SUBMICROSECOND COMPARISONS OF TIME STANDARDS VIA THE NAVIGATION TECHNOLOGY SATELLITES (NTS)

J. Buisson, T. McCaskill, J. Oaks, and D. Lynch
U. S. Naval Research Laboratory, Washington, D. C.
C. Wardrip, NASA Goddard Space Flight Center
G. Whitworth, Applied Physics Laboratory

ABSTRACT

During May through September 1978 a six nation cooperative experiment was performed to intercompare time standards of major laboratories at the submicrosecond level using NTS satellites.

NTS time transfer receivers, which were developed for use with the NTS series of satellites were installed at the Division of National Mapping (DNM), Australia; National Research Council (NRC), Canada; Royal Greenwich Observatory (RGO), England; Bureau International de l'Heure, France (BIH); Institute for Applied Geodesy (IFAG), West Germany; and in the U.S. at the Goddard Space Flight Center (GSFC), National Bureau of Standards (NBS), Naval Research Laboratory (NRL) and the Naval Observatory (USNO).

The results of the clock intercomparisons will be presented.

INTRODUCTION

The major objective was to perform an interim demonstration of the time transfer capability of the NAVSTAR GPS system using a single NTS satellite. Measurements of time difference (pseudo-range) are made from the NTS tracking network and at the participating observatories. The NTS network measurements are used to compute the NTS orbit trajectory. The central NTS tracking station has a time link to the Naval Observatory UTC(USNO,MC1) master clock. Using measurements taken with the NTS receiver at the remote observatory, the time transfer value UTC(USNO,MC1)-UTC(REMOTE, VIA NTS) is calculated. For GPS, a similar procedure could be followed using simultaneous measurements taken between the user and four GPS satellites. With the four GPS pseudo-range (time difference) measurements taken at an (unknown) location the user may solve for three position coordinates in addition to time offset with respect to GPS time. The goal for the NTS effort was to achieve worldwide time transfer of less than one microsecond accuracy.

A second objective was to compute weekly worldwide intercomparisons of the observatory clock offsets using predicted values of satellite clock offset and ephemeris. Each participant enters appropriate measurements into computer files which are later processed. Other objectives include co-location at laser sites and the use of the observatory time scales in evaluating the spacecraft clock performance.

Time Difference Measurements

Time difference (pseudo-range) measurements are made between the spacecraft and the user by side tone ranging (1). The NTS-2 spacecraft also has a GPS pseudo-random sequence transmitter. All measurements presented in this paper were made using the side tone ranging system, which has a resolution of 1.56 nsec (48 cm.). Measurements of time difference may be converted to pseudo-range by multiplying by the speed of light in a vacuum. Units of time are used in this paper to facilitate comparisons with the PTTI community.

The time difference measurement is composed of the difference between the satellite clock and the user clock, plus satellite transmitter delays, propagation path delay, ionospheric delay, tropospheric delay, user antenna delay, cable and receiver delay. All of these factors must be measured or estimated. In addition to the above factors, the spacecraft clock is influenced by the relativistic frequency shift, magnetic fields, energetic particles, and small variations in temperature and drive level.

Receivers of two designs were employed in making the measurements. One receiver (2) made measurements at a nominal UHF frequency of 335 MHz. The second receiver used was capable of making measurements at the L band frequency of 1580 MHz in addition to the UHF frequency. The two channel receiver measurements were combined, by software, to correct for the first order ionospheric refraction.

Spacecraft Frequency Standards

Timing signals transmitted from NTS-2 are derived from a cesium frequency standard; NTS-1 employs both rubidium and quartz oscillators. Frequency stability results have been previously reported (3,4) for one of the NTS-2 cesium standards and for rubidium and quartz oscillators.

The NTS-2 cesium standard was used to measure the relativistic frequency shift (5) at the GPS constellation altitude. The NTS-2 cesium output frequency was adjusted so that the received frequency is near that of UTC(USNO,MC1). In contrast, the NTS-1 quartz oscillator is periodically adjusted in frequency and time. The maximum frequency excursions of the quartz varied from $+2\times10^{-9}$ to -4×10^{-9} with respect to UTC(USNO,MC1). Noteworthy is the fact that the ease of operation is superior with cesium, inasmuch as comparatively large periodic adjustments are required with the quartz frequency standard.

Time Transfer Technique

The time transfer to a remote location is obtained by four time links to UTC(USNO,MC1). The four links are (a) from the remote user clock to the spacecraft clock, (b) the spacecraft frequency time update for the time difference between observations obtained at the remote site and the central site, (c) from the central station clock to the spacecraft clock, and (d) from the central station clock to UTC(USNO,MC1). Figure (1) depicts the four links used in this procedure. This procedure incorporates the short to medium term stability of the spacecraft and control station clock with the long term stability of the U.S. Naval Observatory multi-clock time scale.

Measurements of [UTC(USNO,MC1)-UTC(REMOTE, VIA NTS)] may be taken with a variety of frequency sources of varying stability. The major observatories participating in this experiment possess frequency standards and time scales of proven accuracy, with sufficient difference in geographic location (figure 2), to check the time transfer at different positions of the spacecraft orbit.

Time Transfer Results

Figures (3)-(12) present time transfer results as determined from the NTS spacecraft. The figures are similar in format in as much as each remote observing station is referenced through the NTS central ground observing station located at Chesapeake Bay Division (CBD) of NRL. The CBD site is linked to the USNOMC by a series of portable clock closures to an accuracy of 10-20 nanoseconds.

Table 1 presents the phase offset and frequency difference of each remote station clock against the USNOMC for a given epoch time which is nominally placed in the middle of the observed data span. In addition, the RMS of a straight line least squares fit to all satellite passes observed by the remote station is presented as a measure of the noise in the time transfer values.

TABLE I

NTS
TIME TRANSFER RESULTS
UTC(USNO,MC)-UTC(REMOTE, NTS)

Remote Site	Epoch (day 1978)	Phase Offset (microsec)	Frequency ($pp10^{11}$)	RMS (nanosec)
RGO (JP)	186	-160.734	-.245	369
BIH (OP)	156	1.574	-.006	318
CERGA	130	0.995	-.049	324
IFAG	186	- 10.277	-.017	377
DNM (590)	186	158.902	.329	458
RRL	303	- 18.050	-.010	862
NRLM	304	- 47.829	.003	998
NBS	151	- .474	-.014	398
NRC	186	- 3.716	-.005	152
USNO (MC1)	186	- .036	.000	171

From the table it can be seen that the two Japanese remote sites (RRL and NRLM) exhibit a higher noise level than the other observing stations. These higher noise level measurements were the result of using predicted satellite position ephemeris. Further analysis will be performed using observed orbital trajectory.

Also plotted in figures (3)-(12) are the results of portable clock closures performed by personnel from the USNO. These portable clock closures are used as "truth" or absolute accuracy tie-in for the NTS results.

Figures (13)-(15) present time transfer results from the NTS remote observing station located at the Panama Canal Zone (CZ) site. Results in this data span were obtained with both NTS2 and NTS1 spacecrafts. The NTS2 data included observations available at both 335 MHz and 1580 MHz, allowing for a first order ionospheric delay measurement.

The NTS1 measurements used single frequency measurement at 335 MHz. Table 2 summarizes the CZ results in a similar fashion to Table 1.

TABLE 2

NTS
TIME TRANSFER RESULTS
UTC(USNO,MC)-UTC(CZ)

Epoch (Day, 1978)	Phase (microsec)	Frequency ($pp10^{11}$)	RMS (nanosec)
119	-23.882	-.052	330
177	-26.293	-.093	63
170	-26.357	-.094	9

Figure (13) presents the entire data span consisting of both NTS2 and NTS1 measurements. Figure (14) presents only NTS2 data. The improvement in noise level was from 330 nanoseconds to 63 nanoseconds. This improvement was the results of two major advantages of the NTS2 spacecraft over the NTS1 spacecraft; firstly the use of a cesium oscillator in space (NTS2) as opposed to a quartz oscillator (NTS1) and, secondly, the ability to correct for the ionospheric delay by dual frequency measurement (NTS2).

The additional improvement in noise level between figures (14) and (15) (from 63 nanosec to 9 nanosec) is the result of a systematic effect in the orbit determination method which corresponds to the 2 rev/day orbit configuration. Figure (15) uses observations obtained from the same side of the orbit each day. This noise level of 9 nanoseconds is considered to be indicative of results which can be attained in the full operational GPS constellation.

System Closure

Figure (12) presents the time transfer results for a receiver located at the U. S. Naval Observatory with a direct input from UTC(USNO,MC1). It can be seen that the noise level is 171 nanosec with an offset of -36 nanosec at the epoch presented.

Time comparisons for five of the major observatories are presented in figure (16). The insert in figure (16) presents the offset of three of the observatories to permit relative frequency comparison.

Noteworthy is the line for UTC(USNO,MC1) via NTS; a small slope on the order of a few parts in 10(15) is present which is not statistically significant.

Table 3 presents the differences for the NTS1 time transfers with respect to the interpolated portable clock measurements. The average accuracy indicated by the portable clock is -0.06 usec. This table links the entire experiment to the absolute or "truth" values as determined by the DOD master clock.

