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CALIBRATION OF CARRIER PHASE GPS RECEIVERS*

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ABSTRACT

With the development of better standards we are investigating the use of GPS carrier phase for time transfer. Currently Two-Way Satellite Time Transfer (TWSTT) can be used as a means to compare two remote clocks at an uncertainty of one part in 10^{14}. Using TWSTT as a baseline, we can show some of the promising results obtained with the GPS carrier phase method of time transfer. We also discuss receiver reset calibration using 1 pps data and differences in our results when using predicted versus precise ephemerides.

INTRODUCTION

For our GPS carrier phase and TWSTT comparisons we use geodetic quality dual-frequency GPS receivers installed at USNO (United States Naval Observatory) and Schriever Air Force Base, which are operated by USNO. These particular receivers simultaneously track up to 12 GPS 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). 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 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.

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 USNO, since MC 2 is the reference for the TWSTT system there, while MC 3 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 fiberoptic system; the measurement system has an observed diurnal variation of about 100 ps peak-to-peak and possible seasonal drifts as large as 1 ns.

We used a geodetic software package developed by the Jet Propulsion Laboratory to analyze the GPS carrier phase data [1]. Details of the data analysis can be found in [2,4]. Along with the other geodetic parameters, we estimated the behavior of AMC 1 relative to USNO (MC 3) every 6 minutes. These clock estimates are very loosely constrained and have no correlation with previous estimates. In other words, the carrier phase clock estimates are not smoothed.

DATA ANALYSIS

We have compared GPS carrier phase and TWSTT measurements over a period of nearly 8 months. During that period the USNO made several changes to the carrier phase system which improved overall system performance. In order to make the changes, there were occasionally periods when one of the receivers was not operating, with one of these periods lasting about a week. Otherwise, carrier phase data outages were infrequent, with occasional gaps either because the receiver stopped tracking or the PC which records the data failed to work properly. The TWSTT measurements are generally made each hour. The USNO makes these measurements available on the World Wide Web, along with Kalman-filter smoothed measurements (http://tycho.usno.navy.mil/gpscp_dd.html). The USNO (MC 3)-USNO (MC 2) data are also made available as hourly measurements; we use linear interpolation on these data to compute the correction to the GPS carrier phase measurements.

Large (400 ps peak-to-peak) diurnal signals were visible in the carrier phase clock estimates. As was discussed in [3], these signals were correlated with local air temperature variations at USNO, suggesting that the cable connecting the antenna to the receiver was responsible. Subsequent experimentation by USNO confirmed that the large temperature coefficient of the cable was responsible for the large diurnal signals; a new cable was then installed, yielding carrier phase estimates with diurnal signals of less than 100 ps. We have used a constant temperature dependence of 40 ps/K to model the data collected before the new

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cable was installed. This constant is only appropriate for the USNO installation, as cable delays are dependent on both the length of the cable and its temperature sensitivity.

Over the 8-month period, there were nine power outages associated with the carrier phase receivers. Each time the GPS receiver was brought on-line after a power outage there was an offset in the carrier phase clock estimates. As we are using geodetic GPS receivers, where clock estimates are not the parameter of interest, the receiver makes no attempt to fix this offset. We have estimated the offset after the fact by fitting the carrier phase estimates to the smoothed TWSTT data. For comparisons between GPS carrier phase estimates and TWSTT, we have adjusted each carrier phase segment by a constant time offset with respect to the smoothed TWSTT data.

The final carrier phase clock estimates are shown in Fig. 1, along with the hourly TWSTT measurements. The GPS carrier phase clock estimates agree well in the long-term with the TWSTT measurements. The 6-minute carrier phase estimates are also more precise than the hourly TWSTT measurements. This agreement is also indicated by the comparison of carrier phase with Kalman-filter smoothed TWSTT (Fig. 2).

Figure 3 summarizes the TDEV information in the two systems. For periods of less than a day, the carrier phase estimates are significantly more precise than those from the unsmoothed TWSTT system, with carrier phase TDEV of 15 to 80 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 AMC 1 is steered to USNO MC 2. 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 1 d (Fig. 4). For completeness, we have also shown the TDEV and ADEV values for both TWSTT and smoothed TWSTT.

