USSR NATIONAL TIME UNIT KEEPING OVER LONG INTERVAL USING AN ENSEMBLE OF H-MASERS

N.B.Koshelyaevsky, S.B.Pushkin
National Scientific and Research Institute
for Physical–Technical and Radiotechnical Measurements
VNIIFTRI, Mendeleevo, Moscow region, 14570, USSR

... all is as one day with God,
and time only is measured unto men.
(the Book of Mormon, Alma, 40:8)

INTRODUCTION

Because of lack of official information on the USSR State Time and Frequency Service (STFS) for a long time we shall illuminate it in the first part of this report. The second part of the report will deal with a problem mentioned in a head line.

The STFS is responsible for time and frequency measurement unification both in the field of atomic, TA(SU) and UTC(SU) and universal time UT1(SU) over the whole territory of the USSR. The scientific head of STFS is the Main Metrological Center, it is situated in Mendeleevo near Moscow.

The National Primary Time and Frequency Standard (NPTFS) of the USSR is the instrumentational basis for independent realization of the national unit of time interval — second — in a full agreement with its definition in the SI system and also for the national time scale generation. Then the unit of time interval and time scale information are disseminated to secondary standards (SS), Fig. 1, each of them can keep autonomously the time unit and time scale. The most widespread links for time comparisons between SS themselves and between SS and NPTFS are as follows: micrometeorite (MM) link, portable clock, usually on the basis of HP Cs standard, and beginning from 1988 — on the basis of a small sized H–maser, Fig. 2, and beginning from the second part of 1989 signals of GLONASS system in a "common view" mode. For short range time comparison TV signals are usually used.

The independent realization of the time interval unit is performed by means of three laboratory Cs primary standards, Figures 3 through 5. One can find the detailed information on these instrument in References 1 through 3. At the moment we note only that all the above mentioned instruments have classical, but to some extend various design with magnetic state separation and their accuracy is evaluated at present to be about $\leq 2 \times 10^{-13}$. We don't use the primary Cs like a clock but from time to time put it into operation for frequency comparison with an ensemble of continuously running H–masers.

At NPTFS we usually use about 15 commercial H-masers of CH1–70, CH1–80 types, Figs. 6 & 7. These were designed and manufactured by NPO "QUARTZ" from Nizhnij Novgorod. The actual values of

H–masers output frequencies are intentionally different from each other by more than 1×10^{-13}, but using proper corrections they are recalculated to the same value. The frequency stability of the new H–masers of CH1–80 type is significantly better than that of the CH1–70. The common drawbacks of all our timekeeping instruments are lack of reliability, especially in a clock mode. This prevents applications of time scale algorithm which need continuous statistical weighting over long intervals. In Figs. 8 and 9 one can see ten days averaged relative frequency changes for some of H–masers.

Every hour the output signals (1 pps & 5MHz) from the above mentioned H–masers are compared with each other using time interval meter of 0.3 ns resolution. The 1 pps signals are directly compared, the phase deviation of 5 MHz signal is preliminary multiplied 100 times and then it produces another set of 1 pps signals. The latter is used for frequency evaluations over short intervals, up to several days, while scale measurements are based on the former set of 1 pps signals.

On the basis of such a comparisons the relative frequencies of time keeping instruments are determined, and from 3 to 7 H–masers with the most uniform performance are used for time scale generation. All H–masers have the same statistical weight. If a maser changed its frequency we exclude it from the group, and vice versa, if the frequency of H–maser is quite stable over the period from 2 to 4 weeks it may be returned to the group. In such a way we generate TA(SU) time scale. The present unit of time interval is not matched to a current primary Cs value. It means that since initial matching unit of time TA(SU) is a free time scale supporting by an ensemble of continuously operating H–masers.

The UTC(SU) time scale has the time unit the same as TA(SU), it is shifted by a constant value and "leap" second is inserted into it in accordance to IERS circulars.

All SS, Fig. 1, have from 4 to 8 H–masers of CH1–70 type. Each of SS generates an autonomous time scale TA(SS) which is based on constant time unit. This time unit was established at the beginning of SS operation and is kept constant on the basis of internal comparisons of the individual H–masers. Apart from it, each SS taking into account the results of TA(SU) – TA(SS) comparisons generates UTS(SS), which is matched as precise as possible to UTC(SU).

Up to now the main operational link for time comparison between standards in STFS is MM link[5]. We shall show its characteristics on the basis of TA(SU) – TA(Khark) time comparison results, Fig. 11. If one exclude systematic frequency changes between TA(SU) and TA(Khark) and try to estimate RMS deviation between actual readings and two months averaged values (usually 8 sessions), Figs. 12 and 13, one may find $1\sigma \leq 40$ns. Comparison of the data in a triangle Moscow – Kharkov – Uzhgorod shows the accuracy of this link to be about 20 ns[6].

At the middle of 1989 we started experiments on time comparison via GLONASS in a "common view" mode. At present we have two navigational single frequency receivers, Figs. 14a & 14b, from which we succeeded to extract the time information. The time resolution of these instruments including additional time interval meter is 1 ns. Fig. 15 displays the results of the simultaneous measurements of the same satellites at two receivers. One may see a high phase stability and resolution of the whole instrument. The delay time difference does not exceed 6.8 ± 1.3ns, and its rate does not exceed 0.05 ± 0.1ns/day.

At Fig. 16 one can see results of time comparison at the distance of about 50 km between UTC(SU) and another secondary standard equipped with 4 H–masers. All links: GLONASS, TV and clock give the coinciding in the limit of uncertainty estimation of frequency, but differ in time scales to some extent. Frequency estimations are follows: GL — $(1.16 \pm 0.16) \times 10^{-14}$, TV — $(1.16 \pm 0.39) \times 10^{-14}$, Clock — $(0.69 \pm 0.55) \times 10^{-14}$. RMS deviation of readings from the fitted line about 25 ns for GL and about 35 nS for TV.

One may see quite the same picture for the first GLONASS experiment at the distance of more than 4000 km between Mendeleevo and Irkutsk, Fig.17 — the values of frequency difference determined by GLONASS and by the clock coincide, but there is a gap about 100 nS in scales. The relatively large readings scattering, $1\sigma \approx 58$ns, is due to lack of experience at the first stage of this activity. In Fig. 18 one can see modern results which show nice agreement with clock time scale comparison and better precision, $1\sigma \approx 22$ns.

In the second part of this report we would like to analyze the frequency stability of TA(SU) over the interval of several years.This analysis will be based on time comparisons of TA(SU) with TAI and on frequency comparisons with national primary Cs standards.

The main time link between TA(SU) and TAI is common reception of Loran C 7970 W station emitting from Sylt in Paris Observatory (OP) and Pulkovo Observatory near Leningrad. Pulkovo Observatory is connected with TA(SU) via MM link. In addition from time to time we compare our scale using portable clock.

Fig. 19 displays the time scale difference TAI – TA(SU) for the period of 1985–1989. The Loran C and clock data are taken from Circular T BIPM. Both dependences have a parabolic shape, they coincide qualitatively and quantitatively. Such a parabolic shape says that we have a certain frequency drift rate. The regression analysis gives us the following estimation for this rate: $(7.5 \pm 0.2) \times 10^{-14}/1000$ days for Loran C 7970 W and $(8.8 \pm 1.0) \times 10^{-14}/1000$ days for clock transportation. The result of clock transportation is not so precise due to lack of comparisons and low precision of some part of comparisons, these are comparisons with labs, which time links with OP have not enough precision.

Besides we have an extra link via reception Loran C 7990Y station in Kharkov and MM link between our labs. For these calculations we use the USNO Circular series 4 and the BIPM Circular T. This result presented in Fig. 20. It looks quite similar to Fig. 19 and gives the following frequency rate estimation — $(10.3 \pm 0.2) \times 10^{-14}/1000$ days.

Summarizing these results we may say that the unit of time interval in the TA(SU) system which is based on the ensemble of H–masers has a systematic rate $\leq 10^{-16}$/day with regard to more stable units in the TAI system.

Taking into account this rate we show in Fig. 21 the residual frequency deviation of TA(SU) smoothed by moving average over interval of two months. We can't consider these dependences completely correlated, so it means that the resolution of the experiment was not sufficient for precise detection of TA(SU) frequency changes. Nevertheless it gives us an opportunity of estimating relative frequency instability at the interval of 2 months 3×10^{-14}.

One may be interested in the following: is such a frequency drift of the H–maser ensemble unique? We have the most reliable data on atomic time scale TA(Khark) which is based on the ensemble of the same H–masers for more than 5 years. The data of time comparisons displayed at Fig. 11 show the systematic relative frequency drift between TA(SU) and TA(Khark) with the rate about $\approx (14.5 \pm 0.2) \times 10^{-14}/1000$ days. Then if TA(SU) has the rate about $\sim 8 \times 10^{-14}/1000$ days relative to TAI, TA(Khark) is $\sim -6 \times 10^{-14}/1000$ days. So we may consider such a rate to be typical for a free ensemble of H–masers.

If we remove this constant rate from above mentioned results and apply two–months moving average procedure the residual frequency changes are displayed at Fig. 22. Supposing that TA(SU) and TA(Khark) are equally stable we get an estimation of relative frequency stability of about $\leq 2 \times 10^{-14}$.

If one compare changes of TA(SU) time unit against the national primary Cs standard, Fig. 23, it

becomes obvious that TA(SU) time unit has a relative drift of about $(3.3 \pm 1.6) \times 10^{-14}$/1000 days. The value of this drift is less than half that against TAI.

As far as we discuss such a small frequency changes it is interesting how stable are other laboratories contributing to TAI scale generation. Fig. 24 presents the modified TAI – TA(k) differences for NIST, NRC, PTB, SU and USNO laboratories. The modifications introduce to the scale a constant time shifting and a proper constant frequency adding in order to clarify the scale features. One may look at the obvious similarity in scales — all the scales change the time unit in the same direction — the second becomes shorter, Fig. 25. The relative rate of this changing depends on the laboratory and is as follows: $(16.6 \pm 0.2) \times 10^{-14}$/1000 days, $(14.5 \pm 0.4) \times 10^{-14}$/1000 days, $(2.8 \pm 0.1) \times 10^{-14}$/1000 days, $(8.9 \pm 0.2) \times 10^{-14}$/1000 days, $(14.8 \pm 0.3) \times 10^{-14}$/1000 days. Such a correlation is not our "achievement", the existence of correlations between individual clock and scales was shown in References 8 and 9. We can't explain this phenomenon, but we hope it should force the time and frequency community to think once more what have happened, what is the actual value of stability of national time scales, and what is the best clock?

ACKNOWLEDGEMENT

First of all authors would like to acknowledge the Executive Committee of the PTTI meeting for the warm invitation to give an invited talk, and the PTTI Board for financial support.

This report reflects the state of art of NTFS and is based on industrious work of many persons to whom we are indebted. We acknowledge the head of MMC Dr.V.Tatarenkov, for his support and interest in this work, all our colleagues who are responsible for proper directions: G.Yolkin — primary Cs standards, B.Gaigerov — H-masers, MM link — S.Shustrov, GLONASS — A.Al'shina and G.Cherenkov. We couldn't get such nice results on time scale comparison without friendly cooperation with our colleagues from SS in Irkutsk, Kharkov and Uzhgorod which are headed by N.Tel'puhovsky, A.Tkachuk, and L.Kouharenko to whom we would like to express our thanks.

REFERENCES

Note that the editor does not have Cyrillic characters available. The references below in **bold font** *are transliterated from the original, more or less accurately.*

1. **V. G. Ilyin i dr., Izmeritelynaya technika, No. 10, 43, 1976**
   Yu. G. Abashev i dr., Izmeritelynaya technika, No. 2, 18, 1986

2. Yu. G. Abashev et al., Proceedings of the Fourth Symposium on Frequency Standards and Metrology, 374, Ancona, Italy, September 5–9,1988.

