COMPARISON OF VLBI, TV, AND TRAVELING CLOCK TECHNIQUES FOR TIME TRANSFER

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ABSTRACT

A three part experiment was conducted to develop and compare time transfer techniques. The experiment consisted of: I. a VLBI between Maryland Point Observatory at Riverside, Maryland and NRAO at Green Bank, West Virginia; II. a high precision portable clock time transfer system between the two sites coordinated by the U. S. Naval Observatory in Washington, D. C.; and III. a television time transfer between the U. S. Naval Observatory and the Maryland Point Observatory using a local Washington, D. C. television station, WTTG.

A comparison of the VLBI and traveling clock shows each technique can perform satisfactorily at the five nsec level. There was a systematic offset of 59 nsec between the two methods, which we attributed to a difference in epochs between VLBI formatter and station clock.

The VLBI method had an internal random error of one nsec at the three-sigma level for a two-day period. Thus, the Mark II system performed well, and VLBI shows promise of being an accurate method of time transfer.

The TV system, which had technical problems during the experiment, transferred time with a random error of about 50 nsec.

INTRODUCTION

An experimental time transfer was conducted between the hydrogen maser clocks at the Maryland Point Observatory of the Naval Research Laboratory (NRL) and the National Radio Astronomy Observatory* (NRAO), and the U. S.

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Naval Observatory's master clock to develop and compare time transfer techniques. The experiment consisted of three parts: i) a very long baseline interferometer (VLBI) between the Maryland Point Observatory at Riverside, Maryland and NRAO at Green Bank, West Virginia; ii) a high precision portable clock system time transfer between the three sites; and iii) a television time transfer between the U. S. Naval Observatory and the Maryland Point Observatory using television channel 5 in Washington, D. C., WTTG. The purpose of the experiment was to compare each method of time transfer; to evaluate the errors, internal and systematic, of each method; and to isolate problem areas in the VLBI technique, a time transfer technique that is not fully developed, but has the most promise.

It is interesting to note that while one method transports high precision atomic clocks between sites, the other two methods have "no moving parts". Electronic equipment remains stationary in controlled environments. These two methods reference to external radio signals, one local and man made, the other a celestial radio galaxy or quasar. The TV system, while simplier, has a fixed frequency and therefore cannot overcome propagation delay variations. The reference signal of the VLBI system, however, only propagates through one to two atmospheres and can be at frequencies selected for best results. It has the greatest potential.

THE VLBI TECHNIQUE

The VLBI experiment was conducted February 19-22, 1980 at 1670 MHz between the 26-meter antenna of the Naval Research Laboratory and the NRAO 43-meter antenna with a bandwidth of 2 MHz. The Mark II data recording system we used has been described by Clark (1973). Bandwidth synthesis, a technique which improves the ability to determine the delay between the two antennas by the ratio of synthesized to actual bandwidth, was not used in these observations, which were designed to be a basic, proto-type experiment. Bandwidth synthesis could improve the internal errors in direct proportion to bandwidth, but was not compatible with the other observations that occurred simultaneously.

The Mark II recording system was used because, while it is not now the most advanced system available, it is the most widely used system for VLBI experiments. Therefore it has the greatest potential for distributing time around the world, if it can transfer time with adequate accuracy.

The observations were correlated on the NRAO processor in Charlottesville, Virginia, and then further reduced with a series of programs developed for the TI-ASC computer at the Naval Research Laboratory. The sources used for this study were 3C273, 3C345, 3C120, 3C84, and 4C39.25. We assumed their positions as given by Wade and Johnston (1977). The initial value of the NRL-NRAO baseline was that given by a 1976 VLBI (Waltman et al. 1982), but it was later updated by less than one meter to remove systematic differences between sources.

Because VLBI transfers time by measuring the time of arrival of wavefronts from a distant celestial radio source such as a radio galaxy or quasar, the reference time of these wavefronts must be tied to the local station clock, a hydrogen maser standard. This is done by measuring the wavefront delay from fudicial marks on the telescope through the receivers, cables, and backends to the local video tape recorder. Unfortunately, for the 2 MHz bandwidth of the Mark II recorder, the fundamental clock of the tape is the 4 MHz formatter clock. We found it to be impossible to precisely measure this clock with respect to the 5 MHz station clock using standard equipment.

