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PRELIMINARY COMPARISON BETWEEN GPS AND TWO-WAY SATELLITE TIME TRANSFER

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Abstract

The time scales of the U.S. Naval Observatory in Washington, D.C. and the National Bureau of Standards in Boulder, Colorado were compared during the same time periods by the common view mode using the satellites of the Global Positioning System (GPS) and by the two-way mode using a U.S. domestic communications satellite. Data collected over a 3-month period showed residuals from a linear regression of 10 nanoseconds for the two-way technique and 30 nanoseconds for common view GPS. The two-way technique achieved better than 500 ps of precision with less than 2 minutes of data. Absolute calibration of either technique was not attempted during this measurement period.

Introduction

Satellites have been used for the exchange of timing information as early as 1962. In this first experiment, clocks between England and the U.S. were synchronized by the simultaneous exchange of timing information through the Telstar satellite (Steele et al, 1964). The use of this two-way technique to synchronize remotely located clocks had the advantage of being independent of the motion of the satellite during the course of the performance of the experiment and the geographic positions of the stations participating in the experiment. Since the signals transmitted by both participating stations travel through the same atmosphere, the timing data are only affected by the differential variations that occur in the path delay during the transmission time of the signals (usually about 1/4 second) and those that might arise if different transmit and receive frequencies are used by the stations. If the satellite does not simply reflect the transmitted signals, but retransmits them using some type of transponder, then differential path delay through the satellite must be taken into account.

It is also possible to do one-way time transfers using satellites. In this case either the satellite directly transmits time signals if it has a clock on board or relays signals from some station either by reflection or retransmission. One-way time transfers are used to either distribute time (Klepczynski, 1983) or to synchronize clocks through the use of common view techniques (Allan and Weiss, 1980). In the former case, the user must first account for his distance from the satellite and propagation path delays which might affect the signals. In the latter case many of the effects cancel because both participants are observing the same signal at the same time. This latter technique more closely approaches the precision of the two-way technique. It is the purpose of this study to compare the precisions attainable with the two-way and common view techniques.

Hardware Configuration

At each site, there is a complete satellite Earth station, one at National Bureau of Standards (NBS) in Boulder and another at the U.S. Naval Observatory (USNO) in Washington. Each Earth station is located in close proximity to the primary time scales of the laboratory. These Earth stations are basically identical except for the size of the antennas. The antenna diameters are 6.1 and 4.5 meters for NBS and the USNO respectively. These rather large antennas are not necessary to achieve results typical of that reported in this paper. They were purchased during a period when new FCC rules relating to the Fixed Satellite Service (FSS) were being established. The rules regarding antenna side lobes were severe enough that only the larger sized antennas qualifed at that time. Today, antennas as small as 1.8 meter in diameter qualify for use in the FSS and will work satisfactorily for two-way time transfers with very modest power outputs, a couple of watts being typical. The Earth stations transmit at 14.307 GHz and receive at 12.007 GHz, frequencies assigned by the operator of the satellite transponder. Low noise preamplifiers with noise temperatures less than 250 K are employed. Dual conversion up and down converters are also used. One Hertz pulses from each time scale are converted to pseudo-noise sequences that bi-phase modulate a 70 MHz carrier in a commercially available modem. The modem uses a delay locked loop in the demodulator to recover a 1 PPS signal (Hartl et al, 1983). A commercial U.S. domestic communications satellite provides the channel for the two-way time transfer. The satellite, located in geostationary orbit at 95 degrees West longitude, carries 10 transponders each with 43 MHz of usable bandwidth. The two-way system uses approximately 5 MHz bandwidth of one transponder and 2% of its total available power. This channel has been used one-half hour every Monday, Wednesday and Friday since August of last year. Data are in the form of time interval readings generated using a high precision time interval counter. The data are collected by computer and archived at the USNO where they are available for retrieval by the participating laboratories over telephone line. Final results require that data taken at each end be subtracted on a point-by-point basis. Collocated with each of the satellite Earth stations were GPS timing receivers. Each receiver was connected to a computer for the collection of measurements with retrieval and archiving at the USNO made possible through connection with telephone modems. In all cases, measurements were made with reference to the primary time scales maintained at each laboratory.