3. Comite Consultative pour la Definition de la Second, 11th session, Working document submitted to the 11th session, CCDS/89–6bis, 1989, Pavillon de Breteuil.

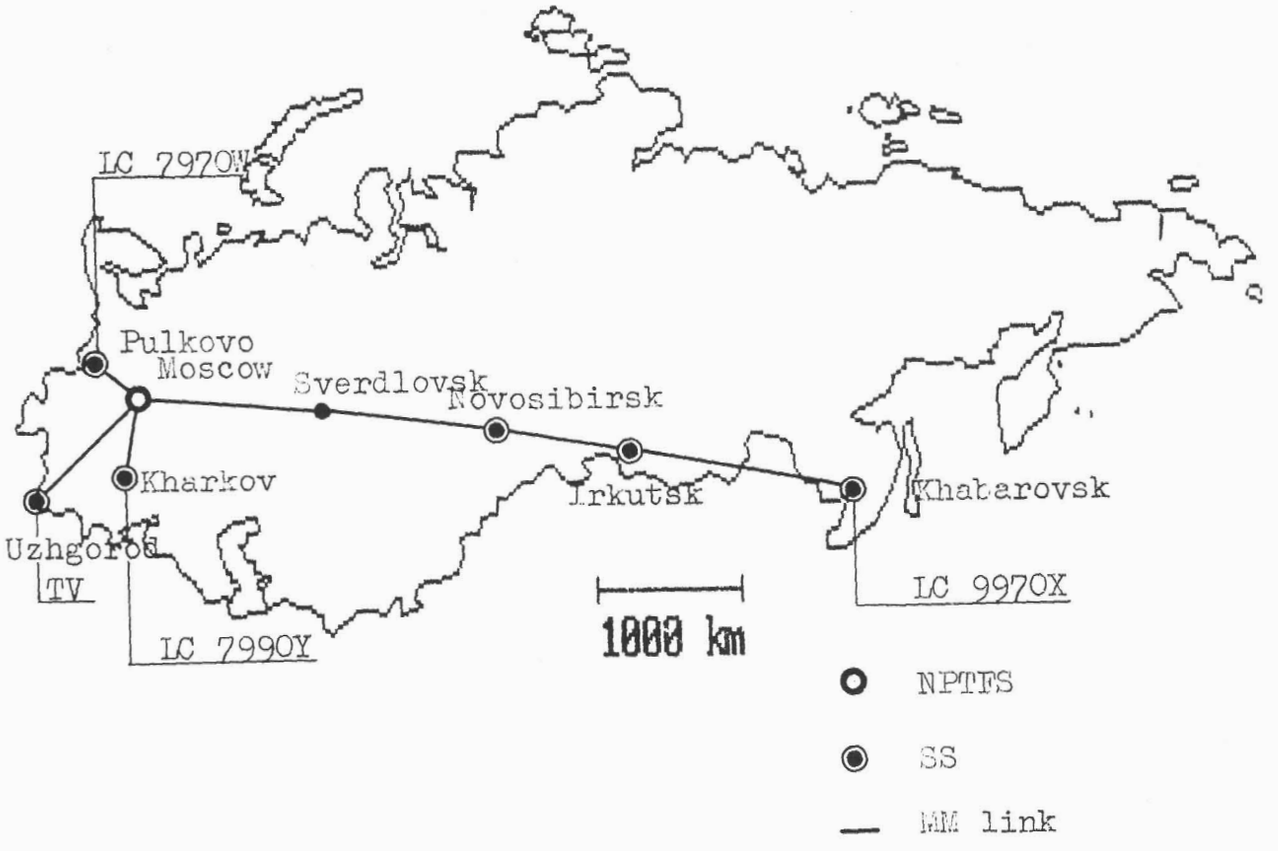
4. **B. L. Kasheev i dr., III Vsesoyuznyayi symposium po issledovaniyam v oblasti ismerenyi vremeni i chastoty, tezisy dokladov, 153, 23–26 oktyabrya 1990, Moskva, 1990**

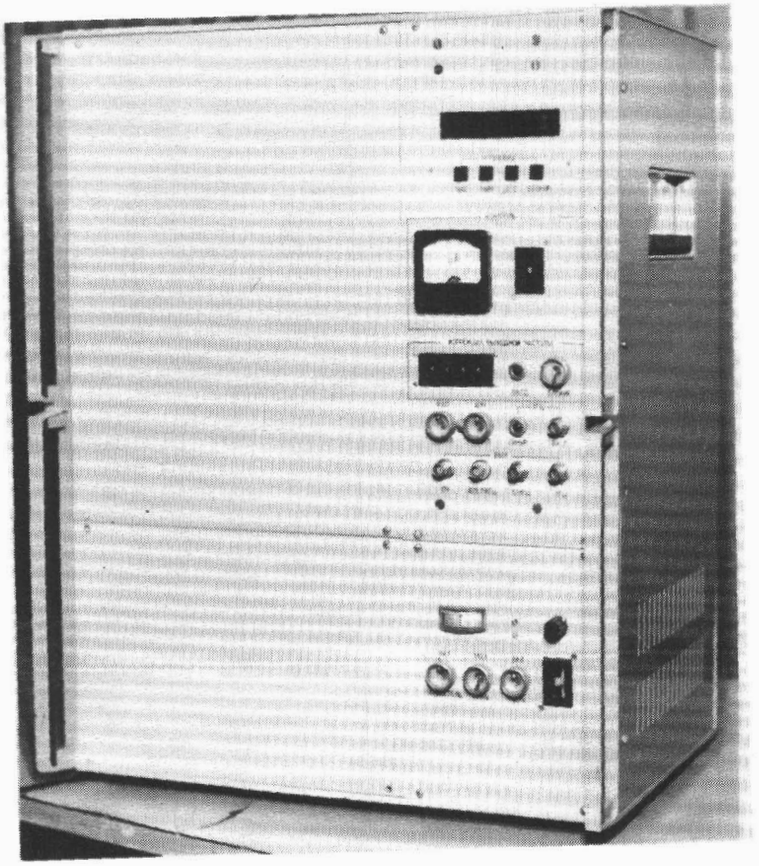
5. **A. P. Alyashyna, S. B. Pushkin, N. B. Koshelyaevsky, VII Vsesoyuznaya nauchno–tekhnicheskaya konferentsia "Metrologia v radiozektronike", tezisye dokladov, 254, Moskva, 1988**

6. N.B.Koshelyaevsky, S.B.Pushkin, G.T.Cherenkov, Soviet–West German Workshop "Scientific and industrial cooperation in the use of global navigation satellite system GLONASS", to be published.

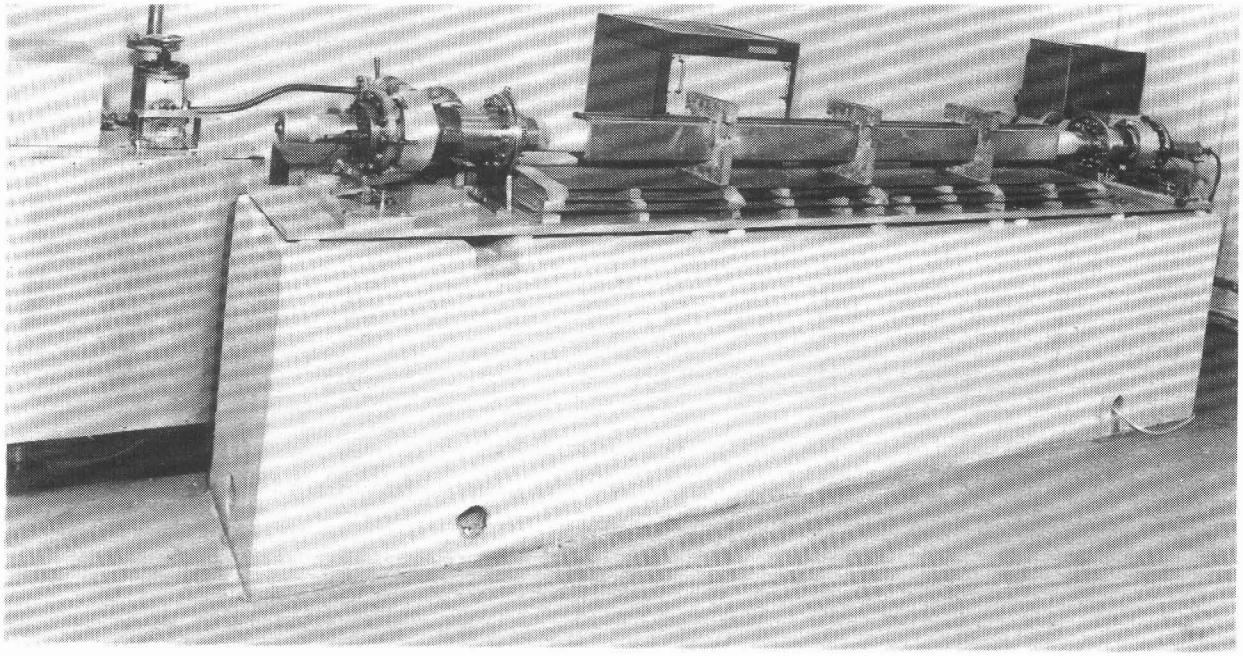
7. Proceedings of the Third International Timescale Algorithm Symposium, 137, 12–13 September 1988, Turin, Italy.

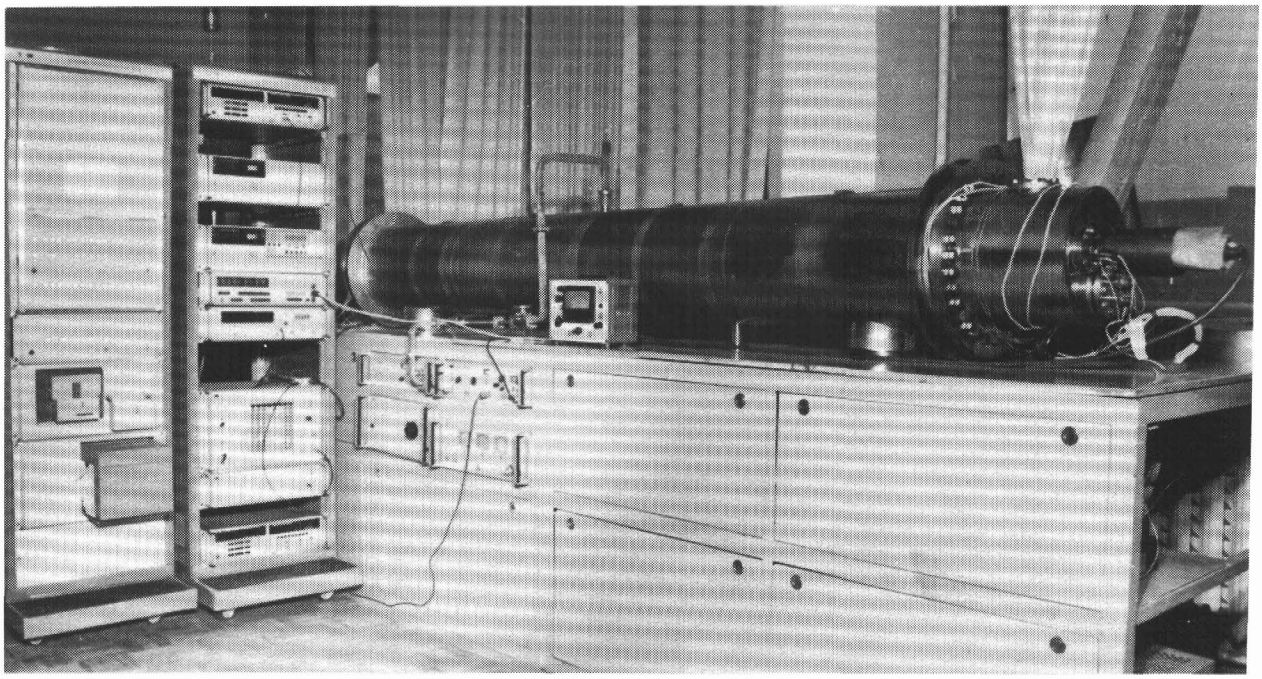
8. Commite Consultative pour la Definition de la Second, 11th session, Declaration S2 (1989).

