A LONG-TERM COMPARISON BETWEEN GPS CARRIER-PHASE AND TWO-WAY SATELLITE TIME TRANSFER

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Abstract

We have conducted GPS carrier-phase time-transfer experiments between the Master Clock at USNO in Washington, DC and the Alternate Master Clock at Schriever Air Force Base near Colorado Springs, Colorado. These clocks are also monitored on an hourly basis with two-way satellite time-transfer (TWSTT) measurements. We compare the performance of the GPS carrier-phase and TWSTT systems over a 167-day period. Apart from an overall constant time offset (due to unknown delays in the GPS hardware at both ends), we find that the systems agree within ±1 ns, with a drift of 1.9±0.1 ps/d. For averaging times of a day, the carrier-phase and TWSTT systems have a frequency uncertainty of 2.5 and 5.5 parts in 10^{15}, respectively.

INTRODUCTION

Initial analysis of GPS carrier-phase data for time-transfer applications has been extremely promising [1]-[5]. Direct comparisons between carrier-phase and code-based common-view GPS show good agreement at times greater than 1 day [2]. As both systems depend directly on the GPS constellation, this is not a truly independent measure of the accuracy of the two systems. Furthermore, the noise of the common-view technique for periods of less than a day limits the value of comparisons between the common-view and carrier-phase techniques.

Initial comparisons between two-way satellite time-transfer (TWSTT) and GPS carrier-phase on continental-scale baselines have also been encouraging, but have been limited because of the somewhat irregular TWSTT observing schedule between most timing laboratories [1]-[3]. None of these studies has compared TWSTT and GPS carrier-phase time-transfer for periods of less than several days. In order to evaluate the accuracy of GPS carrier-phase for these periods, more frequent TWSTT measurements are required. In this study we have concentrated on a time-transfer experiment where such measurements are available. Nearly hourly TWSTT measurements are made between the Master Clock at the U.S. Naval Observatory (Washington, D.C.) and the USNO Alternate Master Clock at Schriever Air Force Base (Colorado Springs, Colorado). These data provide an ideal opportunity to assess both the short-term and long-term accuracy of the GPS carrier-phase time-transfer system.

TIME-TRANSFER SYSTEMS

Geodetic quality dual-frequency GPS receivers have been installed at USNO and Schriever Air Force Base. These particular receivers simultaneously track up to 12 satellites and produce both pseudo-range and carrier-phase measurements at 30 s intervals.

The USNO GPS receiver is supplied with an external 5 MHz reference signal from USNO (MC#3). This master clock includes a hydrogen maser and an auxiliary output generator (AOG), see Fig. 1. Its output is steered to a second Master Clock, which is known as USNO(MC#2). This clock is also realized using a hydrogen maser. USNO(MC#2) defines UTC(USNO) and is the reference source for TWSTT. The USNO GPS receiver was installed in April 1997.

The GPS receiver at Schriever Air Force Base (USNO-AMCT during these experiments) also has an external 5 MHz reference supplied by AMC(AMC#1). This alternate master clock also contains a hydrogen maser and an AOG distribution amplifier. It is steered to USNO(MC#2) using the nominally hourly TWSTT data. The USNO-AMCT GPS receiver was installed in March 1998.

In order to compare the carrier-phase and TWSTT estimates between USNO and USNO-AMC, we must know the difference between MC#2 and MC#3 at the USNO in Washington, since the former is the reference for the TWSTT system there, while the latter drives the GPS carrier-phase receiver. This difference is monitored using a switched/multiplexed time-interval counter. The counter is connected to the clocks using a fiber-optic link; the measurement system has an observed diurnal variation of about 100 ps p-p and possible seasonal drifts as large as 1 ns.

The GPS receivers at USNO and Schriever (USNO-AMCT) are part of the IGS network [6], a cooperative, continuously operating global GPS tracking network. The data are freely available over the Internet and can be accessed through anonymous ftp. Descriptions of all IGS sites and data archiving procedures can be located at http://igscb.jpl.nasa.gov.