Two-Way Time Transfer Data

The fundamental datum obtained during the course of a two-way time transfer experiment is a time interval counter reading and the instant of time at which the reading was made. The time interval counter at Station A is started by the one pulse per second (1 PPS) which is being transmitted by Station A and stopped by the 1 PPS which is received from Station B. The reading is a measure of the difference between the clocks at Station A and Station B plus the total travel time of the signal from Station B to Station A. Similarly, Station B records a time interval counter reading and the time of the measurement. The reading of the time interval counter at Station B is a measure of the difference between the clocks at Station B and Station A plus the total travel time of the signal from Station A to Station B. In order to obtain the difference between the clocks at Station A and Station B, it is necessary to first bring the data from the two stations together. Then one simply divides the difference between the two readings by two. The readings must first be adjusted by any calibrations that have been made at each site. It is also assumed that the propagation path delays that each signal undergoes are approximately equal. Figure 1, adopted from Veenstra et al, 1981, graphically exhibits the process involved.

One pair of readings, i.e., one second worth of data, is not sufficient to allow one to judge the processes affecting the technique and the data. In order to be sure that one is observing over a sufficiently long enough period, there are several tests which can be done. The most significant is to test the data for white noise (Box and Jenkins, 1980) by doing a periodogram analysis. Another simple test which can be done to assure that a sufficiently large span of data has been taken is to look at the dispersion in the value as a function of the sampling interval. Veenstra et al (1981), shows that fifteen minutes of data was found sufficient to get a good average value for the time difference between the two stations. Because new hardware has been developed since those experiments, it is worthwhile to investigate how much of a span of data is now required to get a good value for time transfers. For the day which was closely scrutinized, it was found that the standard deviation of the value using 100 seconds of data was 456 ps. and that using 900 seconds of data was 480 ps. At these levels of precision, it would be ridiculous to think that there is any significance in the difference between these two values. It is obvious that there is no significant improvement in the mean value by using more than 100 seconds of data. Table I summarizes the results obtained.

Table - I
Standard Deviation of Time Transfer Value on 19 February 1988 as function of number of data points used.

Number of Points	Standard Deviation (picoseconds)
900	480
800	485
700	485
600	494
500	500
400	502
300	506
200	467
100	456

In addition, a periodogram analysis was done in order to determine that no significant periodicities are in the data. This test assures that the data are white (random). A second order polynomial was fit to three different data sets: the data obtained at NBS and USNO and the time differences between NBS and USNO derived from this data. As an example, Figure 2 shows that there was a significant period in the data obtained at NBS on one day. Figure 3, which is typical of the time difference data, shows that there are no significant periodicities.

Figure 4 shows a 100 second span of data obtained on 16 March 1988. The residuals with regard to a linear regression are plotted as a function of fraction of a day. This was done in order to remove any slope due to the difference in frequency between the clocks being compared. From the plot of the data, it is difficult to see any structure in the residuals. It is also easy to see that the data are intrinsically sub-nanosecond type of data. None of the residuals are greater than 900 ps.

GPS Time Transfer Hardware and Time Transfer Data

As mentioned earlier, GPS provides the most precise and accurate worldwide time synchronization service presently available. The common view technique takes full advantage of the system, minimizing the effects of certain systematic errors. The precision and accuracy achievable is a function of the amount of processing that is done to the data.