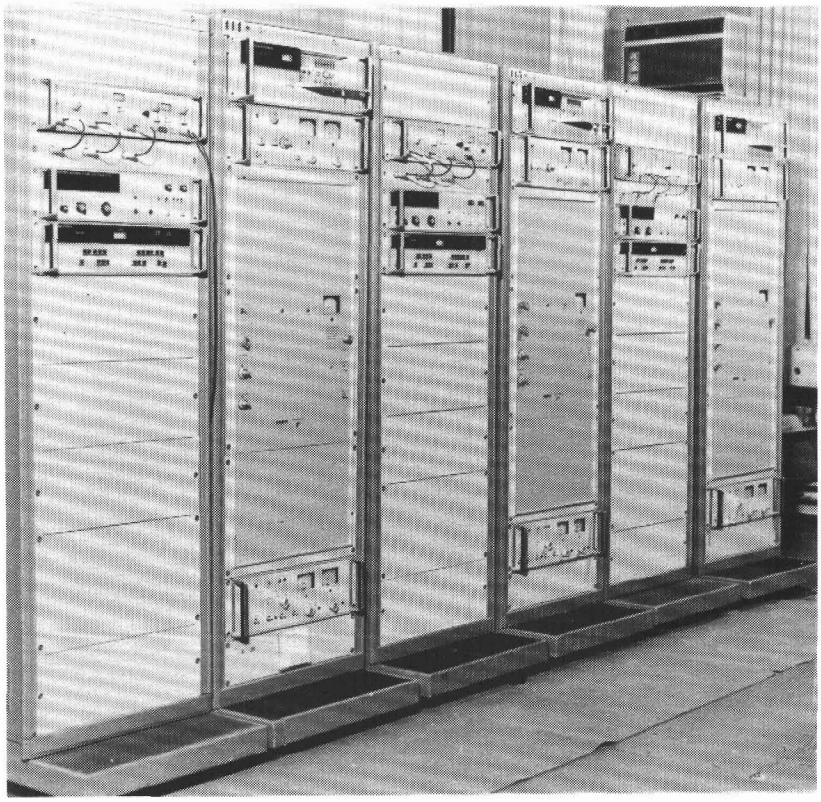

LC 7970W
Pulkovo
Moscow
Sverdlovsk
Novosibirsk
Kharkov
Irkutsk
Khabarovsk
Uzhgorod
TV
LC 7990Y
1000 km
LC 9970X
NPTFS
SS
MM link

