In Search of a New Primary GPS Receiver for NIST*

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Abstract— A previous publication [1] showed problems with the current NIST Time and Frequency Division primary GPS receiver when used for Precise Point Positioning (PPP)-based carrier phase time transfer. We confirm that, for this receiver, boundary discontinuities during overlapping data runs tend to be biased away from zero on average and that this bias increases as the a-priori pseudo-range sigma increases. We show that this problem does not occur for other receivers at NIST, even receivers of the same model or make. Next we review results for selecting a new primary receiver from others now at NIST, focusing on two desired properties: an average overlap bias close to zero using PPP, and a low code instability. We want at least one year of good data on a receiver before considering it as a replacement.

***Key words:* boundary discontinuities, carrier-phase time transfer, precise point positioning**

I. THE NEED FOR A CHANGE: CODE-CARRIER INCONSISTENCY

A. The Problem

The NIST primary receiver for time and frequency transfer, also called *NIST*, was chosen to support code-based time transfer services, and has been used without apparent problems for this since 2006. With the advent of the BIPM's PPP program, which incorporates carrier-phase time transfer, it was shown in [1] that there was a problem with this primary receiver. It was noted that the boundary discontinuities during overlapping data from neighboring runs tended to be biased away from zero on average. Further, this bias increased as the a-priori pseudo-range sigma was increased. This implies that weighting the carrier phase more highly tends to increase the bias in the discontinuities. Thus there is some inconsistency between the code and carrier for this receiver. The first question we address here is whether this problem occurs in only this receiver, or is it common to this model or even the make of receiver. Using two years of data, 2009-2010, we are able here to produce similar results from [1] for our primary receiver and show that these problems do not occur for other receivers at NIST, even receivers of the same model or make. It takes over a year of data to clearly see this code-carrier inconsistency in the current NIST primary receiver. We want at least a year of good data on a receiver before considering it as a replacement.

Next we review code-based time transfer stability results for selecting a new primary receiver. The ability to transfer time in the long term can be no better than the stability of the delay through the receiver. The use of the carrier phase can smooth out some of the code delay variations, but for intervals of about one day and longer, the code variations dominate.

We have a number of candidate receivers, as well as a number of criteria for choosing the next primary receiver. In this paper we identify receiver manufacturers and models, for the purpose of advancing research. No endorsement, nor criticism of any product is intended.

B. The Method

We describe here specifically how the overlap data have been derived. We use the Precise Point Positioning software package (PPP) of the National Research Council of Canada (NRCan). We thank them for their generosity in sharing the package with us. For the data in this study, we have 35 day runs, repeated every 30 days. Hence every 35 days there are 5 days of overlap. During these overlap days, both runs have processed exactly the same pseudo-ranges using the same estimates from the International GNSS Service (IGS) of satellite clock and ephemeris to estimate the receiver clock time against the IGS system time scale. Therefore the difference between the receiver clock estimates during the overlap from a 35-day run ending and the clock estimates from a run beginning can be only due to parameters in PPP that are estimated based on history. For us, the clock for each receiver is UTC(NIST). Two parameters, among others, supplied to the PPP program by the user are the a-priori pseudo-range sigma, and the carrier-phase sigma. These are the two types of measurements from the receiver that are inputs to PPP. The pseudo-ranges are the code measurements on the two GPS frequencies, L1 and L2. The carrier phase measurements are the accumulated phases of the respective carriers on L1 and L2. For normal runs, we use 1.0 m for the pseudo-range sigma and 0.01 m for the carrier phase.

In this study we have varied the pseudo-range sigma from 0.5 m to 3.0 m, in steps of 0.5 m. For each value of pseudo-range sigma we have run PPP for 35 day lengths every 30 days, thus yielding 5 day overlaps every 35 days. The plots in this section use the clock discontinuity values for these overlaps. That is, we obtain the discontinuity values using the receiver clock estimates, UTC(NIST), against IGS time. We difference the run that is starting during a given 5 day overlap, from the run that ended during those 5 days. Since these are a double difference of UTC(NIST) minus IGS time from two overlapping runs, the clocks themselves cancel exactly. What remains can only be the difference of PPP estimators' response to the receiver data from the two overlapping runs. We display these overlap data in two different ways below. Figure 1 gives a summary, using means and standard deviations of the overlap data. Figures 2-5 show the overlap values as a function of date.

C. Summary of Results

Figure 1 illustrates the effect where the receiver *NIST* has an anomaly. This plot shows the average boundary discontinuity for various receivers as a function of the weight given to the code relative to that given to the carrier, as described in the previous section. As we increase the ad-hoc sigma for the pseudo-range, which gives the code less weight, thus giving more relative weight to the carrier, the size of the boundary discontinuity grows only for the receiver *NIST*. Thus there is an inconsistency in how the code data and carrier data represent the clock differences.