TABLE 3

SUMMARY OF
PORTABLE CLOCK CLOSURES
VS
NTS TIME TRANSFER RESULTS

STATION	DAY (1978)	PORTABLE CLOCK-NTS TIME TRANSFER (US)
BIH	124	-.57
CERGA	117	.70
DNM	282	.09
IFAG	199	.03
NBS	221	.19
NRLM	299	-.53
RGO	115	.44
RRL	303	.13
USNO	186	.04

Conclusions

The following items are summarized as a conclusion for the six nation time transfer campaign:

o Time transfers via NTS satellites of better than 1 microsecond accuracy have been demonstrated.

- o Simulated single satellite GPS operation has been demonstrated.
- o A 9 nanosecond time transfer noise level over a 12 day span has been demonstrated as a possible best value of results.

Acknowledgements

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1. Landis, Paul G., Silverman, I., Weaver, Charles W., "A Navigation Technology Satellite Receiver", NRL Memorandum Report #3324, July 1976.
2. Raymond, L., Oaks, J., Osborne, J., Whitworth, G., Buisson, J., Landis, P., Wardrip, C., Perry, J., "Navigation Technology Satellite (NTS) Low Cost Timing Receiver Development", Proceedings of the Eighth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, November, 1976.
3. McCaskill, T. B., White, J. W., Stebbins, S., Buisson, J. A., "NTS-2 Cesium Frequency Stability Results", Proceedings of the 32nd Annual Symposium on Frequency Control, 1978.
4. McCaskill, T.B., and Buisson, J.A., "NTS-1 (TIMATION-III) Quartz and Rubidium Oscillator Frequency Stability Results", NRL Report 7932, December 12, 1975.
5. Buisson, J.A., Easton, R.L., McCaskill, T.B., "Initial Results of the NAVSTAR GPS NTS-2 Satellite", Proceedings of the Ninth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, March, 1978.

