Review of GPS Carrier-Phase and Two-Way Satellite Time Transfer Measurement Results between Schriever Air Force Base and the United States Naval Observatory

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BIOGRAPHIES

Lisa Nelson was born in Denver, Colorado in 1972. She received B.S. and M.S. degrees in Electrical Engineering from the University of Colorado in Boulder, Colorado in 1994 and 1996, respectively. Following her graduation in 1994, she joined the staff at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Her work is centered on GPS carrier-phase time transfer. Ms. Nelson is currently the timing co-chair for the Civil GPS Service Interface Committee and is a member of the Society of Women Engineers, Tau Beta Pi, Eta Kappa Nu, IEEE and is an EIT.

Kristine Larson was born in Santa Barbara, California in 1962. She received an A.B. degree in Engineering Sciences from Harvard University in 1985 and a Ph.D. in Geophysics from the Scripps Institution of Oceanography, University of California at San Diego in 1990. Her dissertation applied the Global Positioning System to measurements of tectonic motion in the offshore regions of southern California. From 1988 to 1990, Dr. Larson was also a member of the technical staff of the radiometric tracking division at the Jet Propulsion Laboratory. Since 1990, she has been a faculty member in the Department of Aerospace Engineering Sciences at the University of Colorado at Boulder where she is currently an associate professor. The primary focus of her work is system development of the GPS and applications to measuring plate tectonics, ice flow, plate boundary deformation, volcanic activity, ice mass balance, and time transfer. Dr. Larson is a member of the American Geophysical Union.

Judah Levine was born in New York City in 1940. He received a Ph.D. degree in Physics from New York University in 1966. He is currently a physicist in the Time and Frequency Division of the National Institute of Standards and Technology (NIST) in Boulder, Colorado and is a Fellow of the Joint Institute for Laboratory Astrophysics, which is operated jointly by NIST and the University of Colorado at Boulder. He is currently studying new methods for distributing time and frequency information using digital networks, such as the Internet, and on ways of improving satellite-based time and frequency distribution. Dr. Levine is a Fellow of the American Physical Society and is a member of the American Geophysical Union and the IEEE Computer Society.

ABSTRACT

We are investigating the use of GPS carrier-phase for high accuracy time transfer measurements. We have conducted a long-term time transfer experiment between the United States Naval Observatory (USNO) Master Clock and Alternate Master Clock (AMC). These clocks are located at the USNO in Washington D.C. and Schriever Air Force Base near Colorado Springs, Colorado, respectively. At both locations two-way satellite time transfer (TWSTT) measurements are made nearly every hour and geodetic dual-frequency GPS carrier-phase data are collected every 30 seconds.

The data are analyzed using a geodetic software package developed by the Jet Propulsion Laboratory combined with precise satellite orbits determined by the International GPS Service (IGS) global tracking network [1,2]. The radial accuracy of these orbits is approximately 10 cm. Instead of computing the difference between the GPS observables, as is common in high-accuracy geodetic GPS analyses, the software explicitly estimates the receiver and satellite clocks at each data epoch. The technical GPS issues investigated include the importance of carrier-phase ambiguity resolution, troposphere modeling, thermal effects, and multipath noise. Given that the error spectra for the GPS and TWSTT systems are quite distinct, we hope to learn more about each system's accuracy potential.

INTRODUCTION

National labs currently use TWSTT and GPS common-view time transfer as the primary means of comparing time and frequency standards. By using GPS carrier-phase we have achieved measurement uncertainties comparable to the TWSTT technique and smaller than the single-channel common view technique [3-5]. However, several environmental and calibration issues must be resolved to provide an accurate measurement solution [6-8].

BASIC SETUP

Initially short-baseline results at NIST and USNO showed great promise [9,10]. To test the full capabilities of GPS carrier-phase time transfer a longer baseline was chosen between Schriever AFB and USNO. Frequent TWSTT measurements are made between these sites, and geodetic receivers are available at both locations (See Figure 1) [11,12]. This allowed us to compare the well characterized TWSTT data to the GPS carrier-phase system.

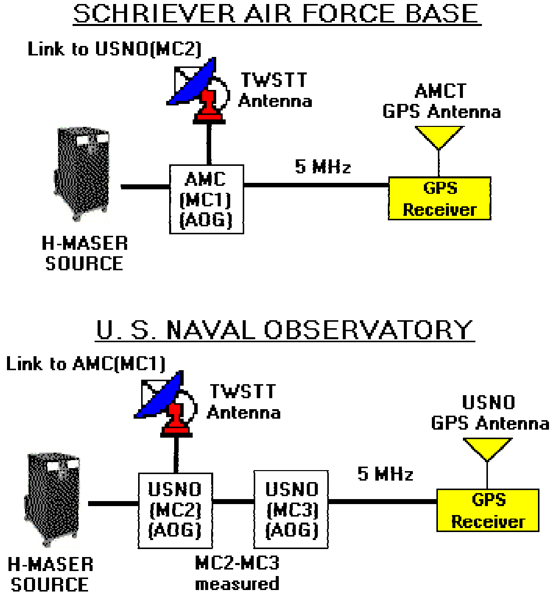

Figure 1: Basic Setup of GPS carrier-phase time transfer and TWSTT systems at Schriever AFB and USNO.

CARRIER-PHASE OBSERVABLE

The carrier-phase measurement is the difference between the satellite-generated phase and the receiver-generated phase. The GPS carrier-phase observable $\Delta\phi^s_r$ for a given satellite s and receiver r can be written as:

$$-\Delta\phi^s_r\,\lambda = \rho_g + c\delta^s - c\delta_r + N^s_r\lambda + \rho_t - \rho_i + \rho_m + \varepsilon\,, \quad (1)$$

where each term is in units of length. The geometric range is ρ_g, or $\left|\vec{X}^s - \vec{X}_r\right|$, where X^s is the satellite position at the time of transmission and X_r is the receiver position at reception time. Proper determination of the geometric range requires precise transformation parameters between the inertial and terrestrial reference frames, i.e. models of precession, nutation, polar motion, and UT1-UTC. The times of the receiver and satellite clocks are δ_r and δ^s, respectively. The carrier-phase ambiguity, or bias, is N^s_r, which is the initial number of integer cycles. The carrier wavelength is represented by λ, ρ_t and ρ_i are the propagation delay due to the troposphere and ionosphere, ρ_m is the multipath error, and ε represents unmodeled errors and receiver noise. A more complete derivation of this observable is given in [10].