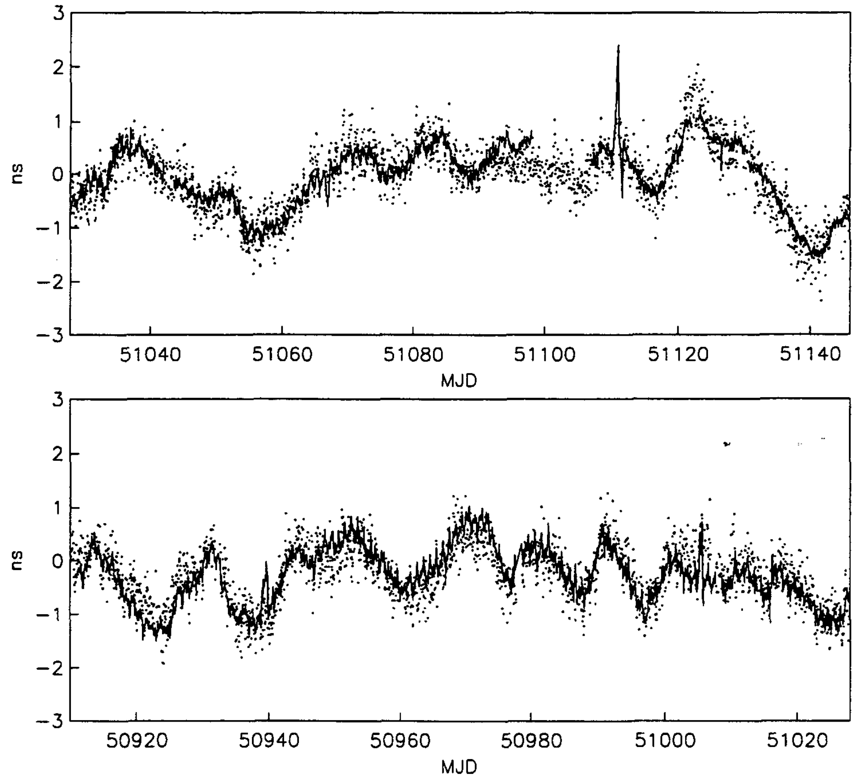

Figure 1: Schriever minus USNO carrier phase estimates, with individual TWSTT measurements shown as dots.

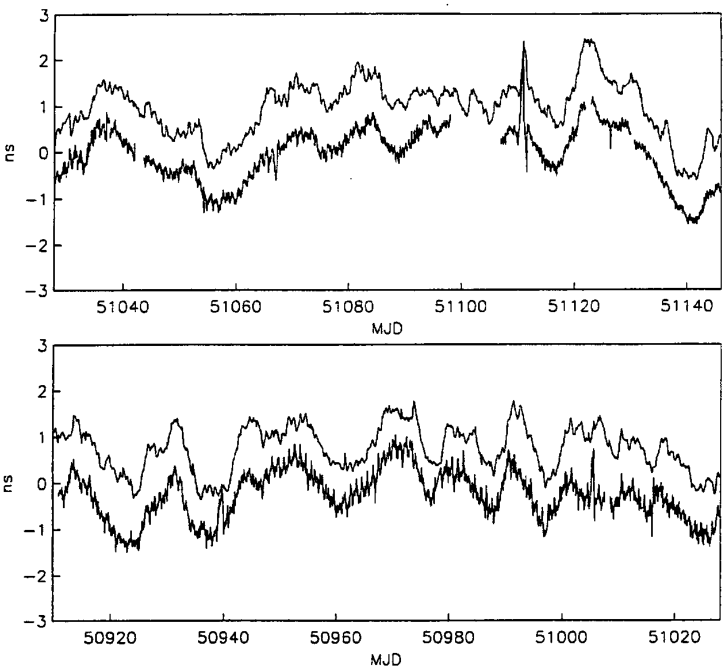

Figure 2: Schriever minus USNO smoothed TWSTT (on top) and carrier phase estimates (below). The measurements are offset for display purposes only.

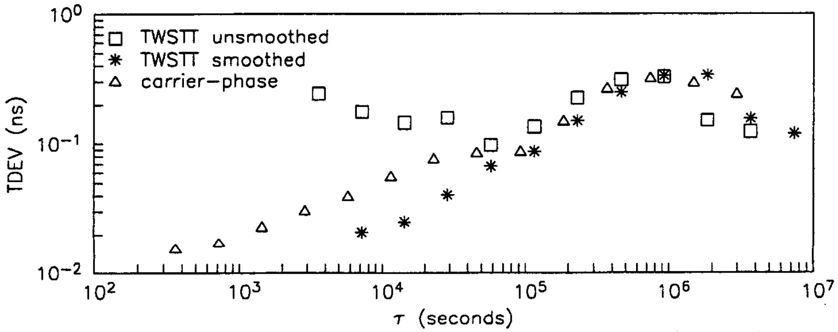

Figure 3: TDEV of GPS carrier phase, unsmoothed TWSTT, and smoothed TWSTT.

