Submicrosecond Comparison of Intercontinental Clock Synchronization by VLBI and the NTS Satellite

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The intercontinental clock synchronization capabilities of Very Long Baseline Interferometry (VLBI) and the Navigation Technology Satellite (NTS) were compared in May 1978 by using both methods to synchronize the cesium clocks at the NASA Deep Space Net complexes at Madrid, Spain, and Goldstone, California. The VLBI experiments used the Wideband VLBI Data Acquisition System developed at the NASA Jet Propulsion Laboratory. The Navigation Technology Satellites, which were designed and built by the Naval Research Laboratory, were used with NTS Timing Receivers developed by the Goddard Space Flight Center. The two methods agreed at about the one-half microsecond level. The VLBI system also obtained long-term stability information on the HP5061A-004 cesium standards by measuring $\Delta T/T$ *over four 3- to 4-day intervals, obtaining stability estimates of* $(1 \pm 1) \times 10^{-13}$ *for the combined timing systems.*

I. Introduction

A series of experiments were conducted in May 1978 to compare the intercontinental clock synchronization capabilities of the Navigation Technology Satellite (NTS) time transfer system and a Very Long Baseline Interferometry (VLBI) system which is in use in the NASA Deep Space Net. The purpose of the experiments was to provide independent verification of the accuracy of both systems. This verification was accomplished at the 0.5-μs level.

The experiments were conducted between the 64-m Deep Space Stations at Goldstone, California (DSS 14) and Madrid, Spain (DSS 63). The VLBI experiments used the Wideband Digital VLBI Data Acquisition System (WBDAS), developed at NASA's Jet Propulsion Laboratory, which has been in routine use in its present configuration since January 1978. The satellite time transfer experiments used the NTS 1 satellite, designed and built by the Naval Research Laboratory, and the NTS Timing Receivers developed by Goddard Space Flight Center. The NTS receivers were brought to the DSS's especially for these experiments. Unfortunately the NTS 2 satellite was not available for the experiments; use of this satellite might have improved the accuracy of the intercomparison by an order of magnitude.

II. Experiment Configuration

The configuration of the VLBI data acquisition system and the NTS time transfer receiver at each DSS is shown in Fig. 1. Of particular interest is the clock system. The primary frequency standard at each station was a HP5061A-004 cesium oscillator. Various frequencies are derived from the reference in a coherent reference generator, including 50 MHz, which is used in the VLBI system, and various coherent timing signals are made available at the output of the Time Format Assembly. For the purpose of this experiment, the station reference clock is the 1-pps signal at the output of the TFA, since both the VLBI and the NTS systems connect to the station timing system at this point. In comparing the results for the two systems we accounted for the cable delays according to the specified or measured physical lengths of the cables, and we measured the delay from the 1-pps input to the 1-pps output of the NTS receivers, which is the reference for these receivers. The delay within the WBDAS units is less than 20 ns and is not significant.

III. NTS Time Transfer Results

Time transfer using a NTS satellite is accomplished by using the stable oscillator onboard the satellite as a portable clock, and reading this clock over a microwave link as the satellite passes near the various ground stations. The two major fundamental sources of error in the time transfer are the instability of the oscillator on the satellite and propagation delays in the ionosphere. These error sources affect the time transfer measurement both directly and through errors in the satellite orbit. Raymond et al. (Ref. 1) describe the timing receiver used here, and present the results of some time transfer experiments between Rosman, N.C. and the Naval Research Laboratory, using the NTS 1 satellite which was also used here. These experiments demonstrated rms errors of 86 ns with respect to a portable clock. Errors over intercontinental distances are somewhat more due to time separation, orbit errors, and larger ionospheric effects. The ionospheric effect and its uncertainty is often on the order of 1 μs at the radio frequency of 335 MHz, but this error source tends to cancel when the time and space separation are small.

The NTS time transfer measurements reported on here were more or less adjunct to the six-nation cooperative experiment described by Buisson et al. (Ref. 2). The receiver used at the Madrid station was the same as the one used at Bureau International de l'Heure, France, and a spare receiver was used at Goldstone, California. As indicated in Fig. 1, the receivers were installed in the DSS control rooms, with the NTS antennas on the roofs. The positions of the antennas were measured to within a few feet with respect to benchmarks at the stations, and errors in the antenna coordinates are not expected to contribute significantly to errors in the results. The data were processed in the same manner as in the six-nation experiment, thereby estimating the offsets in the DSS clocks with respect to the USNO master clock C8D, at the Naval Observatory.

