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NIST-USNO TIME COMPARISONS USING TWO-WAY SATELLITE TIME TRANSFERS

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Abstract

NIST and USNO began making two-way satellite time transfers on August 12, 1987. The time transfers are made using the SBS-3 satellite and take place three times per week. The paper describes the equipment used to make the transfers, the data reduction procedures, and the results obtained.

Introduction

Several two-way time transfer experiments using geostationary satellites have been done over the years [1]. Recent studies of the phase stability of satellite loop tests using present-day equipment have shown that equipment-delay reproducibility over two weeks was 1 ns [2]. Using this same equipment, NIST and USNO have been making routine two-way satellite time transfers since August of 1987.

During the two-way time transfer, NIST and USNO simultaneously transmit and receive two spread-spectrum signals. Both signals are initiated by a 1 pps clock signal that represents UTC(NIST) and UTC(USNO) respectively. The time difference between the local transmitted 1 pps and the received 1 pps from the other station is measured and recorded at each site for a 300 s (5 min) interval. The time differences for each 1 pps epoch are recorded at both sites and stored on a central computer at USNO. These data are then aligned for matching epochs, and the difference between the two values is obtained and then divided by 2. The resulting data show a second-by-second comparison between NIST and USNO.

The mean and standard deviation are also computed for each 300 s measurement run to obtain a single estimate of the time scale difference. Regression analysis shows no discernible slope above the residual white noise, and tests of the residuals show that they follow white noise behavior.

The internal signal delay in each spread-spectrum modem (one at NIST and one at USNO) is measured and recorded before starting each measurement run. These delays are subtracted from the average raw time comparison to obtain an uncalibrated final comparison. Plots of these results are presented in this paper. A full calibration requires subtracting the earth stations' differential time delays, which has not yet been measured, and subtracting the Sagnac effect.

Data reduction was originally done using regression analysis. The regression coefficients were exchanged and the modem delays subtracted to obtain an uncalibrated final comparison. However, this method was sensitive to satellite motion. Although SBS-3 is geostationary, there is some nearly linear motion which can amount to a few nanoseconds per second during the measurement run. The second-by-second comparison has proved to be a cleaner and simpler method of data reduction than regression analysis.

Equipment

The equipment used at NIST and USNO operates in the Ku-band. The configuration at each location is the same except that NIST has a 6.1 m dish with remote positioning capability and USNO has a 4.5 m dish with a fixed mount. Figure 1 shows a diagram of the principal earth station components. Reference 2 contains a description of the earth station equipment at NIST. The earth station operates at an uplink (transmitting) frequency of 14.307 GHz and downlink (receiving) frequency of 12.007 GHz on SBS-3, transponder 7 lower, which is in geostationary orbit at 95°W.

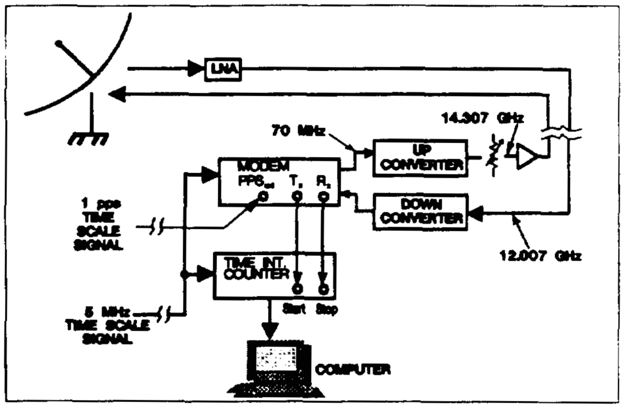

Fig. 1. Earth station equipment.

The 1 pps signal is transmitted from each earth station and received by the other earth station by means of a spread-spectrum modem that operates at 70 MHz [3]. Since orthogonal spread-spectrum code sequences are used, the simultaneous transmissions do not interfere with each other.