GPS CARRIER-PHASE DATA ANALYSIS

The GPS carrier-phase observable $\Delta\phi_r^s$ for a given satellite s and receiver r can be written as follows:

$$-\Delta\phi_r^s\lambda = \rho_g + c\delta^s - c\delta_r + N_r^s\lambda + \rho_t - \rho_i + \rho_m + \epsilon, \qquad (1)$$

where individual terms are in units of length. λ is the carrier wavelength, ρ_t and ρ_i are the propagation delays due to the troposphere and ionosphere, ρ_m is the multipath error, and ϵ represents unmodelled errors and receiver noise. N_r^s is the initial number of integer cycles, known as the carrier-phase ambiguity or bias. ρ_g is the geometric range, or $|\vec{X}^s - \vec{X}_r|$, where $\vec{X}^s$ is the satellite position at the time of transmission and $\vec{X}_r$ is the receiver position at reception time. Proper determination of ρ_g requires precise transformation parameters between the inertial and terrestrial reference frames, i.e. models of precession, nutation, polar motion, and UT1-UTC. Finally, δ_r and δ^s are the time of the receiver and satellite clocks, respectively, in seconds.

In order to achieve the highest precision carrier-phase results, we must model or correct all the terms in Equation 1. We used a geodetic software package to analyze the GPS carrier-phase data [7]. Both satellite and receiver clocks are modeled as white noise, so that the estimates are uncorrelated from epoch to epoch. The receiver clock at USNO is treated as the reference clock, and all other clock estimates are reported relative to it. Coordinates of the GPS satellites are taken from the IGS (International GPS Service) [6]. The effect of the ionosphere is removed by using an appropriate linear combination of the *L1* and *L2* phase data. Variations in the troposphere, station coordinates, and carrier-phase ambiguities are estimated from the data. In order to minimize multipath errors, carrier-phase data observed below elevation angles of 15 degrees are discarded.

While carrier-phase receivers typically record data at 30 s intervals, we have decimated the data to 6-minute intervals to reduce the computational burden. Although in theory we only require the data from the two receivers located at USNO and Schriever, in practice we have also used data from Algonquin (Ontario, Canada) to help define the terrestrial reference frame and Goddard Space Flight Center (Greenbelt, Maryland) to help resolve carrier-phase ambiguities. The 167-day time series can be analyzed in 24 hours on a dual-processor 200 MHz workstation. A large fraction of that time is spent on ambiguity resolution.

RESULTS

This comparison covers a period of 167 days. There are 39,083 GPS carrier-phase observations, or a loss rate of 2.5% for the 167-day period (an average of 234 measurements per day). The TWSTT measurements are made on nearly an hourly basis, with 3,105 measurements during this period (an average of about 19 measurements per day). The USNO MC#3-MC#2 data are made available as hourly measurements; we use linear interpolation on this data set to compute the correction to the GPS carrier-phase measurements.

SYSTEMATIC ERRORS

Initial analysis of the carrier-phase data demonstrated that there were some difficulties with the carrier-phase time-transfer system. The GPS receiver at Schriever frequently reset its internal clock, at one point doing this as often as once every 5 days. These resets occur in two circumstances: when the internal clock has drifted by more than 0.03 s or when the receiver has recorded a "clock set" command. The first scenario should not be relevant to receivers which are connected to hydrogen masers. The second occurs when power has been turned off or when the receiver has lost track of several satellites, rendering it incapable of determining position. Since position is the primary output of a geodetic receiver, the receiver resets all parameters, including the clock, and searches the sky to re-acquire all visible satellites. Since geodetic GPS receivers were designed to be used by surveyors and geophysicists, it was expected that the units would be used in the field on battery power. Thus, power is frequently turned off. For laboratory use and timing applications, power outages should be eliminated as much as possible.

We still do not fully understand why the Schriever receiver reset its clock so frequently. The Schriever and USNO GPS receivers lost power at least three times during the 167-day period described in this paper. But, this does not explain the remaining 16 resets, all of which occurred at Schriever. A new GPS receiver was installed at Schriever in late October, 1998. We are currently monitoring data from the new receiver to see if this alleviates the problem. It is possible that other factors, such as RF interference, may be responsible for the clock reset problem at Schriever.

