GPS Carrier Phase Analysis Noise on the USNO-PTB Baselines

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Abstract **Carrier Phase GPS observations between a geodetic receiver at the Physikalisch-Technische Bundesanstalt (PTB) and two geodetic receivers at the USNO are processed using applications and extensions of the GIPSY and Bernese GPS Software packages. Their results are compared with Two Way Satellite Time and Frequency Transfer (TWSTFT) data. It is found that algorithms that eliminate day-boundary effects require careful handling in the presence of receiver instrumental delays. Depending upon the approach chosen, time differences of several ns and frequency differences of up to 100 ps/day can develop between solution types.**

I. Introduction

Time and frequency transfer using GPS carrier phase measurements [1, 2] is currently a widely accepted method for high precision applications. It provides consistent, precise clock information with a high temporal resolution in large networks. The method can also be applied for frequency comparisons [3].

Independent daily time-transfer solutions frequently show discontinuities of up to 1 ns at the day-boundary due to noise in the code (pseudorange) data. Code data provide timing information but because they are much noisier than the (carrier) phase data, they are usually weighted much less than the phase data, which provide frequency. The GIPSY GPS software (developed by JPL) can mitigate day-boundary discontinuities by applying a continuous Kalman filter across consecutive days [4]. Recently, extensions of the Bernese GPS Software package (developed by AIUB) have been developed that remove day boundary discontinuities through the method of ambiguity stacking [5], which passes ambiguity information across day boundaries by reconnecting the phase ambiguity parameters of consecutive days.

Using different algorithms within GIPSY and the Bernese GPS Software, data from three geodetic receivers were processed for the interval October 1, 2005 through January 31, 2006 (MJD 53644-53766) and the results compared. The receivers were all Ashtech Z12T units. The two at the USNO are attached to antennas 150 meters apart, with IGS designations USNO and USN3. USN3's clock reference is UTC(USNO), and the receiver USNO's data can be re-referenced to UTC(USNO) through the use of interpolated hourly ground measurements [4]. Both of the USNO time references are steered masers. The geodetic receiver at the PTB is designated PTBB, and its reference is cesium-based. In this work PTBB's frequency transfer with receivers at the USNO is measured against the TWSTFT link between the PTB time references and the USNO Master Clock [6]. For the purpose of this work, all GPS-derived time series were adjusted to zero the first point in each time series because only one of the geodetic GPS receiver systems is calibrated (and therefore none of the GPS baselines is calibrated).

II. GPS Data Processing

The GIPSY software was run in Precise Point Positioning mode using USN3-referenced satellite clocks. USN3 is directly tied to UTC(USNO) as a reference. Independent daily solutions were generated for the entire interval, and continuously filtered solutions were produced over selected intervals. The receiver USNO uses a reference that is steered to UTC(USNO), and its data were corrected to UTC(USNO) using fiber-optic links [4].

Alternative independent daily solutions were generated for comparison using Version 5.0 of the Bernese GPS Software. The ambiguity stacking method was used to generate a continuous time transfer solution using code and phase measurements as well as a continuous frequency transfer solution using only the phase data. Because in the latter sense no code measurements are introduced the impact of multipath is reduced and the solution is insensitive to variations in the code receiver biases (induced, e.g., by changing environmental conditions or by episodic changes, such as at MJD 53692 for USNO).

III. Independent Daily Solutions

Previous work [4] found only subnanosecond systematic time differences between the independent daily operational solutions from the USNO (using GIPSY) and AIUB (using Bernese GPS Software) analysis centers. The bias differences are not zero, but almost always significantly less than 200 ps. When GIPSY's continuous filter solution was introduced in [4] no systematic time differences with GIPSY's conventional independent daily solutions were identified.

With data from the past 5 years, we have confirmed the consistency of the pairwise time differences between the operational USNO and AIUB solutions. We have also noted that the average daily frequency differences (determined by fitting an average and rate to each day's time differences) between the two software sets usually differ by less than 100 ps/day in both range and (nonzero) bias. The statistics of the time differences for the baselines described in this paper are summarized in Table 1.