Data Acquisition and Analysis

Satellite time on SBS-3 is scheduled for 30 min on Monday, Wednesday, and Friday mornings beginning at 10:30 am eastern time. Raw data are the time differences between a local clock's 1 pps signal and the 1 pps signal received from the other station and demodulated by the spread-spectrum modem (see fig. 2). The once-per-second time interval counter readings at NIST and USNO are respectively

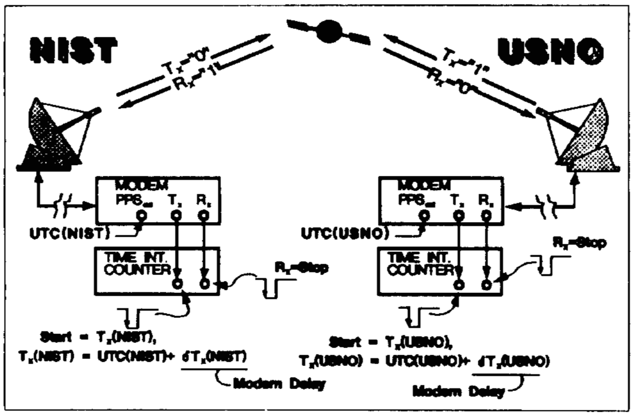

Fig. 2. Each spread-spectrum modem transmits a 1 pps signal(Tx) to the other earth station location via SBS-3. The Tx signal is slightly delayed from the external 1 pps (UTC(NIST) and UTC(USNO)) by δTx.

$$\mathrm{TI(NIST) = Tx(NIST)-[Tx(USNO) + UpC(USNO) + Sat.path(EW) + DnC(NIST)]} \qquad (1)$$

$$\mathrm{TI(USNO) = Tx(USNO)-[Tx(NIST) + UpC(NIST) + Sat.path(WE) + DnC(USNO)]} \qquad (2)$$

where "Tx" is the 1 pps signal as sampled on the front panel of the modem, "UpC" and "DnC" are the upconverter and downconverter equipment delays at either NIST or USNO, and "Sat.path" is the signal path up to, through, and down from the satellite going from East to West (EW) or West to East (WE). Sat.path includes a nonreciprocal delay due to the rotating satellite-earth system (the Sagnac effect). Subtracting equations and rearranging, we obtain

$$\mathrm{TI(NIST)-TI(USNO) = 2Tx(NIST) - 2Tx(USNO) + 2R(1)} \qquad (3)$$

where $\mathrm{2R(1) = [UpC(NIST)-DnC(NIST)] - [UpC(USNO) - DnC(USNO)] - [Sat.path(EW) - Sat.path(WE)]}$. (4)

Thus,

$$\mathrm{Tx(NIST)-Tx(USNO)} = \tfrac{1}{2}\mathrm{[TI(NIST)-TI(USNO)] - R(1)}. \qquad (5)$$

The designation "1" for R refers to the NIST-USNO link. There is a combined cable delay and internal modem delay between the local clock and "Tx," the 1 pps signal actually transmitted by the modem. We shall denote this delay as δTx, where

$$\delta\mathrm{Tx(NIST) = UTC(NIST) - Tx(NIST)} \qquad (6)$$

and $\delta\mathrm{Tx(USNO) = UTC(USNO) - Tx(USNO)}$. (7)

Combining these equations into Eq. 5 and rearranging, we obtain

$$\mathrm{UTC(NIST)-UTC(USNO)} = \tfrac{1}{2}\mathrm{[TI(NIST)-TI(USNO)]} - [\delta\mathrm{Tx(USNO)}-\delta\mathrm{Tx(NIST)}]\mathrm{-R(1)}. \qquad (8)$$

This equation is the basis for the data reduction for the time transfers between NIST and USNO. It contains the raw counter readings, the cable and modem delays (calibration delay), and the nonreciprocal equipment and Sagnac effect R(1) for this specific communications link. Taking one-half the raw counter readings between NIST and USNO relates directly to the difference of the time scales. The calibration delay (difference of the modem delays) remains constant within ±100 ps for a 30 min interval and therefore is essentially a constant during the time transfer. R(1) is unknown but will be determined by using a mobile earth station and by calculating the Sagnac effect.