To analyze carrier-phase results with the highest precision we must model or correct all the terms in Equation 1 using a geodetic software package [1]. The satellite and receiver clocks are modeled as white noise to keep the estimates uncorrelated from epoch to epoch. The reference clock is the USNO receiver clock with all other clock estimates being reported relative to this clock. GPS satellite coordinates are taken from the IGS [2]. The ionospheric effects are removed by using a linear combination of the L1 and L2 phase data. Carrier-phase ambiguities, variations in the troposphere [13], and station coordinates are estimated from the data. To minimize multipath error, we do not use carrier-phase data observed below elevation angles of 15 degrees.

The analysis uses carrier-phase data decimated to 6-minute intervals to help reduce the data to a more manageable computational level. Data are also included from geodetic receivers located at Algonquin (Ontario, Canada) to help define the terrestrial reference frame, and at Goddard Space Flight Center (Greenbelt, Maryland) to help resolve carrier-phase ambiguities. In theory, however, we would require only data from the two receivers at USNO and Schriever AFB to perform our comparison.

COMPARISON WITH TWSTT

Figures 2a-f and 3a-f show the results of the analysis period of nearly 8 months. There are several periods when data were lost due to a measurement system change or failure. Larson, et al. [12], describes these periods and the reasons for each occurrence in detail, including some of the recalibration events. The data loss rate was 3% over the 236 d analysis period. The formal errors reported for the carrier-phase measurements are on the order of 75 ps. The hourly individual TWSTT measurements (an average of 18 measurements per day) have a formal error of about 225 ps. To compute the correction for the clock reference difference between the two time transfer systems, as seen in Figure 1, the USNO local hourly MC#3-MC#2 difference data are linearly interpolated. It is also important to note that the carrier-phase clock estimates have an unknown time offset with respect to the two-way observations, because the delays through the GPS receivers are not known. The mean of the carrier-phase data has been adjusted to compensate for this overall time offset.

The smoothed TWSTT and GPS carrier-phase measurements are shown in Figure 3. In Larson, et al. [12], time differences between the smoothed TWSTT and carrier-phase are calculated to be 5.4 ps/d over a specific 188 d period. These residuals place an upper bound on the long-term stability of the carrier-phase system.

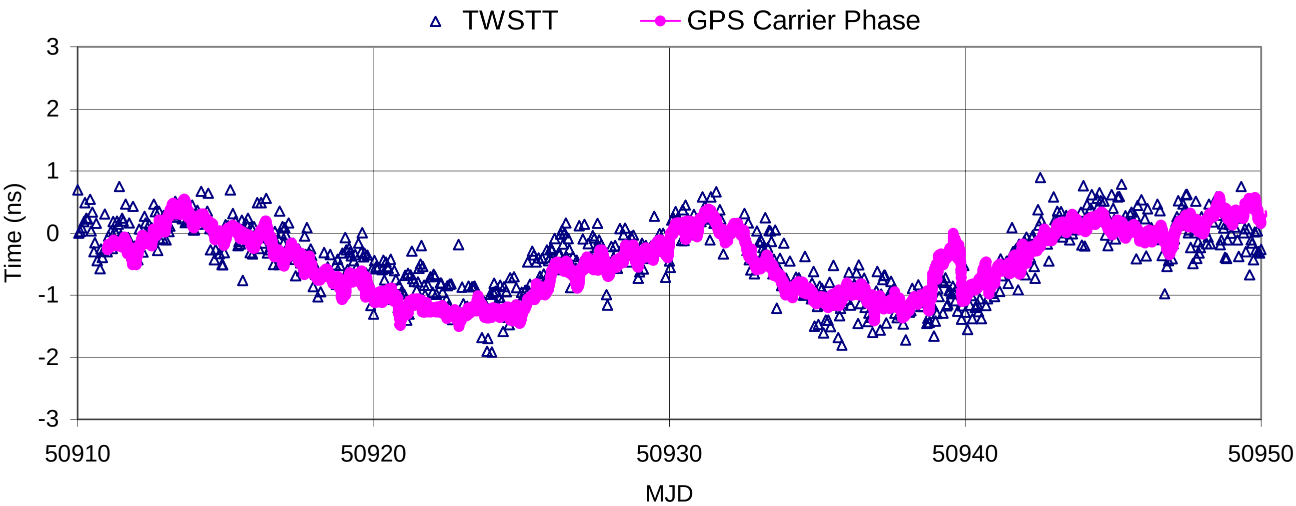

Figure 2a: TWSTT and carrier-phase estimates.

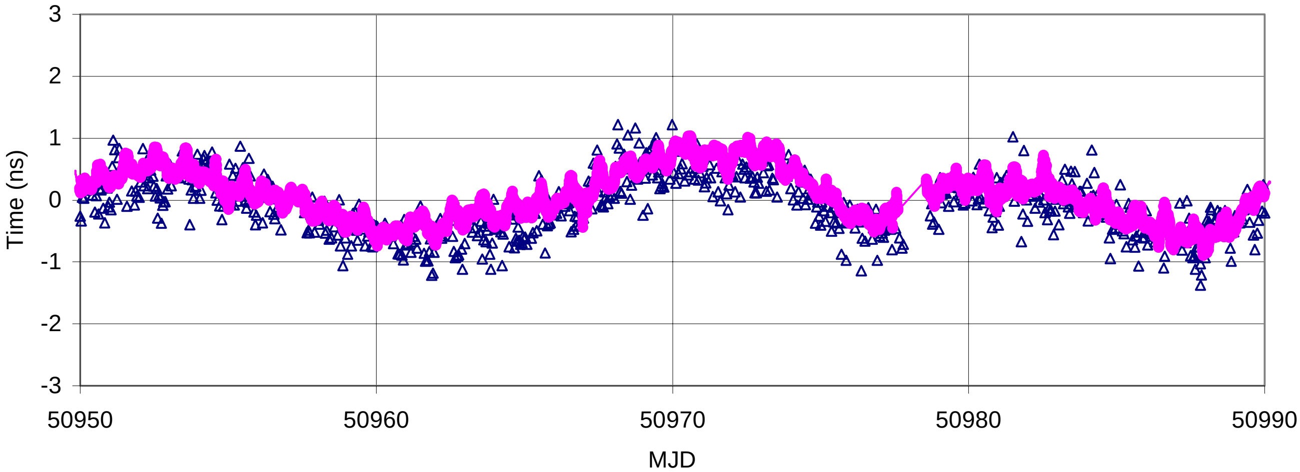

Figure 2b: TWSTT and carrier-phase estimates.