The two sites used in this experiment both have GPS Time Transfer Units collocated with the Earth Stations. Unfortunately, the receivers at each site are not identical nor are they similar in their mode of operation. The receiver at the USNO is a STel (formerly STI) 502 TTU.* It is the GPS TTU which is designated as the USNO's primary GPS TTU. Therefore, it adheres to a rather inflexible observing schedule. The receiver at the NBS Earth station is a Trimble 5000 A.* It is programmed to operate in the automatic mode. This means that it selects GPS satellites to observe for time transfer according to an internal algorithm which is weighted by satellite altitude. Thus, the two receivers do not exactly observe the same satellites at the exact same times. The only thing that the two receivers have in common is that they both observe a single satellite for 13 minutes (780 seconds).

Common view values for UTC(USNO)-UTC(NBS) were obtained for a 90-day period by combining observations of the same satellite which occurred within 10 minutes of each other at the two sites. An inspection of Figure 5 reveals a surprisingly large spread in these values. The dispersion is probably due to two factors. One arises from errors in the ionospheric model used by the single frequency GPS TTU's. Miranian (1988) reports that he observes a difference of about 30-40 ns. between the ionospheric correction measured by a dual frequency GPS TTU and that predicted by the model contained within the single frequency TTU's. Another factor probably arises from the Kalman filter parameters which are used to optimize the navigation function of the GPS System. It was also discovered that there was an error in the receiver's location at NBS. The error was approximately 0.0280 minutes of latitude.

Because of the large dispersion in the GPS data, two different approaches in reduction techniques have evolved in order to maximize the precision obtained from GPS time transfer data. One can either average the GPS data obtained from all the satellites over a span of several days, or one can average the data from one satellite obtained at the same time over several months. In both cases, calibration by some other technique is also needed for the ultimate in accuracy. In the study presented here the data are averaged over all satellites for one day. This rather simplistic approach was taken in this case because the Earth Station data was also treated simplistically and accuracy was not of concern in this preliminary study. Calibration techniques will be a part of a future study. Figure 6 shows the daily difference between UTC(USNO)-UTC(NBS) obtained by averaging the Common View GPS values over one day. The peak-to-peak spread is about 30 ns.

Comparison and Discussion of the Two Techniques

During the period of time covered by the GPS data, estimates for the difference between UTC(USNO)-UTC(NBS) were also obtained from the two-way Earth station time transfers. Figure 7 shows the values, each point represents an average of only 100 seconds of data. Unfortunately, some data were inadvertently lost through a programming error. These data are not irretrievably lost. They can be recovered through additional processing of the archived data. But, it was not possible to reconstruct it before the deadlines of publication.

In this study, only the deviations from linear regressions are being investigated, not the actual values themselves. Here, we are only concerned with the difference in precision between the two techniques, not with their difference in actual values (accuracy). This will be the subject of a later investigation.

A linear regression was done to the data shown in Figures 6 and 7. The residuals to these linear regressions are exhibited in Figures 8 and 9. In comparing Figures 8 and 9, it should be noted that each GPS value for UTC(USNO)-UTC(NBS) is a daily average of about 12-18 points with each point being thirteen minutes of observation, while each Earth Station data point represents only 100 seconds of observation. During the interval covered by the observations, the USNO introduced a change in frequency in its time scale. Both the GPS and Earth Station observations were corrected for this change.

Conclusions

The two-way Earth Station Time Transfer data seems to exhibit smaller fluctuations over the interval covered by the data used in this study than the GPS data. Because the signals in the case of the Earth Station data are reciprocal and travel through the same atmosphere, we expect that the majority of the propagation delays will cancel each other except for the differential effects due to the use of different frequencies on the up and down links. For the GPS data, the signals from the satellite travel through different atmospheres to the observing stations, therefore the delays are not reciprocal. Furthermore, the GPS timing units are single frequency receivers. They assume a model for the atmospheric propagation path delays. Other evidence indicates that there are some deficiencies in the assumed model. Therefore,it is thought that the Earth Station data should be inherently smoother than the GPS data in showing the difference between the two time scales. These preliminary data tend to support this thesis.