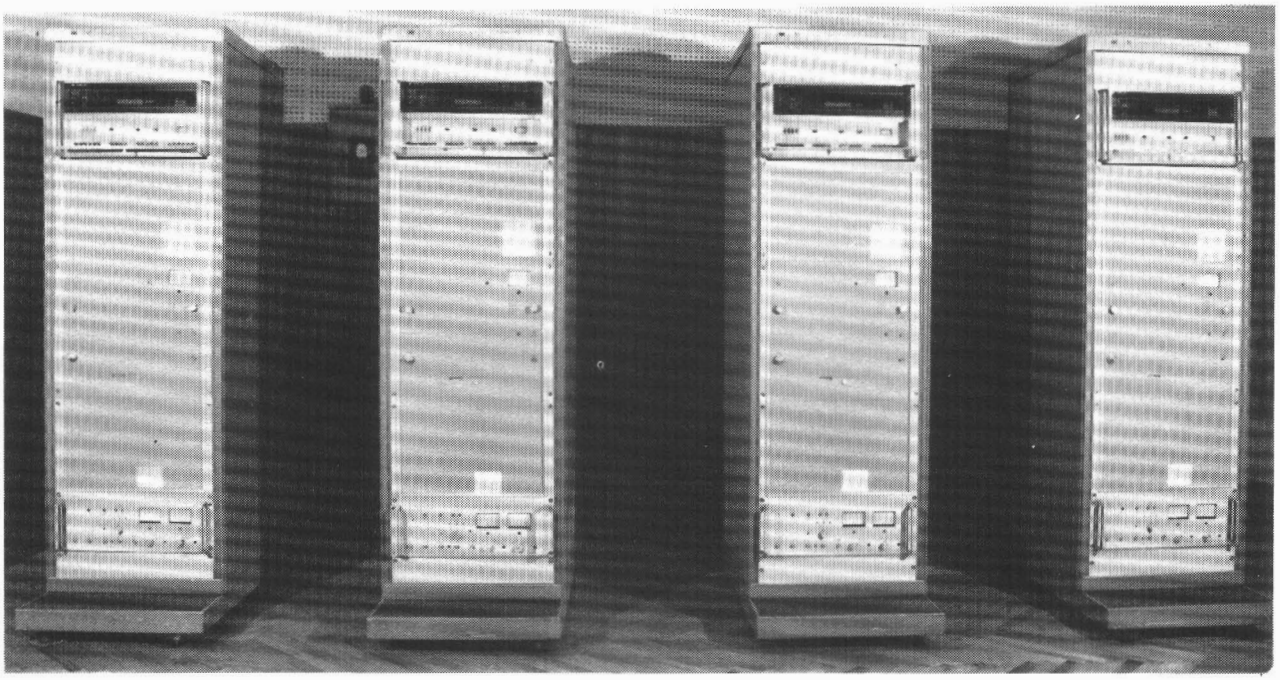


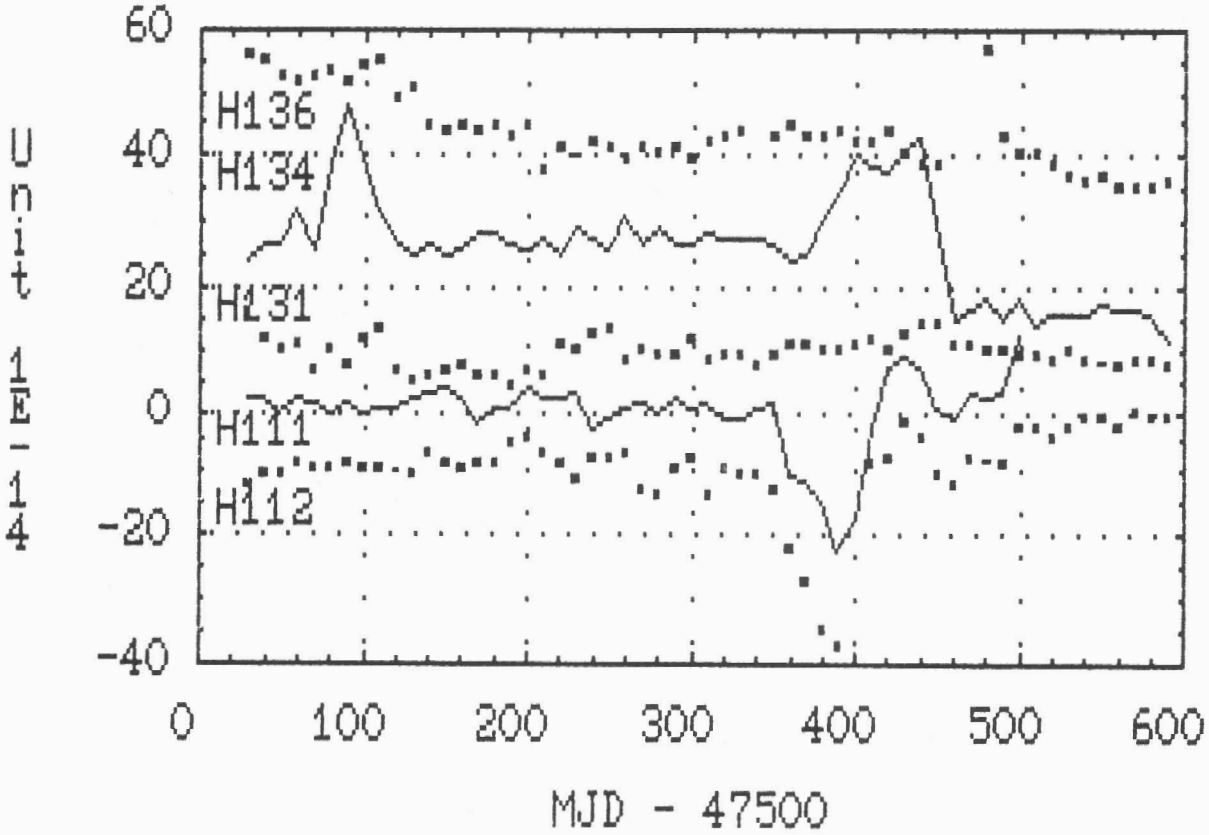
9192631770,00
133
Cs

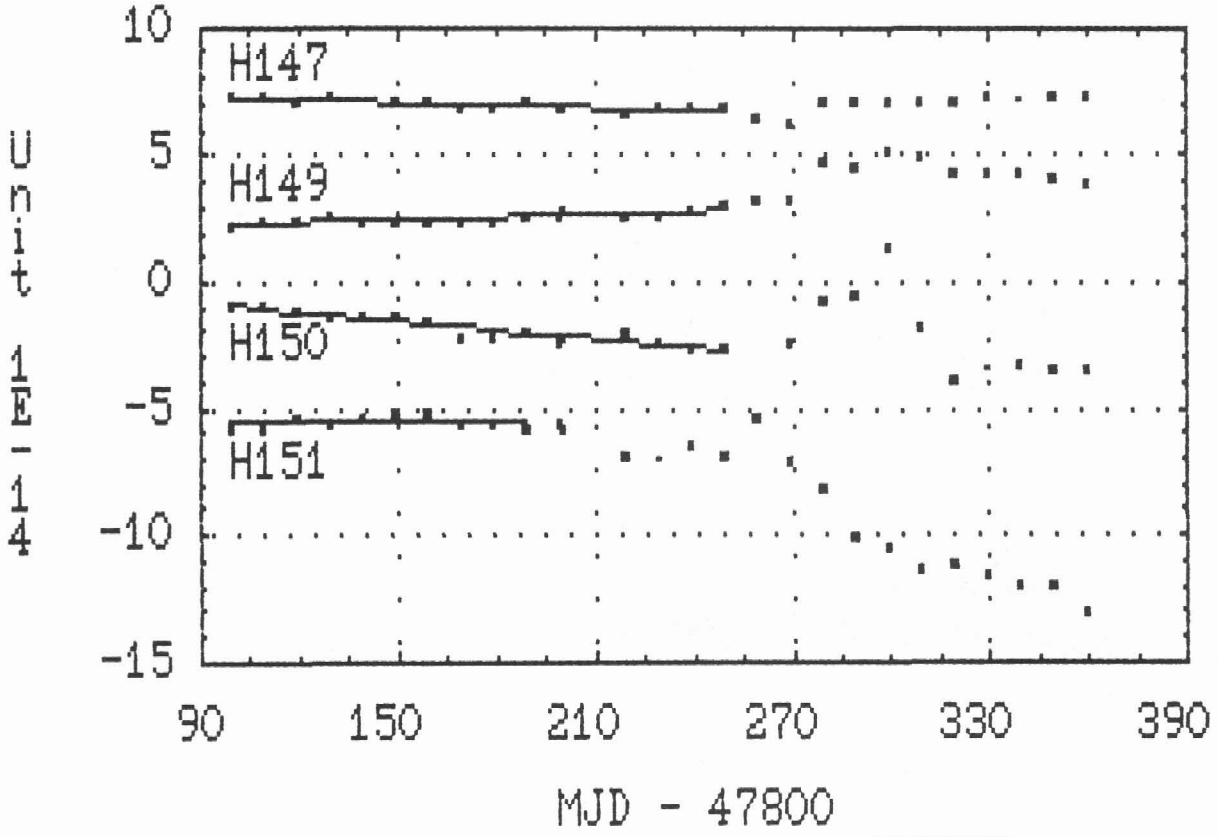


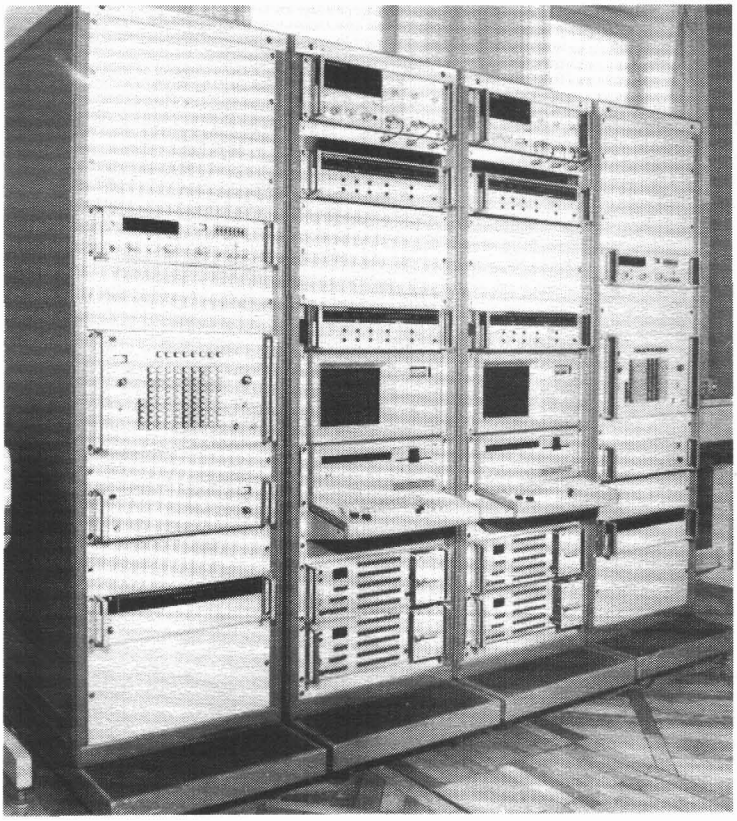