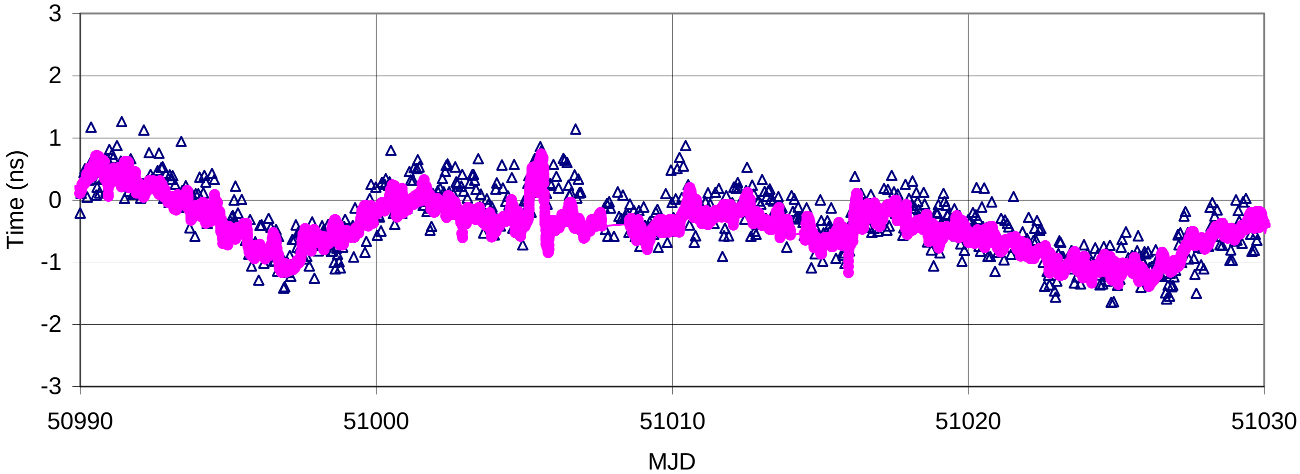

Figure 2c: TWSTT and carrier-phase estimates.

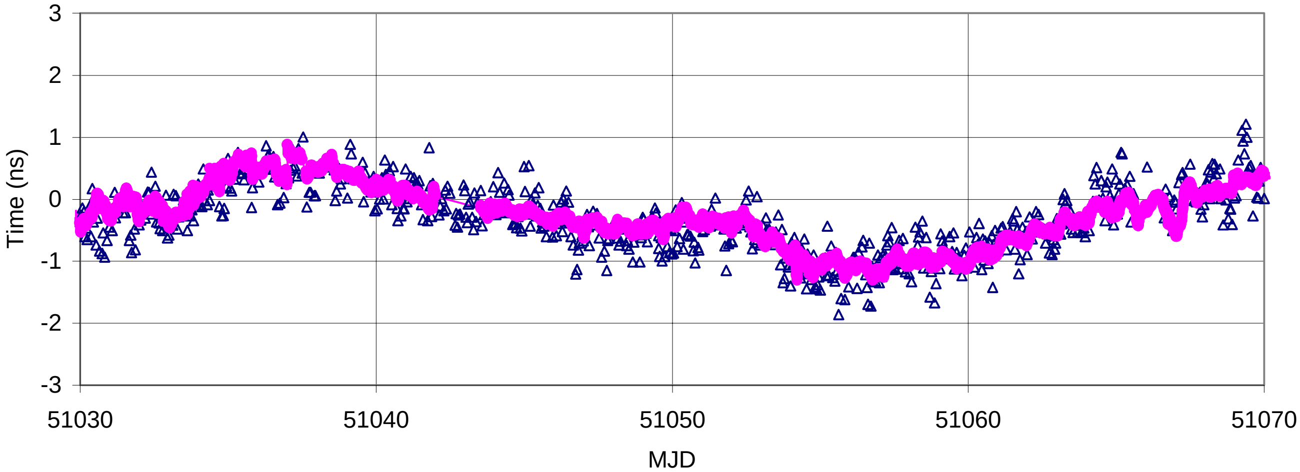

Figure 2d: TWSTT and carrier-phase estimates.