Large (peak-to-peak amplitude of ~400 ps) diurnal signals were visible in the carrier-phase clock estimates. Comparisons with records at USNO suggested that these periodic signals were highly correlated with local air temperature. The antenna cable being used at USNO to connect the GPS antenna to the GPS receiver was 89 m long, and nearly all of it was exposed to full sunlight. The sensitivity of the cable delay to temperature was not known, but was thought to be in range of 0.5 to 1.25 ps/m-°C. A similar cable was tested and was found to have sensitivity of 0.53 ps/m-°C. Assuming that 90% of the cable was exposed to a daily temperature variation of 10°C, a cable with this sensitivity to temperature would have a 420 ps p-p diurnal change in its delay. See [8] for more details.

In Figure 2a) we show typical carrier-phase clock estimates for the Schriever-USNO baseline. Superimposed on the estimates are the hourly TWSTT measurements, which indicate that the long-term behavior of the carrier-phase estimates is in good agreement with TWSTT. Nevertheless, the diurnal variations in the carrier-phase estimates are readily apparent. In Figure 2b) we remove a low-order polynomial from the time series, so that we can more directly compare to temperature records, which are shown in Figure 2c), using a sensitivity of the cable delay to temperature of 40 ps/°C. In Figure 2d) we demonstrate that subtracting a simple correction, which depends solely on temperature, can significantly improve the precision of the GPS carrier-phase clock estimates.

Several days after these data were collected, a new cable was installed at USNO. This cable was expected to a have a temperature sensitivity better than 0.02 ps/m-°C. This new cable was installed mostly in the ceiling of the building instead of on the roof where it was exposed to the elements. In Figure 3 we show carrier-phase clock estimates directly before and after the cable was changed at USNO. This new cable has substantially improved the stability of the carrier-phase GPS clock estimates.

We estimated the change in the receiver delay due to the reset of its internal clock using an average of the observations 30 minutes before and after each reset, and assuming that the local reference oscillator was well-behaved during this period. This method is straightforward, but is obviously not optimum – at the very least it introduces a random-walk into the long-period observations. In a future analysis we plan to compare our current reset estimates with reset calibrations computed using the change in the 1 Hz output pulses from the receiver.

Unlike the clock resets where the data loss is typically small (often less than a few minutes), a lengthy power outage could produce a bias in the clock estimates that would be difficult to remove. In this analysis, we assumed that there was no change in the clocks during power outages, which is adequate only for short periods. In one instance (the day the new cable was installed at USNO) we did adjust the GPS carrier-phase estimates by ~1 ns to bring the carrier-phase time series into agreement with TWSTT. We corrected for the local MC#3 oscillator by using the calibrations provided by USNO. Finally, we applied a 40 ps/°C temperature correction for data collected before the new cable was installed at USNO.

Since the delay through the carrier-phase GPS receivers was not known, these data have an unknown constant time offset with respect to the two-way observations. (This constant delay is in addition to the time steps whenever the internal clock of the receiver is reset). We adjusted the mean of the carrier phase data to compensate for this overall time offset.

STATISTICS

The final carrier-phase clock estimates are shown in Figure 4, along with the hourly TWSTT measurements. Despite the problems we discussed in the previous section, it is clear that the corrected GPS carrier-phase clock estimates agree well in the long-term with the TWSTT measurements.

If we difference the carrier-phase and TWSTT at common epochs (by interpolating to the higher rate of the GPS data), we can see the agreement between the two systems is better than ±1 ns over the

167-day period (Figure 5). The trend of the difference between the systems is 1.9±0.1 ps/d, which is well within the uncertainty of drift in the MC#3-MC#2 measurement system at USNO.

Figure 6 summarizes the TDEV information in 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 (Figure 5). The rolloff in TDEV at long time intervals is consistent with the fact that AMC(AMC#1) is steered to USNO(MC#2). If we calculate the TDEV of the difference of TWSTT and GPS carrier-phase, we see that nearly all the noise at periods of less than a day comes from the TWSTT system. 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 and 5.5 parts in 10^{15} at one day (Figure 7).