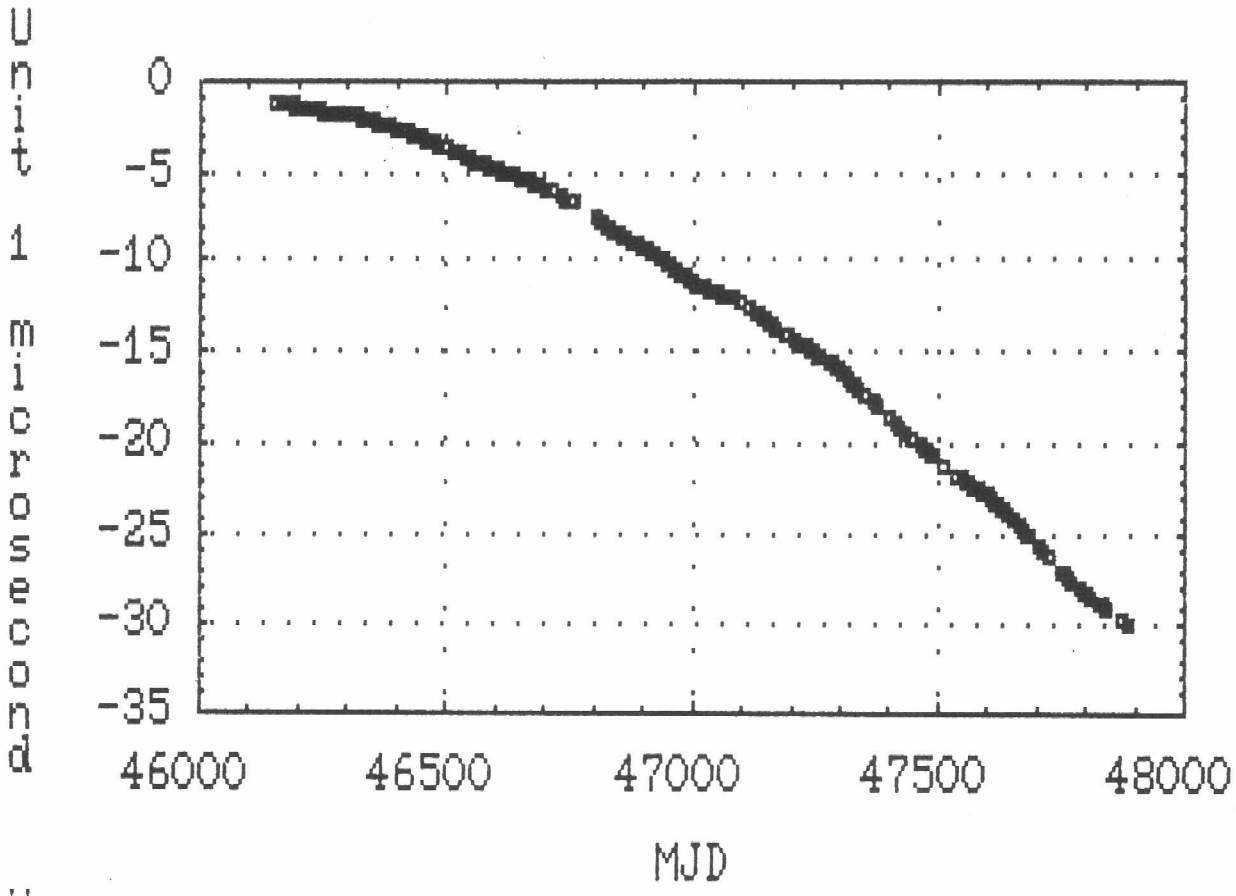


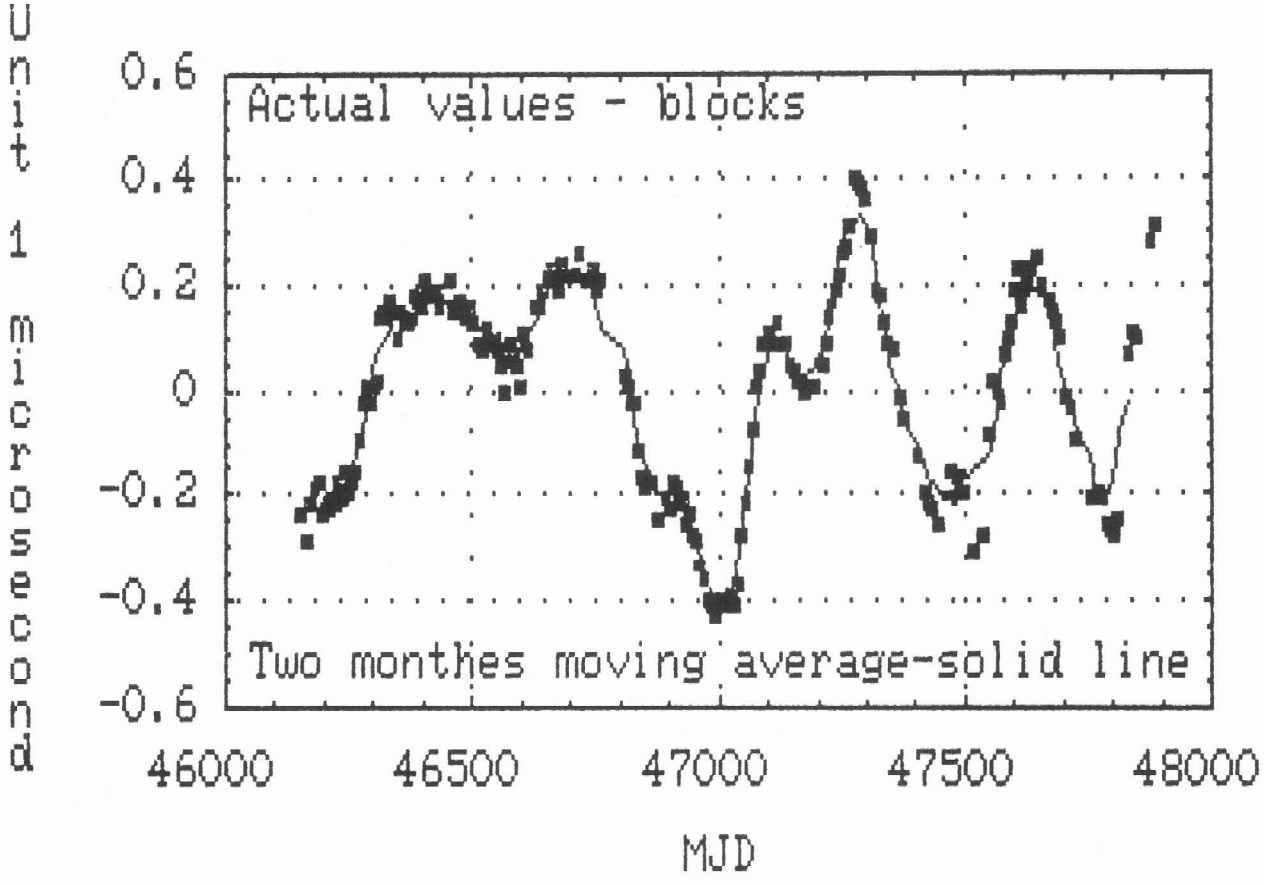


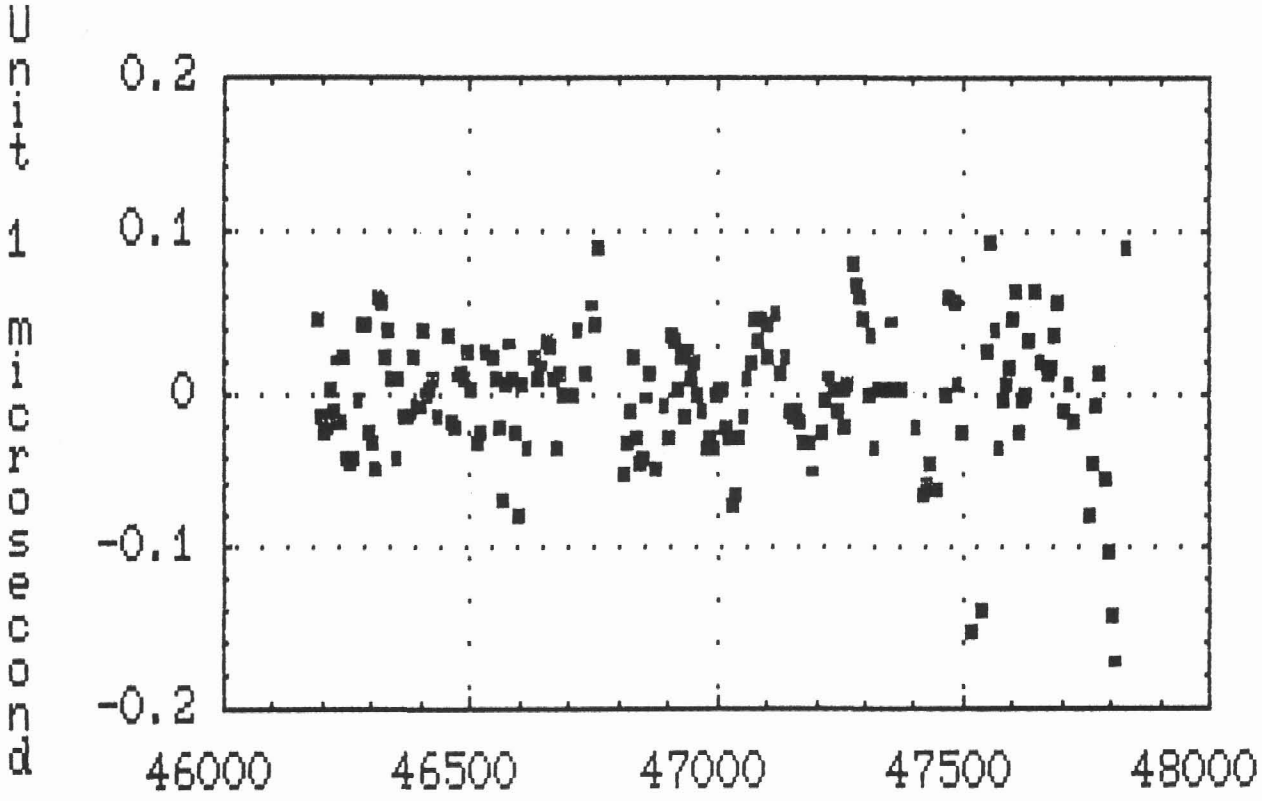

60
40
20
0
-20
-40
H136
H134
H131
H111
H112
Unit 1E-14
0
100
200
300
400
500
600
MJD - 47500