Figure 2 shows the results of 13 measurements made at Goldstone from day 145 (May 25) through day 151 (May 31), 1978. The results are corrected for a delay of 0.232 μs from the Goldstone clock reference point to the NTS receiver clock. A least squares linear fit to the data results in an offset USNO minus Goldstone of -0.688 μs at 0 hours on day 147, with a rate offset of -0.9×10^{-12} and an rms residual of 0.341 μs.

Ten measurements were conducted at Madrid during the same time frame, with results shown in Fig. 3. These results are corrected for a delay of 0.279 μs from the DSS clock reference point to the NTS receiver output. The least squares fit indicates an offset USNO minus Madrid of 8.593 μs at 0 h on day 147, with a rate offset of -0.28×10^{-12} and rms residuals of 0.226 μs.

IV. VLBI System Description

Station clock offset is one of the many parameters which can be estimated by Very Long Baseline Interferometry. The random radio signal from an extragalactic radio star is observed at two antenna stations. Because the antennas are widely separated and the Earth is rotating, there is a time varying time delay between the arrival of the signal at the two stations. This time delay and its derivative can be estimated from the geometry, and can be measured by cross-correlating the signals received at the two stations. Because the arrival of the signal is time-tagged by the clocks at the stations, the difference between the measured and the predicted time delays forms an estimate of the offset between the station clocks.

The Wideband VLBI Data Acquisition System (WBDAS) has been described elsewhere (Ref. 3), together with results of experiments held in 1976, so we present only a brief description here. A simplified block diagram of the WBDAS is given in Fig. 4. As shown in Fig. 1, the system interfaces to the standard DSN receiving system at the 55 ±18 MHz output of the Block IV receiver. The receiver output is digitally demodulated to baseband by sampling at 50 MHz in each of two phase-quadrature 3-bit analog-to-digital converters. The A/D converter outputs are then low-pass-filtered, if desired, by summing N consecutive samples in a digital integrate-and-dump filter. These experiments used both unfiltered sampling, and filtering with $N = 3$, for a filter bandwidth of 16 2/3 MHz, which was a reasonably good match to the receiver system bandwidths.

The digital filter outputs are quantized to 1 bit and stored in a high-speed buffer of 4096 bits. When the buffer is full, which takes about 120 μs for $N = 3$, sampling is inhibited and the buffer is emptied through the control computer onto digital magnetic tape. The total data rate onto magnetic tape is 57 kb/s, consisting of 14 bursts of 4096 bits. The control computer utilizes knowledge of the radio source position to predict the geometric signal delay from the source and controls the hardware buffer so that the same segments of the signal wavefront are sampled and recorded at both stations.

The utilized receiver bandwidth of 16 2/3 MHz is sufficient to achieve measurement resolutions of under 10 ns for any radio source which is strong enough to be detected. Resolution of about 1 ns is achieved with strong sources, using 1 minute of data (3×10^6 bits).

The accuracy of the system is limited primarily by propagation uncertainty in the ionosphere, which is often 20 ns at the S-band receiving frequency of 2290 MHz; by uncertainty in the Earth's orientation (UT1), which causes errors of about 5 ns; by errors in the positions of the radio sources; and by receiving system delays. We currently estimate the total day to day consistency in results to be about 30 ns, and the constant bias due to unknown but constant receiving system delays to be another 40 ns, for an estimated total error of 50 ns. (It is possible that the error in the receiving system delays is greater than 40 ns, because the delays have not been measured, but were estimated from cable length specifications).

V. VLBI Results and Comparison to NTS Results

Four VLBI clock sync experiments were conducted on May 15, 20, 24, and 27, 1978. The last three experiments consisted of from 8 to 13 total observations of 7-11 radio sources over total time spans of 1.5 to 3 hours. On May 15, due to operational problems, only two sources were observed, about 10 minutes apart. Despite the discrepancy in the amount of data, the expected clock sync errors are about the same on all days, except that the expected error on May 15 is slightly larger. As shown in Fig. 4, the computer associated with the WBDAS is interfaced to data transmission lines. We used this capability to transmit some of the data from Madrid to JPL, and processed this data between experiments to provide confirmation that the stations were properly configured.

Figure 5 shows the final clock offset estimates for the four days. The results are compensated for all known clock and signal delays, and are expressed as Goldstone clock minus Madrid clock. A linear least squares fit to the data yields an estimated clock offset of 8.775 μs at 0 h on day 147, with a rate offset of 0.33×10^{-12}. The rms of the residuals is 20.7 ns, and the sample standard deviation is 29.3 ns, with the difference due to estimating two parameters with only four data points. This is compatible with our a priori estimate of day-to-day consistency of 30 ns.

