

## TIME TRANSFER USING THE PHASE OF THE GPS CARRIER

*Kristine M. Larson, University of Colorado, Boulder, CO  
Judah Levine, NIST Time and Frequency Division, Boulder, CO*

### Abstract

We have conducted several time-transfer experiments using the phase of the GPS carrier rather than the code as is done in current GPS based time-transfer systems. We connected atomic clocks to geodetic GPS receivers. We then used the GPS carrier-phase observations to estimate relative clock behavior at 6 minute intervals. GPS carrier-phase time transfer is more than an order of magnitude more precise than GPS common-view time transfer, and agrees within error with two-way time-transfer measurements. GPS carrier-phase time-transfer has an uncertainty of 100 psec and a frequency uncertainty of 2 parts in  $10^{15}$  for averaging times of a day.

### Introduction

GPS in the precise time-transfer community has been dominated by the common-view technique, which uses the pseudorange observable and explicit differencing of the GPS data collected at the two timing observatories. Observatories using single-channel single-frequency C/A code receivers routinely report accuracies of 3 ns for a standard 13 minute pass and frequency uncertainty of several parts in  $10^{14}$  over one day [1]. Single frequency multi-channel receivers have also been used for common-view analysis, with recent results suggesting that these receivers are capable of 2.5 ns RMS over short baselines and 5 ns or better over baselines 2400 km in length [2].

In the geophysical communities, where geologic deformation rates are often on the order of 1 mm/yr, the pseudorange observable is not sufficiently precise [3]. Therefore geophysicists use geodetic GPS receivers which measure the carrier of the phase as well as the pseudorange. Using carrier-phase data and geodetic analysis techniques, the accuracy of GPS position estimates are approaching one centimeter for averaging periods of a day [4]. Since clocks and positions are both inherently related to the GPS carrier-phase observable, GPS carrier-phase techniques can also be used for accurate time-transfer.

The potential of GPS carrier-phase for time-transfer has been recognized and described by others [5-9]. In this paper, we describe experiments we conducted to test GPS carrier-phase techniques at both short (200 meters) distances and long distances (2400 km). In all cases we connected atomic clocks to geodetic GPS receivers. We then used these data to assess system accuracy and precision of GPS carrier-phase time-transfer. An important aspect of our analyses is that we compared the results we obtained using carrier-phase meth-

ods with other independent estimates of the performance of the clocks that were connected to the receivers.

### Data Analysis

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

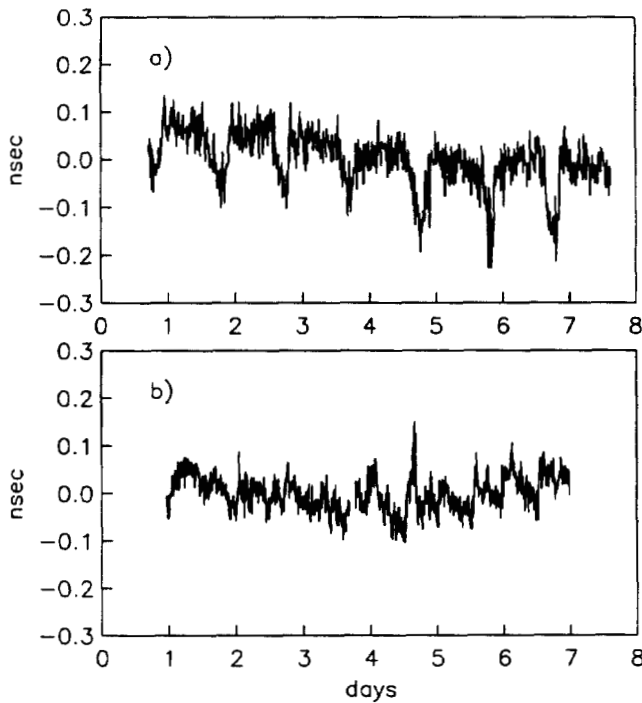
$$-\Delta\phi_r^s\lambda = \rho_g + c\delta^s - c\delta_r + N_r^s\lambda + \rho_t - \rho_i + \rho_m + \epsilon \quad (1)$$