CONCLUSIONS

The carrier-phase data in the USNO-AMC/USNO link (after temperature correction) have exhibited a stability similar to that observed using the NIST/USNO link reported in [2]. For time intervals less than 1 day the stability of carrier phase is well below 100 ps. The high quality TWSTT link between the AMC(AMC#1) and USNO(MC#2) provides a unique opportunity to obtain information about the long-term stability of both links. The combined noise of the two links is at the 100 ps level.

In spite of the new antenna cable at the USNO, the carrier-phase data are undoubtedly still degraded to some extent by thermally induced changes in the hardware delay and by the small residual time steps due to the resets in the receiver clock. We plan to address both of these problems in the near future.

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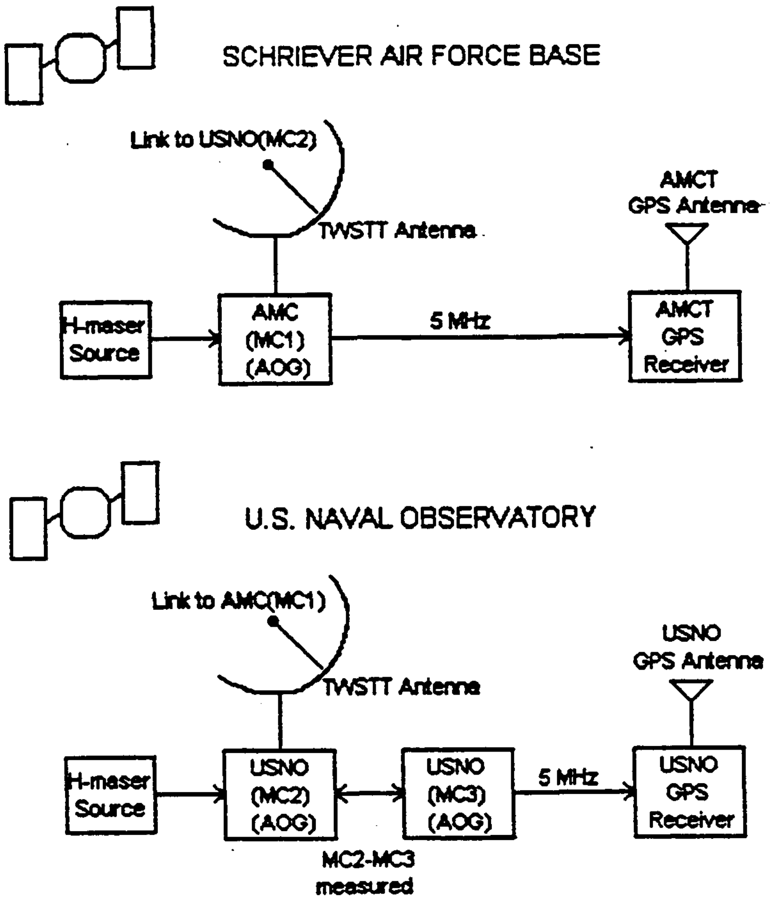

Figure 1: Measurement schematics at the U.S. Naval Observatory and Schriever Air Force Base.