IV. Long Baseline Comparisons

Figure 1 shows the differences between the GPS solutions types for the clock differences on the

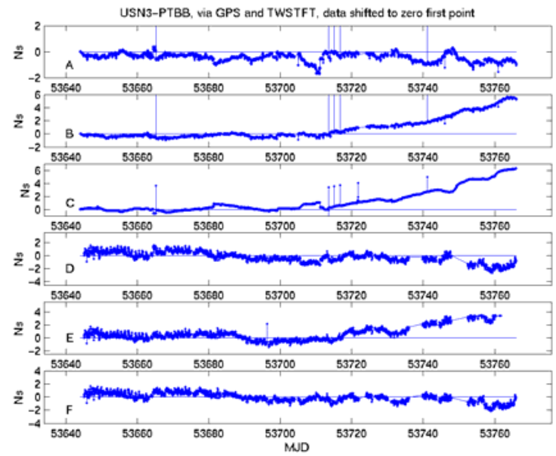

Figure 1. Comparison of GPS analyses with each other and with TWSTFT for the baseline USN3-PTBB. Top plot, labeled A, is Bernese Code+Phase minus GIPSY; B is Bernese Phase Only minus GIPSY, C is Bernese Phase Only minus Bernese Code + Phase. Lower three plots, labeled D, E, and F are Bernese Code+Phase, Bernese Phase Only, and GIPSY, each minus X-Band TWSTFT.

baseline between the receivers designated USN3 and PTBB. TWSTFT X-band measurements are included as an independent reference. The analogous comparisons for the receivers USNO and PTBB are shown in Figure 2.

In both figures the phase-only solutions develop a frequency offset at about MJD 53710, of over 100 ps/day. This effect is still not completely understood. For other stations equipped with other receivers, analogous behaviors were reported [3,7].

Figure 2 shows a 2 ns jump in some of the solutions, at about 15:00 UTC on MJD 53692. This has to be assigned to the GPS station USNO, whose rinex data files were missing two 30-second entries near 18:18:00. The solution residuals indicate a discontinuity of 2 ns in the code data whereas the phase measurements are continuous during this period. This indicates a

Table 1. Statistical properties of time differences between GIPSY and Bernese GPS Software independent daily operational solutions by USNO and AIUB.

Baseline	MJD	Num. points	AVE ns	RMS ns	RMS of 1^{st} Diff. ns/day
USNO-USN3	53275-53854	115K	.002	.072	.023
USN3-PTBB	53273-53854	148K	.065	.117	.123
USNO-PTBB	52285-53854	331K	.047	.173	.037

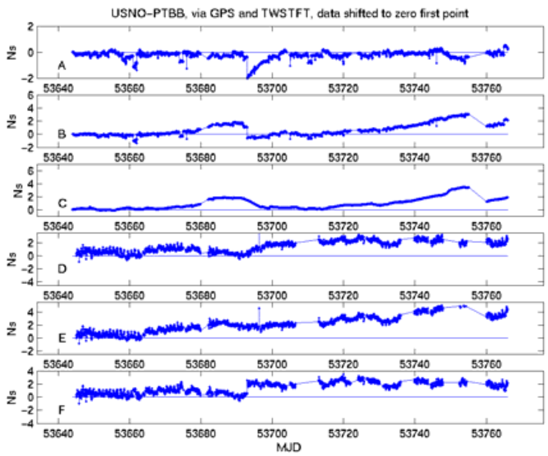

Figure 2. As in Figure 1, but for the baseline USNO-PTBB. TWSTFT data are tied to the receiver USNO using fiber-optic measurements.

variation in the receiver's code delay. Such instrumental variations have previously been reported, and can be temporary or indefinite in duration [5,8].

V. Short Baseline Comparisons

The time series obtained with the two continuously working algorithms of the Bernese GPS Software and the daily independent solution from the GIPSY software for the 150 meters baseline between USN3 and USNO are shown in Figure 3. The data are reduced to a common clock by applying the interpolated hourly fiber-optic measurements between stations USN3 and USNO as described in [4]. The differences between the three solutions are shown in Figure 4. In Figure 3 features can directly be addressed to one of the GPS solutions or receivers whereas the comparison in Figure 4 is independent of the local measurement between USN3 and USNO.

Both figures contain the 2 ns jump in the instrumental delay for the code data in the receiver of USNO at MJD 53692.7. Because only the code but not the phase measurements are affected, this results in an inconsistency between these two observation types. This is of course a problem for a combined analysis. Figure 3 confirms that the phase-only solution is, as expected, insensitive to the code variation. This may be seen as an advantage of the phase only solution strategy.