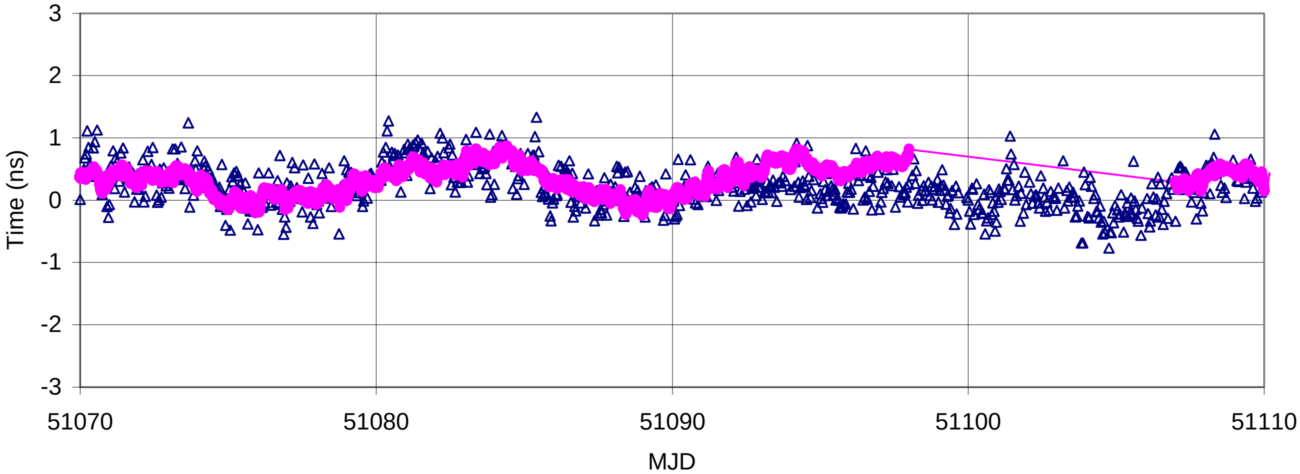

Figure 2e: TWSTT and carrier-phase estimates.

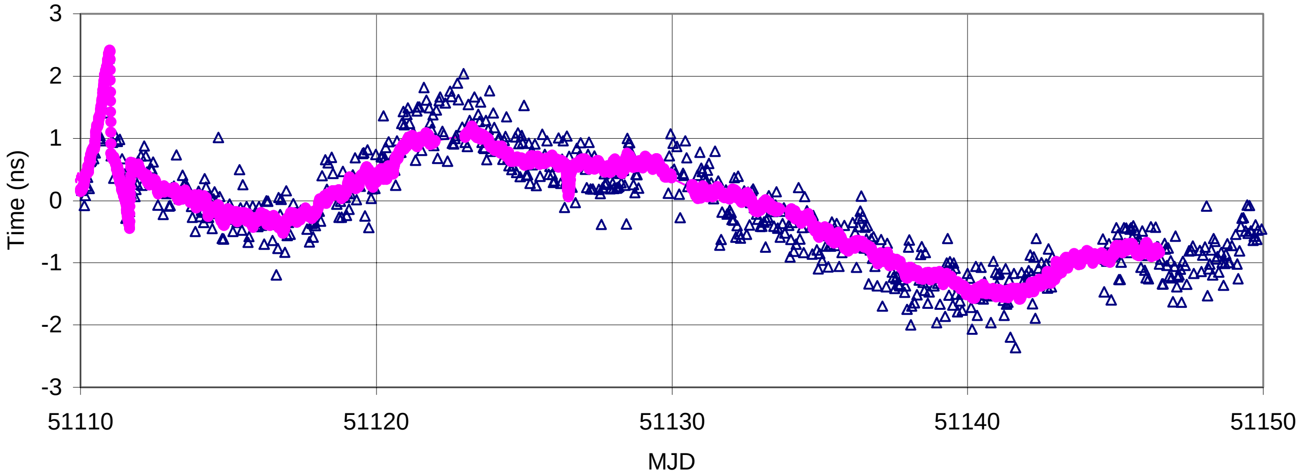

Figure 2f: TWSTT and carrier-phase estimates.

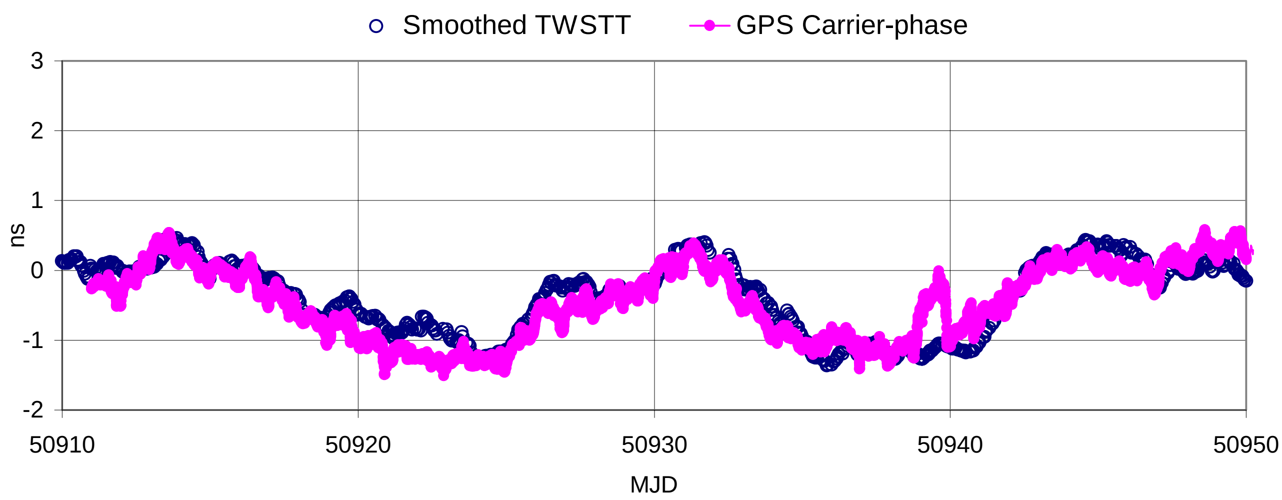

Figure 3a: Smoothed TWSTT and carrier-phase estimates.