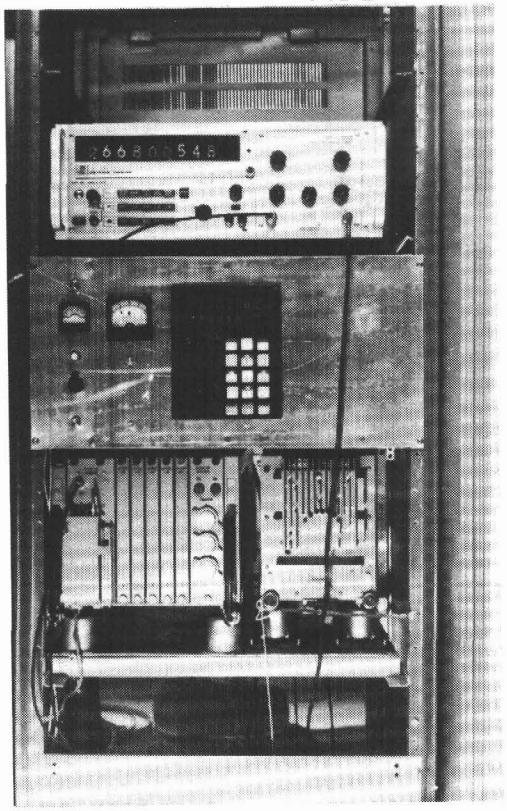

10
5
0
-5
-10
-15
H147
H149
H150
H151
90
150
210
270
330
390
MJD - 47800
Unit 1E-14

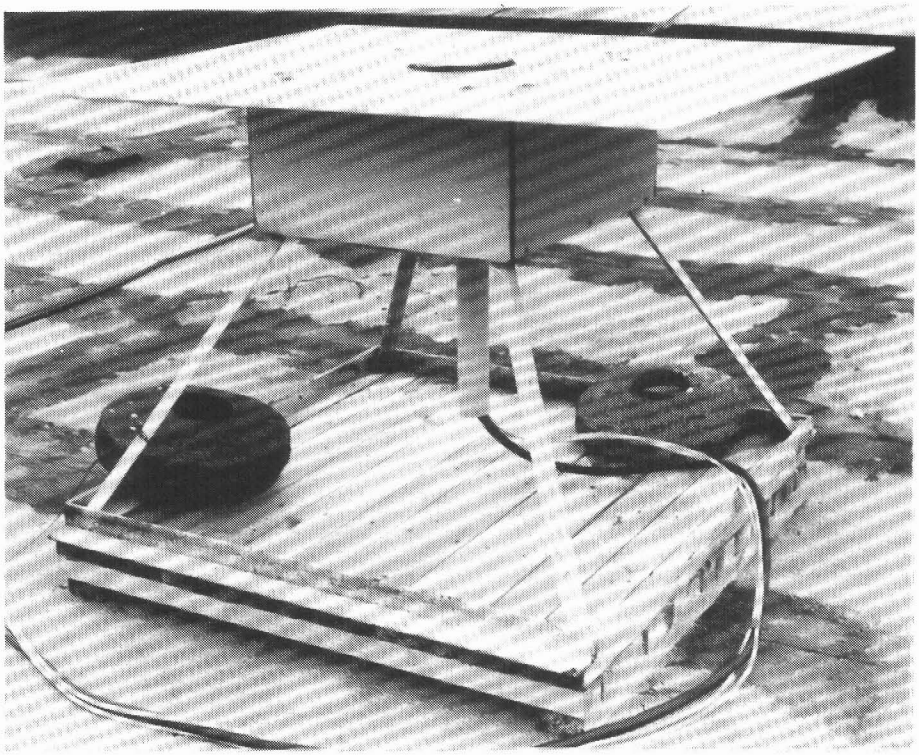


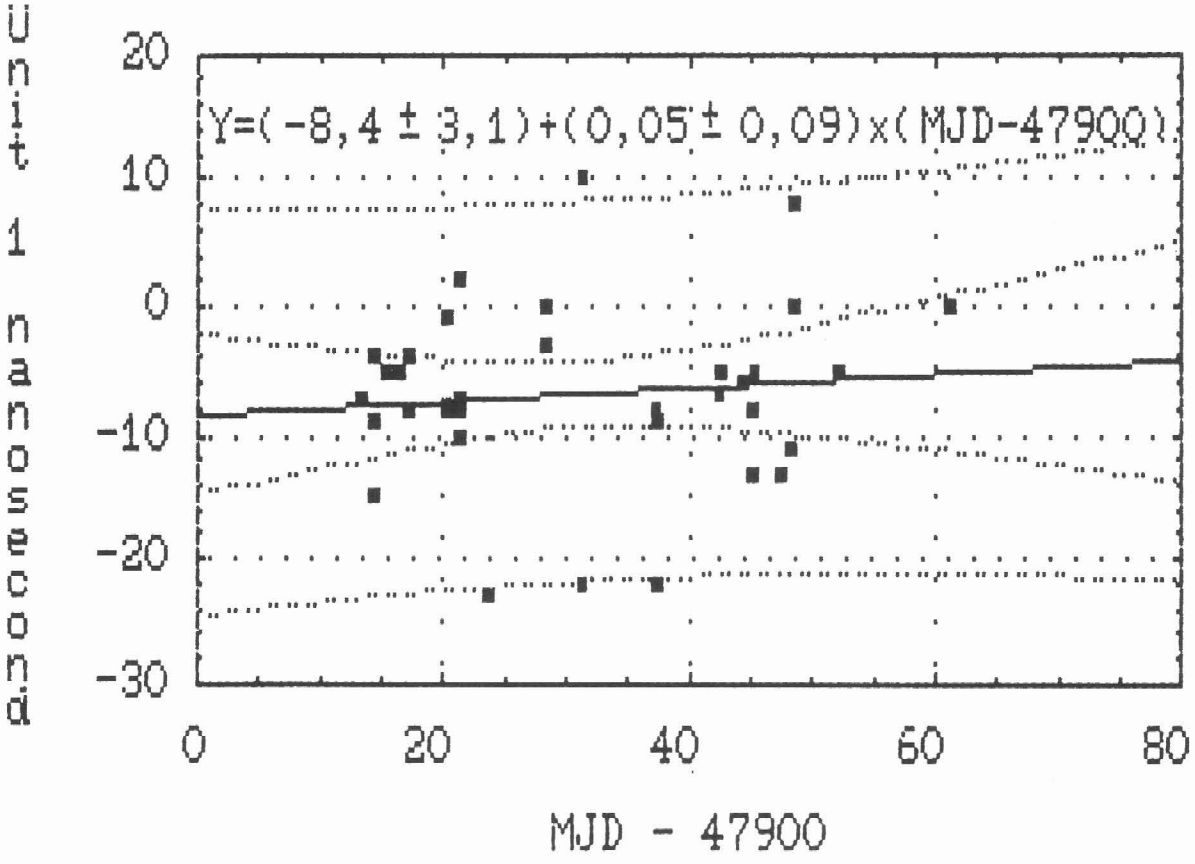

Unit 1 microsecond
0
-5
-10
-15
-20
-25
-30
-35
46000
46500
47000
47500
48000
MJD

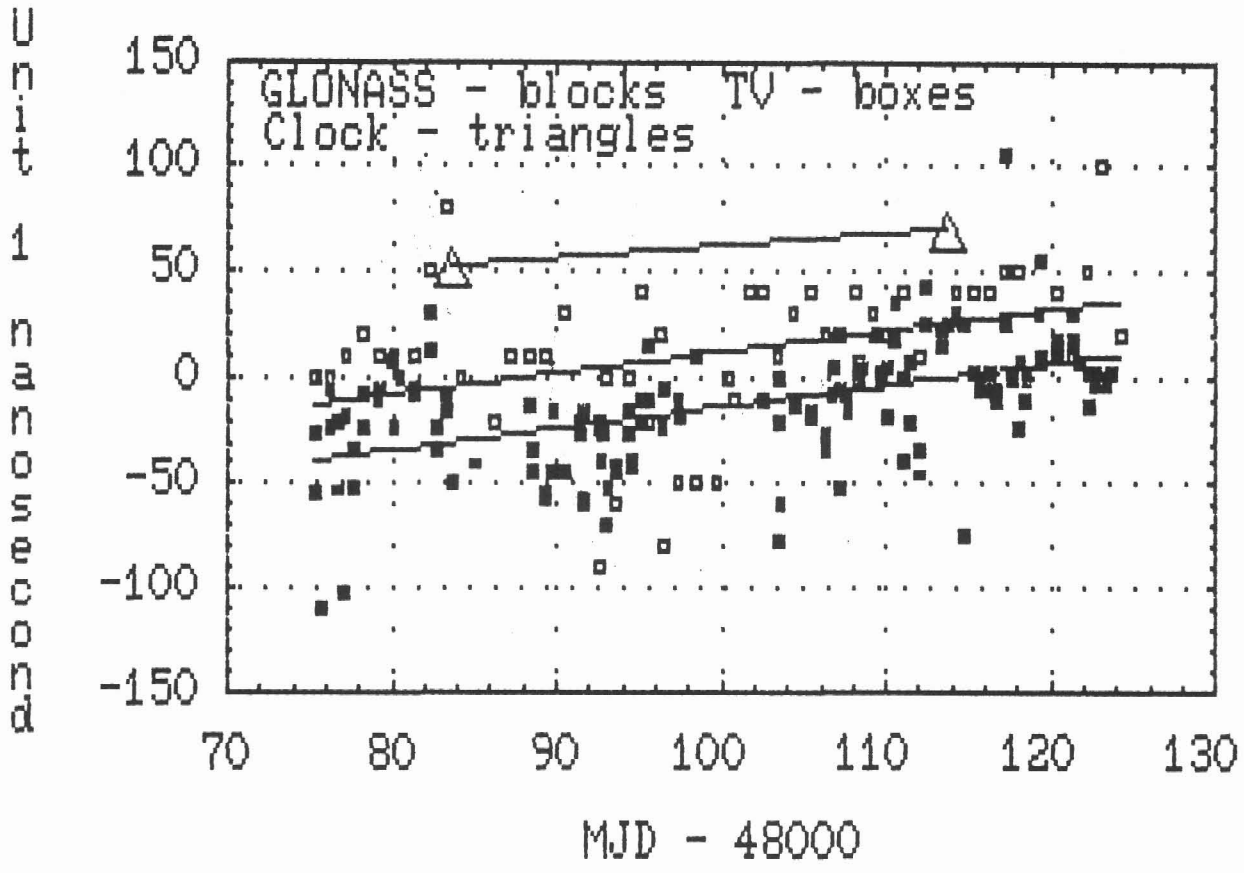

Unit 1 microsecond
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Actual values - blocks
Two monthes moving average-solid line
46000
46500
47000
47500
48000
MJD