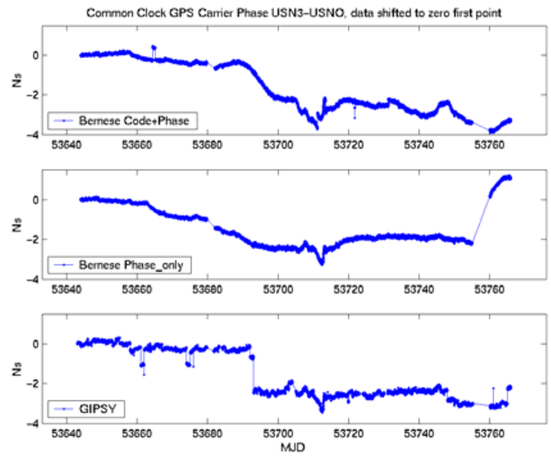

Figure 3. Three GPS solutions for the 150-meter USN3-USNO baseline. The solution for the GPS receivers USN3 and USNO are reduced to a common clock using local measurements. The notation is as in Figure 1.

For the combined analysis of the code and phase data the consistency must be recovered by correcting either the code or the phase data. This requires of course a reliable detection of the jumps during the preprocessing of the data. This was implemented into the Bernese GPS Software in the context of the ambiguity stacking algorithm for events with a magnitude greater than 15 ns [5].

The event at 53692.7 was not specially accounted for by any of the GPS solutions, so it is interesting to see how the results are affected.

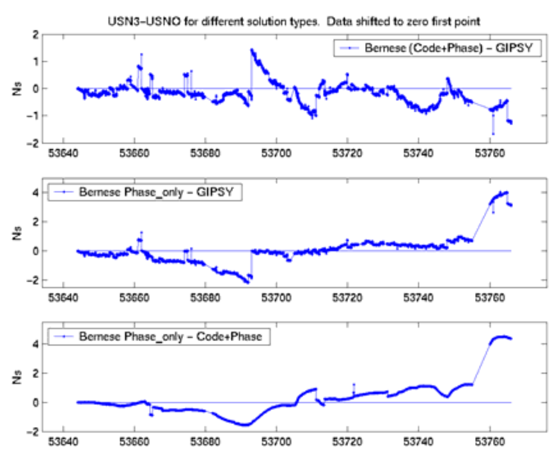

Figure 4. Difference between the GPS solutions for the baseline USN3-USNO. The notation is as in Figure 1.

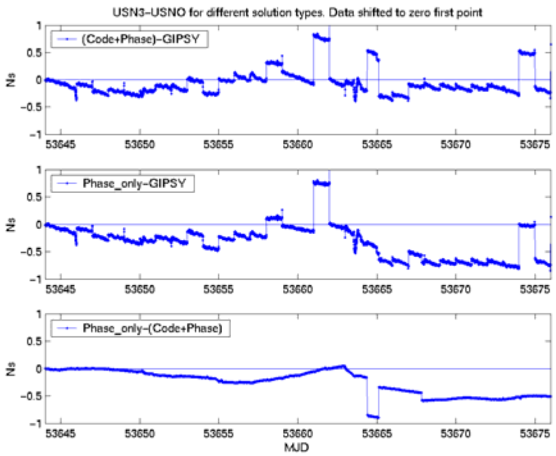

Figure 5. Detailed plot of the differences between the solutions for the 150-m baseline USN3-USNO over October, 2005.

Figure 3 shows that the independent daily solutions by GIPSY responded by producing two large discontinuities at the day boundaries that absorb the 2 ns discontinuity. This immediately incorporated the receiver's delay change into the analysis. The independent daily solution obtained with the Bernese GPS Software responded in the same manner as GIPSY. Ambiguity stacking is designed to eliminate day-boundary discontinuities to provide continuous solutions. In a combined analysis of the code and phase measurements, the result was to gradually introduce the variation over several days. A similar effect would be expected in a continuous Kalman filter as used for a continuous GIPSY solution. The number of days that are affected depends on the weighting scheme between the code and phase measurements.

There are also several short spike-like features in the solutions using the two Bernese ambiguity-stacking methods. These are due to lack of valid data for the algorithm to use for connectivity.

The lowest plot in Figure 5 is the difference between two continuous solutions of the Bernese GPS Software. Nevertheless, a few discontinuities can be found in their difference: MJD 53664 at 09:00 UTC, MJD 53665 at 02:50 UTC, and MJD 53667 at 20:05 UTC. At these three epochs the ambiguity parameters have been interrupted to prevent inconsistencies between the code and phase data in the combined analysis as it has been discussed for the event at MJD 53692.