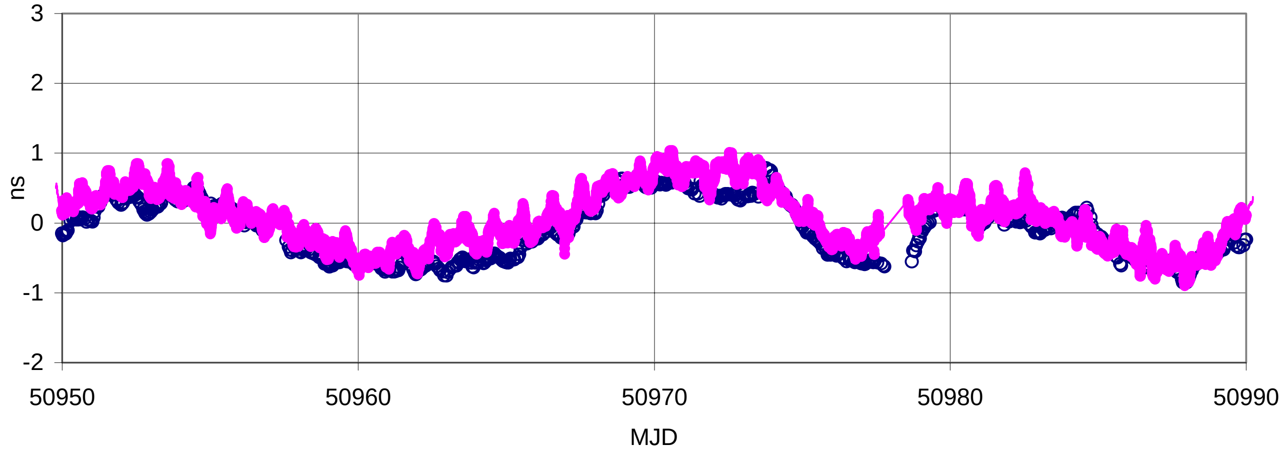

Figure 3b: Smoothed TWSTT and carrier-phase estimates.

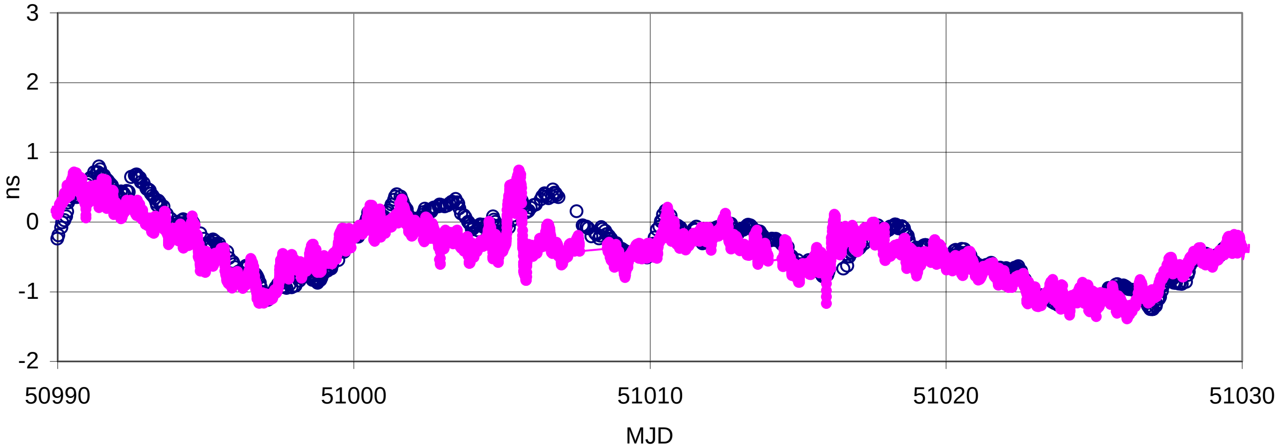

Figure 3c: Smoothed TWSTT and carrier-phase estimates.

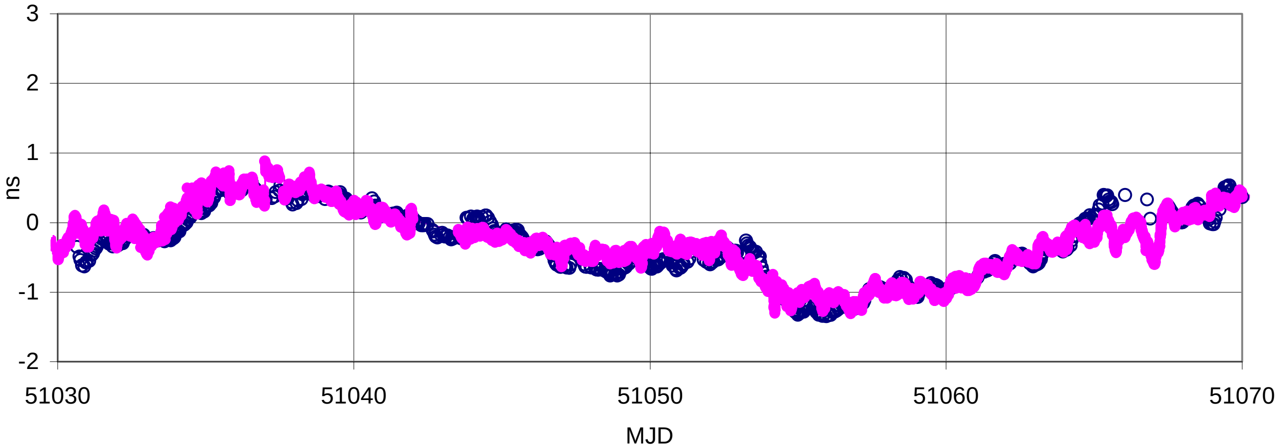

Figure 3d: Smoothed TWSTT and carrier-phase estimates.

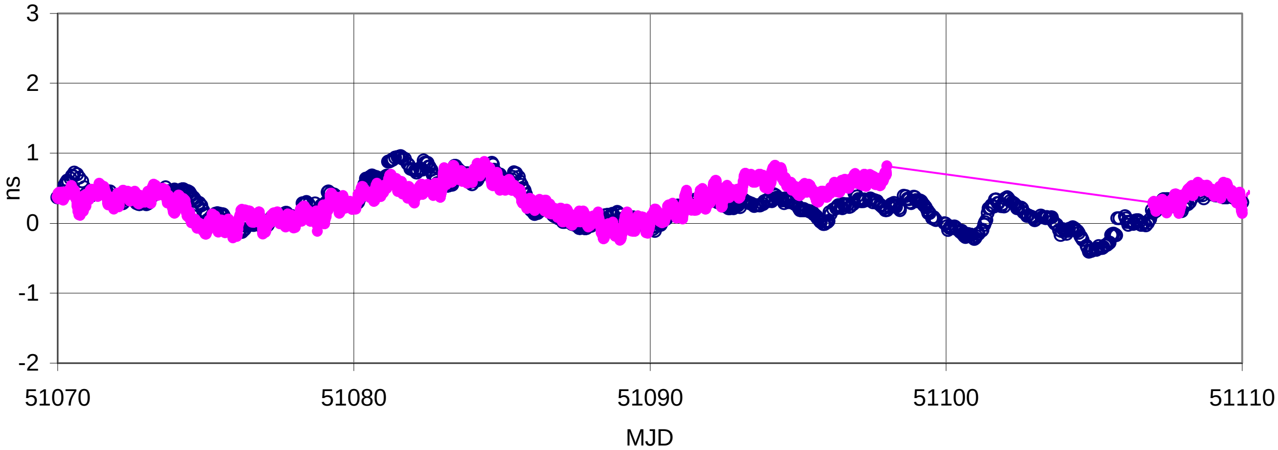

Figure 3e: Smoothed TWSTT and carrier-phase estimates.