The delay between video tapes was found by performing a Fourier transform in lag to get the bandpass at the peak fringe rate frequency. A straight line fit to the phase across the bandpass then yielded the delay. After the data was corrected for atmospheric effects, retarded baseline, antenna geometry, and earth tides, a least-squares solution for the clock rate and offset was found using paired observations of the same source from February 20 and 21. The use of paired scans on consecutive days minimized the error contributed by the atmosphere, source structure, and other repeatable error sources and allowed the baseline to be determined more precisely.

We measured the cable delays through the receivers to the formatters at each telescope and corrected for this effect. The result is that the time difference for NRL-NRAO is shown in Figure 1 after removal of a straight line with a slope of 5.509 psec per second and an offset of -14.397 ± 0.005 μsec at 0^h UT on 21 February. In this figure the different symbols indicate the source of the data. The sources are coded: 3C273 observations •; 3C84 by X; 3C345 by □ ; and traveling clock by ⊠. The one sigma errors are shown for each 3 minute scan of the VLBI data except near February 20 where the one error bar at 12:30 is representative.

The sources of error are uncertainty in the formatter clock synchronization, uncertainty in the cable delay measurements, and the internal VLBI random errors. We estimate the error in the cable delay measurements to be 2 nsec (1 sigma). The random error of the VLBI fit was 1 nsec at the three sigma level. Thus, the random internal errors in the VLBI solution made a negligible contribution to the error assigned to the final VLBI result.

While each formatter was "synchronized" to the station clock, this is usually to only a fraction of a microsecond. A correction was made for the offset between the formatter 1 pulse per second and the station clock, but we do not know the timing between that formatter 1 pps and the internal 4 MHz clock used to record and time the video signals on tape.

THE TRAVELING CLOCK TECHNIQUE

A high precision portable clock time transfer system consisting of four cesium clocks (three of which were "super tubes") and a data acquisition system were transported by van between the three observatories almost continuously during the period of the VLBI observations. This resulted in one measurement per day at each radio observatory and three per day at the USNO Master Clock. The four traveling clocks were intercompared continuously using an HP-9815 computer that also traveled in the van in order to form a mean-time scale through which we monitored the performance of the individual cesium clocks. Comparison of the mean time scale, based on the four cesium clocks, with the USNO Master Clock indicated that it remained stable over the period of the experiment. Figure 2 shows the behavior of each of the four clocks compared to the mean after a best fit straight line has been subtracted. Clock 2 is not a super tube. The results of the traveling clock are summarized in Table 1 and the clock difference of NRL-NRAO is plotted in Figure 1 after an offset of -14,339 ± 3.4 nsec at 0^h UT on February 21 and a clock rate of 5.509 psec per second have been removed.

THE TV TIME TRANSFER TECHNIQUE

It is possible to transfer time by synchronizing to the television signal transmitted by a local commercial station. In the Washington, D. C. area, channel 5, WTTG, broadcasts a signal that is phase locked to a cesium frequency standard and monitored daily by the Naval Observatory. Since this signal can be received at the Maryland Point Observatory, about 70 kilometers from the transmitter, it can be used to transfer time from the USNO to the Maryland Point Observatory.

Unfortunately, as shown in Figure 3, the behavior of the cesium standard at the transmitter was erratic during the period of the experiment. We are therefore limited to simultaneous measurements at both observatories in order to eliminate the large randomness of the transmitter signal. This reduces the data to four measurements where the TV and van can be directly compared. These results are shown in Table 2. The data point for February 19 is almost 900 nsec different from the mean of the other three (approximately 19 standard deviations). We can not explain this except to point out the erratic behavior of the TV cesium standard for this day and that during this period the TV signal was frequently not locked to the standard as a result. Because the clock rate differences at the transmitter and Maryland Point Observatory are not of direct interest, the most interesting method to compare van and TV time transfer methods is to compute the difference of USNO master clock minus Maryland Point Observatory via TV and via "traveling" clock. The result of 230.119 μsec is largely due to the free space propagation delay, but also includes antenna, cable, and receiver delays of the system at the Maryland Point Observatory. The standard deviation of this mean is 50 nsec, much larger than the error of the van alone or when compared to VLBI. We therefore conclude that for a 70 kilometer transmission, 50 nsec represents the short term (1-3 day) standard deviation of a time transfer. Seasonal effects could be expected to degrade this value further for time transfers that last longer.