FIGURES

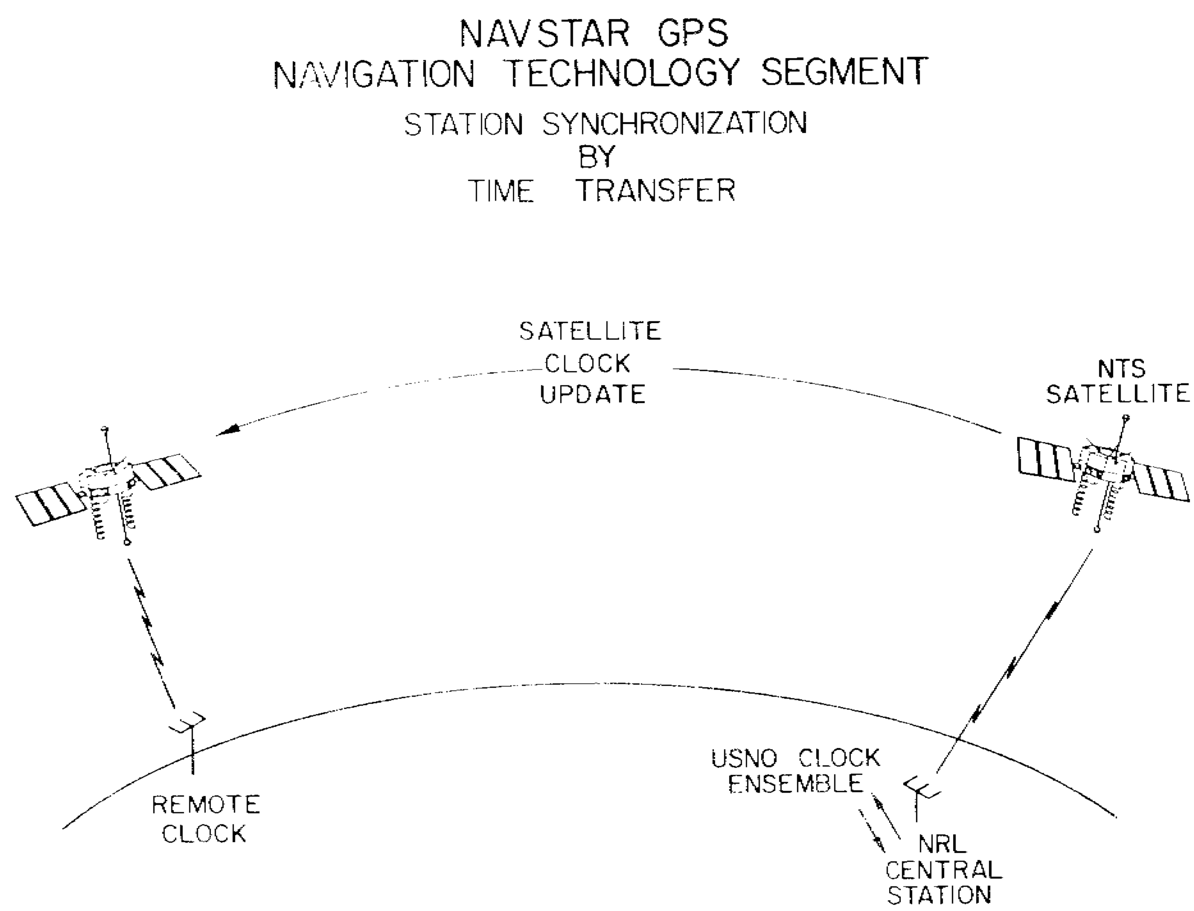

Figure 1 Time Transfer Configuration

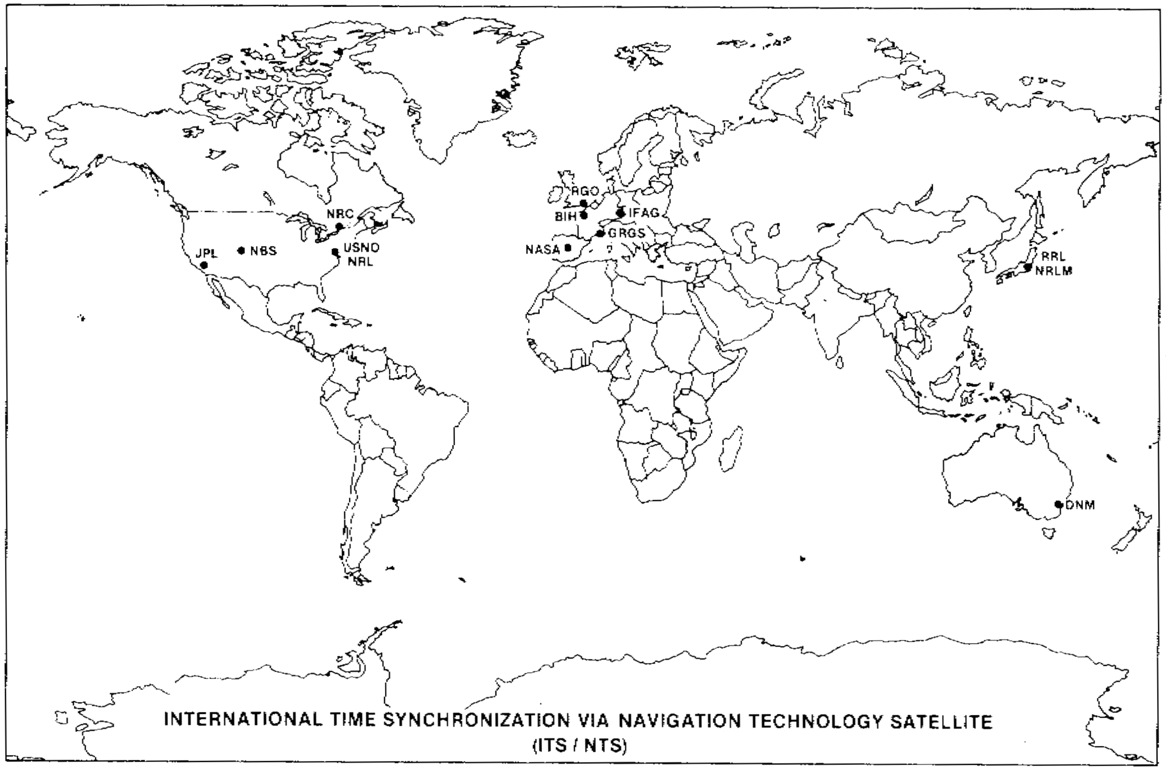

Figure 2 International Time Synchronization via Navigation Technology Satellite

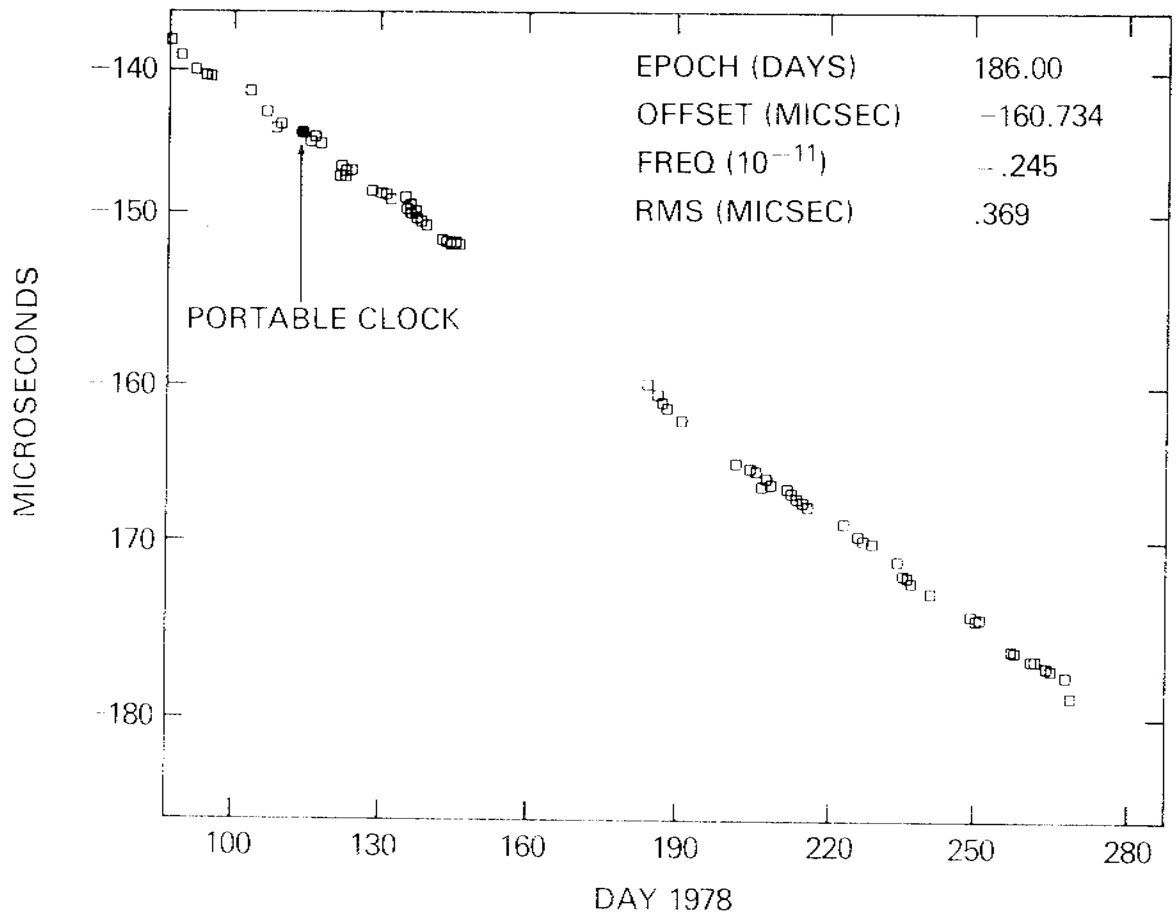

Figure 3 Time Transfer Results from Royal Greenwich Observatory (USNO,MC1)-(RGO,JP)

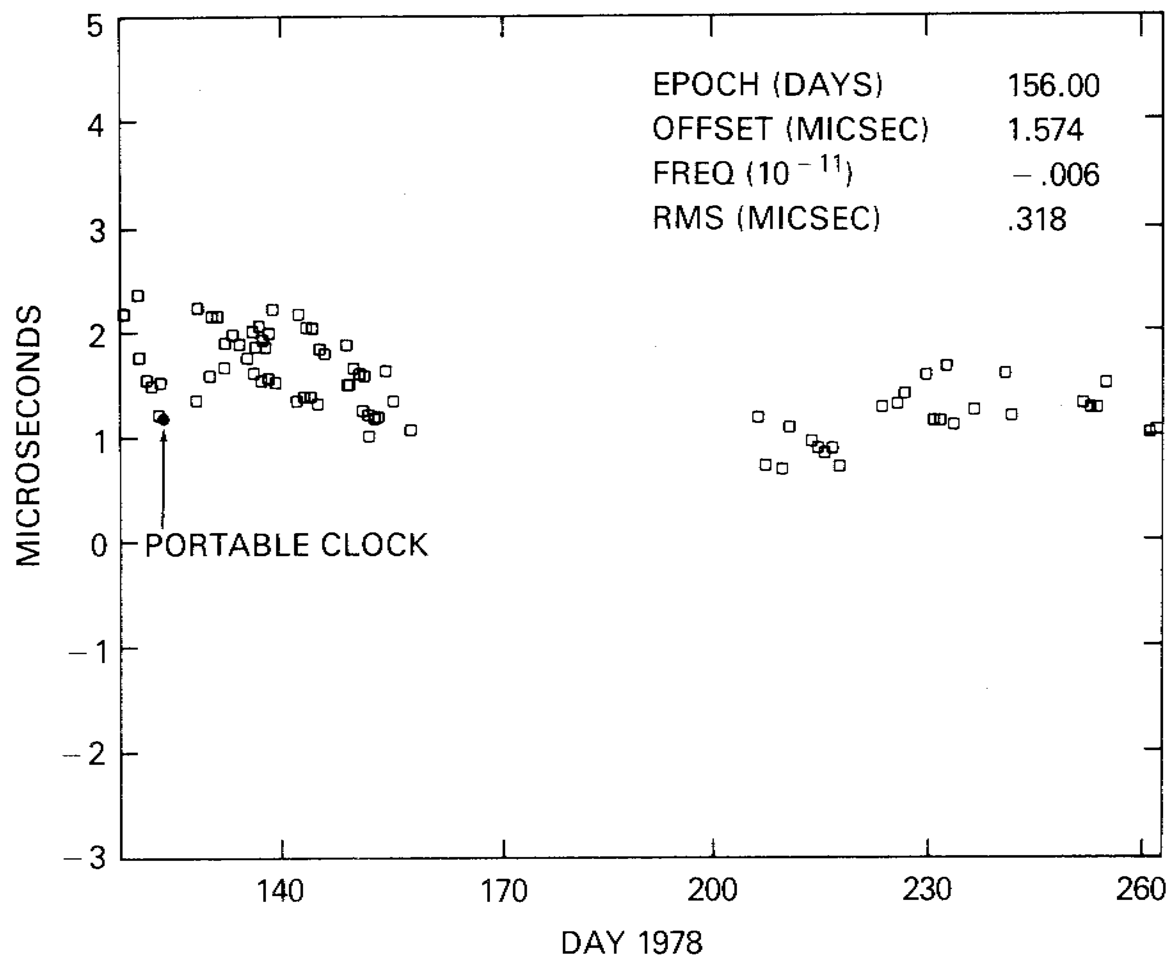

Figure 4 Time Transfer Results from Paris OP
(USNO,MC1)-(OP)

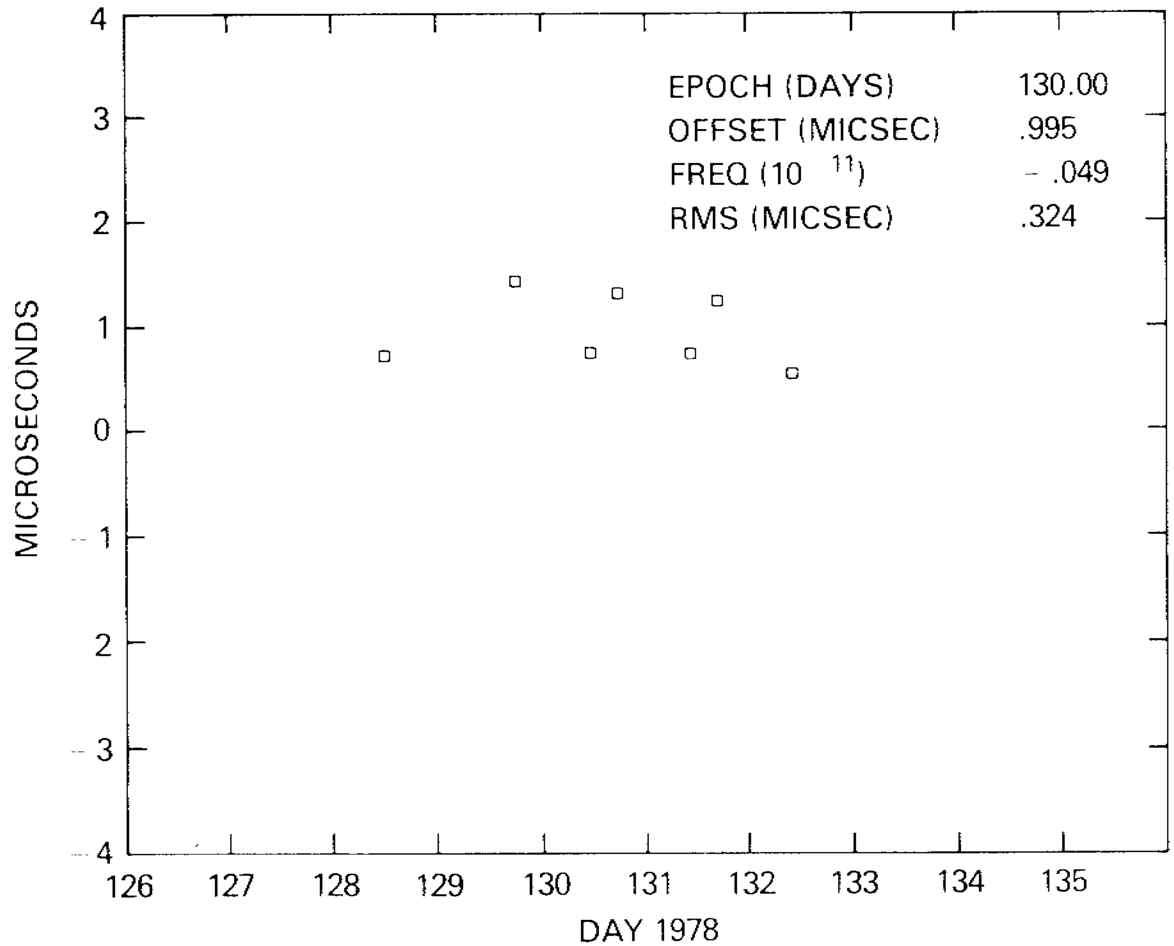

Figure 5 Time Transfer Results from Cerga, France (USNO,MC1)-(CERGA)