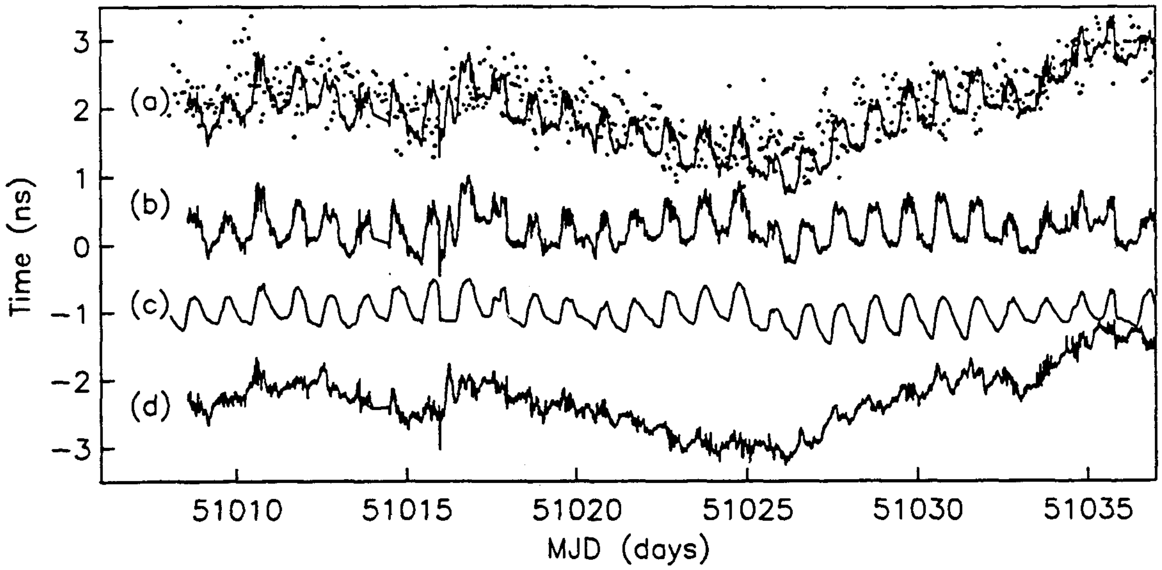

Figure 2: (a) Carrier-phase estimates of USNO-AMC (Schriever) minus MC-USNO plotted with TWSTT measurements; (b) Carrier-phase data from (a) with low order polynominal removed; (c) Local USNO air temperature records, converted using 40 ps/°C; (d) Carrier-phase estimates of USNO-AMC (Schriever) minus MC-USNO with 40 ps/°C temperature correction applied. The time series are offset with respect to each other for display purposes only.

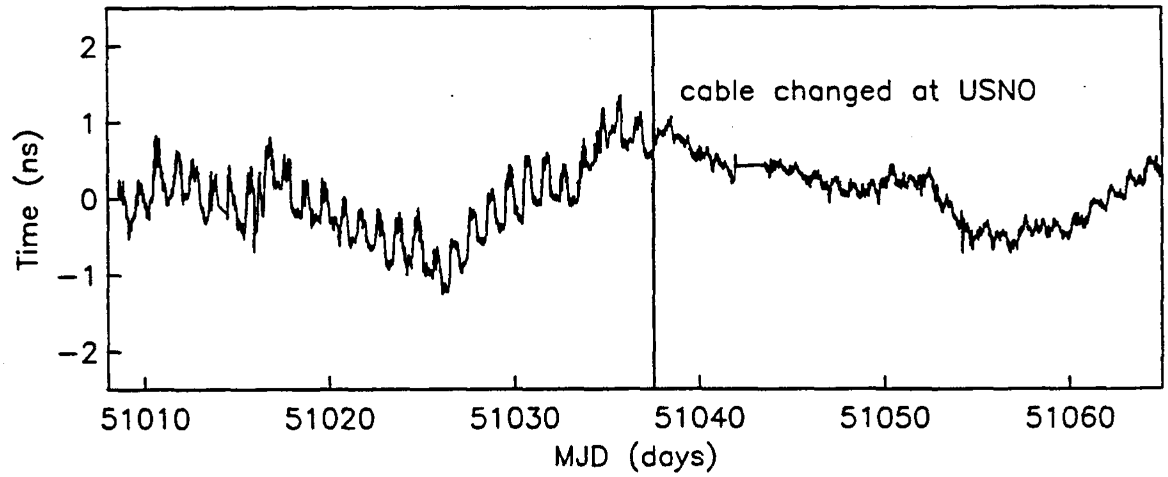

Figure 3: Carrier-phase estimates of USNO-AMCT relative to USNO. Note change in diurnal signal apparent after the cable was changed at USNO.