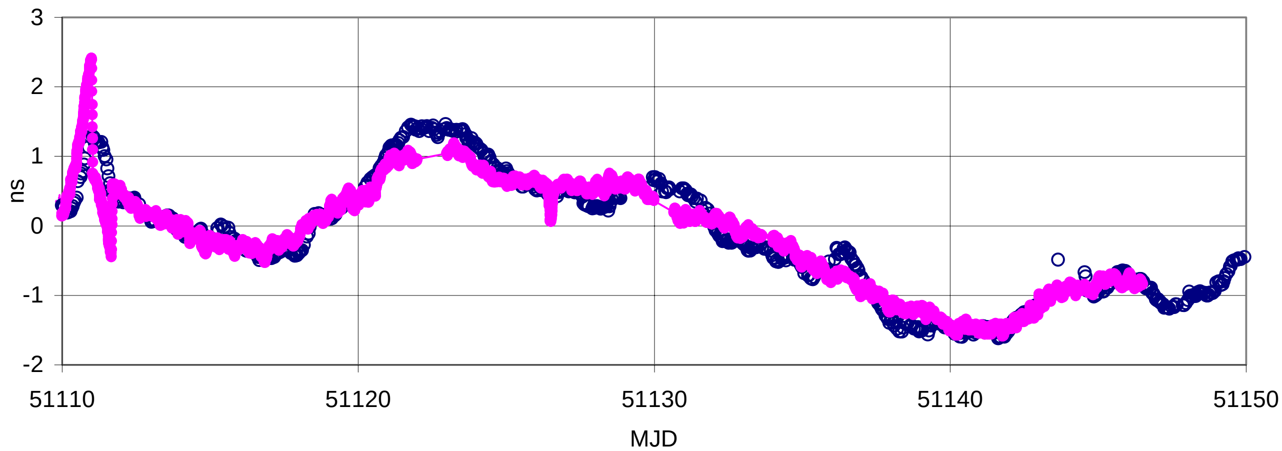

Figure 3f: Smoothed TWSTT and carrier-phase estimates.

CABLE CONCERNS

Initial analysis of the clock estimates showed diurnal fluctuations of ~400 ps peak-to-peak. Using local USNO temperature records it was found that these fluctuations were highly correlated with air temperature. The sensitivity of the cable delay to temperature was not exactly known, but testing on a similar cable was found to have sensitivity of 0.53 ps•m^{-1}•K^{-1}. With approximately 90% of the GPS antenna cable outdoors, and assuming a daily temperature variation of 10 K, the cable would have a 420 ps p-p diurnal change in its delay [7, 12].

Figure 4a shows 30 days of carrier-phase clock estimates and hourly TWSTT results for the AMC-USNO baseline. The carrier-phase and TWSTT measurements are shown to be in close agreement with each other. However, the diurnal variations are readily apparent. In Figure 4b a low-order polynomial has been removed from the time series in 4a to make a more direct comparison to local temperature records in 4c. Then using cable delay sensitivity to temperature of 40 ps/K to correct the GPS carrier-phase clock estimates in 4a, we made a considerable improvement to the measurements (see Figure 4d).

Figure 5 shows the results before and after the cable was changed at the USNO site. The new cable was reported to have temperature sensitivity better than 0.02 ps•m^{-1}•K^{-1} [7,12] and was installed in the ceiling of the building, instead of on the roof. The new cable installation significantly improved the stability of the GPS carrier-phase clock estimates. In order to take the temperature of the antenna cable into account, all the data prior to the cable change has had the 40 ps/K correction applied to the clock estimates.

EQUIPMENT ENVIRONMENTAL CONCERNS

Some fluctuations in the data correlated with temperature fluctuations in the USNO laboratory, with sensitivities on the order of 200 ps/K. Figures 6 and 7 show these events more closely. Similar receiver dependence on temperature has been shown with other geodetic GPS work [7, 8]. To minimize this effect the USNO placed the GPS receiver in an isolated thermal chamber on MJD 51037. Aside from a large spike on MJD 51126, which appeared to be attributed to a MC#2-MC#3 data correction rather than from the carrier-phase system, the temperature control has improved the system performance considerably. The largest limit to the long-term study is the significant data outages, which require a recalibration [7,12].