DISCUSSION

For the NRL-NRAO time transfer, the final clock rate determined from the VLBI experiment is in agreement with the traveling clock rate calculated for the same two-day time period. The VLBI data yielded a clock rate of 5.483 ± 0.013 psec per second (2 sigma error); the traveling clock experiment gave 5.5 ± 1.0 psec per second, which is within the quoted error.

Incorporating the residuals of Figure 1 into the offsets removed, we find the clock comparison between NRL and NRAO has an unexpected systematic offset of 59 nsec between the VLBI and traveling clock methods of time transfer. This is probably due to the difference in epochs of the 4 MHz formatter clock used to write the video tape and the 5 MHz station frequency standard as used in the VLBI system. In future experiments, equipment must be developed to measure the 4 MHz formatter clock signal relative to the 5 MHz frequency standard.

The comparison of the TV to traveling clock techniques between the USNO and NRL shows the TV method to be good to ∿ 50 nsec over 70 kilometers as given in the last section. The simplicity of this method may make this technique attractive where precise time transfer is not required.

CONCLUSIONS

The Mark II VLBI system performed well in the time-transfer experiment, and a comparison of the VLBI results with the traveling clock experiment was useful in identifying possible problem areas in developing the VLBI technique of time transfer.

In the future the use of bandwidth synthesis and better formatter synchronization should greatly improve the VLBI results, making the widely used Mark II system a promising technique for time transfer.

The intercomparison of the VLBI and the four traveling clocks shows each technique can perform satisfactorily at the 5 nsec level. This supports claims made in the past as to the accuracy of traveling clocks.

The television transfer system was shown to work over 70 kilometers with short term errors of 50 nsec.

The VLBI method of time transfer had an internal random error to the solution for a two-day period of one nsec at the three sigma level. Thus, VLBI shows promise of being an accurate method of time transfer.

REFERENCES

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TABLE 1

NRL -NRAO Via Traveling Clock and VLBI

Date	Time	Traveling Clock (μsec)	VLBI (μsec)	VLBI -Traveling Clock (μsec)
Feb. 18	$08^h54^m44^s$	-15.554		
Feb. 19	09 29 00	-15.088	-15.141	-0.053
Feb. 20	09 45 13	-14.619	-14.680	-0.061
Feb. 21	09 28 28	-14.152	-14.209	-0.057
Feb. 22	06 16 55	-13.742	-13.796	-0.054

TABLE 2

TV Experiment Compared to Traveling Clock Experiment

Date[a]	USNO -TV (μsec)	USNO -NRL Via TV (μsec)	USNO -NRL Via Traveling Clock (μsec)	Traveling Clock -TV (μsec)
Feb. 19	2.0003	-218.083	+11.154	229.237
Feb. 20	0.678	-219.519	10.615	230.134
Feb. 21	0.214[b]	-220.081	10.075	230.156
Feb. 22	-0.251	-220.531[b]	9.536	230.067

[a]Corrected to 17:00 UT.

[b]See text.