Figure 1 plots the mean value of overlaps over the two years versus the sigma given to the pseudo-range for each of five different receivers. The standard deviations around these means are plotted as error bars. We note two significant aspects from Figure 1. First, the mean values for receiver *NIST* behave differently from those for all other receivers. There is a clear increase in the bias of the discontinuities as the carrier phase is weighted more highly. However, we also note that the standard deviation around the mean values is large enough that we cannot claim for some of the receivers other than *NIST* that they do not have similar anomalies. We investigate in Section D the significance of these large standard deviations.

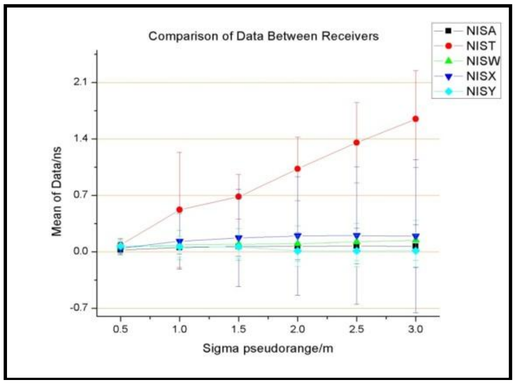

Figure 1. Means of 5 d overlap data every 35 d, from 2009-2010 as a function of the sigma for the pseudorange for five different receivers at NIST.

D. Detailed Results

To investigate the cause of the large standard deviations, we plot the boundary discontinuities as a function of time for several receivers in Figures 2-5. These data cover the period from 2009 through early August 2012, MJD's 54861 – 56142. Data are missing from some intervals for various reasons. In some cases the receiver or data retrieval system was down. In other cases, the PPP overlap values were extremely large and were removed. We further discuss this issue later.

To separate the curves visually on the plots, we have added integers to each curve as follows:

Offset added	sigma pseudo-range	line color
+0	0.5 m	blue
+1	1.0 m	green
+2	1.5 m	red
+3	2.0 m	light blue
+4	2.5 m	purple
+5	3.0 m	yellow

Thus, if the mean values were close to 0 for all overlap differences, the curves should appear as approximately horizontal lines at integer values of 0 through 5.

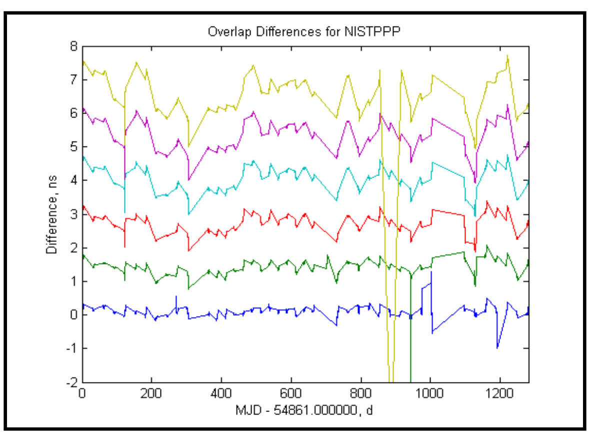

Figure 2. Overlap differences for the current NIST primary GPS receiver, for MJD's 54861-56142, successive sigma pseudoranges offset by integers.

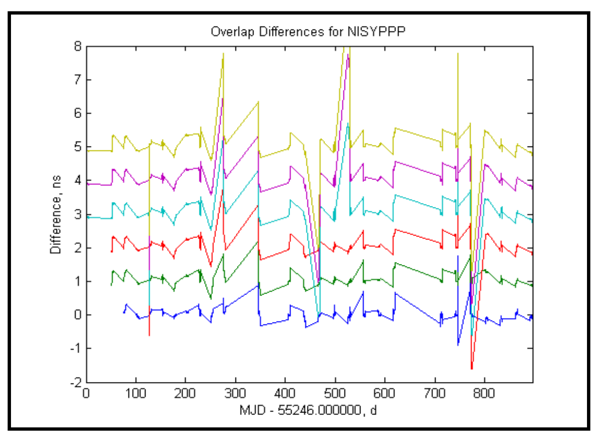

Figure 3. Overlap differences for a potential new primary GPS receiver, for MJD's 55246-56142, successive sigma pseudoranges offset by integers.

In Figure 2, we can see that successive lines generally increase by more than the applied unit of 1 as the sigma for the pseudo-range is increased. There are overlap periods where there are significant variations from the mean effect. Thus, the receiver *NIST* indeed appears to have an incoherence between the code and carrier data: as the code measurement is de-weighted the bias in the overlaps tends to increase. However, there is a large standard deviation around the mean biases, apparently because the PPP program has occasional large variations in the overlap periods from these mean biases. Thus, the anomalous effect can require a long period of study to be seen clearly: perhaps several years, unless the outliers could be corrected otherwise.

By contrast, Figure 3 shows the overlap values for the receiver *NISY* for a similar period. Here, the lines appear to increase by the applied value of 1 in the mean as the sigma of the pseudorange increases. Thus, the mean of the overlaps stays around 0, which is what we would expect for a normal receiver. Again we see that there are occasional large variations around the mean values. Again, we understand from this that the PPP program can have occasional large variations from one run to the next in the overlapping period.