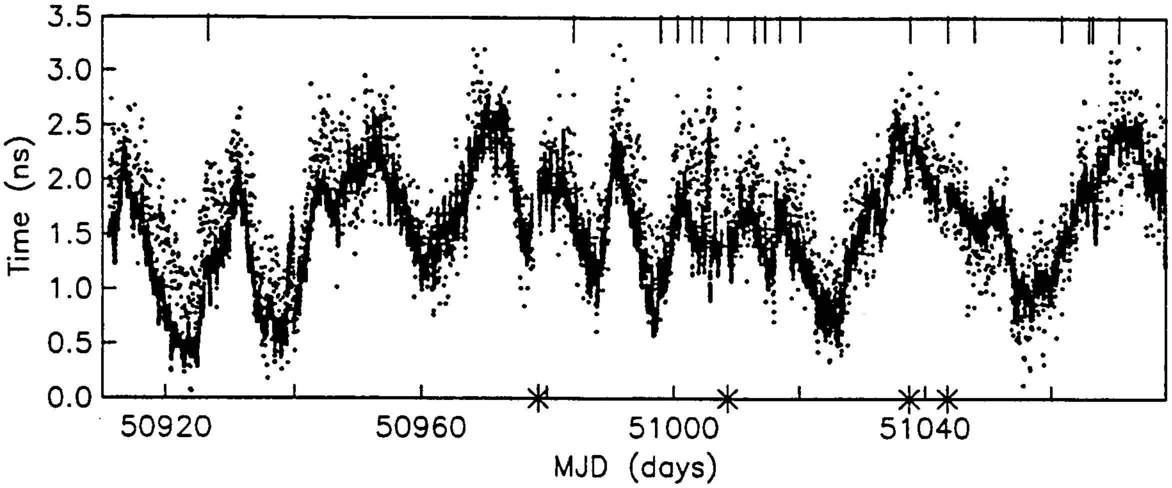

Figure 4: Schriever minus USNO carrier-phase clock estimates, with TWSTT measurements shown as dots. Clock resets are shown as tick marks above. Significant data gaps in the carrier-phase data are shown as asterisks below.

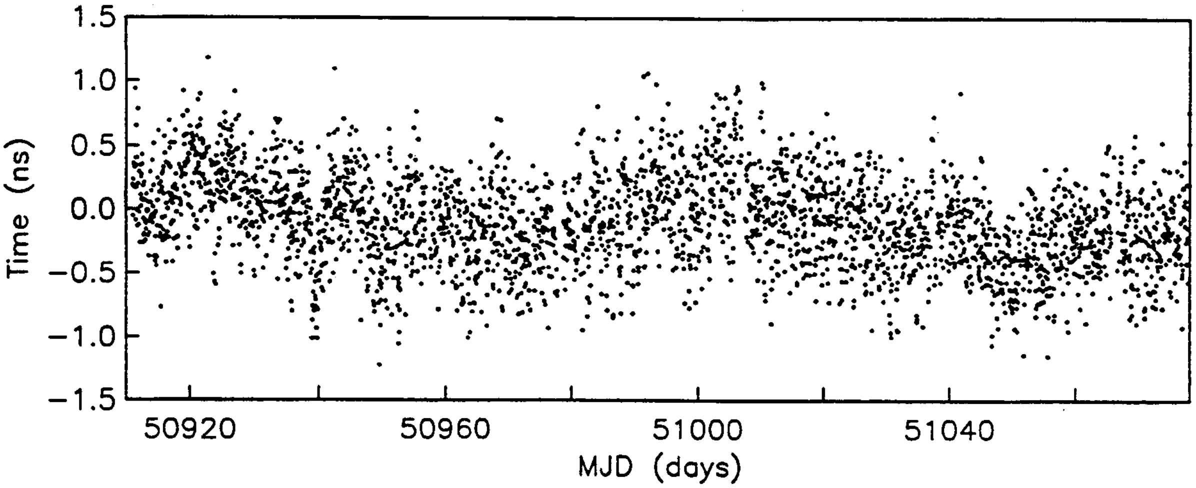

Figure 5: The difference between TWSTT and GPS carrier-phase estimates at common epochs.