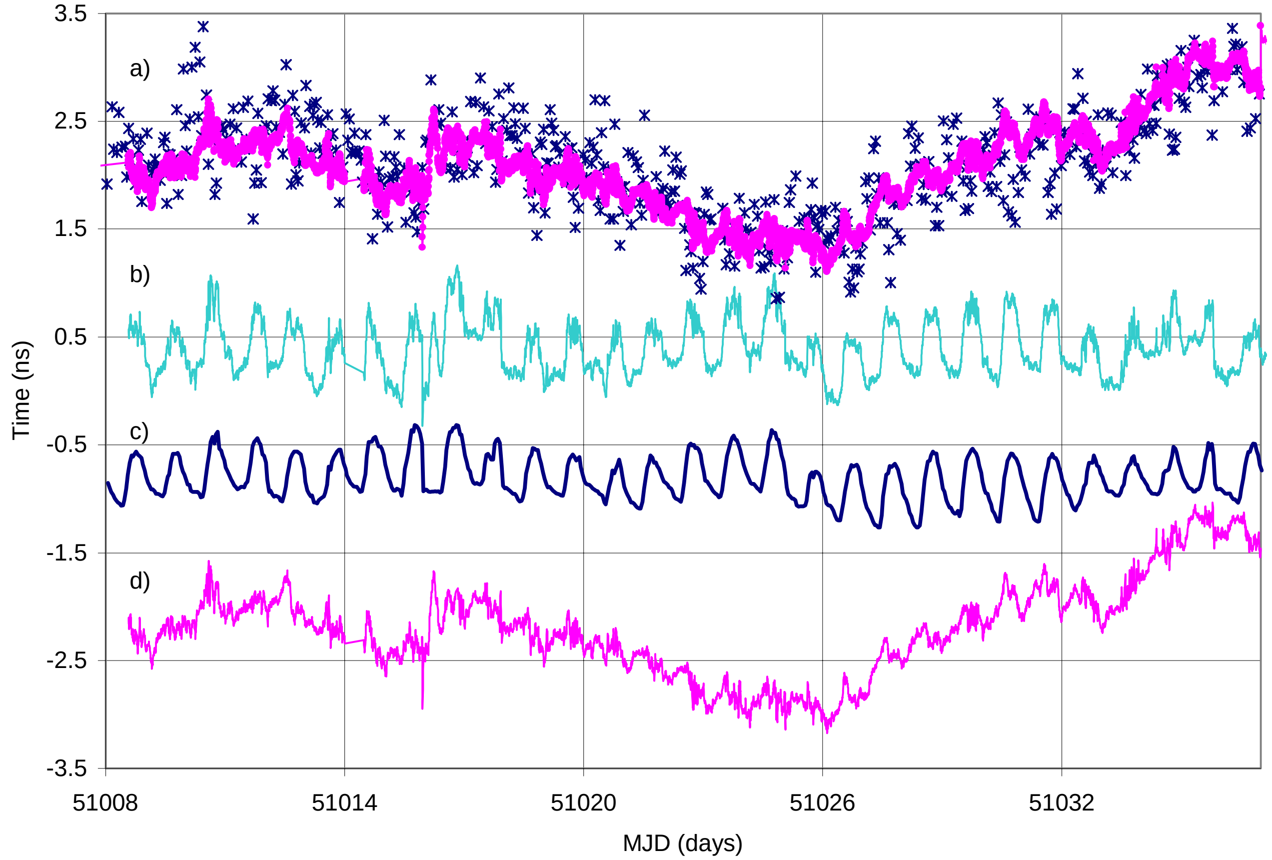

Figure 4: (a) Carrier-phase estimates plotted with TWSTT measurements; (b) Carrier-phase data from (a) with low-order polynomial removed; (c) Local USNO air-temperature records, converted using 40 ps/K; (d) Carrier-phase estimates with temperature correction of 40 ps/K applied. The time series are offset with respect to each other for display purposes only.

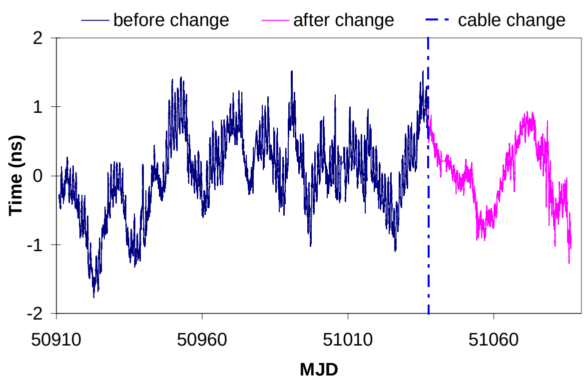

Figure 5: Carrier-phase estimates of USNO(AMC) relative to USNO(MC). Note changes in the diurnal signal after the cable was changed at the USNO.

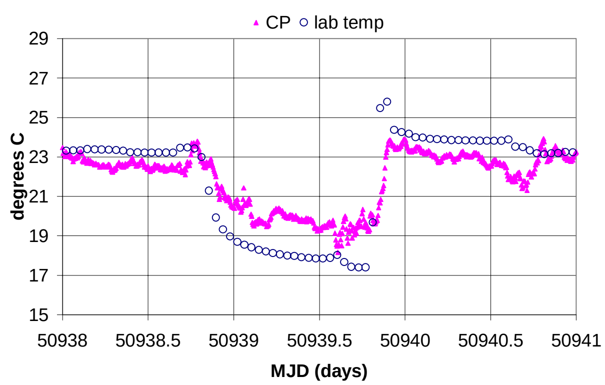

Figure 6: Hourly temperature records for the USNO receiver room, plotted along with detrended carrier-phase clock estimates. The carrier-phase estimates have been converted to degrees assuming a conversion relation of 200 ps/K.

TIME AND FREQUENCY STABILITY

Figure 8 summarizes the time deviation (TDEV) information for the two systems. For periods of less than a day, the carrier-phase estimates are significantly more precise than the TWSTT system, with carrier-phase TDEV of 15 to 88 ps between 6 minutes and 12 hours. At approximately one day, the two systems overlap in TDEV and agree for longer periods, which is consistent with their long-term agreement in the time domain. The rolloff in TDEV at long time intervals is consistent with the fact that USNO-AMC#1 is steered to USNO-MC#2. It is shown in [12] that nearly all the noise at periods of less than a day comes from the TWSTT system by computing the TDEV of the difference of the TWSTT and GPS carrier-phase.

The combined noise of TWSTT and carrier-phase is flicker PM in nature beyond 1 day, with a level of about 100 ps. GPS carrier-phase frequency uncertainty at periods of less than a day is significantly better than for TWSTT, with values of 2.5×10^{-15} and 5.5×10^{-15} at one day, respectively (Figure 9).