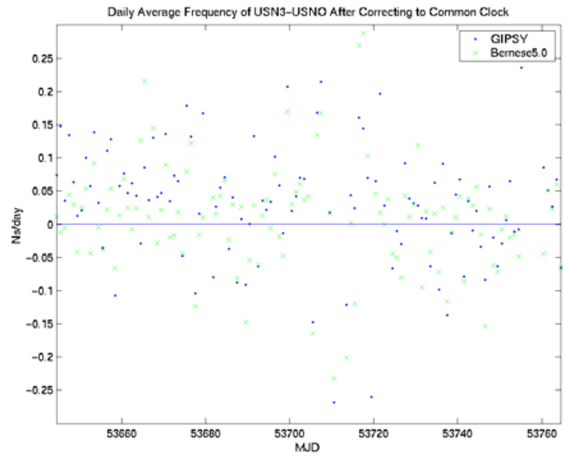

Figure 6. Frequency fitted to phase data over individual days for the independent daily solutions of both software packages under investigation Initially, the frequencies fitted to GIPSY-determined phases appear biased away from the zero slope expected in common clock differences.

The 3 ns discontinuity in the phase only solution for USNO after MJD 53760 immediately follows a 4-day data gap for the receiver USNO. It has no physical meaning since the phase measurements do not provide any time information, and the ambiguities cannot be reconnected over this interval. This demonstrates a disadvantage of the phase only solution, since the result contains two completely independent parts with independent timing information. Figure 5 shows some of the features in greater detail, as well as the day-boundary discontinuities in the GIPSY independent daily solutions.

It was observed that the daily independent GIPSY solutions are often frequency shifted with respect to the continuous solutions obtained by the Bernese GPS Software package. The magnitude is steady in the short run, and can be up to 100 ps/day. The frequency shift of the GIPSY solution is not observed in the analogous independent daily solutions obtained from the Bernese GPS Software (Figures 6 and 7), and should not be present in common clock solutions. As reported in [9] the observed frequency variations in the GIPSY solution can be brought about by ambiguity fixing, or direct networking. The impact of these different processing modes of GIPSY on the frequency and time transfer results needs further investigation.

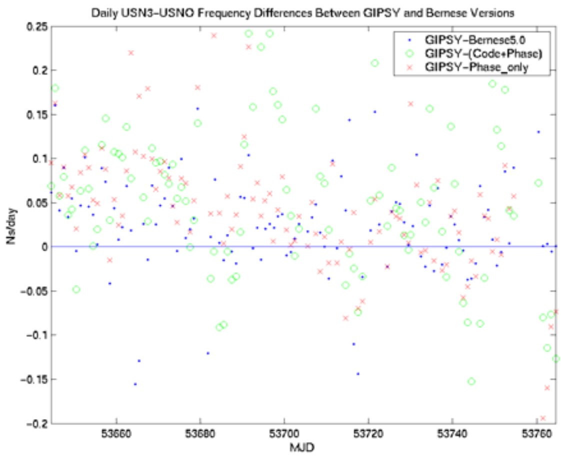

Figure 7. Difference between fitted daily slopes of common clock USN3-USNO data from GIPSY independent daily solution and three Bernese solution types.

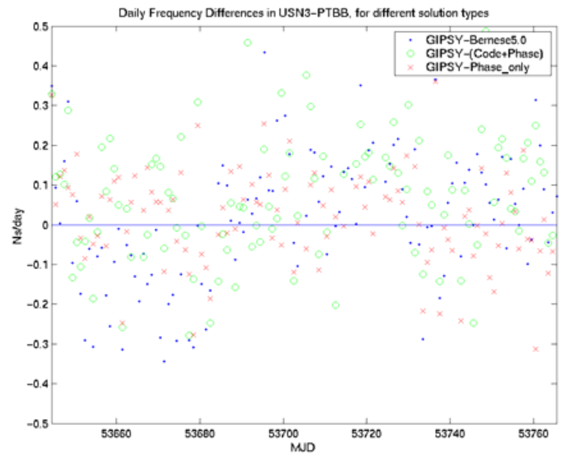

Figure 8. Difference between daily average frequencies of USN3-PTBB, determined by GIPSY with those determined by Bernese GPS Software solutions.

Because GPS common clock data were not available on the USN3/USNO-PTBB baselines, only clock differences are presented. Similar effects are evident, as shown in Figure 8. Note that the frequency variations evolved over 10's of days.

