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UNDERSTANDING LIMITATIONS OF GPS CARRIER PHASE FREQUENCY TRANSFER ON A TRANSATLANTIC BASELINE

Lisa M. Nelson and Judah Levine, NIST, Time and Frequency Division, Boulder, CO 80305-3328

Abstract

This work is made in an effort to determine and understand the limitations of GPS carrier-phase frequency transfer between the National Institute of Standards and Technology (NIST) in Boulder, Colorado and the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. Here we compare two analytical software packages and report on possible reasons for differences in results. Specifically we look at bias fixing, merging routines, data outages, and sampling and analysis period effects. We hope to determine and reduce the contributions of these effects and lower the overall error budget of the carrier-phase GPS comparison technique.

Introduction

In past work [1] nanosecond level differences were observed between clock comparisons at NIST and PTB using two different techniques of time and frequency transfer: Two-Way Satellite Time Transfer (TWSTT) and GPS carrier-phase (CP). In this work we attempt to understand the reasons for these differences. The carrier-phase analysis uses 6 network stations to compare frequency standards at NIST and PTB. Figures 1 and 2 show the configuration of the GPS receiver and TWSTT station at each location, with their respective hydrogen maser frequency references. AOG2 is the Auxiliary Output Generator #2 that is steered to UTC(NIST). UTC(NIST) is generated from an ensemble of hydrogen masers. H2 is a hydrogen maser located at PTB. Four other stations, seen in Figures 3 and 4, are also used in this analysis to help resolve ambiguities and estimate coordinates of reference stations. More information about the network selection is given in [1].

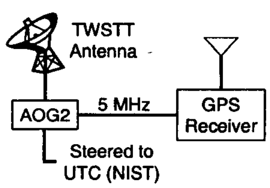

Figure 1. Configuration of NIST TWSTT and CP.

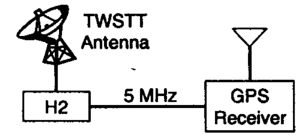

Figure 2: Configuration of PTB TWSTT and CP.

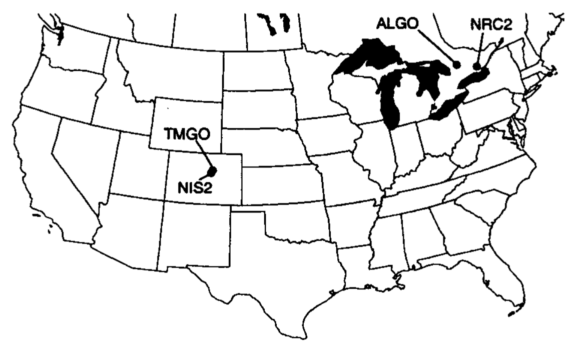

Figure 3. North American Network Stations.

Figure 4. European Network Stations.

Results

In Figure 5 the TWSTT and CP data are shown comparing the time difference of PTB's hydrogen maser H2(PTB) with UTC(NIST). The TWSTT data are plotted on top of the GPS carrier-phase data for comparison. TWSTT data, shown by asterisks, are nominally recorded every Monday, Wednesday, and Friday. The GPS carrier-phase technique estimates the relative clock behavior at 6-minute intervals, shown by the solid line. The dotted vertical lines show when jumps occur in the carrier-phase data; their correction will be discussed later in this section

Over the long term the TWSTT and carrier-phase data are in close agreement. For instance, there was a frequency change in H2(PTB) on Modified Julian Day

(MJD) 51858, which both techniques similarly observed. Unfortunately, a reliable comparison between CP and TWSTT during the period of MJD 51925-52018 cannot be made because of problems with H2(PTB) and outages in the TWSTT link. Around MJD 51925 H2(PTB) began experiencing fluctuations and on MJD 51967 TWSTT started having outages. H2(PTB) was back to normal operation as of MJD 52018. The TWSTT anomalies were somewhat resolved after MJD 51993; however, equipment changes continue to be made over this link.