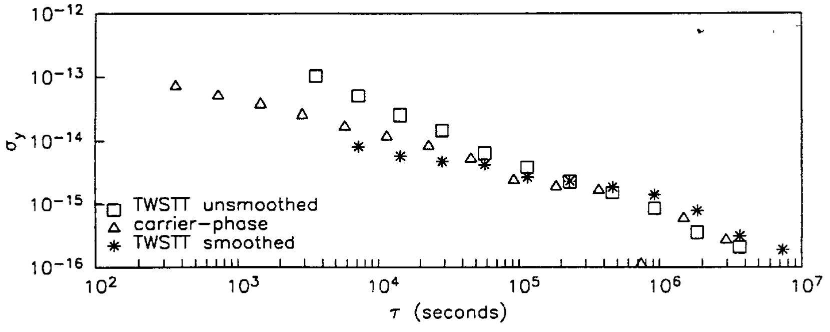

Figure 4: Allan deviation of GPS carrier phase, unsmoothed TWSTT, and smoothed TWSTT.

RESET CALIBRATION USING 1 PPS DATA

Previously we estimated receiver reset offsets by fitting carrier phase data to smoothed TWSTT data. By directly using the 1 pulse/s (1 pps) output from the geodetic receiver we hoped to determine and calibrate the magnitude of resets seen in the carrier phase measurements. The receiver 1 pps output is derived by dividing down the external 5 MHz, and is initially steered by a first-order loop to GPS time. Once the receiver 1 pps has been synchronized to GPS time it follows the external reference. Our hope was that the carrier phase data solution resets would match those of the 1 pps measurements taken with an external counter, which uses UTC(NIST) as its reference. An initial simulated receiver reset had a 50 ns jump that was seen identically in both the 1 pps data as well as in the carrier phase measurements. However, in a subsequent test we saw approximately 40 ns difference between data sets. We plan to investigate this further.

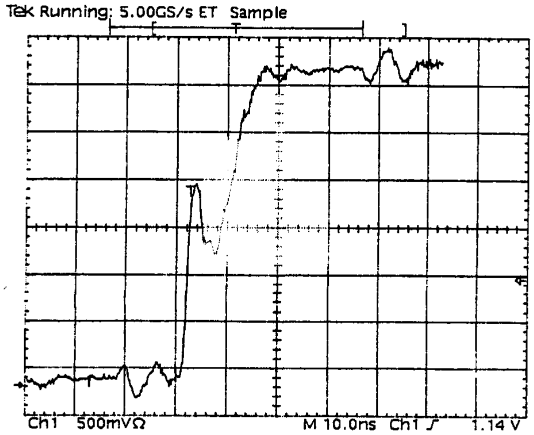

Figure 5: Geodetic receiver 1 pps pulse shape output.

We found another problem with this reset calibration approach because of the shape of the rising edge of the 1 pps pulse output by the receiver. Figure 5 shows the shape of one pulse out of one of the geodetic receivers. The glitch in the rising edge changes shape; depending on the trigger level, it can occasionally force the counter to falsely indicate that a reset has occurred. To remedy the situation permanently we can attach a buffered line driver at the output of the signal from the receiver to smooth the rising edge of the pulse and therefore get a more stable trigger point and accurate reset indication.

PREDICTED, RAPID, AND PRECISE ORBITS

The accuracy of carrier phase time transfer estimates depends greatly on the accuracy of the GPS orbits. We used orbits provided by the International GPS Service (IGS) [5]. These orbits are computed using carrier phase data from over 40 globally distributed dual frequency geodetic quality GPS receivers. The IGS computes 3 different orbit solutions. A precise orbit product that is available with 2 week delay. A rapid orbit that is available in 24 hours and a predicted orbit that is available 24 hours prior to the day of interest. The accuracy of the precise orbits is better than 5 cm. Rapid orbits have accuracies approaching 5 cm, however the predicted orbits can vary daily from cm to m, depending on the satellite in question.

We wanted to look further into the impact of orbits on time transfer analysis. How large are the carrier phase time transfer differences when using the predicted, rapid, or precise orbits? Do they vary daily? The advantage of using predicted orbits is that it allows us to compute time transfer estimates in real time, within 5 minutes like TWSTT, but it is not as accurate. The largest problem is seen when a satellite maneuver takes place, because predicting the maneuver in advance is unlikely. Eclipsing satellites are also not well modeled by predicted orbits. Fortunately, the 24-hour latent rapid data seems to be a good estimate for the time transfer solution. However, to do real-time time transfer one would need to develop software to identify poorly modeled orbits.