It was also noted that the last 5-minute point of each day in GIPSY's independent daily solutions displays more variation than the other points. This can only be seen when the reference clocks at both ends are masers. In such cases, the difference between each point and its preceding point is typically 20-30 ps, however the last point shows a variation over double that.

VI. GIPSY Continuous Kalman Filter on the Short Baseline

Seventeen days of the baseline USN3-USNO from MJD 53659-53676 (October 2005) were processed with the GIPSY software's continuous filter baseline. The results are consistent with [4], in that they tracked the independent daily solutions while being free of day-boundary discontinuities. Figure 9 compares the GIPSY independent daily and continuous filter results with the continuous solutions generated with the Bernese GPS Software package. In Figure 10 the corresponding fitted daily slopes are compared.

As noted previously, the most positive slopes are from GIPSY independent daily solutions. Similar solutions with Bernese 5.0 are slightly less positive on the average, while the continuous filter and ambiguity-stacking solutions are most consistent with the zero mean expected in common clock frequency differences.

VII. Discussion

The ambiguity stacking algorithm implemented in the Bernese GPS Software successfully removes day-boundary discontinuities due to variations in the code data, as do the continuous filter GIPSY solutions. A semi-persistent daily frequency offset between the software packages can be present, which on the USN3-USNO baseline appears only in the independent daily GIPSY solutions. It does not appear in any of the Bernese solutions or the continuously-filtered GIPSY solution.

It is up to the user to decide what sort of algorithm would be best for a given hardware instability level and data requirement. Independent daily solutions lead to discontinuities at the day boundaries, but can give a quick warning of receiver delay discontinuities. The other approaches are free of day boundary discontinuities, but could incorporate true receiver delay variations so gradually they would not to be noticed. Combinations of different solutions coupled with clock steering could combine the benefits of each technique, but would increase the required level of complexity.

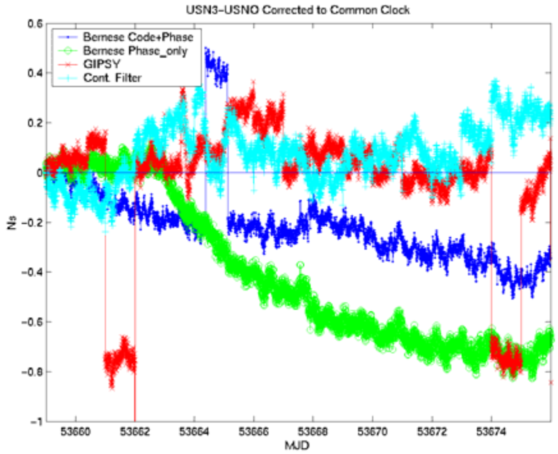

Figure 9. Four different solutions of USN3-USNO GPS data over nearly three weeks. The solution for the GPS receivers USN3 and USNO are reduced to a common clock using local measurements. Solutions identified as GIPSY are independent daily solutions. Cont. Filter refers to continuous Kalman filter solutions also generated with GIPSY.

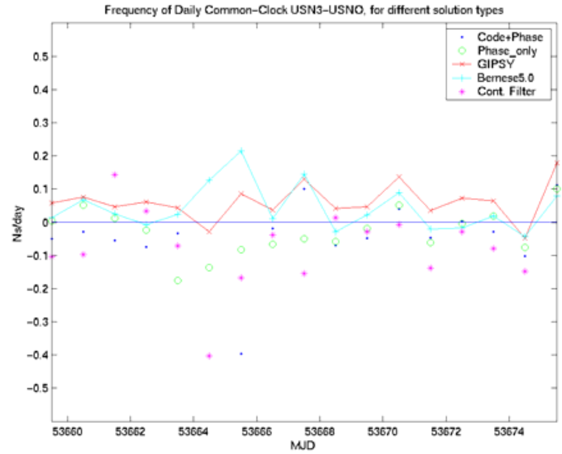

Figure 10. Daily average fitted frequency of software solutions over 17 days on the short baseline. Data on MJD 53664, 53665, and 53667 required ambiguity resets as noted in text. For clarity, only independent daily solutions points are connected.

VIII. Disclaimer

We caution that our observations of receiver performance are valid for the particular environment and receivers employed for the data-taking. Other receivers made by their manufacturer and other manufacturers' geodetic receivers, antennas, or environments may show a different pattern of delay variations.

IX. Acknowledgements

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X. References

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