Several additional stations will participate in two-way satellite time transfers in the future. Comparisons will be performed between two locations at a time designated as the I^{th} two-way link. With regard to the raw difference data, a generalized expression for an I^{th} link involving locations "A" and "B" is

$$M_k(I) = \frac{TI_k(A)-TI_k(B)}{2}\ . \qquad (9)$$

Although this paper discusses only one link (USNO-NIST), this generalization is useful for future reference. We refer to the raw difference data between NIST and USNO as

$$M_k(1) = \frac{TI_k(\mathrm{NIST}) - TI_k(\mathrm{USNO})}{2}\ , \qquad (10)$$

or one-half the k^{th} difference of the time interval counters at NIST and USNO. The designation "1" for M_k refers to the USNO-NIST link. Five minutes worth of data (300 readings) are collected at a time. The time-interval counter readings at both USNO and NIST are stored by PC-type computers. A large computer at USNO is used for data preparation, archiving, and retrieval. Preparation consists of obtaining the computer files by telephone modems, aligning the data so that 1 pps epochs match from each station, and computing each 1 s difference and dividing by 2 (computing $M_k(1)$). The spread-spectrum modem calibration delay is also part of the file and is archived in a separate file at USNO. Both USNO and NIST can retrieve the data from the USNO computer.

Typical 1 s phase stability $\sigma_y(1s)$ is between 3 and 20 × 10^{-10}, with C/N_0 between 65 and 55 dB-Hz at both USNO and NIST. The range of signal levels encountered is dependent on weather and antenna conditions, shared satellite traffic, and antenna pointing error. C/N_0 (carrier-to-noise density ratio) is a general figure of merit parameter used by the satellite communications industry to describe a link [4].

Figure 3 shows typical plots of the second-to-second difference, $M_k(1)\Big|_{k=1}^{300}$.

Spectral analysis of this kind of data shows that the power spectrum is consistently white over the range of frequencies between 1/2T, or 1.67 mHz, and 1/2t, or 1/2 Hz (the Nyquist frequency), where T is the entire measurement duration (here, 300 s) and t is the minimum sampling interval (here, 1 s). Figure 4 shows a plot of a power spectrum on log-log scale taken from typical data. The method of spectral analysis is a direct, or non-parametric

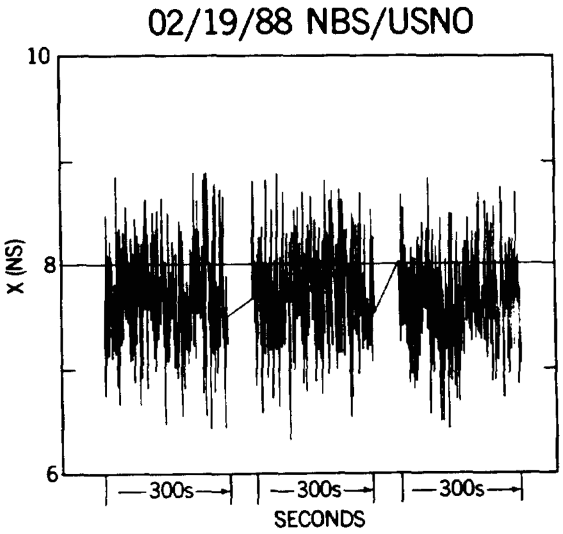

Fig. 3. Example plots of raw time-difference data. Three plots of 300 seconds (5 min) each are shown with a separation between each measurement series of 1 min.

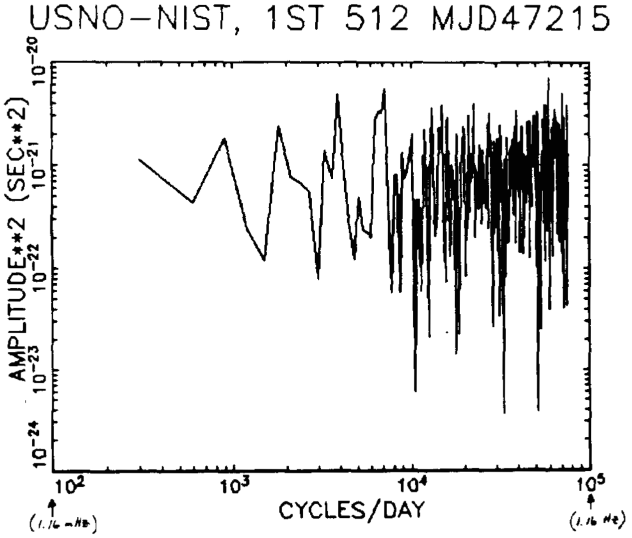

Fig. 4. Typical spectrum of raw time-difference data. This is a direct estimation of the power spectrum using the Fourier transform of the raw data.