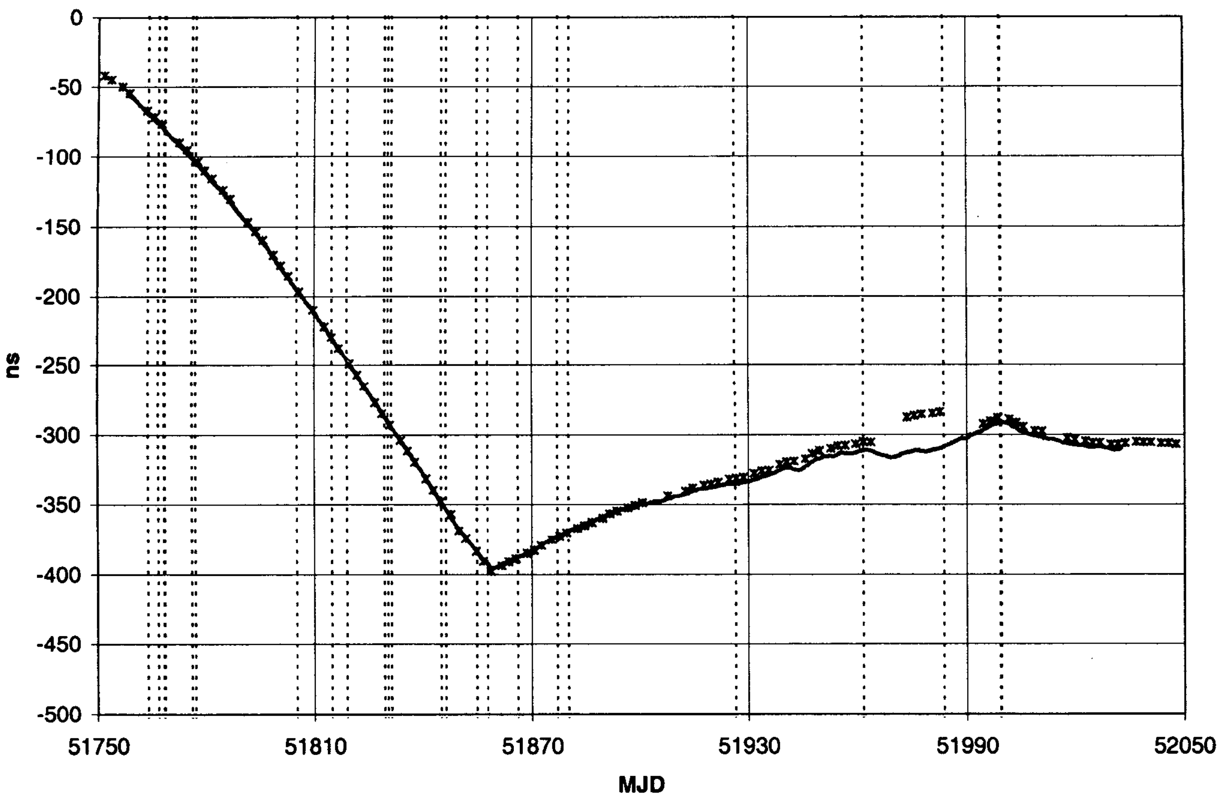

Figure 5. H2-UTC(NIST) TWSTT and GPS carrier-phase solutions over a period of approximately 270 days. The TWSTT points are taken every 2 to 3 days and the carrier-phase points are taken every 6 minutes. The vertical dashed lines indicate data outages or jumps in the data.

Carrier-phase jumps/outages

Data outages, or jumps, in the carrier-phase data normally result from the receivers losing lock, from satellite maneuvers, or from equipment changes at the network station locations. However, because of the large number of variables and instances when outliers in the data do not directly correspond to any of these events, it is very difficult to resolve all of the outages into just these three specific categories. This makes it extremely difficult to determine the "true" source of each outage or jump.

Currently we bridge the gaps in the data by using the slope of the previous 12 hours of data to estimate where the next series of data should begin. We have found this to produce data that compares favorably with the TWSTT solution. However, this assumes that there are no frequency changes in the clocks we are comparing over the interval of the gap. Since we normally know when frequency changes occur, this works reasonably well, but not always. For this reason, there are still issues that need to be resolved, especially when bridging across outages that span a significant length of time.