While the two-way time transfer technique using Earth Stations seems to be more precise than Common View GPS, it should be pointed out that the former technique is not universally practical. The two-way technique requires that the practitioners be able to receive and transmit. The latter requires a license which may be difficult to obtain. In addition, the costs involved with operating an Earth Station are considerably greater than in operating a GPS TTU. Therefore, we expect that the two-way technique will only be used by a few laboratories which require the highest precision attainable for the comparison of state-of-the-art oscillators and time scale algorithms.

References

Allan, D. W.. and Weiss, M. A., May, 1985, "Accurate Time and Frequency Transfer During Common View of a GPS Satellite", Proceedings of the 34th Annual Frequency Control Symposium.

Box, G. E. and Jenkins, G. M., "Time Series Analysis; Forecasting and Control", Holden-Day, San Francisco, 1970

Hartl, P., Veenstra, L., Gieschen, N., Wende, D. M., Klepczynski, W. J., Nau, H., and Stoiber, R., "Spread Spectrum Time Transfer Experiment via INTELSAT", Proeedings of 15th Annual Precise Time and Time Interval Applications and Planning Meeting, December 6-8, 1983, Washington, D.C.

Klepczynski, W. J., October, 1983, "Modern Navigation Systems and Their Relation to Timekeeping", Proceedings of the IEEE, Vol. 71, No. 10, 1193-1195.

Miranian, M., 1988, Private Communication

Steele, J. McA., Markowitz, W., and Lidback, C. A., December 1964, Telestar time synchronization, IEEE Trans. Instr. and Meas., Vol. IM-13, 4, 164-170.

Veenstra, L., Kaiser, J., Costain, C., Klepczynski, W. J. and Allan, D., "Frequency and Time Coordination via Satellite", Comsat Technical Review, Vol 11, No. 2, Fall 1981, 369-402.

* "The use of trade names does not imply endorsement."

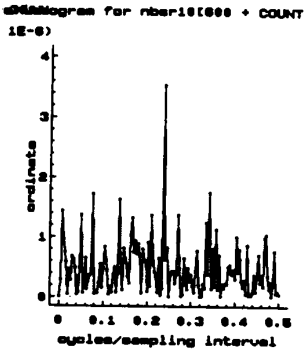

Figure 2 - Periodogram Analysis of NBS data on 19 February 1988.

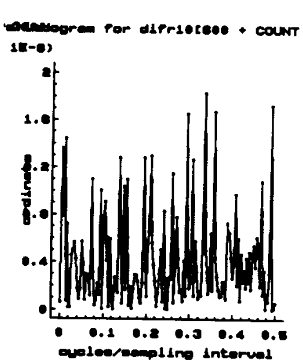

Figure 3 - Periodogram Analysis of UTC(NBS)-UTC(NBS) on 19 February 1988.