where individual terms are in units of length.  $\lambda$  is the carrier wavelength,  $\rho_t$  and  $\rho_i$  are the propagation delays due to the troposphere and ionosphere,  $\rho_m$  is the multipath error, and  $\epsilon$  represents unmodelled errors and receiver noise.  $N_r^s$  is the initial number of integer cycles, known as the carrier-phase ambiguity or bias.  $\rho_g$  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  $\rho_g$  requires precise transformation parameters between the inertial and terrestrial reference frames, i.e. models of precession, nutation, polar motion, and UT1-UTC. Finally,  $\delta_r$  and  $\delta^s$  are the receiver and satellite clocks, in seconds.

In order to achieve the highest precision carrier-phase results one must model or correct all the terms in equation 1. We used a geodetic software package to analyze the GPS carrier-phase data [10]. Both satellite and receiver clocks are modeled as white noise, so that the estimates are uncorrelated from epoch to epoch. The receiver clock at NIST 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 service [11]. 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. Carrier-phase ambiguities are known to be integers, and the most powerful uses of GPS carrier-phase data require that these integer values be determined. We use an ambiguity resolution algorithm which requires the pseudorange data as well as the carrier-phase data [12]. In order to minimize multipath errors, data observed below elevation angles of 15 degrees are discarded. We have not modeled the multipath component of the data, but will discuss its impact later in the paper.

### Results-Short Baselines

Over short baselines, most geodetic parameters, including clocks, are insensitive to orbit error. This is also true of



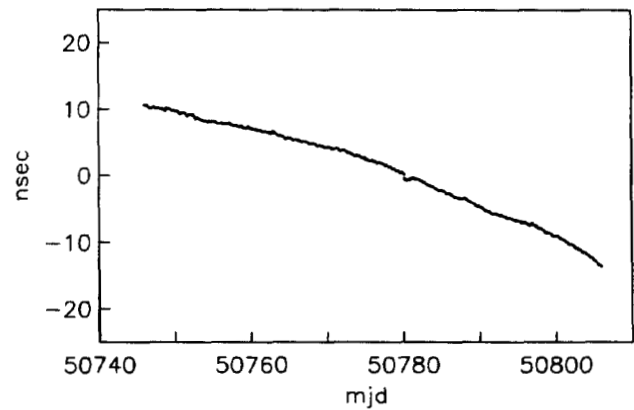
**Figure 1.** Residuals between the carrier-phase relative clock estimates and the local measurement systems. A mean has been removed from each time series. a) NIST short baseline test; b) USNO short baseline test.

atmospheric conditions, which are common to both antennas for a short baseline. The limiting error sources in this case will be multipath and measurement noise.

We have conducted short-baseline experiments in two locales. In each case we connected two geodetic-quality GPS receivers to atomic clocks, and used the GPS carrier-phase data to estimate the difference between the two clocks. We then compared the carrier-phase estimates with the local measuring systems in place. Each baseline was less than 200 meters in length.

In Figure 1a we plot the residual of the carrier-phase estimates to the local clock measurements at NIST. The RMS agreement about the mean of the two series is 55 ps. Note the variations in the residuals which appear to have a 24 hour period. A pure multipath signal will produce identical residuals from day to day, shifted 4 minutes to account for the orbital period. In practice, residuals will also reflect data quality, and changes in the reflective characteristics of the nearby surfaces. There may also be thermal effects in the data, but since the antennas are in the same thermal environment, thermal effects would be evident only if the thermal sensitivities of the antennas were different. As the antennas are the same model and from the same manufacturer, we expect these to be negligible.

We repeated this type of experiment at USNO and the residuals to the local measurements are shown in Figure 1b.