Comparing TWSTT and Carrier-phase Results

Using daily interpolated values for TWSTT and the corresponding daily point from the carrier-phase 6-minute data we compared the results from the different transfer techniques more closely. Figure 6 shows the daily difference between the TWSTT and carrier-phase solution for H2(PTB)-UTC(NIST). The thin line indicates the daily differences in the period where there were problems with TWSTT and H2(PTB). Unfortunately these problems forced us to concentrate on the data prior to MJD 51925, shown by the thick black line. For this period, there is approximately ± 2 ns difference between the two techniques. Initially the differences appear that they may have an annual fluctuation. However, until we are able to get a longer span of data without interruptions it will be difficult to determine the cause of the difference between the two techniques. In any event, the results are promising.

The statistics for the difference between TWSTT and CP for the first 170 days are shown in Figures 7 and 8. Figure 7 shows the overlapping Allan deviation and the Total deviation at 3×10^{-15} at one day. Figure 8 shows the Time Total deviation and the Time deviation at 200 ps at one day. In [2] the cesium fountains at NIST and PTB are compared by using portions of this series of carrier-phase and TWSTT data.

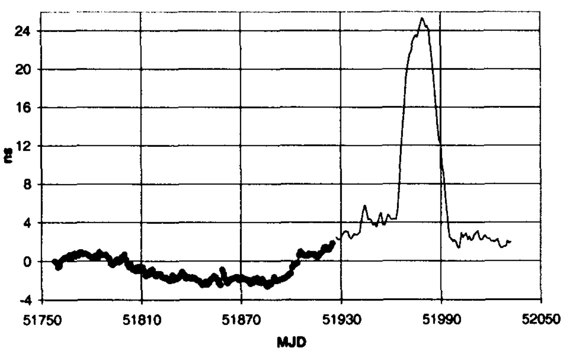

Figure 6. Interpolated daily values of TW and daily CP for the bias fixed case.

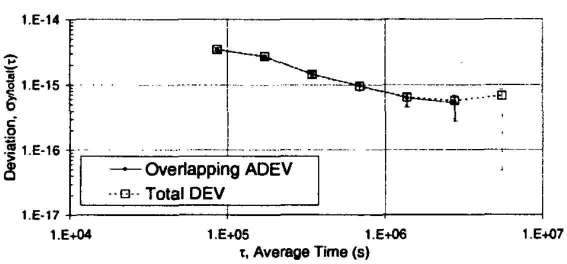

Figure 7. Overlapping Allan deviation and Total deviation for the first 170 days of TWSTT-CP data over the NIST/PTB link.

Merging Routines

One possible error source in the CP technique lies in the merging of the carrier-phase data. The carrier-phase solution is processed on 3.5-day intervals, using a half-day overlap with neighboring data series. The overlapping problem we have experienced is due primarily to an edge effect in the data analysis, see [1]. This is known to arise from errors in resolving carrier-phase ambiguities and estimating atmospheric delays in the analysis. Over shorter baselines we did not experience noticeable problems with merging the data in this manner. However, with a significantly longer baseline we observed a change in the slope at the endpoints of the analysis period, whether the analysis period is 1 d or 3.5 d. With longer data series, errors due to overlapping tend to be minimized when comparing with the TWSTT technique. We continue to investigate better methods of overlapping the data; however, edge effects in the data are difficult to resolve and cannot be ignored. Ideally, to minimize merging errors, we want to process the longest data series possible.

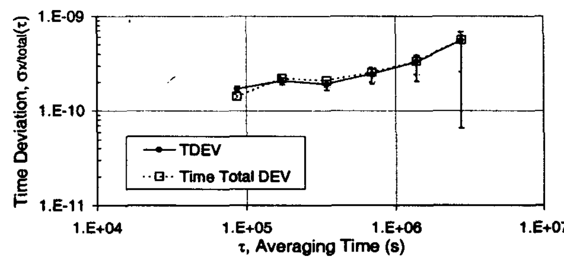

Figure 8. Time deviation and Time Total deviation for the first 170 days of TWSTT-CP data over the NIST/PTB link.