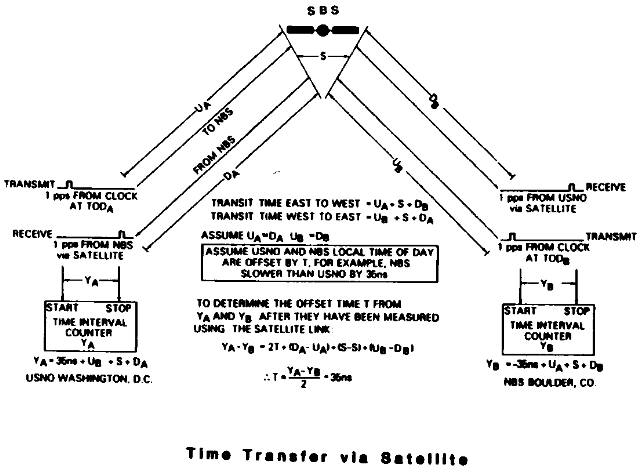

Figure 1 - Satellite and Earth Station Geometry for Time Transfor

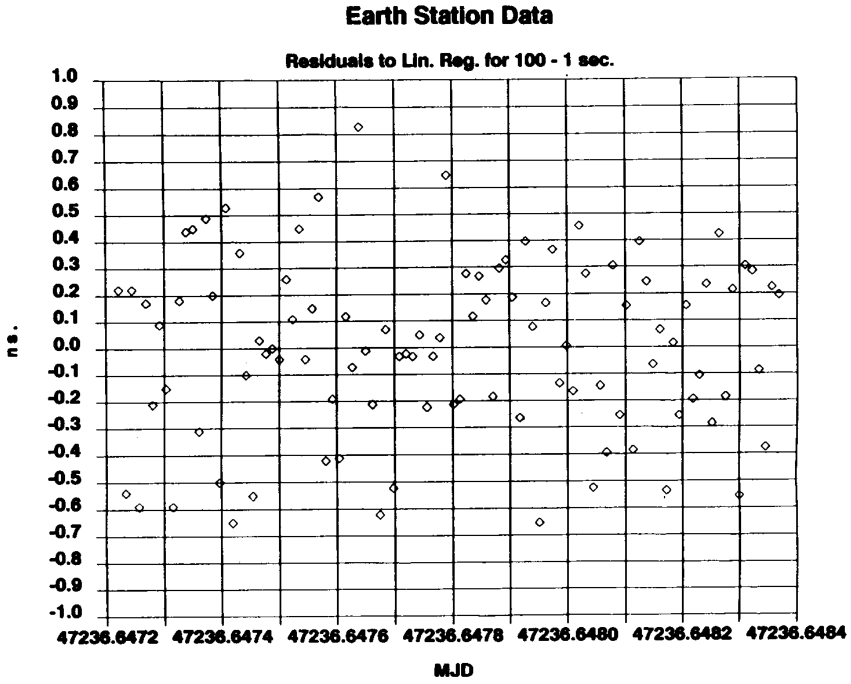

Figure 4 - 100 second span of data on 16 March 1988.

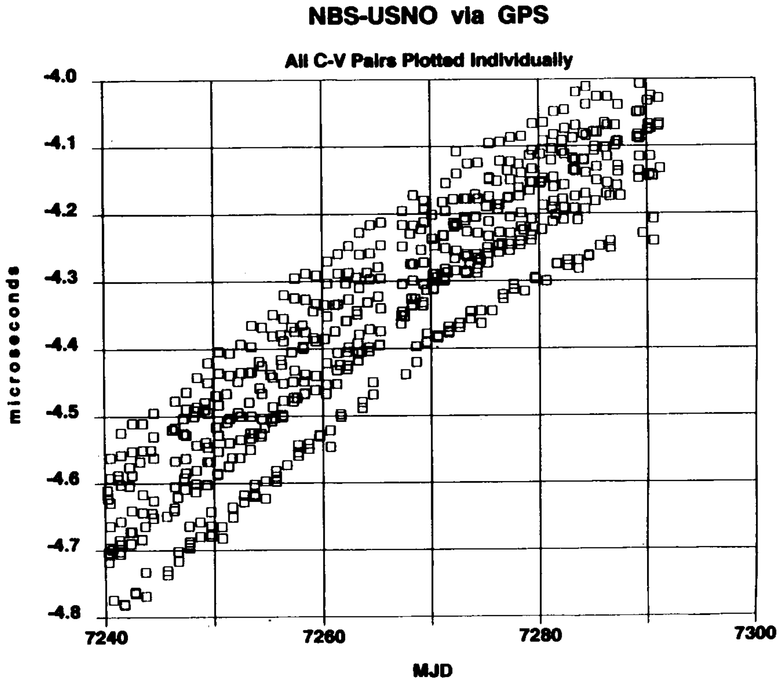

Figure 5 - UTC(USNO)-UTC(NBS) via GPS Common View.