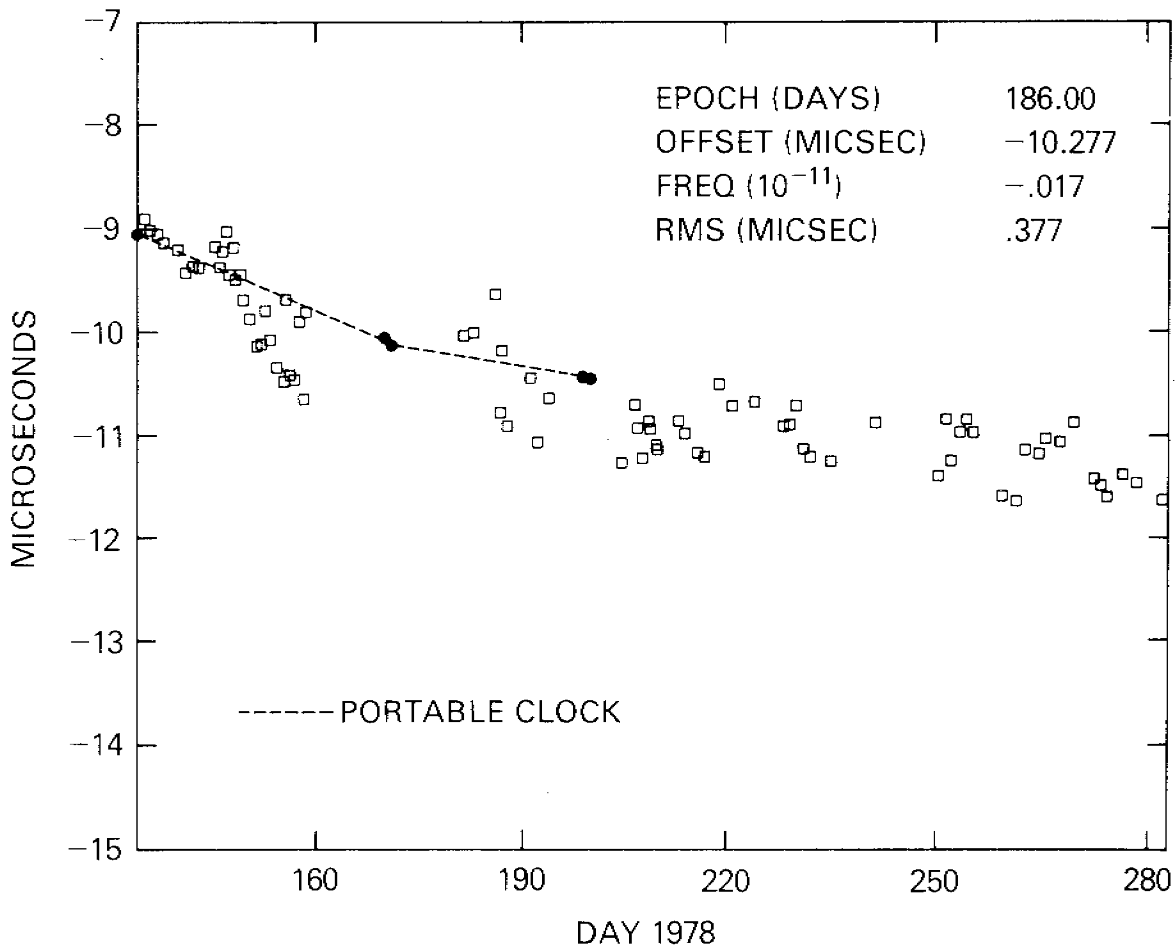

Figure 6 Time Transfer Results from the Institute for Applied Geodesy, Wettzell, West Germany
(USNO,MC1)-(IFAG)

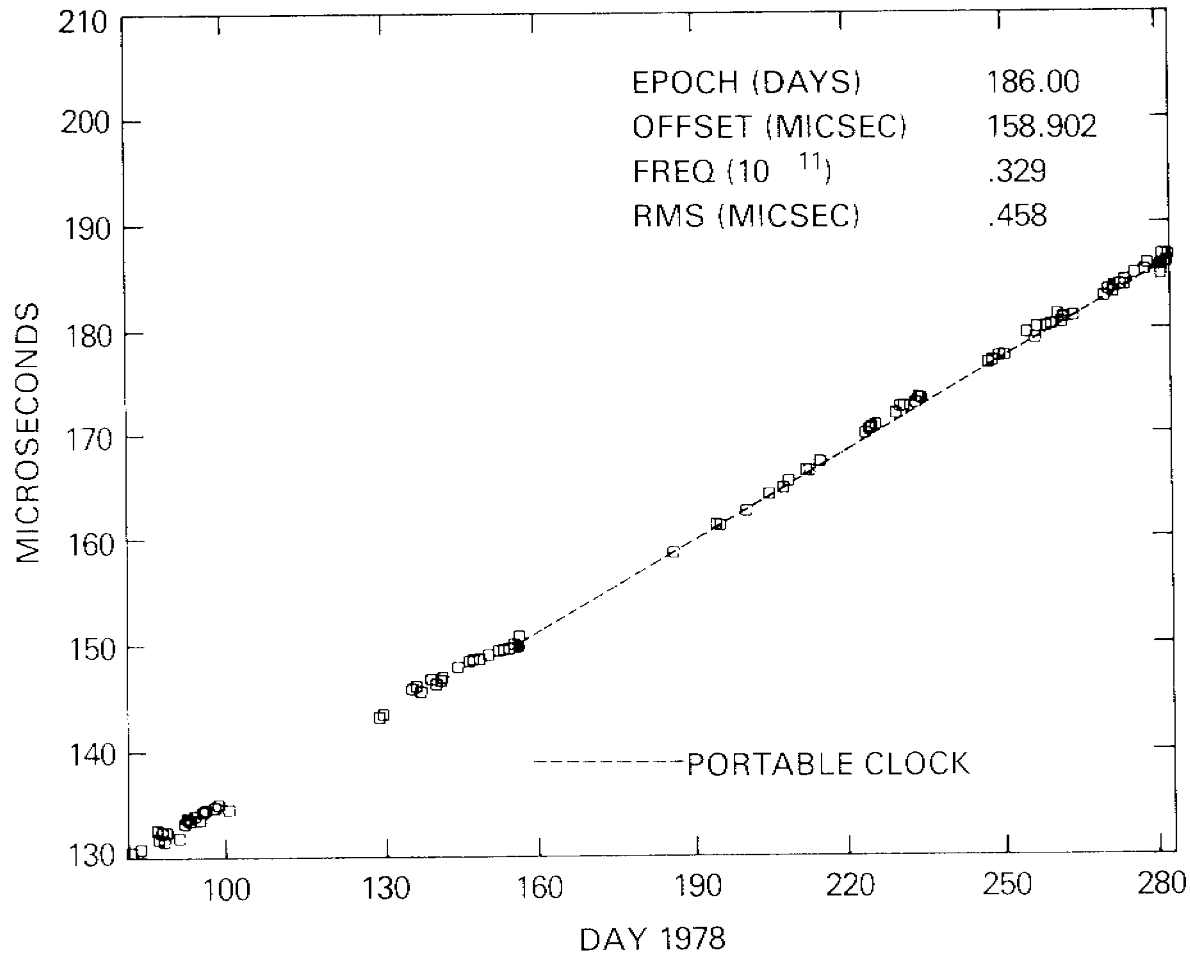

Figure 7 Time Transfer Results from the Division of National Mapping, Australia
(USNO,MC1)-(AUS,DNM)