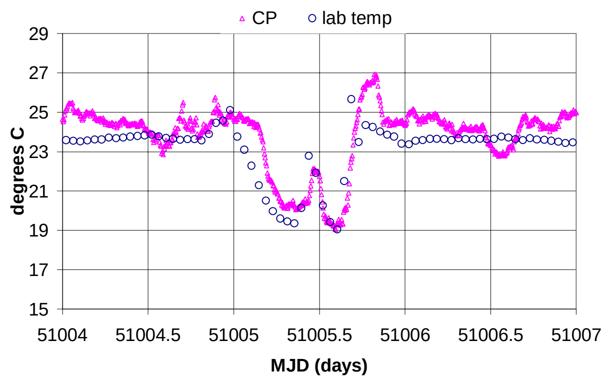

Figure 7: Hourly temperature records for the USNO receiver room, plotted along with detrended carrier-phase clock estimates. The carrier-phase estimates have been converted to degrees assuming a conversion relation of 200 ps/K.

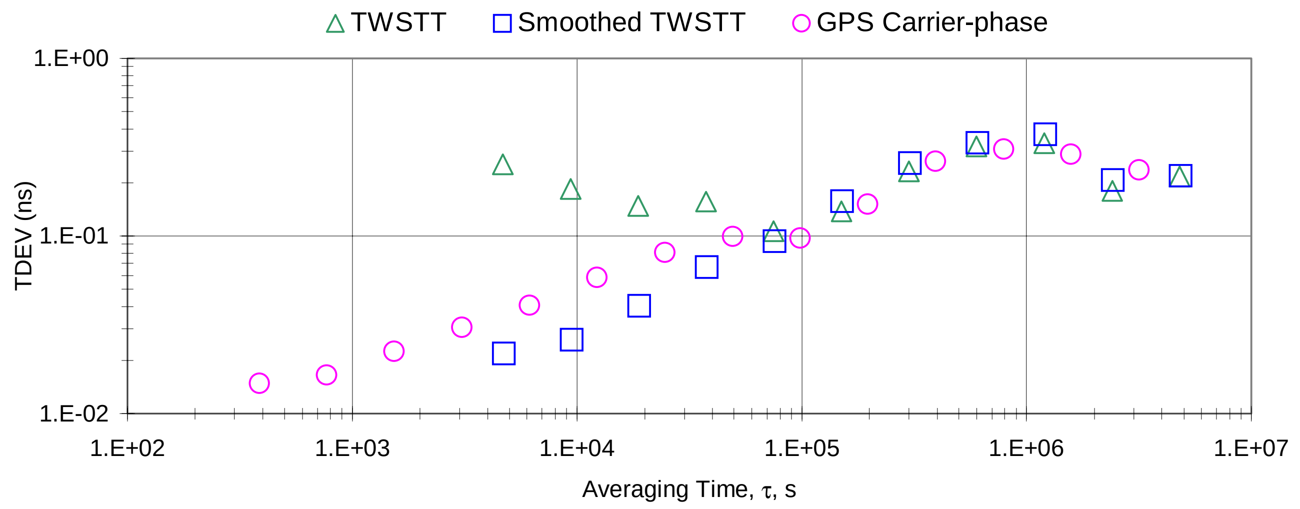

Figure 8: TDEV of TWSTT, smoothed TWSTT and GPS carrier-phase data.

CONCLUSIONS

Our experiments have shown that carrier-phase GPS can provide timing stabilities of well below 100 ps at intervals of less than 1 d. However, there are some issues that must be taken into account to improve the stability of the link. Foremost, high-quality cables and environmental extremes must be considered in maintaining the best conditions for the time transfer system. Receivers should be installed in thermally controlled chambers, with temperature fluctuations less than 0.1 K. Elimination of errors in local timing links should be minimized by connecting GPS receiver reference clocks directly to their sources as much as possible. Furthermore, any kind of receiver clock reset requires a recalibration, especially in the case of a power outage when a complete receiver reboot takes place. In this case, a nearest integer increment correction of the receiver reference signal, 24.4427 ns, will not suffice [12]. For GPS carrier-phase to provide a complete time transfer system, the receivers, antennas and cables must be calibrated. More work with the long-term accuracy of carrier-phase needs to be pursued as well as the possibilities for a real-time solution, which requires real-time orbit information.

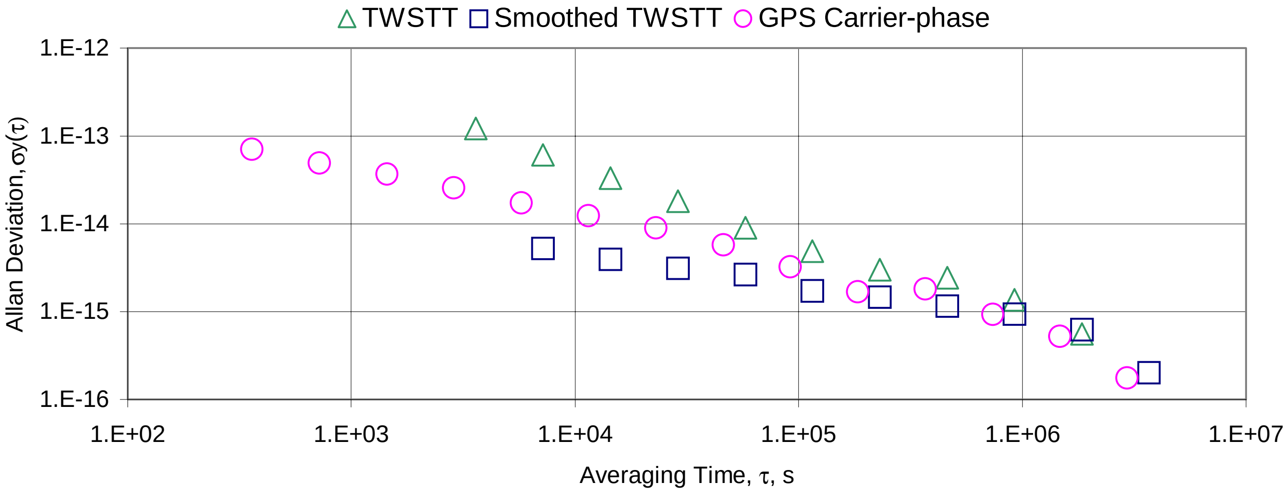

Figure 9: Allan deviation of TWSTT, smoothed TWSTT and GPS carrier-phase data.

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