**Figure 2.** Time difference between USNO Clock 52 and NIST Clock 16. A bias has been removed from the time series.

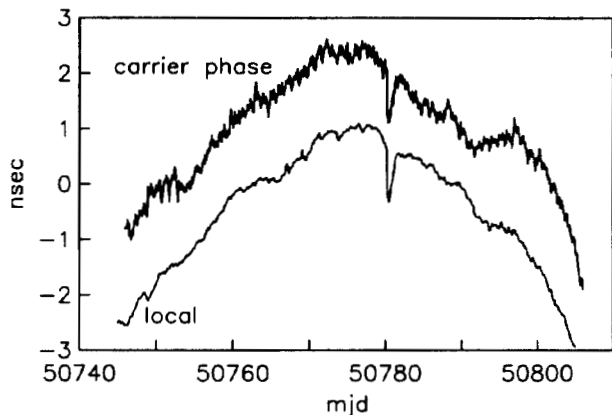
Any multipath signature at this site is significantly smaller than we observed at NIST. The RMS agreement between the carrier-phase estimates and local measurements is 35 ps. The carrier-phase analyses at USNO and NIST are consistent with frequency transfer of 1-2 parts in  $10^{15}$  for averaging periods of a day, in agreement with a zero-baseline test, where one hydrogen maser and one antenna were used to drive two geodetic receivers.[7]

## Results-Long Baselines

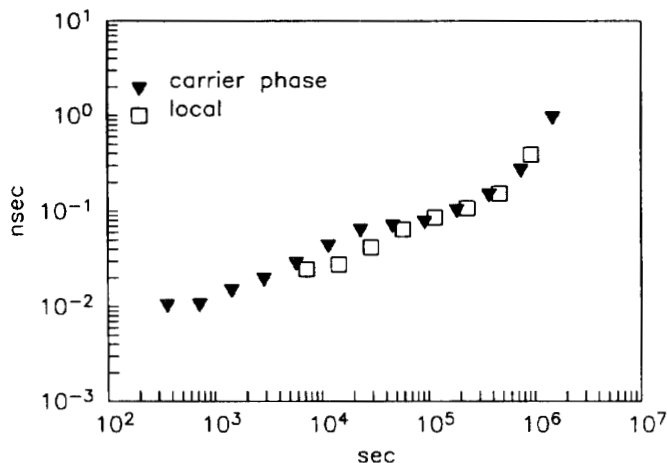
An experiment over a longer baseline is a more realistic assessment of the potential of GPS carrier-phase time transfer. Unfortunately, on longer baselines we are limited in our ability to define a truth standard, which was readily available for the shorter baselines. Time transfer is regularly monitored using two other techniques: GPS common-view and two-way satellite time-transfer systems (TWSTT). Common-view can be conducted frequently but has a precision of several nsec. TWSTT systems are more precise in the short term but expensive to operate. At USNO and NIST, TWSTT measurements are made at most three times a week, for periods of 5 minutes. The time stability for this system is about 1 ns for  $\tau$  of a day [13].

In order to compare the carrier-phase estimates with TWSTT and common-view we first estimate the difference between the clocks connected to the GPS receivers, NIST Clock 16 and USNO Clock 52. Figure 2 shows the difference between NIST Clock 16 and USNO Clock 52 over a 60 day period.

The detrended time series for NIST Clock 16 relative to USNO Clock 52 is shown in Figure 3. This detrending is needed because of the large frequency offset of NIST Clock 16 and the clock used in the comparison between carrier-phase data and measurements obtained using other methods. In addition to long-wavelength features and a diurnal signal, we also note a small transient offset of approximately



**Figure 3.** Detrended carrier-phase estimates of the time difference between USNO Clock 52 and NIST Clock 16; local measurements of the time difference between NIST Clock 16 and NIST Clock 30. A mean has been removed from both time series, and the series have been offset for display purposes.