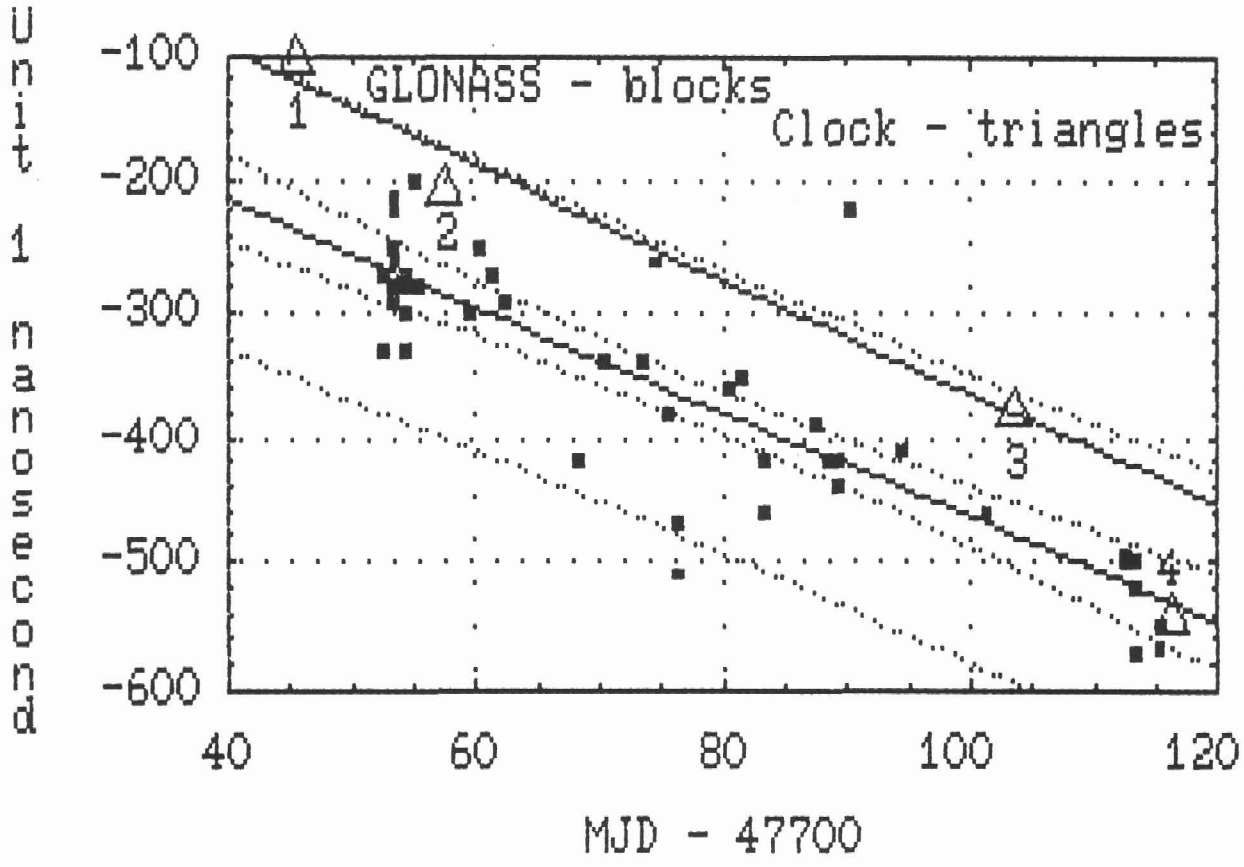

Unit 1 microsecond
0.2
0.1
0
-0.1
-0.2
46000
46500
47000
47500
48000
MJD

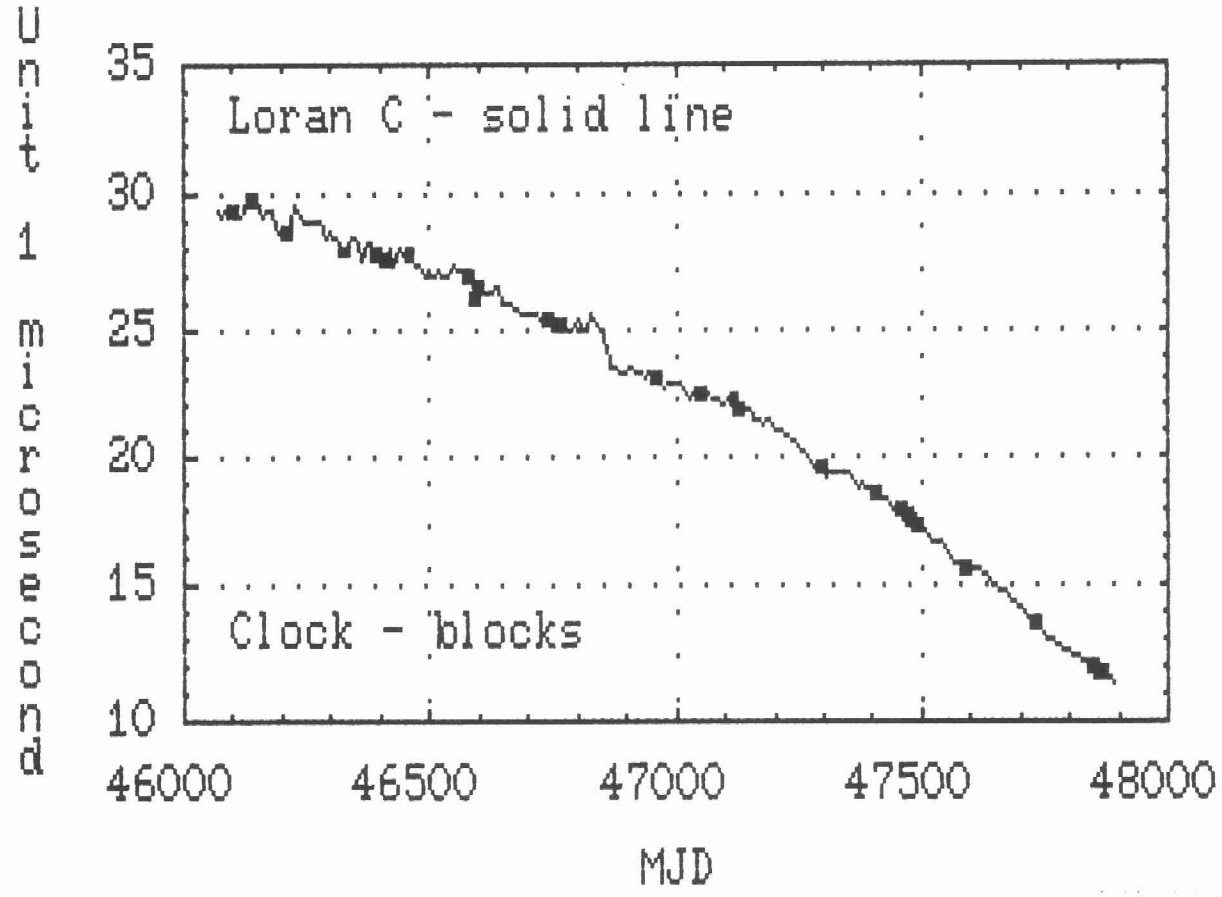


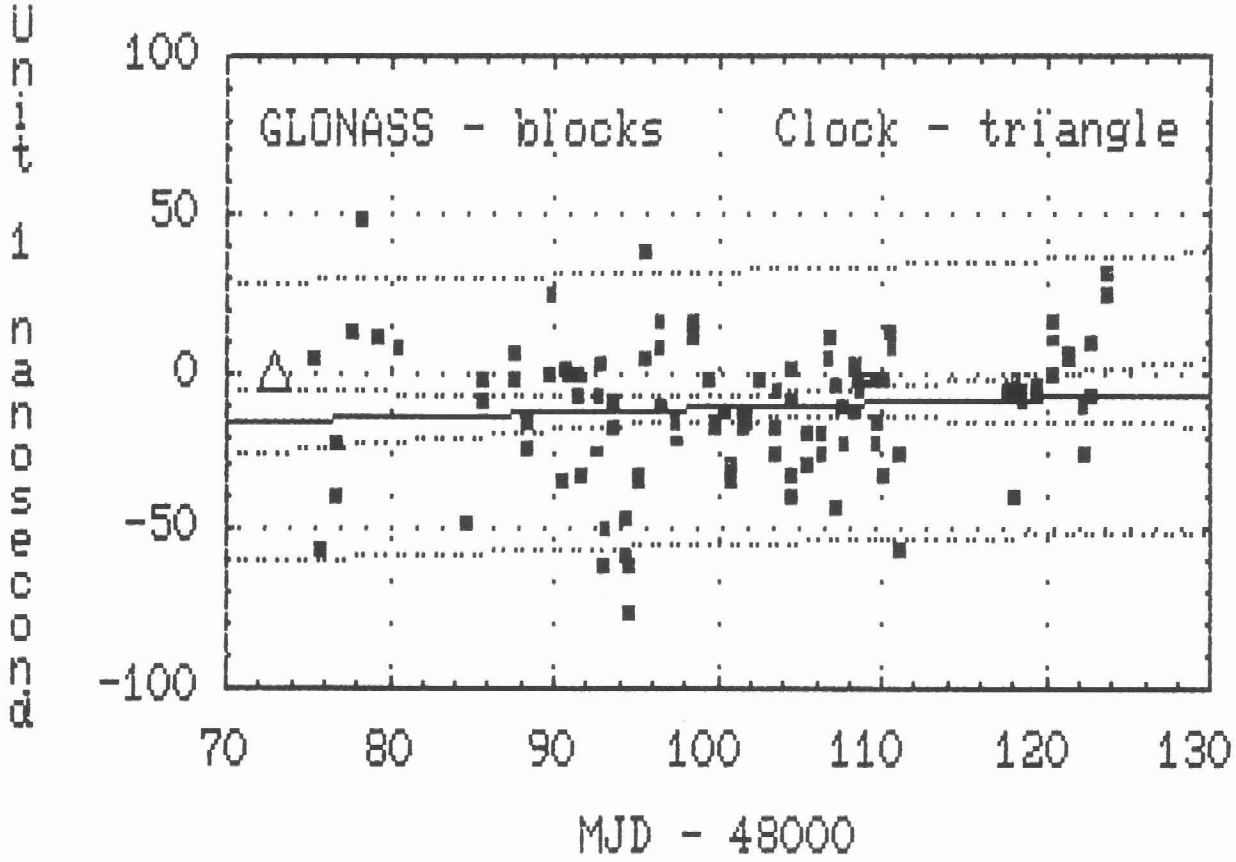


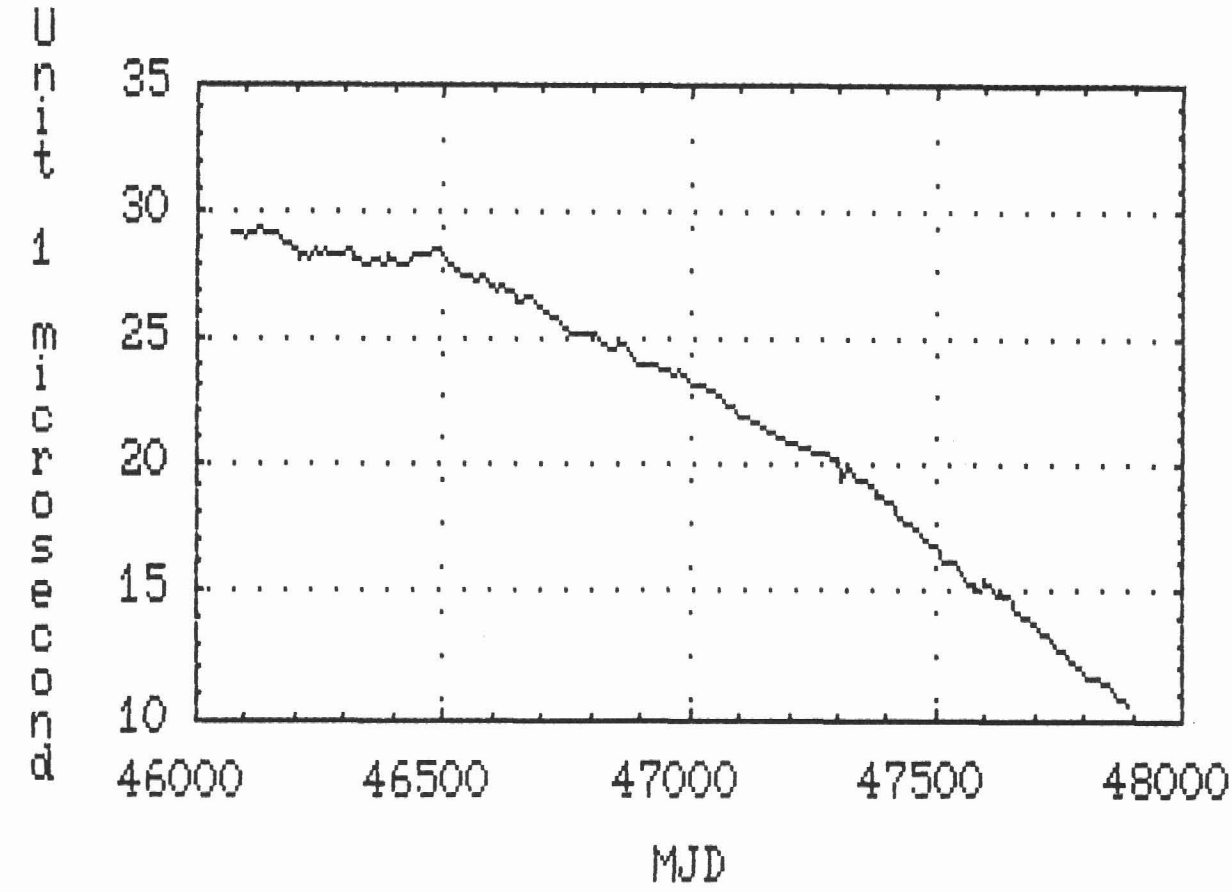

Unit 1 nanosecond
20
10
0
-10
-20
-30
Y=(-8,4 ± 3,1)+(0,05 ± 0,09)x(MJD-47900)
0
20
40
60
80
MJD - 47900

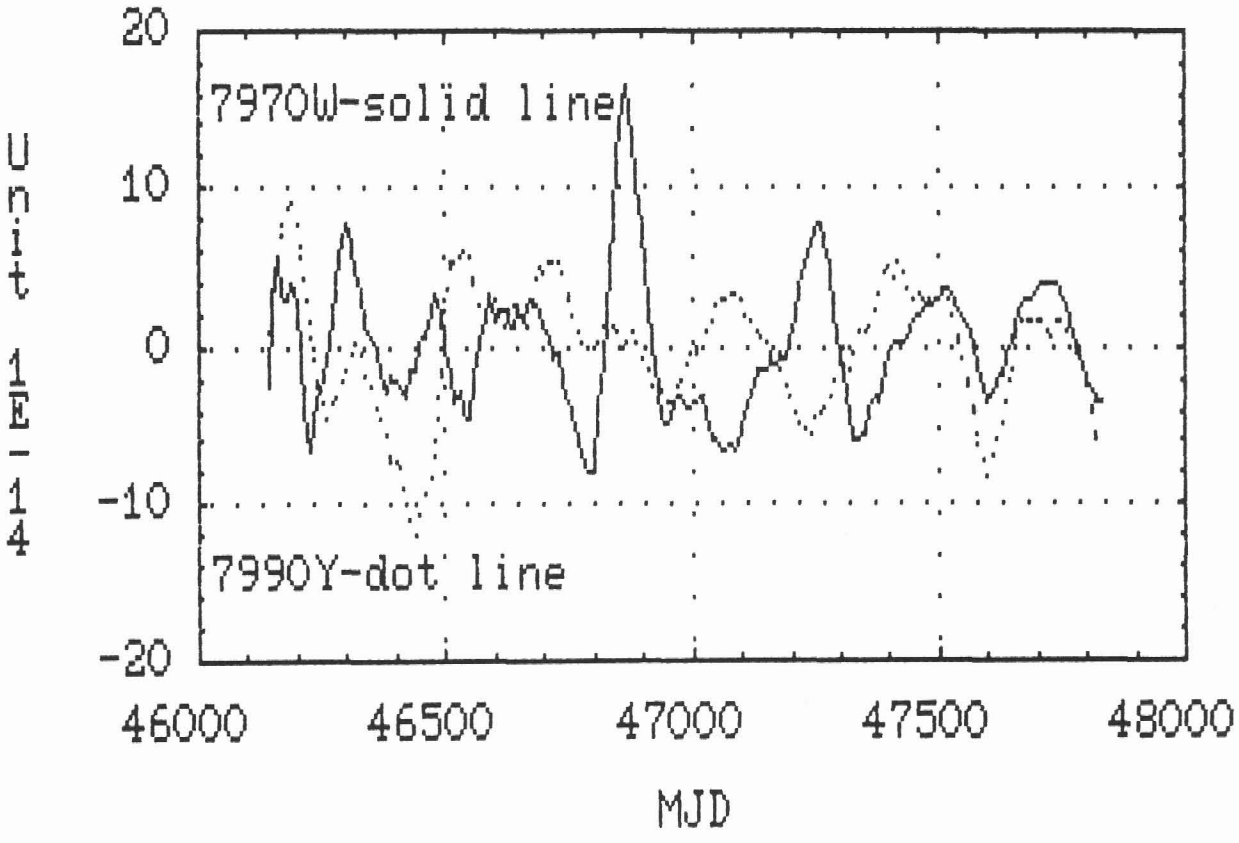

GLONASS - blocks TV - boxes
Clock - triangles
Unit 1 nanosecond
150
100
50
0
-50
-100
-150
70
80
90
100
110
120
130
MJD - 48000

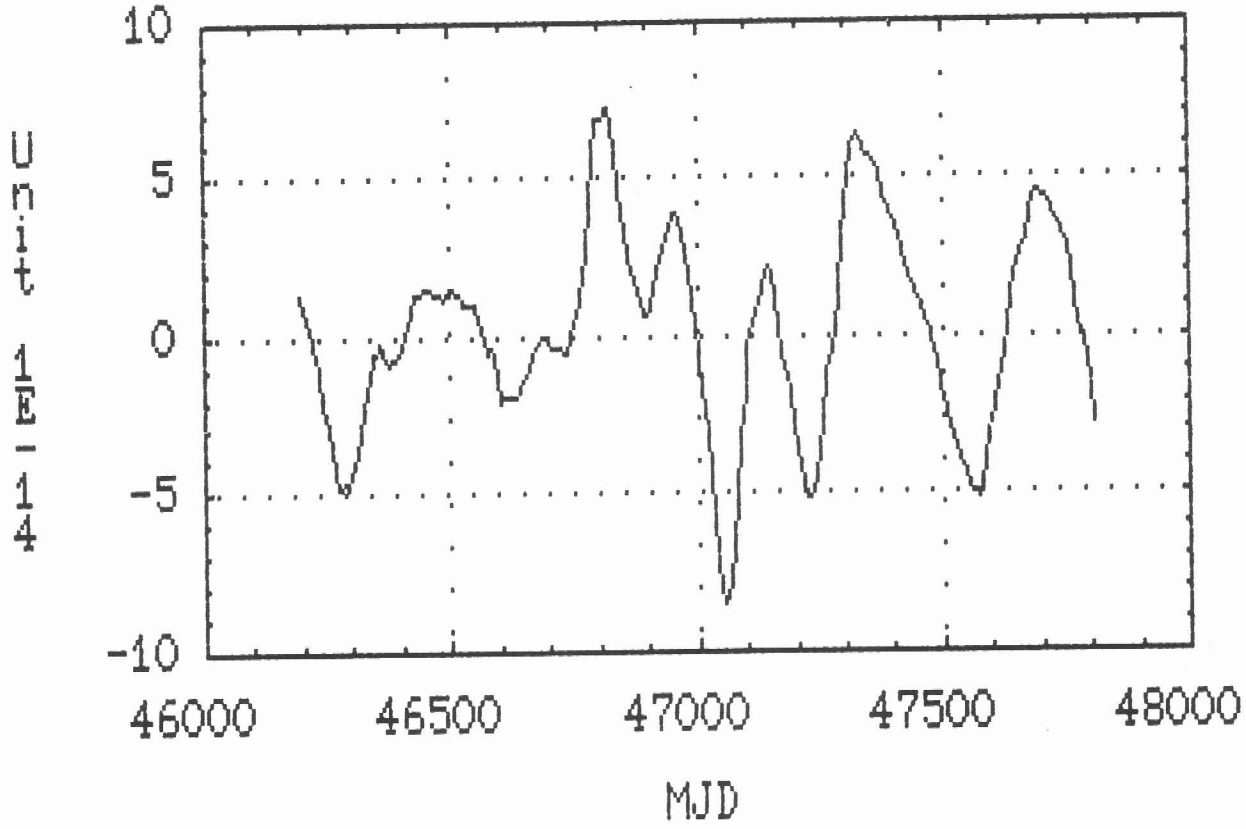

GLONASS - blocks
Clock - triangles
Unit 1 nanosecond
-100
-200
-300
-400
-500
-600
1
2
3
4
40
60
80
100
120
MJD - 47700