Also shown in Fig. 5 is the NTS time transfer experiment estimate of the clock and clock rate offset between the two stations. This estimate is 9.281 μs at 0 h on day 147, with a rate offset of 0.62×10^{-12}, which is just the USNO-Madrid result of Fig. 3, minus the USNO-Goldstone result of Fig. 4. The difference between the VLBI and the NTS estimates is 0.506 μs at 0 h on day 147, with a rate offset of 0.29×10^{-12}. Day 147 was chosen as the reference epoch because both experiments were in progress at that time.

The difference of 0.5 μs between the two experiments is probably mainly due to the ionospheric effects on the NTS measurements, both directly and through errors in orbit determination. There may also be a larger constant error in the estimated station delays for the VLBI experiment than the anticipated ±40 ns. The difference between the rate estimate is within the error bounds of the NTS experiment.

VI. Oscillator Stability Estimate from the VLBI Data

The instabilities of the HP5061A-004 cesium oscillators at the two stations can be bounded by using the VLBI results. The four experiments form three time intervals of 3 to 4.5

days. Differencing the clock offset estimates for successive experiments leads to frequency offset estimates of 1.85×10^{-13}, 4.26×10^{-13}, and 3.63×10^{-13}. Successive absolute differences between the offsets, divided by root 2, yield Allan variance σ's of 1.70×10^{-13} and 0.44×10^{-13}. The average of the two Allan variance pairs yields an average σ of 1.07×10^{-13} with a sample sigma of 0.9×10^{-13}.

We have estimated the combined instability of the two cesium oscillators, the station time distribution systems, and the VLBI measurements, over 3- to 4-day intervals, to be approximately one part in 10^{13}, with an uncertainty of one part in 10^{13}. By increasing the time interval to about 10 days and reducing the ionospheric effect on the VLBI measurements by use of X-band, long-term frequency stability measurements at the 10^{-14} level seem feasible.

VII. Conclusion

By intercomparison of results, we have demonstrated the absolute accuracy of the NTS time transfer system and the WBDAS VLBI system to be 0.5 μs or better between Goldstone, California, and Madrid, Spain. For the VLBI system, we have produced clock sync residuals which demonstrate day-to-day consistency at the 20- to 30-ns level and the ability to use this system to measure long-term frequency stability at the 10^{-13} level. Frequency stability measurements at the 10^{-14} level are indicated to be feasible.

References

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2. Buisson, J., et al., “Submicrosecond Comparisons of Time Standards Via the Navigation Technology Satellites (NTS),” Proceedings of the Tenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, U.S. Naval Research Laboratory, Washington, D.C., Nov. 28-30, 1978.
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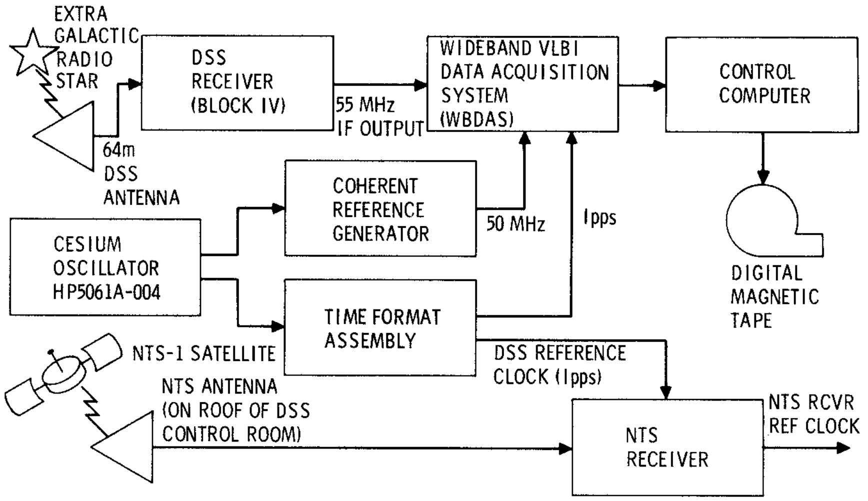

Fig. 1. Configuration of the NTS receiver and the VLBI system in a Deep Space Station