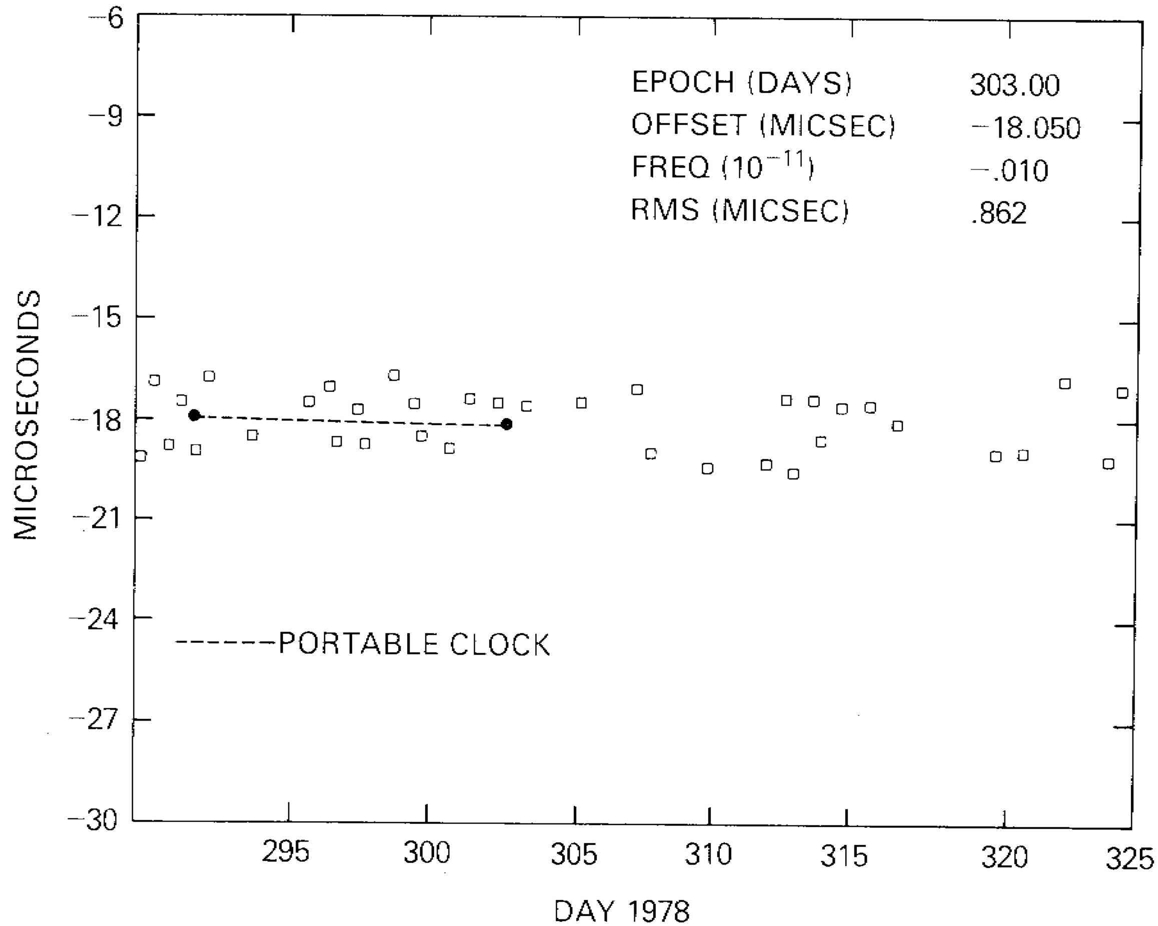

Figure 8 Time Transfer Results from RRL, Japan
(USNO,MC1)-(RRL)

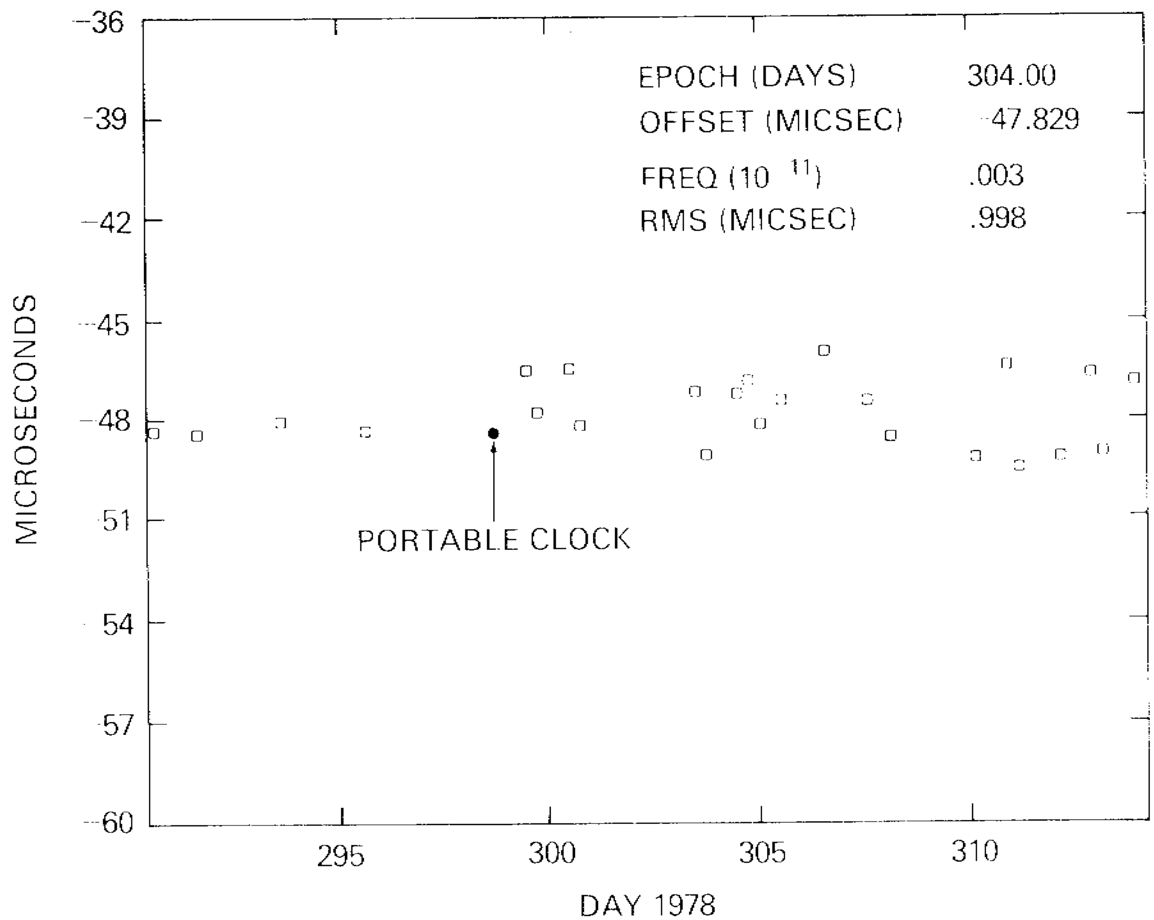

Figure 9 Time Transfer Results from NRLM, Japan (USNO,MC1)-(NRLM)

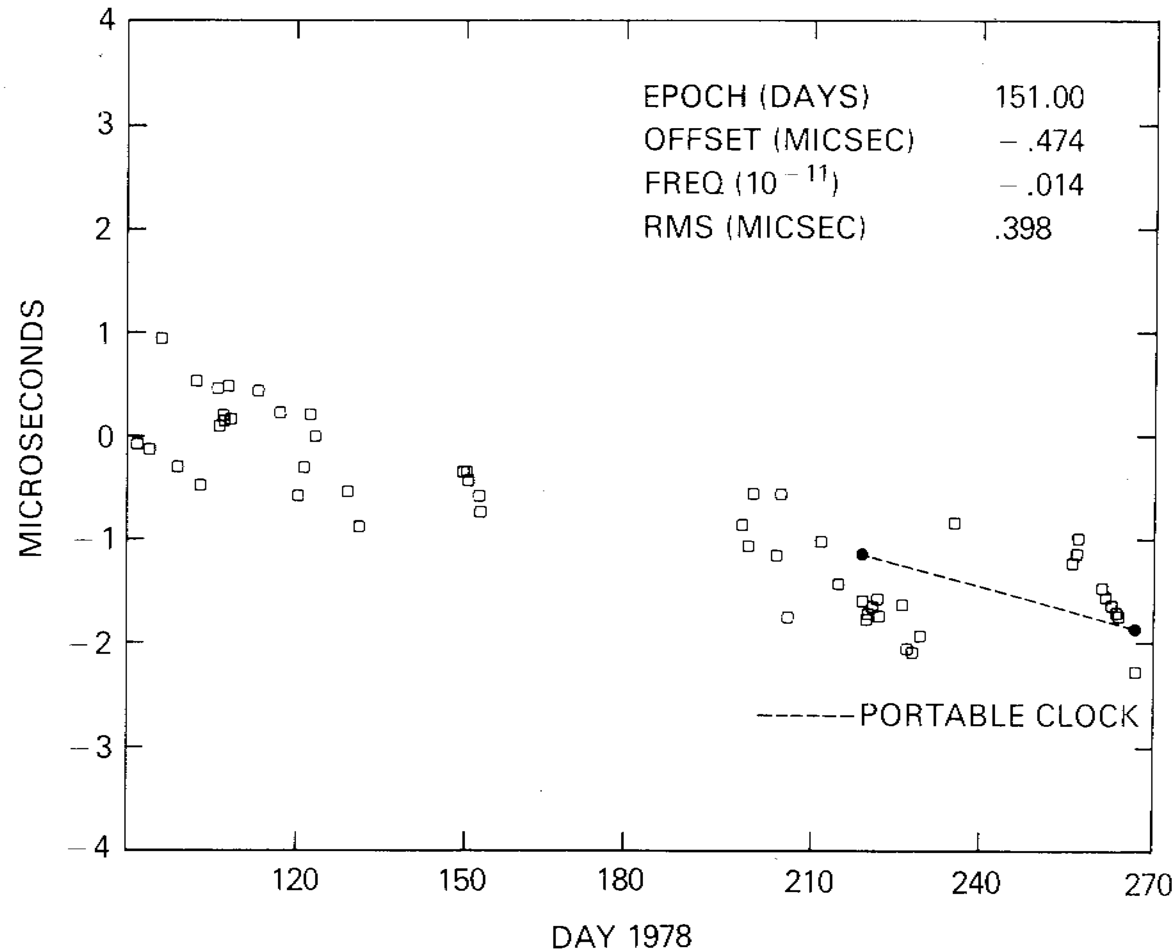

Figure 10 Time Transfer Results from NBS in Colorado, U. S.
(USNO,MC1)-(NBS)