Bias Fixing

Another area where significant errors may arise is in the resolution of ambiguities, or bias fixing. Bias fixing is attempting to the resolve the ambiguities, N_R^S, in the carrier-phase observations. The equation for one carrier-phase observation is as follows:

$$\lambda\phi_R^S = \rho_g + c\delta^S - c\delta_R + \rho_{trop} - \rho_{ion} + \rho_{mult} + \varepsilon_{cp} + N_R^S\lambda, \quad (1)$$

where

λ = carrier's wavelength, c/f, (f is the carrier's frequency and c is the speed of propagation of the signal in the medium carrying it),

ϕ_R^S = carrier-phase observable for satellite S and receiver R,

ρ_g = geometric range, $((X^S-X_R)^2+(Y^S-Y_R)^2+(Z^S-Z_R)^2)^{1/2}$,

δ^S = satellite clock error,

δ_R = receiver clock error,

ρ_{trop} = propagation delay due to troposphere,

ρ_{ion} = propagation delay due to ionosphere,

ρ_{mult} = multipath error,

ε_{cp} = unmodelled errors and receiver noise,

$N_R^S\lambda$ = carrier-phase ambiguity or bias.

Ambiguity resolution does not have to be performed, but it reduces the station coordinate errors related to orbital parameters. This can be critical, especially because ambiguity resolution is affected by baseline length. The primary software package we use, GIPSY-OASIS II [3], uses a sequential approach to estimate the correct integer values for the ambiguities [4]. Fortunately, this algorithm allows resolution for very long baselines when nearby shorter baselines are simultaneously estimated, especially with the use of precise orbits. This is the reason for our six-station network selection described in [1]. The second software package used in this data analysis, Bernese [5], does not yet have bias fixing capability for our purposes. Therefore, a comparison of the non-bias fixed solutions using both software packages is made later in this work.

For comparison purposes with Figure 6 the difference in solutions for the non-bias fixed GIPSY and TWSTT is plotted in Figure 9. The results show that without a robust ambiguity resolution a significant trend appears between the two transfer techniques. The difference is approximately 12 ns over the first 170 days, before problems with H2(PTB) and TWSTT in the analysis. This compares to only a few nanoseconds in Figure 6. However, it is important to note in Figure 9,that the trend changed slope once the TWSTT equipment and H2(PTB) became more stable after MJD 52000. This might give insight into the difference seen between the techniques using the bias-fixed case, assuming we have no further equipment failures. Unfortunately, TWSTT operations are not yet at their optimal configuration because of expected hardware replacements, so it might be difficult to resolve this until the equipment situation stabilizes.

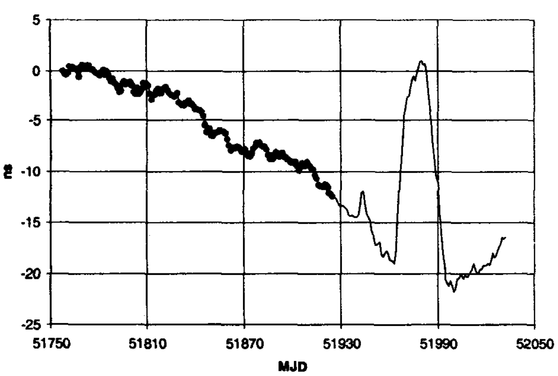

Figure 9. Interpolated daily TW – daily CP values for the non-bias fixed GIPSY case.

Sampling and Analysis Period Effects

GPS carrier-phase data are normally analyzed on a 6-minute interval; however, the receiver takes data at intervals of 30 s. For this reason we compared the 6-minute data sampling solution to the 30 s solution to find any differences in the final solution, as shown in Figures 10 and 11. Unfortunately, with the 30 s rate we were not able to process more than 2 hours of data at a time. This is due primarily to limitations in the GIPSY software, so we joined successive 2-hour solutions to form a half-day solution. For comparison we also calculated the 6-minute data solution over the same half-day period. We found a difference of approximately 250 ps between the two solutions, not enough to justify using a higher sampling rate, especially with the significant increase in processing time.