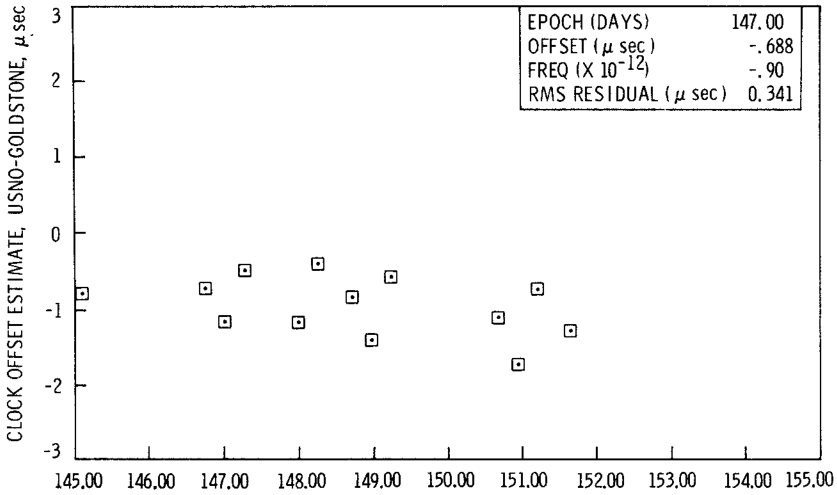

Fig. 2. NTS 1 time transfer results for Goldstone: USNOMC (C8D) – Goldstone (DSS 14)

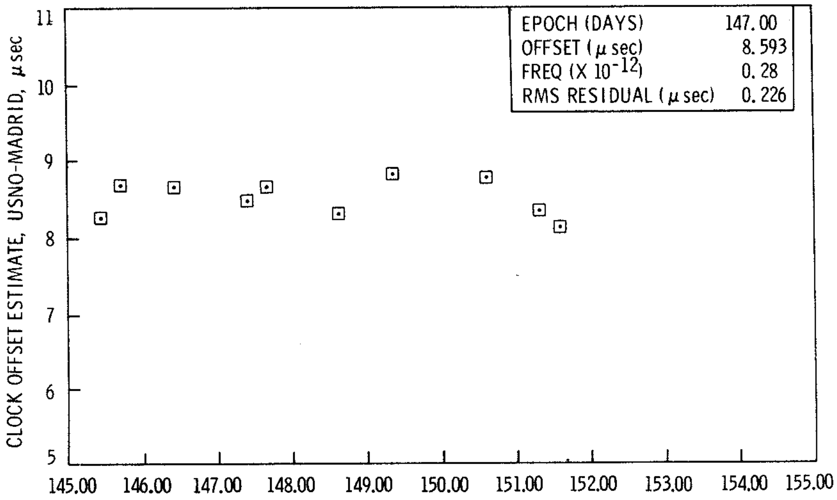

Fig. 3. NTS 1 time transfer results for Madrid: USNOMC (C8D) – Madrid (DSS 63)

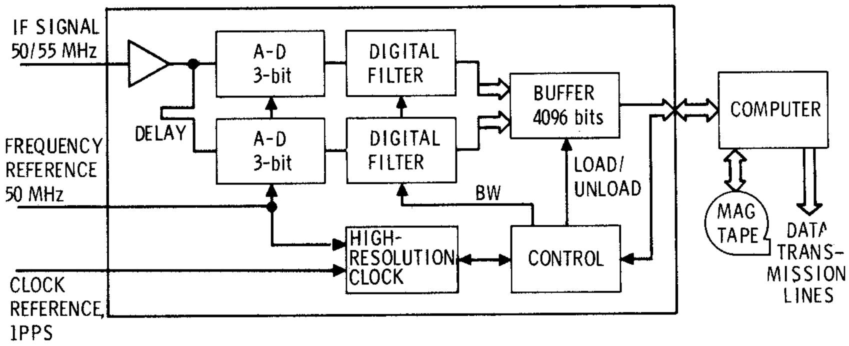

Fig. 4. Wideband digital data acquisition system block diagram

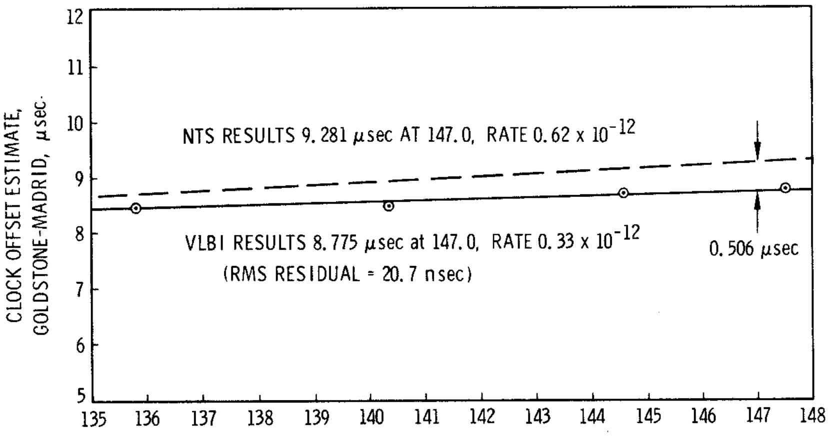

Fig. 5. VLBI clock offset measurements and comparison to NTS results: Goldstone (DSS 14) – Madrid (DSS 63)