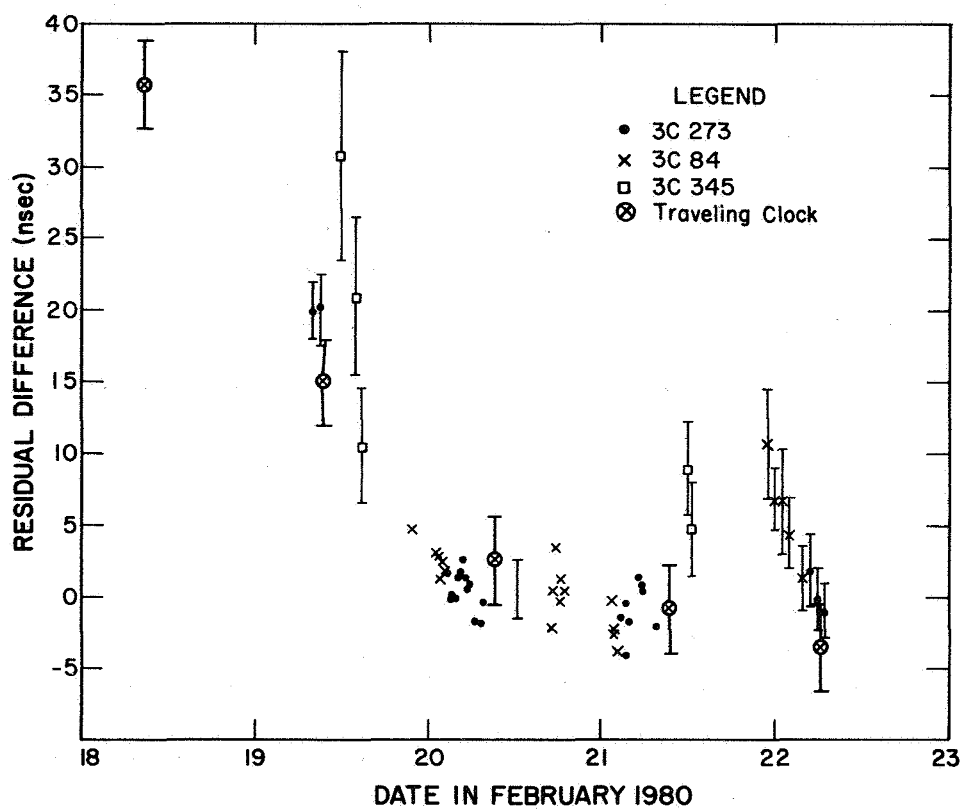

Fig. 1--VLBI and traveling clock results from NRL -NRAO

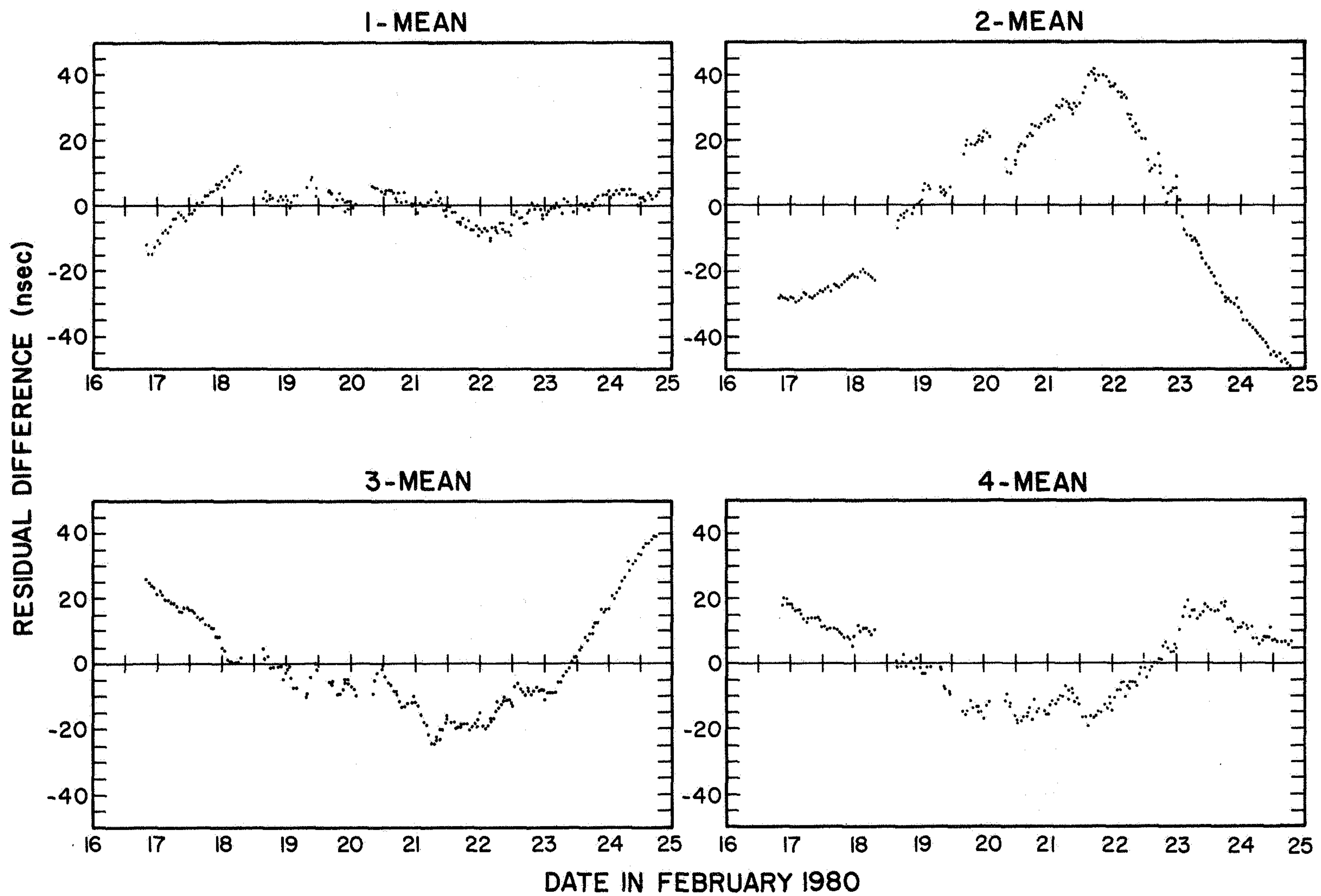