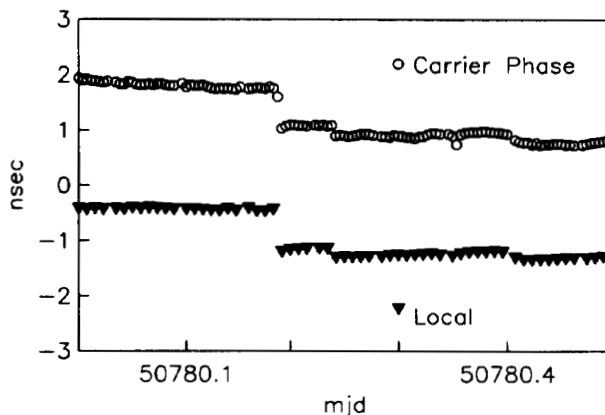


**Figure 4.** TDEV calculations for time series shown in Figure 3.

0.8 nsec near MJD 50780. We can correlate much of what is shown in Figure 3 by inspecting local clock records. In Figure 3 we also show the difference between two hydrogen masers at NIST, Clock 16 and Clock 30. One sees good agreement not only over long periods but also for the transient at MJD 50780. The good agreement between the local NIST measurements and the USNO-NIST carrier-phase estimates is further demonstrated by TDEV calculations for each time series (Figure 4). Transfer noise is limited to periods of less than one day.

In Figure 5 we show a close-up view of the clocks at MJD 50780 for a period of 12 hours. The RMS agreement about the mean between the local clock records and the GPS carrier-phase measurements (between USNO and NIST) is 68 ps.

We can also compare the GPS carrier-phase estimates in

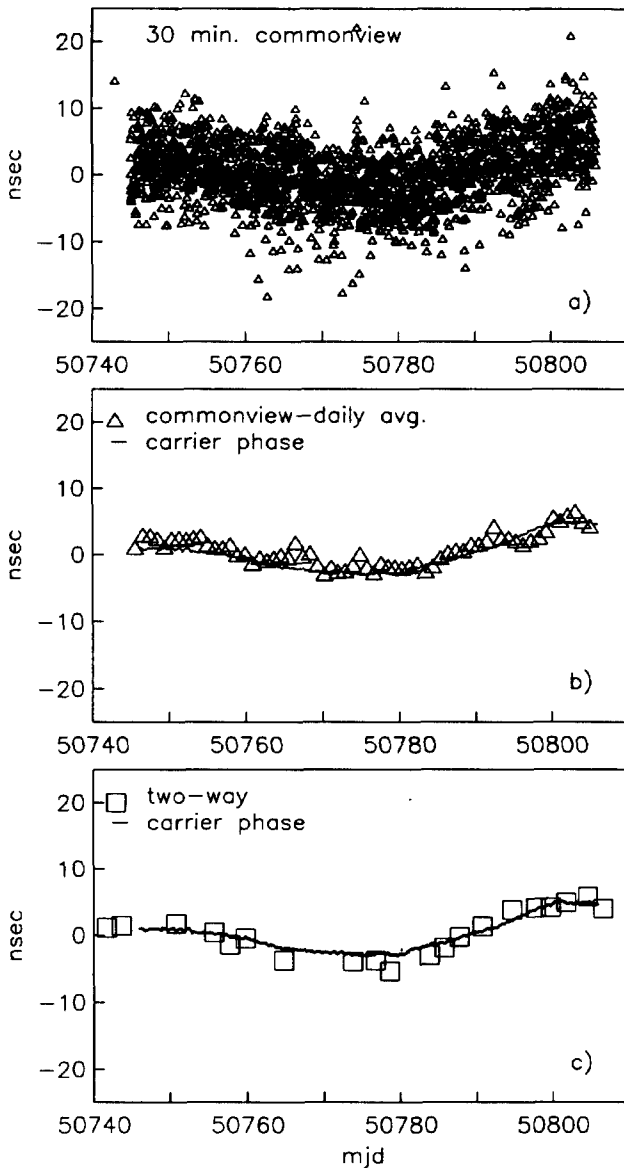


**Figure 5.** Close-up view of the clock difference between USNO Clock 52 and NIST Clock 16 estimated using carrier-phase, and local measurements of NIST Clock 16 relative to NIST Clock 30. A mean has been removed from each time series, but they have not been detrended.

the time domain with common-view and TWSTT. Both of these techniques are used to conduct time-transfer experiments between NIST and USNO. Neither common-view nor TWSTT at USNO/NIST are connected to the clocks we used in the carrier-phase analysis, so we must use local clock records to correct the USNO Clock 52-NIST Clock 16 time series. The correction time series are measured every hour at USNO and every two hours at NIST. We used linear interpolation to correct the carrier-phase estimates. These corrected carrier-phase estimates have not been detrended or altered in any other way, although for plotting purposes, a mean has been subtracted from each time series shown. In Figure 6a we show 30 minute common-view results for the USNO-NIST baseline. If we average the common-view values for 24 hours (Figure 6b), we can begin to see good correlation with the GPS carrier phase analysis. In the last panel we compare to TWSTT. Good agreement between TWSTT and GPS carrier-phase suggests that there is no long-term error in the carrier-phase time-transfer analysis.