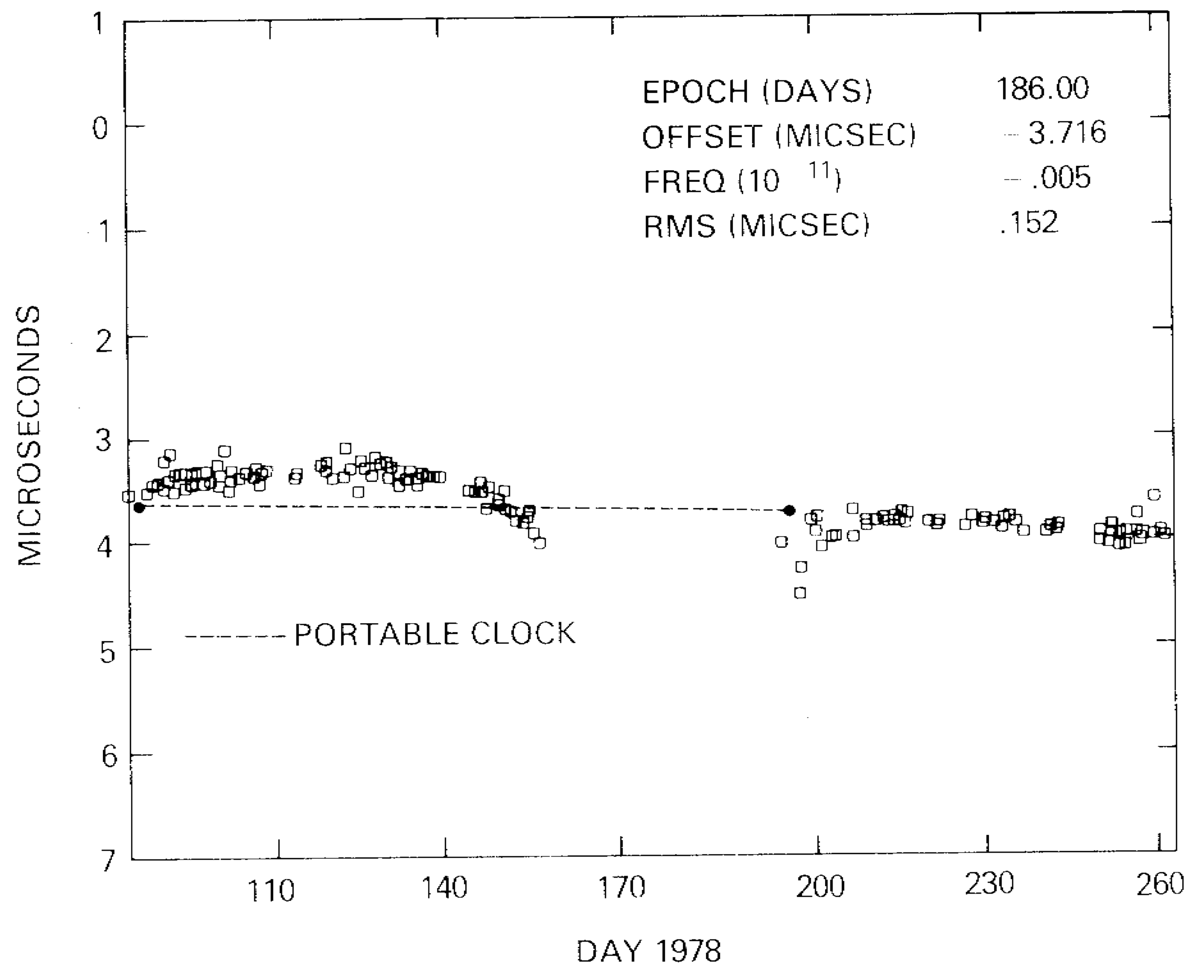

Figure 11 Time Transfer Results from National Research Council, Canada

(USNO,MC1)-(NRC)

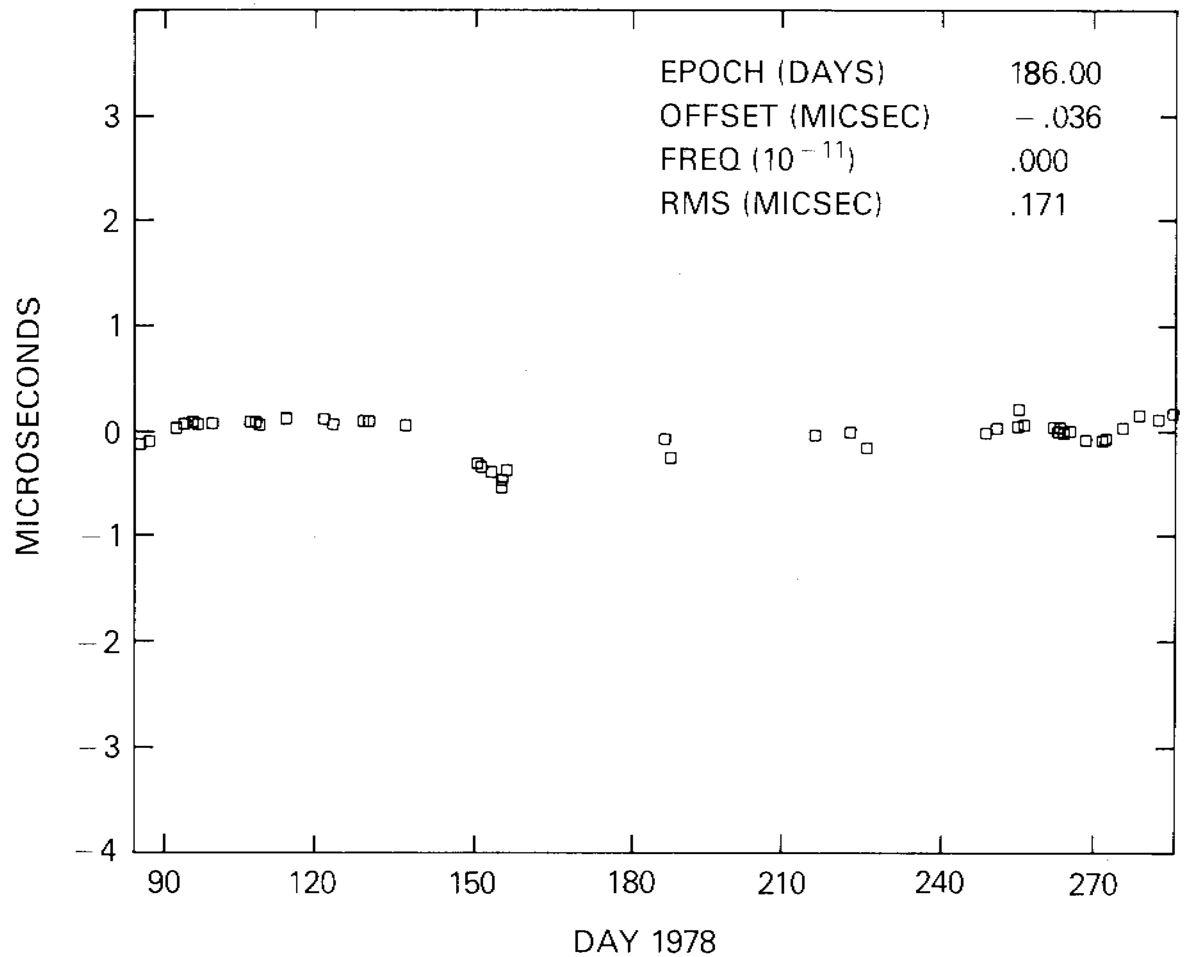

Figure 12 Time Transfer Results from USNO
(USNO,MC1)-(USNO,MC1,NTS)