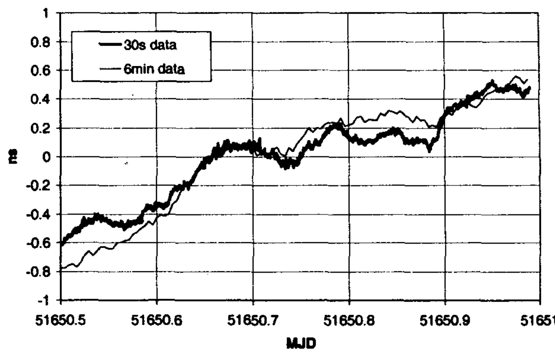

Figure 10. H2-UTC(NIST) carrier-phase analysis with 30 s and 6-minute sampling rates.

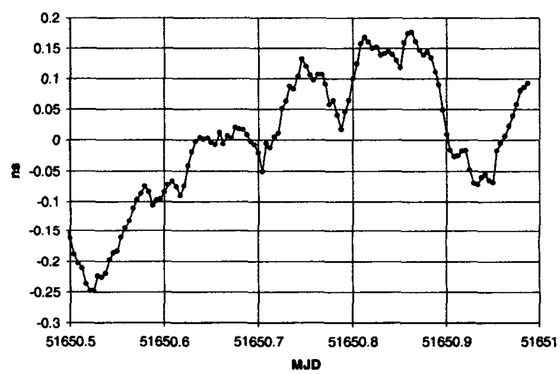

Figure 11. Difference in 30 s and 6-minute H2-UTC(NIST) carrier-phase analysis.

To show some of the effects of dependence of station coordinate estimation on analysis length, Figure 12 shows the difference between a 3.5-day solution and 1-day solution using Bernese over one day. The thin line shows the difference in the 3.5-day solution and 1-day solution using the coordinates estimated in the 3.5-day run. The difference is approximately 400 ps peak-to-peak. However, when the one-day solution is run separately and estimates its coordinates based on just one day of data, the 3.5 and 1-day solution differ by 1.5 ns. This indicates that the software coordinate estimation is somewhat dependent on the length of interval over which data is observed.

Table 1 shows the maximum difference in estimated coordinate solutions in picoseconds for three different successive Bernese 3.5-day data runs. Even from series to series we see a maximum difference of approximately 400 ps. The differences for ALGO are zero because this is the reference station chosen for this network. It is also interesting to note that the three stations located at geodetic installations (ALGO, NRC1, and WTZR) appear to have smaller variations between data runs than those at the non-geodetic locations.

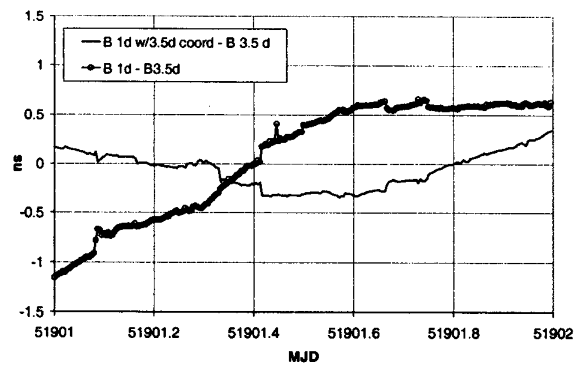

Figure 12. Differences between 3.5 and 1-day non-bias fixed analysis using Bernese. In one case the analysis uses coordinates solved for a 1-day run separately and one where the 1-day solution uses the coordinates estimated by the 3.5-day run.

Table 1. Maximum station coordinate estimate differences between three consecutive 3.5-day data series using Bernese.

Station Name	X difference (ps)	Y difference (ps)	Z difference (ps)
ALGO	0	0	0
NRC1	24	13	28
TMGO	140	56	233
NIS2	171	74	258
WTZR	65	85	122
PTB1	367	94	274

Data Outages

Errors are also introduced into the clock comparison with data outages or jumps, as discussed previously. This shows why continuous data is so critical. To determine the magnitude of error that could be introduced we used the 30 s data shown in the previous section and introduced a 2-hour data gap to see its effect on the final solution. In this case we use a merging routine that uses the slope of the data prior to the gap to bridge across to the next data point, similar to that used in the 6-minute data analysis. In Figure 13 our final solution with the 30 s data appears to match the 6-minute data closer at the endpoints than in Figure 10, but leaves a similar peak-to-peak error with an approximate 400 ps phase step where the outage occurred, shown in Figure 14. This error might become a problem if it accumulates over a longer series of analysis where merging is required.