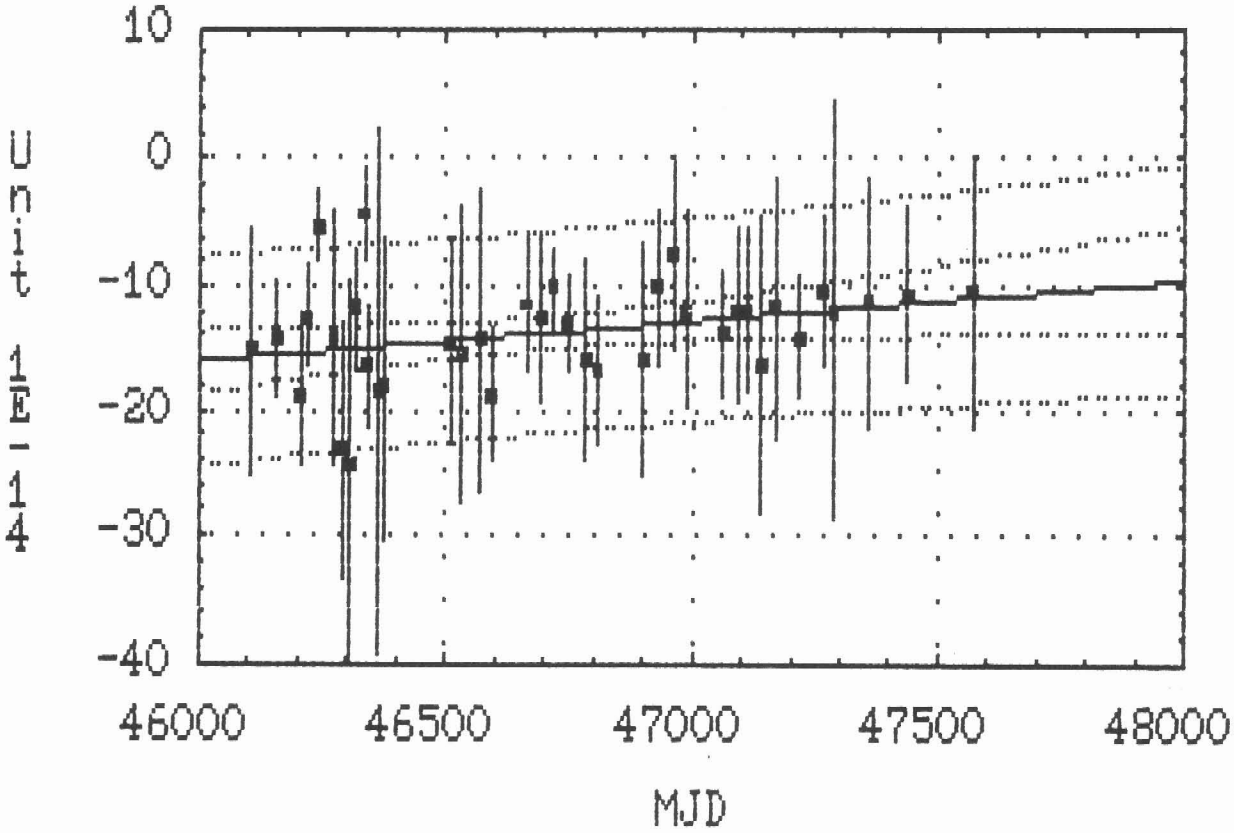

Unit 1 microsecond
35
30
25
20
15
10
Loran C - solid line
Clock - blocks
46000
46500
47000
47500
48000
MJD

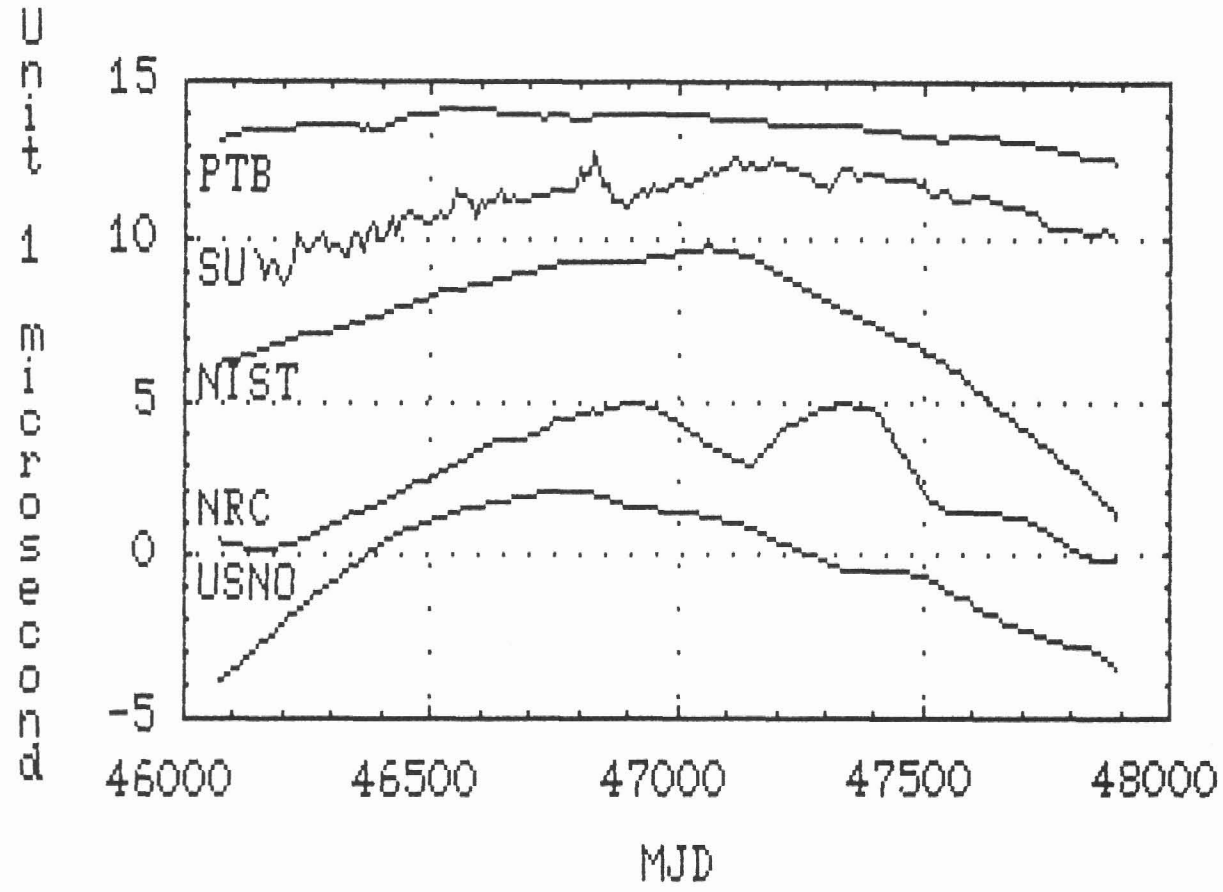

Unit 1 nanosecond
100
50
0
-50
-100
GLONASS - blocks
Clock - triangle
70
80
90
100
110
120
130
MJD - 48000

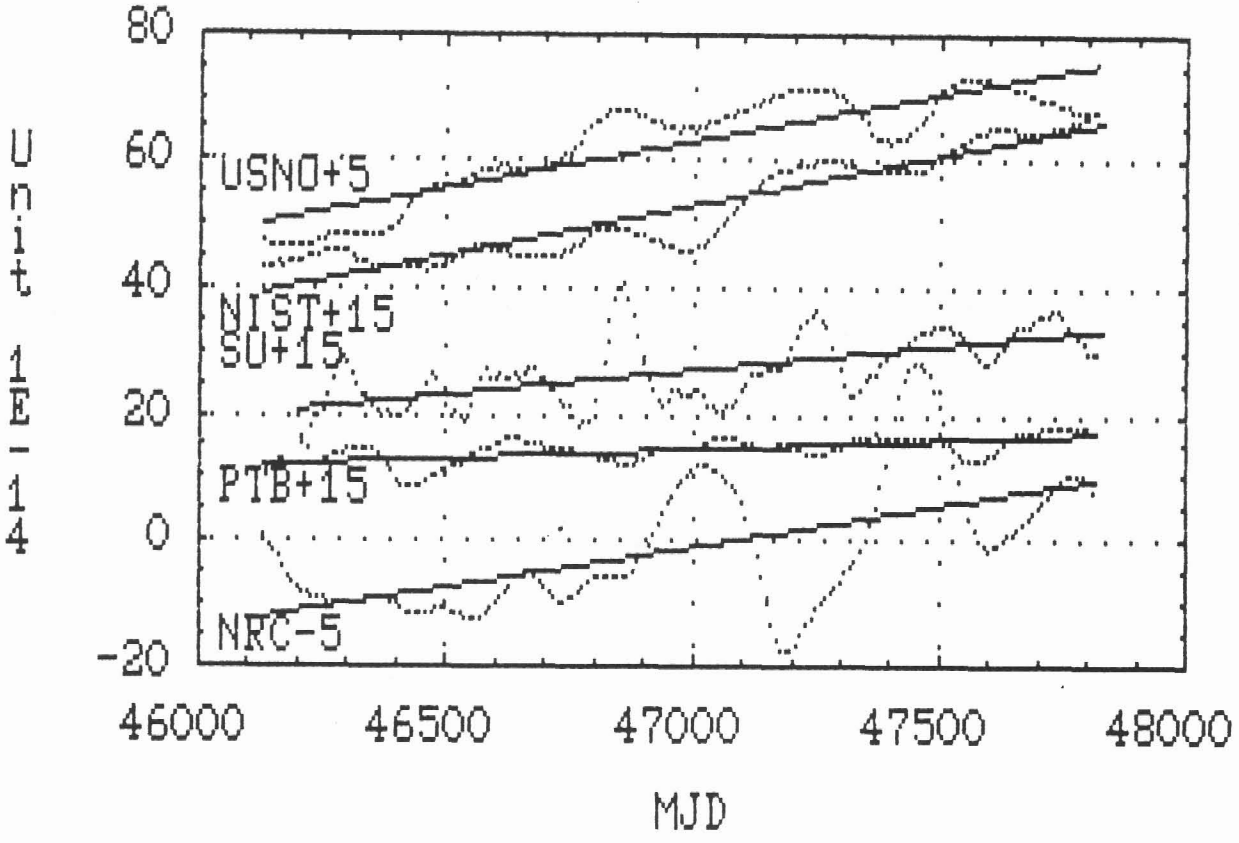

Unit 1 microsecond
35
30
25
20
15
10
46000
46500
47000
47500
48000
MJD


Unit 1E-14
20
10
0
-10
-20
7970W-solid line
7990Y-dot line
46000
46500
47000
47500
48000
MJD


10
5
0
-5
-10
Unit 1E-14
46000
46500
47000
47500
48000
MJD


10
0
-10
-20
-30
-40
Unit 1E-14
46000
46500
47000
47500
48000
MJD


Unit 1 microsecond
15
10
5
0
-5
PTB
SUW
NIST
NRC
USNO
46000
46500
47000
47500
48000
MJD


Unit 1E-14
80
60
40
20
0
-20
USNO+5
NIST+15
SU+15
PTB+15
NRC-5
46000
46500
47000
47500
48000
MJD

Carroll Alley, University of Maryland: Dave, did you visit there yourself?

Mr. Allan: Yes, I was there last September.

Professor Alley: How do they transport the Hydrogen Masers?

Mr. Allan: With difficult. They are not small. They have taken them on several trips — to TAI in Paris, to other sites that they have around the world. I don't know how difficult it is. The one maser that I saw there was probably transportable by two people. Our colleagues here could probably answer that if you asked them. They have two small maser models, I am not sure which one it is, but they were developing one while I was there that had a dynamic magnetic field servo with an attenuation factor of about 200,000. It looked like it would make a beautiful portable clock. It was fairly small.

Unidentified Questioner: David, what do you know about their passive masers?

Mr. Allan: We will show the data tomorrow night on their passive masers. I think it is fairly new for them, most of the masers that they have made are active masers. The stability is comparable to some that we have built, better than some, but not as good as others.

Harry Peters, Sigma Tau: I thought that it would be an appropriate question to ask whether these masers in the ensembles are being automatically spin-exchange tuned or otherwise tuned to achieve this stability.

Mr. Allan: Yes, they are.

Unidentified Questioner: In the chart that showed the various links, it showed the different sites where they have the hydrogen masers. How many masers do they have at each site? Do they all have the same number of clocks?

Mr. Allan: The paper said that they have up to eight hydrogen masers at each of those secondary sites.

Mr. Thomann, Neuchatel Observatory: Do we know whether they have the same design of masers at Gorky and at VNIIFTRI, and is the material for coating of the bulbs the same?

Dr. Demidov: All the coatings since 1975 have been made with F10.