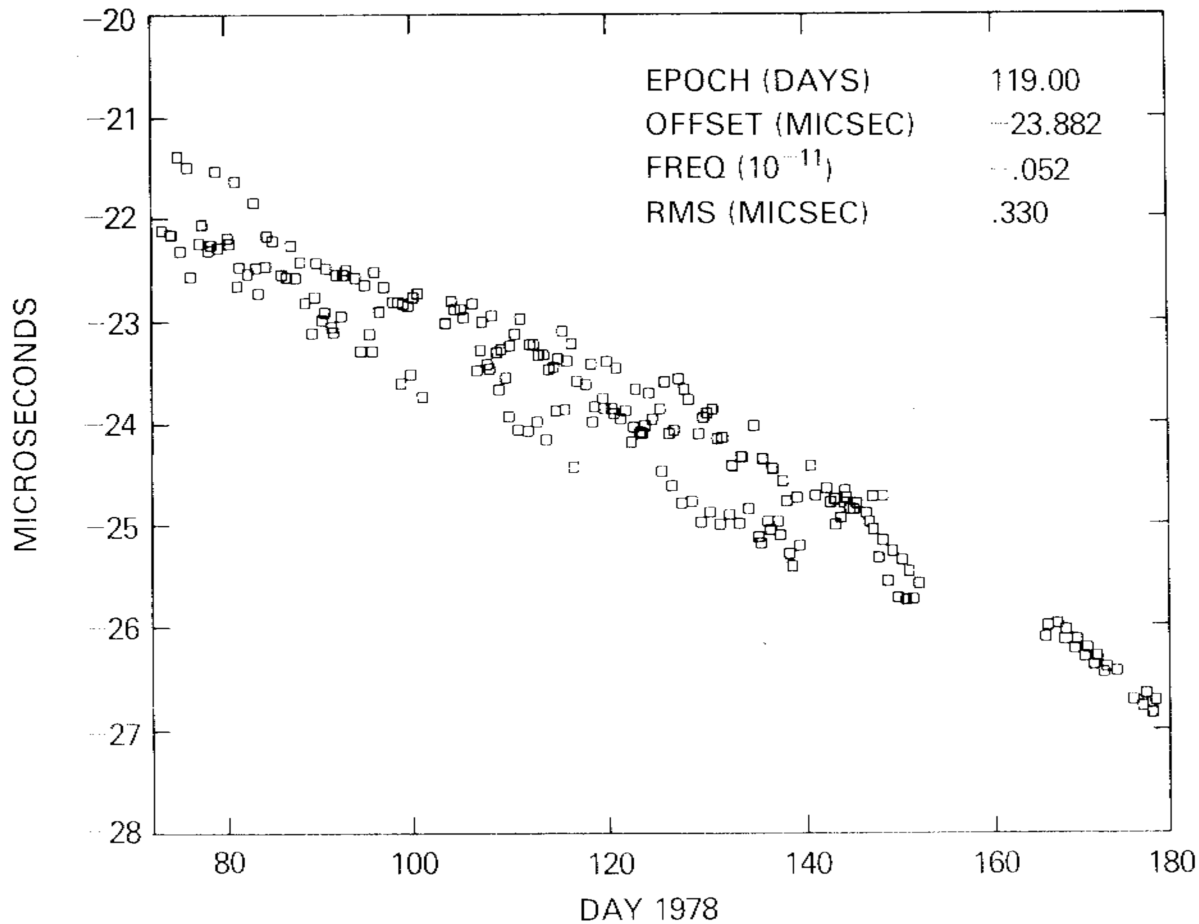

Figure 13 Time Transfer Results from Panama
(USNO,MC1)-(PMA)

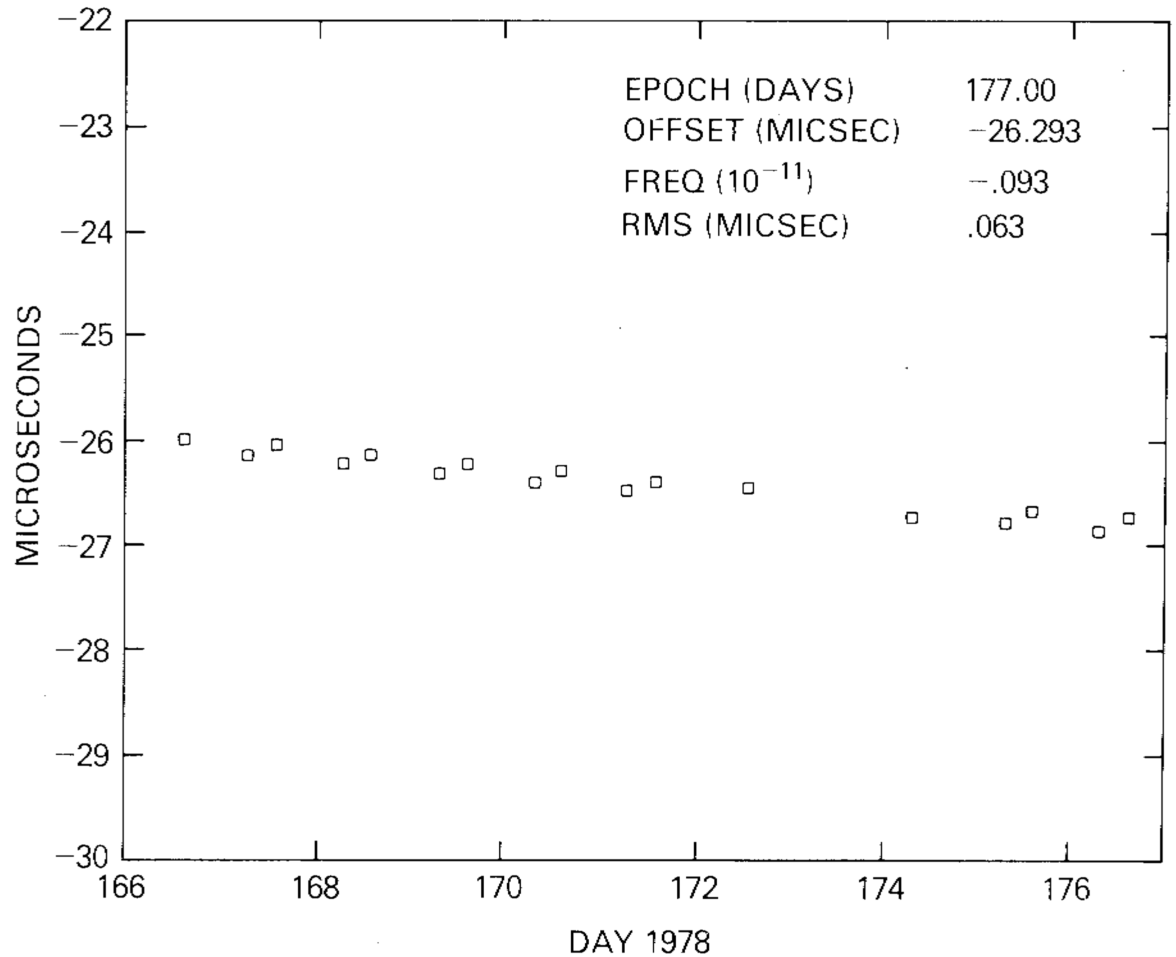

Figure 14 Panama Results (12 day segment)

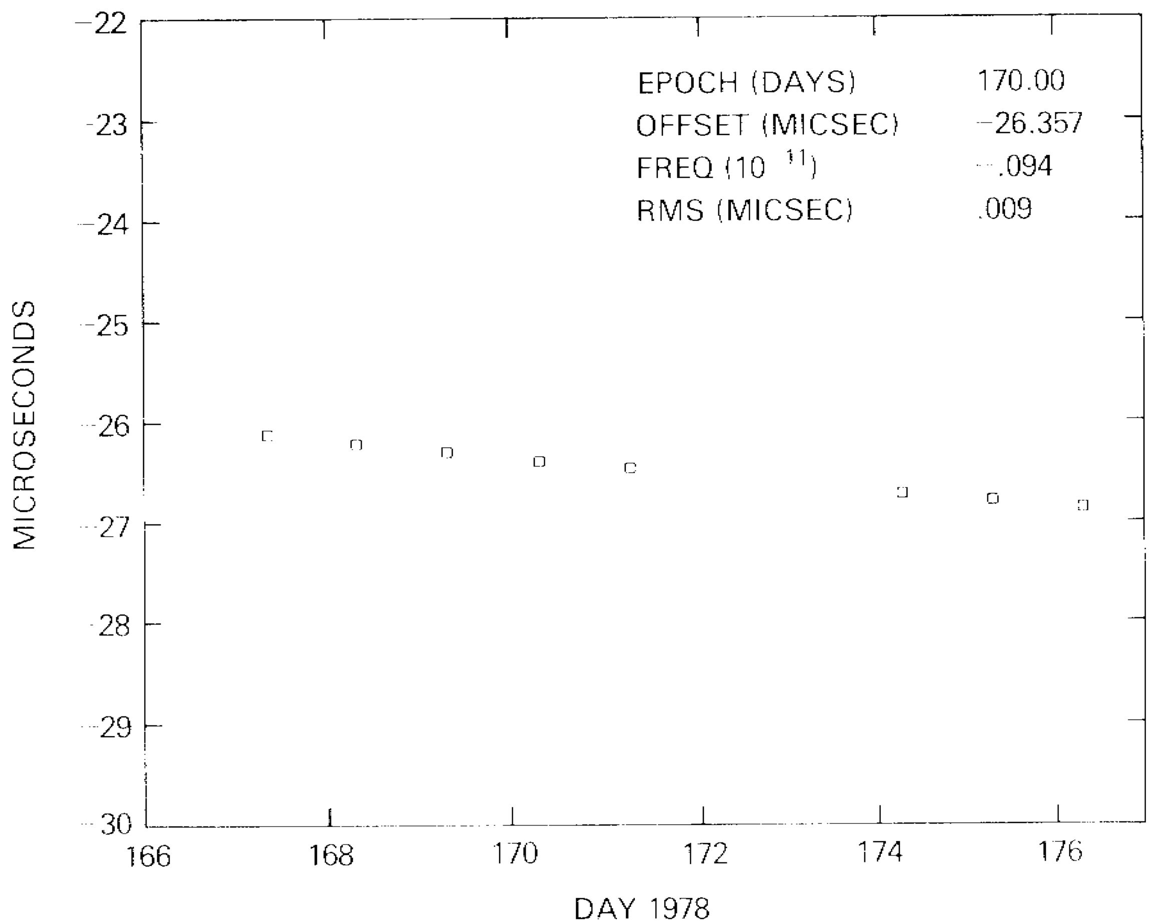

Figure 15 Panama Results (same successive revolution)