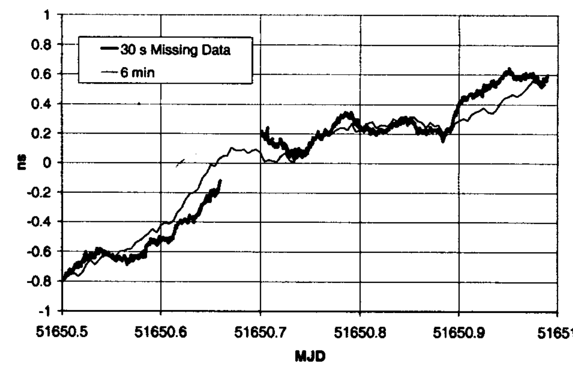

Figure 13. H2-UTC(NIST) carrier-phase analysis with 30 s and 6-minute sampling rates. A data gap has been introduced in the 30 s data to determine the difference in the 30 s solution in comparison with the 6-minute solution.

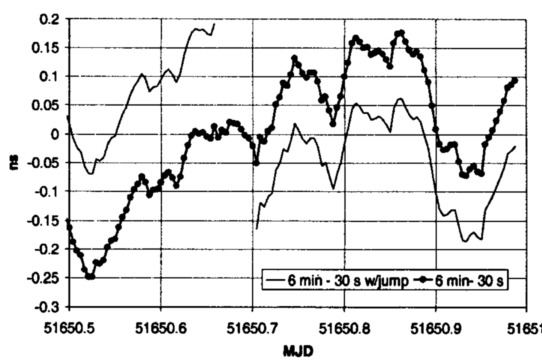

Figure 14. Difference in 30 s and 6-minute H2-UTC(NIST) carrier-phase analysis with and without gaps in the data.

Comparing Software Packages

Using the two different software analysis packages, GIPSY and Bernese, we were able to make comparisons to determine whether any of the observed errors are inherent to the software that we use in our analysis. Unfortunately Bernese did not have bias-fixing capabilities, but we were able to successfully compare it with the non-bias fixed GIPSY solution. In Figure 15 we compare three 3.5-day runs that are overlapped with 12 h as before, and found that the results from the two different software packages agree within 500 ps over the last 6.5 d. The first data run comparison had problems, showing a difference of 1.5 ns. This difference results from problems with outlier rejection in the second software package for that series of days. However, it is promising that the two analytical methods agree so closely and we hope to conduct further comparisons, especially once bias fixing capabilities are added to Bernese.

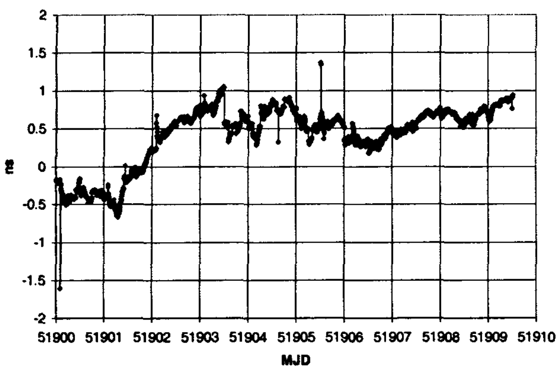

Figure 15. Overlapped Differences between GIPSY and Bernese non-bias fixed solutions over a 9.5 day interval.

Conclusion

The primary concern with GPS carrier-phase frequency transfer lies with station outages, overlapping of various data runs, and bias fixing in obtaining a final solution. In general a limitation to the analytical software is the size of the data run and the number of stations that can be processed at one time. It has been suggested that using more stations would help to resolve some of the ambiguities and atmospheric delays more completely; however, that would limit the number of days we could process at one time and continue to create edge effects that we cannot ignore.

It has also been suggested to investigate temperature and cable multipath effects [6]. To this end, we have recently upgraded the GPS carrier-phase antenna cable at NIST with a new phase and temperature stable cable, similar to the one already installed at PTB.

We hope that investigating the next series of data, once equipment problems have been resolved and bias fixing has been added to Bernese, that we will be able to determine more about the underlying causes for the variations between the TWSTT and CP techniques.

Acknowledgements

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