Fig. 2--The traveling clock performance

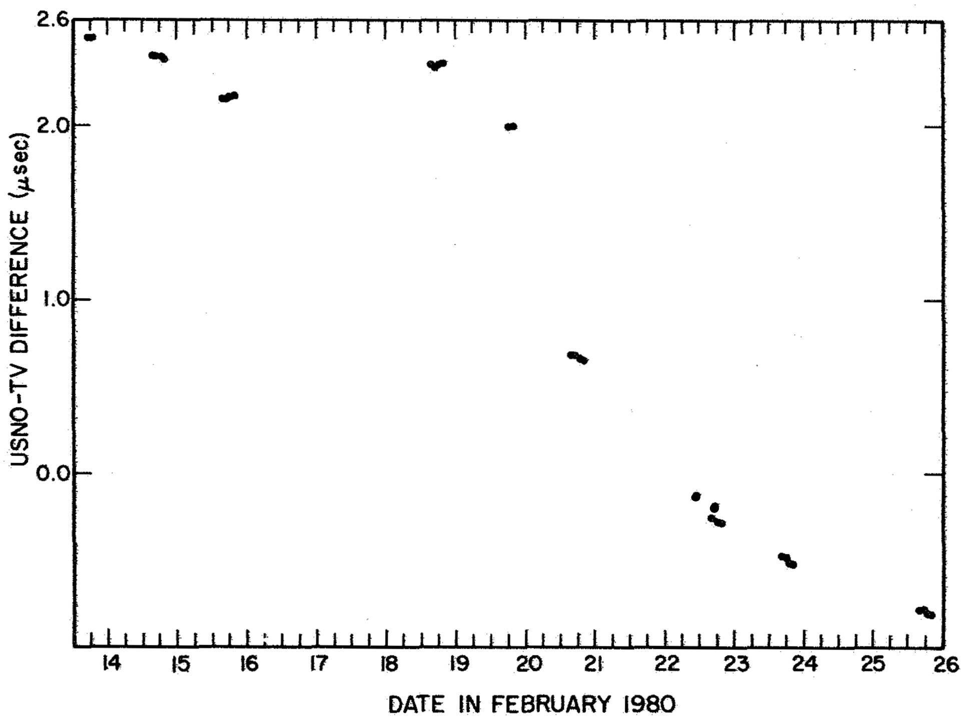

Fig. 3--Behavior of the cesium standard at the TV station