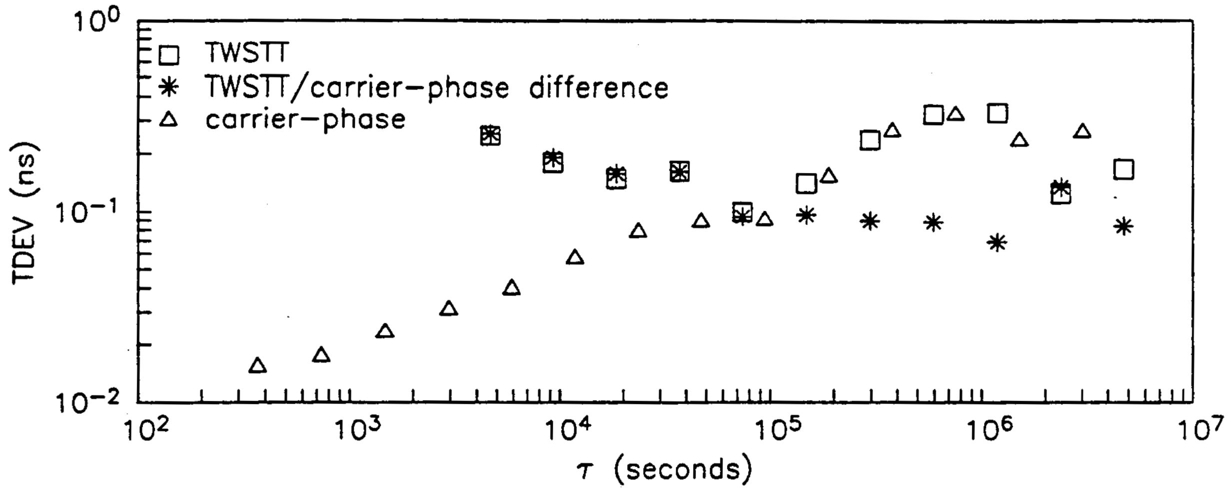

Figure 6: TDEV of GPS carrier-phase, TWSTT, and the difference between GPS carrier-phase and TWSTT.

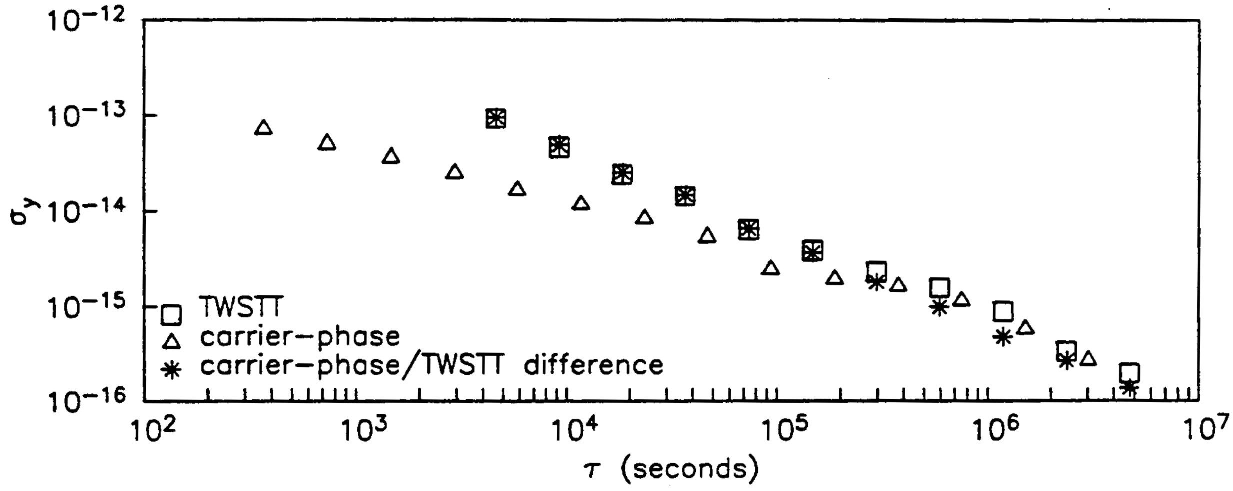

Figure 7: Allan deviation of GPS carrier-phase, TWSTT, and the difference between GPS carrier-phase and TWSTT.