estimation in which the Fourier transform of the 300 s time series $M_k(1)$ is computed. For confirming the presence (or lack thereof) of bright lines in the power spectrum, the highest resolution is obtained using an unsmoothed direct method of the entire data set as an appropriate first approximation of the spectrum. This first-level analysis is biased, however, because the Fourier transform of the "window" function (here, a simple rectangle) results in a passband filter which follows a sin(f)/f function around the discrete frequency intervals of the spectrum. This bias is termed "leakage" [5,6]. We are less concerned with bias and more concerned with establishing that the time series $M_k(1)$ is indeed white since the variance can easily be computed classically. Although the unsmoothed spectrum estimate of Fig. 4 is noisy (as noisy as the original data), the distribution of power over frequency f is fairly constant.

The simple mean of $M_k(1)$ is used as the value of the raw time comparison. The level of the spectrum is an estimate (although biased, as explained in the preceding paragraph) of the variance of $M_k(1)$, and its square-root is the standard deviation with respect to the mean. The standard deviation is the measurement precision. For every scheduled transfer, it is simpler to compute the classical standard deviation of the mean to get a measure of precision for that transfer. Typical precisions range from 200 ps (high C/N_0) to 1.5 ns (low C/N_0).

Averaging data for about 100 s exceeds the performance specifications of limiting components, even with transfers having low C/N_0. This is so because the poorest $\sigma_y(\tau)$ is of order $2 \times 10^{-9}\tau^{-1}$. Therefore, the standard deviation of the mean is 115 ps for a 100 s interval. In the best case, the time-interval counter at each location has an inaccuracy of ± 35 ps rms. Furthermore the 1 pps signal from the NIST computer-controlled microstepper has an error of 350 ps rms relative to UTC(NIST), although it is usually better. A test of the round trip delay through the earth station equipment in an in-cabinet test showed reproducibility over two weeks to the level of 1 ns [2]. From this we could expect the "differential" delay to be reproducible to a better level, but it would be presumptuous to say it is reproducible to less than 100 ps without a specific test of this.

Another observation is that regression analysis of $M_k(1)$ shows no discernible linear slope above the measurement precision in 300 s. Daily observations show the rate difference between UTC(USNO) and UTC(NIST) to be several nanoseconds per day (actual data will be given in the next section). This amounts to 30 ps during a 300 s interval. Short-term clock phase fluctuations are expected to be lower than 200 ps/s rms. Therefore, simply computing the mean value of $M_k(1)$ is sufficient for obtaining a time transfer from a second-to-second comparison of 100 s to 300 s given typical two-way transfer precisions.

Results

Second-to-second records of time-interval readings taken simultaneously at NIST and USNO started in mid-February of 1988. A plot of time comparison results since that time is shown in Fig. 5. This plot represents $\bar{M}_k(1)$, or the mean value of the second-to-second differences (300 s per measurement) divided by 2, and corrected by the spread-spectrum modem delays, δT(NIST) and δT(USNO). There is no correction for the differential equipment delay and Sagnac effect (collectively as R(1) in eq. 8) and for cable delays from the UTC signal point of origin (NIST and USNO) to the corresponding spread-spectrum modem. The cable delays are incorporated when a determination of R(1) is completed.

Figure 6 is the two-sample, or Allan, variance $\sigma_y(\tau)$ of the USNO-NIST master clock comparisons plotted in Fig. 5. From 1 d to 10 d, $\sigma_y(\tau)$ behaves as white frequency noise with a level of $1.35 \cdot 10^{-11}\tau^{-½}$. The 1 pps estimate of UTC(NIST) is derived from a commercial Cs-standard member of the NIST clock ensemble whose output is fed to a microstepper which is updated every 12 min. Therefore the short