In earlier carrier phase analysis our carrier phase measurements experienced some divergence from TWSTT data. The separation resulted from using predicted orbits rather than rapid or precise orbits in our analysis. At that time, only the predicted orbits were available, and this prevented us from getting an accurate solution. Using predicted values resulted in many outliers that forced our solution to drop some individual satellite data completely.

Figures 6-7 show how the precise orbit results differed from the rapid and predicted orbits for MJDs 51087 and 51094. The difference between the rapid-precise and predicted-precise orbit clock solution estimates for USNO-AMCT vs. USNO in our comparison can be seen in Fig. 6. There is a maximum of 0.7 ns difference between the rapid and predicted orbit clock estimate value differences. The predicted orbit difference from the precise orbit in Fig. 7 varies 3 ns over one day. Overall the difference between the rapid and precise orbits is small, but the predicted orbit clock estimate differences can prevent us from getting good initial solutions due to the large number of outliers that are produced resulting in nanosecond variations.

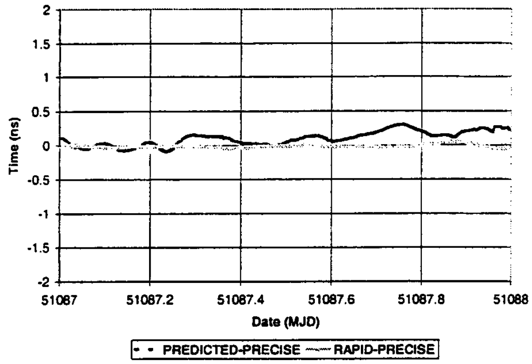

Figure 6: Differences between precise and predicted and precise and rapid orbit carrier phase time transfer solutions between AMCT and USNO for MJD 51087.

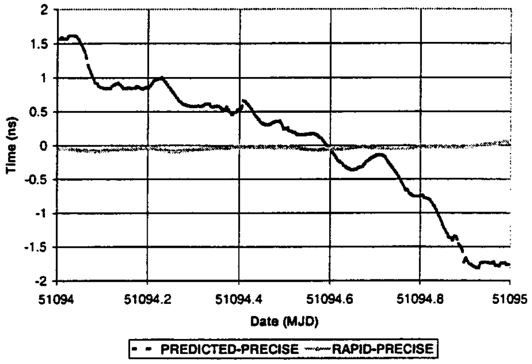

Figure 7: Differences between precise and predicted and precise and rapid orbit carrier phase time transfer solutions between AMCT and USNO for MJD 51094.

CONCLUSIONS

The high quality TWSTT link between Schriever Air Force Base (AMC 1) and USNO (MC 2) provides a unique opportunity to determine the relative long-term stability of TWSTT and carrier phase links. The carrier phase data in the USNO-AMC/USNO link (after temperature correction) have exhibited stability well below 100 ps. The long-term agreement between TWSTT and carrier phase over this eight month period is better than 1 ns.

The issue of calibrating the GPS carrier phase receiver resets using 1 pps data gave inconclusive results. It is of great importance to be able to estimate the magnitude of receiver resets during power outages. In order for geodetic receivers to provide a time-transfer system, this calibration must be done. We have also shown the importance of using precise orbit information in GPS carrier phase analysis.

ACKNOWLEDGEMENTS

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REFERENCES

[1] S. Lichten and J. Border 1987, ``Strategies for high-precision Global Positioning System orbit determination,' *Journal of Geophysical Research*, 92, 12,751-12,762.

[2] K. Larson and J. Levine 1998, ``Time-transfer using the Phase of the GPS Carrier,'' Proceedings *of the 1998 IEEE International Frequency Control Symposium*, pp. 292-297.

[3] K. Larson, L. Nelson, J. Levine, T. Parker and E. Powers 1998, ``A long-term comparison between GPS Carrier-Phase and Two-Way Satellite Time Transfer," *Proceedings of 30th Annual Precise Time and Time Interval Systems and Applications Meeting*, in press.

[4] K. Larson and J. Levine 1999, ``Carrier-Phase Time-Transfer," *IEEE Transactions on Ultrasonics, Ferroelectronics and Frequency Control*, in press.

[5] G. Beutler, I.I. Mueller, and R.E. Neilan 1994, "The International GPS Service for Geodynamics (IGS): Development and start of official service on January 1, 1994," *Bulletin Geodesique*, 68(1),39-70.