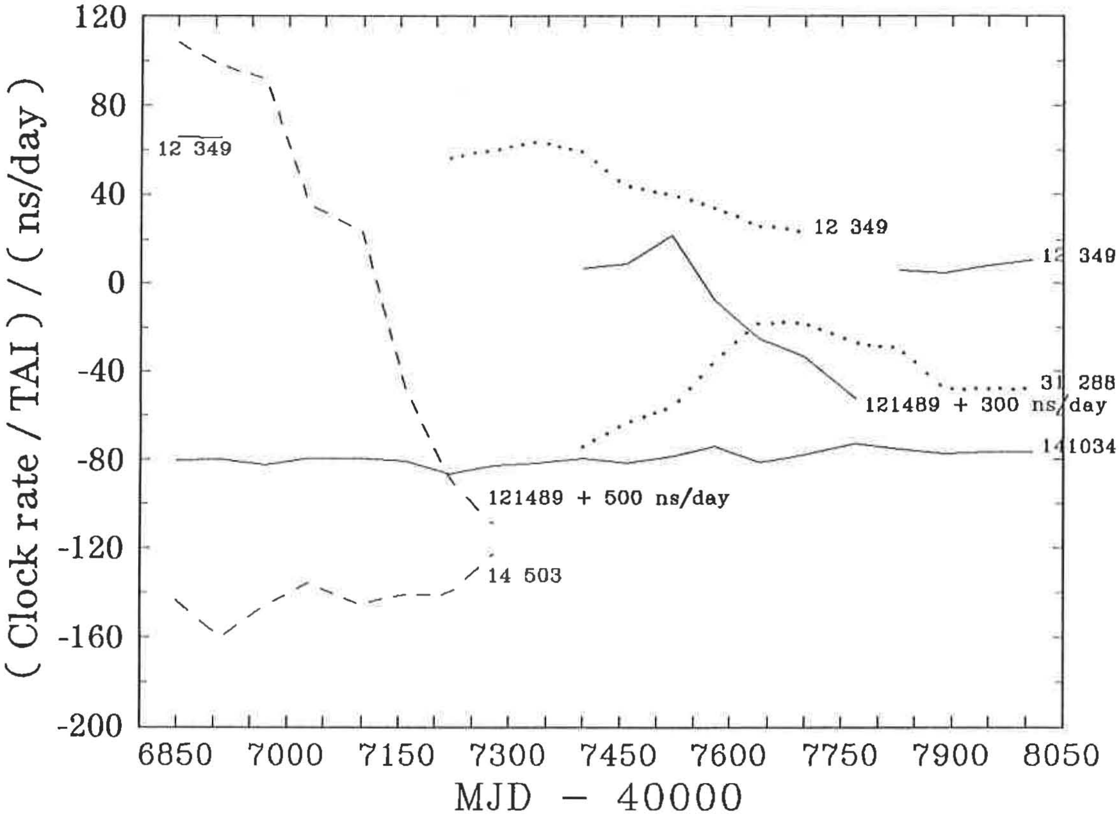


Fig. 35: Frequencies relative to TAI of VSL clocks.

CONCLUSIONS

Correlations exist in the frequency data of the clocks contributing to TAI. They are not reproducible and occur both fugitively and indirectly, so that they cannot easily be modelized or forecast. It is then very difficult to take account of them in TAI computations.

As correlations among frequency changes are often related to environmental variations, one way to reduce them is to control their environment, specifically the temperature and humidity changes to which they are exposed. Another way is to make clocks less sensitive to such variations by applying techniques such as that suggested by De Marchi [5].

It is noticeable that the weighting procedure used in the TAI computation helps to diminish the impact of some of the existing correlations. As the weight of a given clock in TAI reflects its behaviour over the previous twelve months, seasonal variations and drifts are recognized and lead to deweighting.

Nevertheless, TAI inherits a low but actual seasonal variation. For more precise studies, it may be necessary to issue a different time scale in which seasonal fluctuations are smoothed out more completely by post-processing; an *a posteriori* time scale such as TT(BIPM) [9] provides an example of how this may be done.

References

[1] B. Guinot and C. Thomas, 'Establishment of the International Atomic Time', *Annual Report of the BIPM Time Section*, 1988, Part D, pp. D3-D22.

[2] P. Tavella and C. Thomas, 'Comparative Study of Time Scale Algorithms', *Metrologia*, 1991, 28, pp. 57-63.

[3] P. Tavella and C. Thomas, 'Study of the correlations among the frequency changes of the contributing clocks to TAI', *Proc. 4th European Frequency and Time Forum*, 1990, pp. 527-541.

[4] G.P. Box and G.M. Jenkins, Time Series Analysis, 1976, Holden-Day, Oakland, California.

[5] A.L. Edwards, An Introduction to Linear Regression and Correlation, 1976, W.H. Freeman and Co, San Francisco, California.

[6] A. De Marchi, 'The accuracy of commercial cesium beam frequency standards', Frequency Standards and Metrology, 1989, pp. 52-56, Edited by A. De Marchi, Springer-Verlag.

[7] P. Daly and I.D. Kitching, 'Progress in Transferring Time using GLONASS Satellites', *Proc. of the 21st Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, 1989, pp. 59-70.

[8] G. Fréon, 'Preventive Maintenance and Stability of Commercial Cesium Clocks', *Proc. of 4th European Frequency and Time Forum*, 1990, pp. 549-553.

[9] B. Guinot, 'Atomic Time Scales for Pulsars Studies and other Demanding Applications', *Astron. and Astrophys.*, 1988, 192, pp.370-373.

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