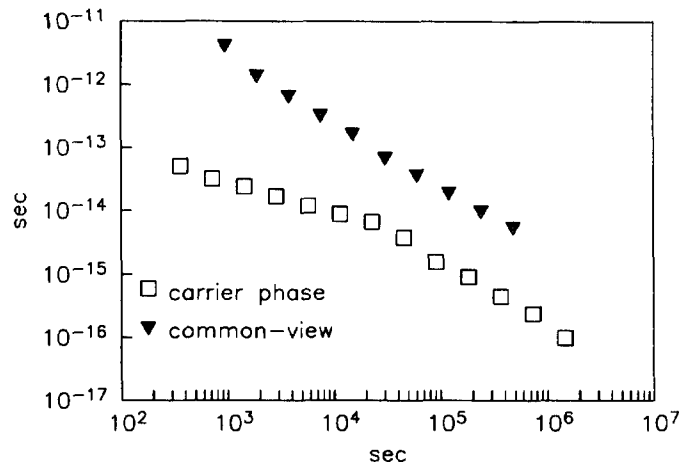
We have also used the USNO-NIST carrier-phase estimates to compute the Allan deviation (Figure 7). For comparison, we have also included traditional common-view analysis for the same baseline and the same 60 day period. Frequency uncertainty for carrier-phase estimates is 2 parts in  $10^{15}$  for averaging times of a day, more than an order of magnitude better than can be achieved with the common-view technique. For periods less than 10,000 seconds, the slope of the Allan deviation is  $\approx -0.5$ . For periods greater than 100,000 seconds, the slope of the Allan deviation is  $\approx -1.0$ .

While TWSTT measurements between USNO and NIST are very limited, hourly measurements using this technique are made between the USNO Alternative Master Clock (AMC) and the USNO Master Clock (MC), located at Falcon

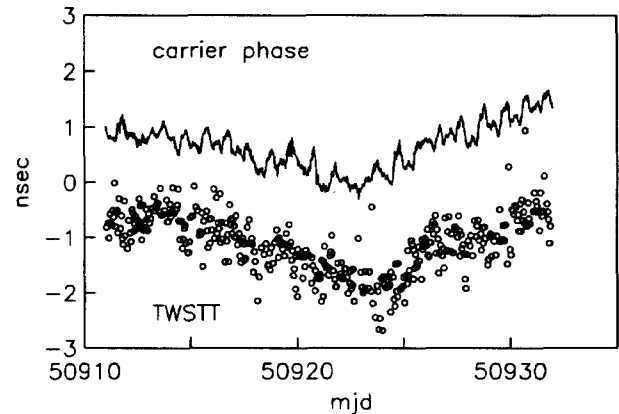


**Figure 6.** a) Thirty minute common-view time estimates between USNO and NIST; b) Daily averages of common-view and carrier-phase; c) TWSTT and carrier-phase. A bias has been removed from all time series for plotting purposes.

Air Force Base and USNO, respectively. A geodetic GPS receiver was installed at Falcon Air Force Base in April 1998 and connected to the Auxiliary Output Generator (AOG) of the AMC. The TWSTT measurements and carrier-phase estimates for a 21 day period for the Falcon-USNO baseline are shown in Figure 8. The agreement between the two systems is good, and consistent within the 200 ps standard errors of the TWSTT system. Nevertheless, the daily variation of the GPS carrier-phase estimates is much larger, 250 ps, than was observed on the NIST-USNO baseline, which was less than 100 psec. It is quite possible that this degrada-



**Figure 7.** Allan deviation of carrier-phase estimates for USNO-NIST, after removal of local NIST Clock 16 behavior. Also shown are estimates using the common-view technique.