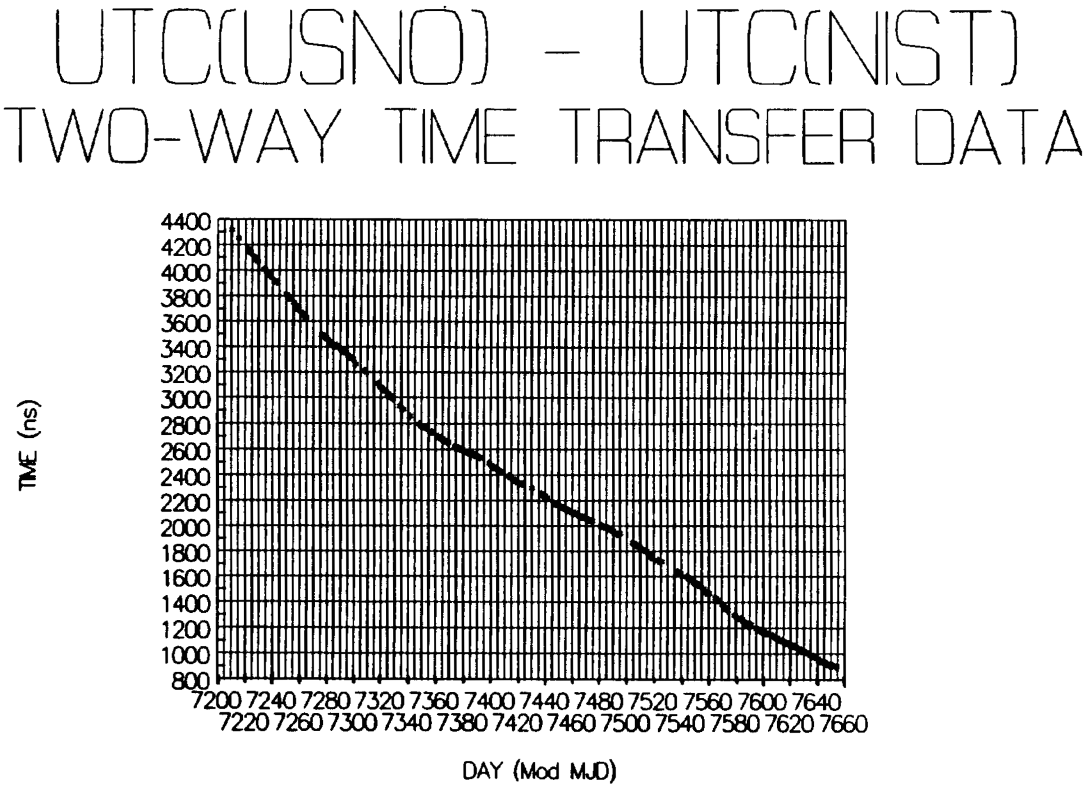

Fig. 5. Over one year of time comparison results taken at scheduled satellite availabilities beginning in mid-February of 1988. Differential signal delays due to earth station equipment and Sagnac effect have not been accounted for.