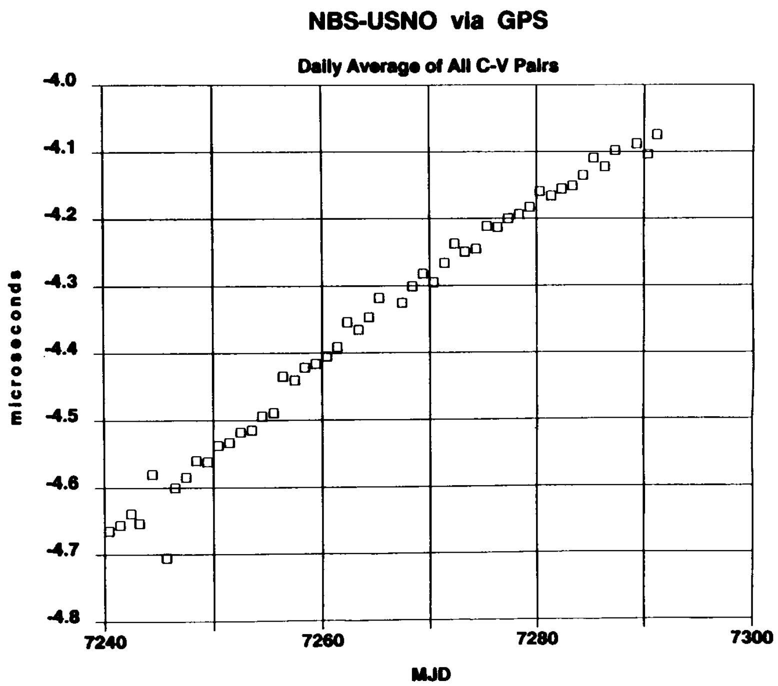

Figure 6 - Averaged Values of UTC(USNO)-UTC(NBS) obtained via GPS Common View.

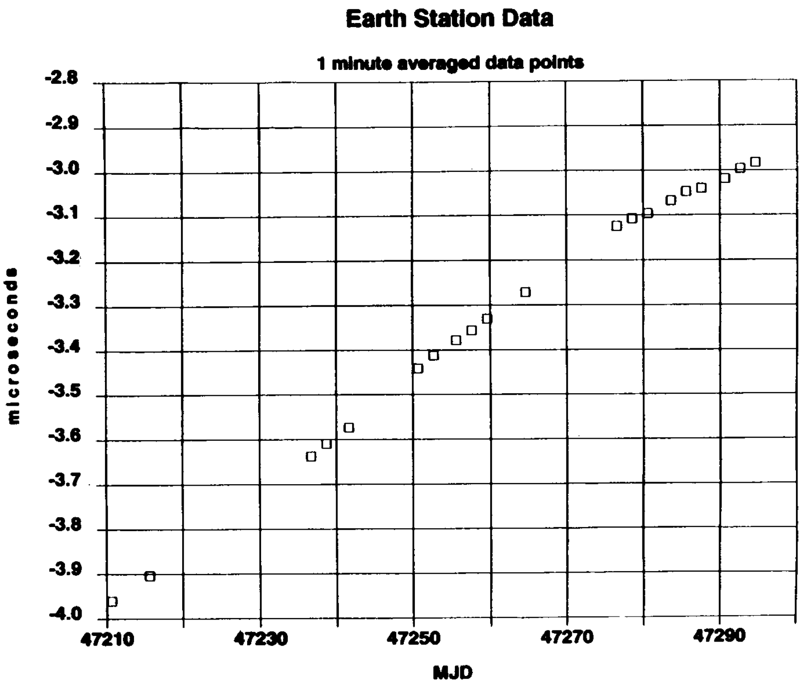

Figure 7 - UTC(USNO)-UTC(NBS) obtained via Two-Way Earth Station Time Transfers.