**Figure 8.** GPS carrier-phase estimates and TWSTT measurements between Falcon Air Force Base and USNO. A mean has been removed from both time series, and the offset is for display purposes.

tion in precision is due to temperature effects in the cables or antennas.

## Discussion

These results confirm the resolution that can be realized by applying carrier-phase methods to time and frequency distribution. In the long run, however, the usefulness of the technique for frequency comparisons will depend on the stability of the delays and other systematic offsets in the hardware; to be useful for time distribution these biases must be both stable and accurately known. It is not clear at this point whether these requirements can be satisfied with existing receivers.

Previous studies have reported that the delay through the receiver is affected by temperature and similar effects [14]. While these are important issues, they can be solved (or

at least addressed) by appropriate choice of components. Our discussion is directed towards issues that arise from the nature of the phase measurement itself.

All hardware phase measurements are inherently ambiguous because the integer number of cycles cannot be determined as part of the measurement process. The process becomes more complicated in a GPS receiver, since the local oscillator and the GPS carrier are at very different frequencies. The difference between these two frequencies is usually bridged in two steps – a fixed-frequency local oscillator that translates the carrier from L band to a much lower frequency using conventional mixers, and a digital tracking loop that locks onto the heterodyned carrier from each satellite and deals with Doppler shifts and other offsets that are constant or vary at most relatively slowly with time.

This two-step process exploits the best aspects of analog and digital systems, but it introduces a fundamental ambiguity in the phase-measurement process, since the effective delay through the receiver is the sum of the offsets introduced by both procedures. The first requirement for a carrier-phase receiver is therefore that the output data accurately reflect this physical phase delay and not just the digital part of it. The simplest way of realizing this requirement is to ensure that the hardware component of the phase delay is a simple constant that must be determined only once during the calibration of the receiver.

Phase measurements have a second class of difficulties associated with "cycle slips" – jumps of an integral number of cycles in the phase tracking system caused by a noise pulse or by something similar. These events are usually detectable because they have a well-known magnitude. They also stand out because they are large compared to the TVAR of the local clock at short time intervals. The success in detecting and removing them largely depends on their purely digital nature and a-priori defined magnitude. They would not be nearly so easily removed if the receiver responded to the cycle slip by changing the phase of the analog heterodyne oscillator, for example, or by re-initializing the overall system clock. Either of these strategies would change the effective delay through the receiver by an amount that would not necessarily be a multiple of the carrier period and would therefore not be perfectly and unambiguously removed by the cycle-slip detector in the post-processing software.

These problems are present in geodetic measurements as well, but the statistics of the observables are usually more favorable in those situations. The fluctuations in baseline-length data can be modeled as the equivalent of white phase noise (i.e., the velocity between the two stations is essentially 0), or perhaps by white frequency noise (i.e., constant velocity) even for averaging times on the order of days or weeks. Averaging either the data or their first differences is both appropriate and effective in either of these cases. Clock data, on the other hand, are dominated by various flicker (or

random-walk) processes at those averaging times, and averaging times must be kept significantly shorter as a result. It is therefore much more important that glitches and other similar effects be handled in such a way that the inherent resolution of the measurements is not degraded by changes in the effective time delay through the receiver.

It is not clear at this time whether there are any receivers that can satisfy these requirements; the receivers we have used to date do not do so consistently – at least in their normal operating configurations.

## Conclusions

Hydrogen masers at NIST and USNO were connected to geodetic GPS receivers for a period of 60 days. We made no modifications to these receivers. Carrier-phase data from these receivers were then analyzed using geodetic techniques. We have demonstrated time-transfer with an uncertainty of 100 psec and a frequency uncertainty of 2 parts in  $10^{15}$  for averaging times of one day. Carrier-phase time-transfer is significantly more precise than the GPS common-view technique. The comparisons with TWSTT are very promising, although it would be beneficial to compare carrier-phase and TWSTT over a longer period of time, along with careful measurements of local temperature. There remain several important areas for GPS carrier-phase time-transfer research: the stability of receiver biases, thermal sensitivities in antennas, cables, and receivers, troposphere modelling, and multipath mitigation.

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