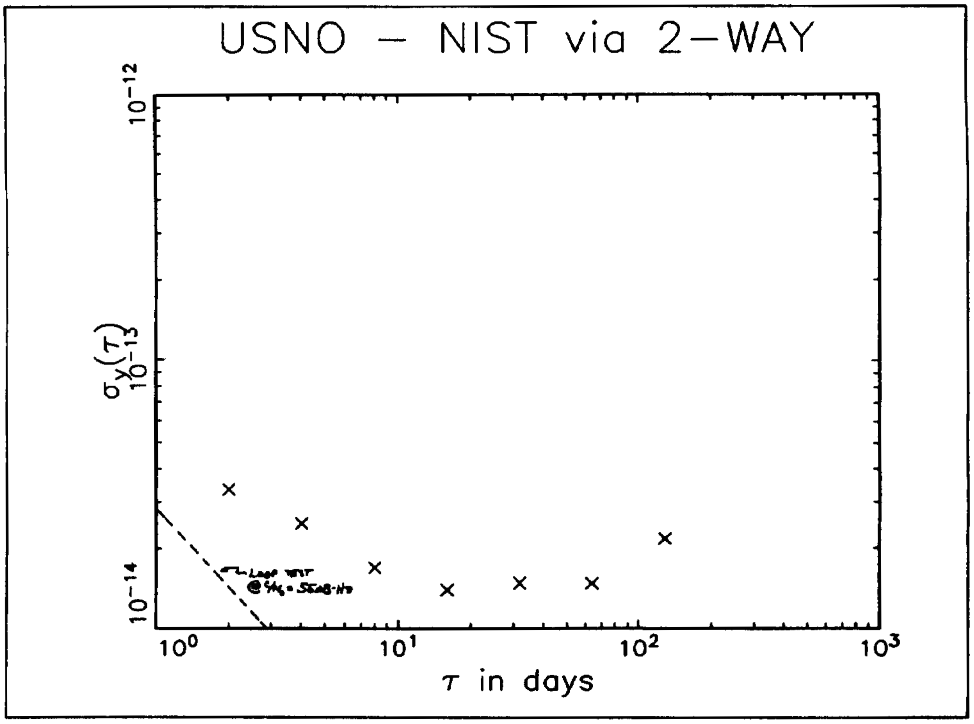

Fig. 6. Plot of $\sigma_y(\tau)$ of data shown in fig. 5. From 1 to 10 d, stability goes as $1.35 \times 10^{-11}\tau^{-\frac{1}{2}}$, which implies white frequency behavior. From 10 to 100 d, stability is 1.4×10^{-14} flicker of frequency. The rightmost point at 2.1×10^{-14} is due to steering corrections applied to UTC(USNO) and UTC(NIST).

term noise of this 1 pps signal is the noise of the commercial Cs standard plus the small steering corrections applied every 12 min. The 1 pps estimate of UTC(USNO) is derived directly from a hydrogen maser which is steered by its frequency synthesizer in time periods of a few days. In-cabinet loop test data of $\sigma_y(\tau)$ of two-way satellite equipment through a satellite simulator is plotted in Fig. 6 [2]. This $\sigma_y(\tau)$ level of $2.0 \cdot 10^{-9}\tau^{-1}$ was the measured result at C/N_0 of 55 dB-Hz; usually the USNO-NIST time transfers have a C/N_0 better than this.

The NIST-USNO time-transfer procedure, although routine, is still in the experimental stage and some equipment was not the same throughout the 1½ years of operation that these data represent. There was every effort to maintain an unperturbed set up and procedure at NIST and USNO, however; there were changes and occasional malfunctions along the way. Since transfers were completed every 2 or 3 d, unknown phase-delay variations of as much as a few nanoseconds are within the full set of data.

In longer term, the level of the flicker of frequency noise extends from roughly 10 to 100 d and shows a level of $1.4 \cdot 10^{-14}$. This agrees with expected results and in-cabinet loop tests show equipment limits to be in the 10^{-15} region, a factor of 10 better. There is therefore no reason to assume any degradation due to the two-way satellite system, and this flicker level is agreeably due to UTC(NIST) and UTC(USNO).

Beyond 100 d, long-term rate corrections of UTC(NIST) and UTC(USNO) account for the increase in $\sigma_y(\tau)$ in Fig. 5 (rightmost point) to $2.1 \cdot 10^{-14}$. Granted there is poor confidence for this point; nevertheless the increase in $\sigma_y(\tau)$ is consistent with noise resulting from these long-term corrections. If a second-order least-squares fit is subtracted from the data, this point drops to $1.6 \cdot 10^{-14}$. Figure 7 shows the time comparison results of Fig. 5 with removal of a first difference of -6.29 ns/d, second difference of 0.003 ns/d^2, and mean of 221 ns.

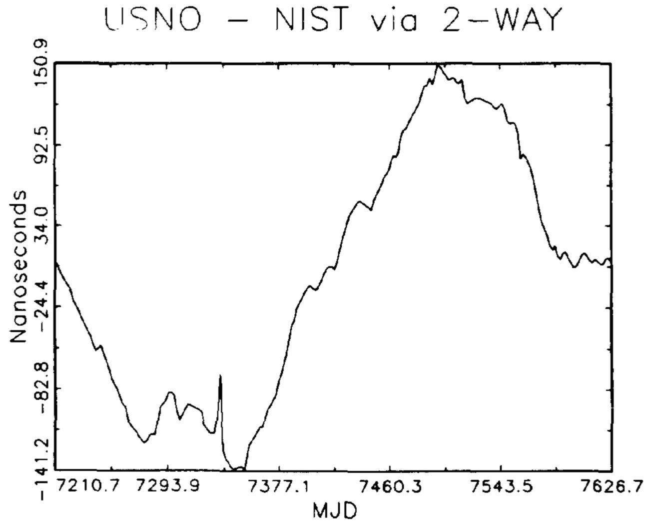

Fig. 7. Time comparison data of fig. 5 with first and second difference and mean removed.