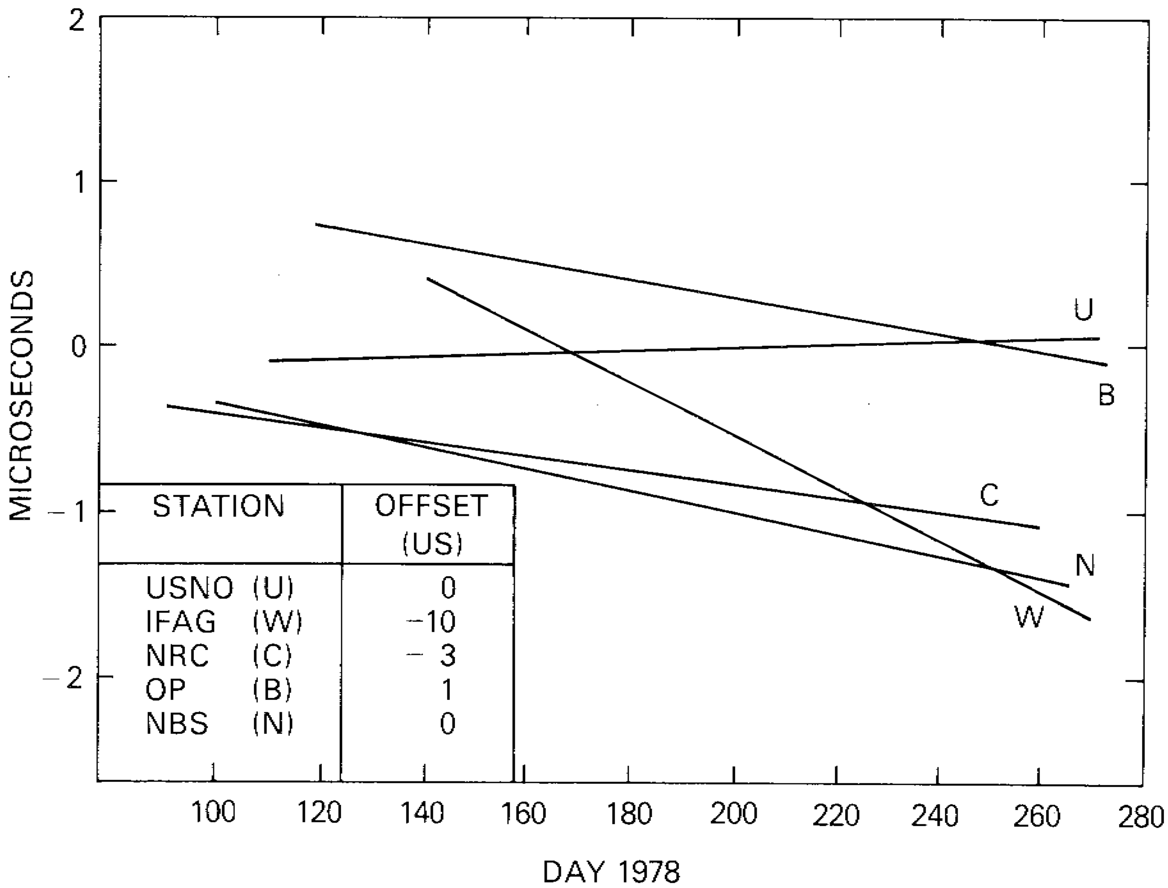

Figure 16 Time Comparisons via NTS

Questions and Answers

DR. DAVE CURKENDALL, Jet Propulsion Lab:

The data actually looks quite a bit better than the title of "Submicrosecond." Would you care to venture just how good you think it is, really? How good do you think you have achieved time sync?

MR. MCCASKILL:

I would really prefer not to give an answer to that except that we are very well encouraged with the results. I don't really want to give an absolute number on it. In terms of what the GPS system might do, that slide that showed the nine nanoseconds, provided we can get all the biases out, which are fairly small and fairly well known right now, then probably in the neighborhood of 10 to 20 nanoseconds with no problem. Yes, sir.

DR. GERNOT M. R. WINKLER, U.S. Naval Observatory:

Since you don't want to say anything I would just like to give you my impressions on the basis of your data.

It appears that the NTS-1 comparisons have a noise level of about 150 nanoseconds, just because of the time transfer to the satellite and down. That is derived from your data of that closed loop, with the NTS receiver at the observatory.

The reason why the more distant stations show consistently larger sigmas, the larger the distances, is simply because NTS-1 only has a relatively poor frequency standard, and you depend on increasingly longer extrapolation times for the greater distances. So therefore, the data with Australia and with Japan are larger than one half microsecond, while those which are close by, such as NRC, have been down to 180, 200 nanoseconds. That is the NTS-1 results.

However, NTS-2 seems to be better by at least an order of magnitude because you have a cesium standard and therefore are much less sensitive to long extrapolation times. Also, it appears to me that you have a much better signal to noise; and I wonder whether you have any comments to that.

MR. MCCASKILL:

The only comment I would like to add to that is that the measurements with NTS-1 were made using a single frequency at 335 megahertz.

In those measurements we presented, there is no correction for the ionospheric delay, which is quite considerable. And in the NTS-2 results, we did have dual-frequency measurements available.

I certainly appreciate the comments concerning the quartz oscillator, but I think most of it is due to the ionosphere. Even though quartz is certainly not as good as cesium, I believe the ionosphere is the major contribution there.

DR. TOM CLARK, NASA Goddard Space Flight Center:

I will take the prerogative of making a couple of instant analysis comments also. I notice a great deal of odd-even effect in the data points taken on the orbits, one side and the other, which to me says either a satellite ephemeris error and/or station location errors are contributing considerably to the scatter you are seeing on the plots.

Second of all, another one which I observed as it went by very quickly, the comparison of NRC to CBD versus the comparison of USNO to CBD both. The first half of the plot showed a very systematic parabola which looked just the same on the two of them, which indicates that the common clock, the CBD clock, was the one which was setting that part of the curve. And in fact, you might find it more instructive to subtract out CBD, and do a direct USNO-NRC comparison, which could then be tied into the previous paper. Do we have some other comments?

DR. BILL RECKERT, Rockwell:

I would like to know if there is any data that has come in on spacecraft now-- You said something about some intermittent problems. Is there another frequency that is being transmitted down in regard to useful data?

MR. MCCASKILL:

The answer to your first question is there is no data being acquired right now. It was on briefly last week. The last time it was on was during the eclipse period, which happens every six months; and it is not fully understood why it is on then not the rest of the time, but the next one comes up in about February. So we are hoping to see some more data from it, but there is no way to promise data.

DR. RECKERT:

What frequency is that data being transmitted on?

MR. MCCASKILL:

The NTS-2 results you saw were two frequencies at 335 and 1580 MHz, which were of course combined to make the ionospheric correction.

DR. VICTOR REINHARDT, NASA Goddard Space Flight Center:

Were both the NTS-1 and the NTS-2 data taken with the same type of receiver?

MR. MCCASKILL:

Some of the data were taken with the same type of receiver. However, part of the NTS-2 data were taken with a different type of receiver. Two different receivers were used.

DR. REINHARDT:

Is that the nine nanosecond data, two receivers?

MR. MCCASKILL:

Sir? Which--

DR. REINHARDT:

On the nine nanosecond data, two receivers were used?

MR. MCCASKILL:

That is correct; the other type.

DR. REINHARDT:

Thank you.

DR. WILLIAM KLEPCZYNSKI, U.S. Naval Observatory:

I am not sure I understand something which was said earlier in conjunction with the slide I saw. Earlier, Dr. Costain indicated that through the Hermes data, he came to the conclusion, or verified the conclusion, that NBS and USNO are going at the same rate, and NRC is running at a little bit different rate in the other direction. But your slide indicates that both NBS and NRC are running off with respect to the Observatory. I am wondering whether we are comparing the same thing: Are we comparing time scales, or individual cesiums, or what--I am not sure I understand.

MR. MCCASKILL:

Let me answer the question in two parts. First, we have not had a chance to cross-check with the Hermes results. The basic measurement is one of a start-minus-stop measurement; that is, as if you started with USNO Master Clock Number One and stopped with the result. So when you see a slope, it is a slope of the start-minus-stop measurement.

DR. WINKLER:

I think that both of you have indicated that there is no frequency difference between NBS and USNO, but that there is a frequency difference between NRC and both of us. Only that value is different; it is something like 1.1 in 10^{13} for the Hermes results, and only five parts in 10^{14} for your NTS results. This is my recollection. So they are in the same direction, and I don't think there is this discrepancy as Dr. Klepczynski seems to have seen.

You can go to the same slide, and there was no frequency difference between NBS, and there shouldn't be.

DR. CLARK:

Since it is ordained that there is no frequency difference between Boulder and Washington, let's go on.