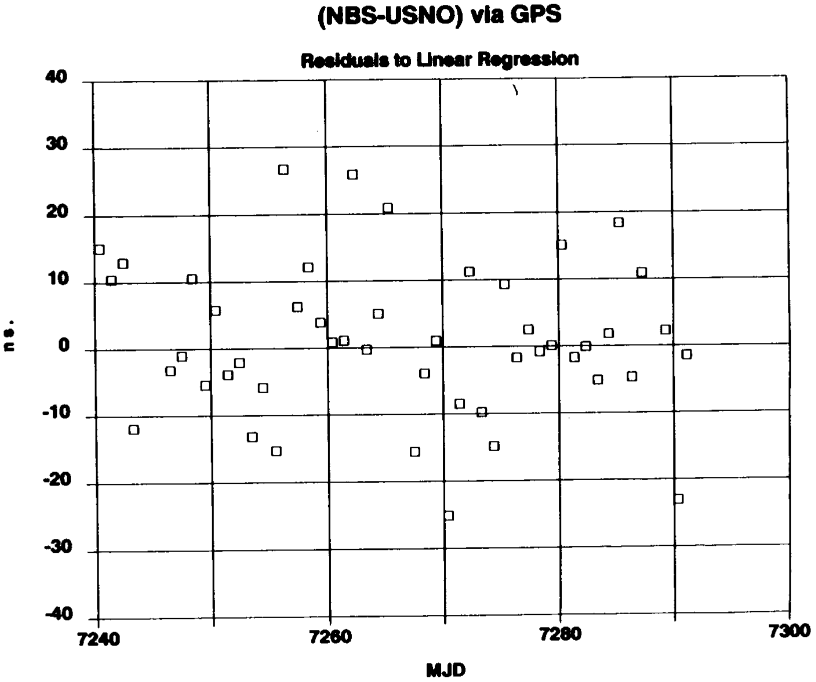

Figure 8 - Residuals to a Linear Regression of the Averaged Values of UTC(USNO)-UTC(NBS) obtained via GPS Common View.

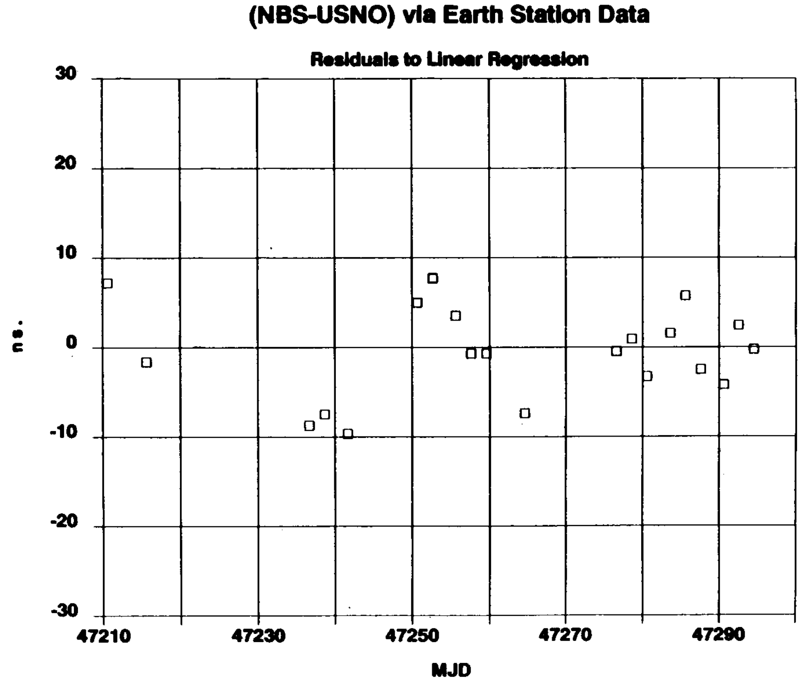

Figure 9 - Residuals to a Linear Regression of the values of UTC(USNO)-UTC(NBS) obtained via Two-Way Earth Station Time Transfers.