Routinely scheduled two-way time comparisons between NIST and USNO began in August, 1987. The data reduction now involves the exchange of all 300 time-interval counter readings and corresponding times in hours-minutes-seconds. The initial procedure involved regression analysis of the 300 time-interval counter readings taken at each location simultaneously. A fourth-order polynomial was fitted to the readings, and a difference of the coefficients was computed to obtain a mean raw time difference. Curve fitting is less satisfying than taking the simple average of second-to-second differences because uncertainty in the polynomial fit is not readily quantified even by analysis of white-noise residuals. Figure 8 is a plot of the difference between time comparisons using the curve-fit procedure vs. the second-to-second average for a series of days in which both procedures were used. This difference never exceeded ± 1 ns.

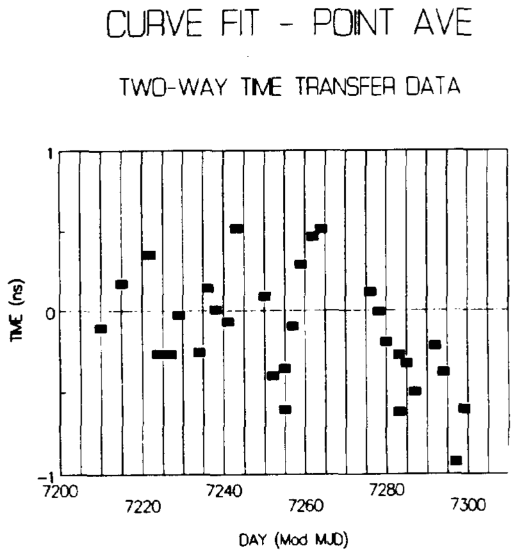

Fig. 8. Difference between reduction of raw data using curve fitting and using the average of second-to-second differences, $\bar{M}_k$.

Conclusion

Time comparison data between UTC(USNO) and UTC(NIST) has been presented along with some analysis of that data. A measurement of the offset time delay due to the earth stations will be performed in the near future so the comparisons here remain uncalibrated. Second-to-second raw difference data is white with no discernible slope for a 300 s measurement, and a simple mean is computed for the value of the time comparison. Long-term $\sigma_y(\tau)$ results are consistent with expected results of a comparison between NIST and USNO, and in-cabinet loop tests of the two-way satellite equipment point to system noise being a factor of 10 below the stability of these results. Therefore the noise contribution due to the two-way time transfer method is assumed to be negligible. Our results show that the measurement time could be reduced from 300 s to 100 s with little or no compromise in precision even with a C/N_0 of as low as 55 dB-Hz.

Acknowledgements

The assistance of M. Weiss and J. Gray are greatly appreciated.

References

[1] See, for example, A. R. Chi and E. Byron, "Two-way time transfer experiment using a synchronous satellite," in Proc. 7th Annual Precise Time and Time Interval Planning Meeting, Dec. 1975; also C. C. Costain et al., "Two-way time transfer via geostationary satellites NRC/NBS, NRC/USNO, and NBS/USNO via Hermes and NRC/LPTF (France) via Symphonie," in Proc. 11th Ann. Precise Time and Time Interval Planning Meeting, Dec. 1979.

[2] "Progress toward one-nanosecond two-way time transfer accuracy using Ku-band geostationary satellites," D. A. Howe, IEEE Trans. on Ultrasonics, Ferroelectrics, and Freq. Control, Vol. UFFC-34, No. 6, Nov. 1987.

[3] Mitrex 25000 documentation, P. Hartl et al., Institute for Navigation, Univ. Stuttgart, Germany, Jan. 1985.

[4] Digital Communications Satellite/Earth Station Engineering, K. Feher, Prentice-Hall Inc., Englewood Cliffs, NJ, 1983.

[5] Spectral Analysis for Physical Applications, Percival and Walden, to be published.

[6] "Pitfalls in digitizing the data," D. A. Howe, D. W. Allan, and J. A. Barnes, in Frequency Stability: Fundamentals and Measurement, edited by Vencesler F. Kroupa, IEEE Press (1984), PC01644, pp. 177-186.