Here we note the make and model for the receivers: the *NIST* receiver is a Novatel OEM4, and the *NISY* receiver is a Novatel OEM5. We emphasize that there is neither endorsement nor critique implied by this information. It is important, in particular, to show how we conclude that the anomalous behavior we see in the receiver *NIST* does not appear in other receivers of the same manufacture or even the same model. Consider Figure 4, below. Here the receiver is a Novatel OEM4, identical in model to *NIST*, but the anomalous effect does not appear. This receiver, being an older model, is not a candidate for the new primary receiver.

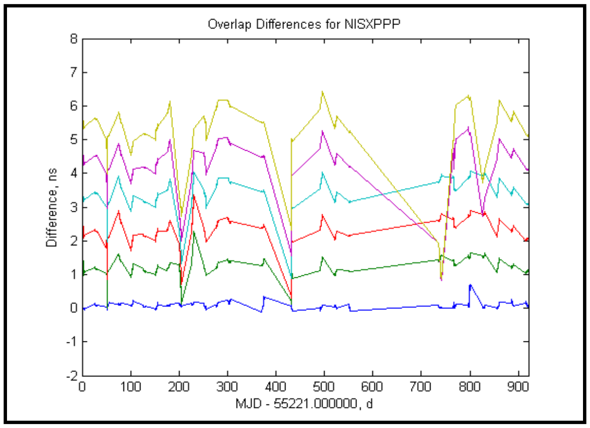

Figure 4. Overlap differences for the *NISX* receiver, of the same model and make as *NIST*, over MJD's 55221-56142, successive sigma pseudoranges offset by integers.

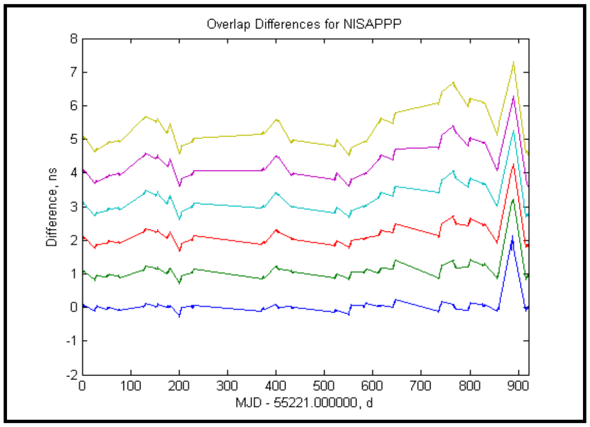

Figure 5. Overlap differences for the *NISA* receiver, of a different manufacture from *NIST*, over MJD's 55221-56142, successive sigma pseudoranges offset by integers.

Figure 5, above, shows the overlap differences for an Ashtech Z12T receiver, again offset by +1 for successive sigma pseudorange values. We see again, the expected behavior of the mean differences during overlaps being about zero, though again with occasional large variations. This receiver is also not a candidate for primary NIST receiver, since it is owned by a different agency, but the data are presented here to show the similarity with other normal functioning receivers. We omit the data from other receivers that are candidates for primary NIST receiver, since the pattern is similar to these normally functioning receivers: mean overlap values around zero, with occasional large variations.

The occasional large variations in the overlap differences may have several sources. This paper is focused on the performance of receivers, and we have not delved into the PPP program itself. It is possible that the overlap outliers are due to outliers in the GPS data, and the differential response of PPP to those outliers. We note in particular, that during the periods of variations, there seem to be larger variations as the code measurement is de-weighted compared to the carrier phase. This suggests that some aspect of the PPP systems treatment of carrier phase is less stable than that of the code phase. It seems likely this has to do with the resolution of cycle ambiguity.

II. Requirement: Code-Based Time Transfer Stability

NIST uses GPS *differentially* to compare and transfer UTC(NIST). GPS time transfer can be no more accurate than the stability of the delay through the receiver between calibrations.

In this section we look at the differential stability of GPS receivers at NIST by computing the Time Deviation (TDEV) [2] of their delays differentially against the receiver *NIST*. All receivers are timed by a common clock, UTC(NIST), and the antennas are all within 100 m of each other. This allows for a simple processing technique, as follows, to determine relative stability. We start with pseudo-range data from RINEX files, taken every 30 s on the C1 and P2 codes. These are corrected for the range to the satellite for each satellite, then differenced between pairs of stations. For each 30 s measurement time, we average across all satellites tracked in common by the multi-channel receivers. We omit corrections for delays due to the ionosphere, troposphere and Sagnac effect, because the baselines are so short. What remains is the differential receiver delay and differential multipath and measurement noise between pairs of receivers.

We show the stability of the C1 and P2 delays of various receivers against the NIST primary GPS receiver (called *NIST*). All plots use 90 days of data. The receivers here that are candidates for being the primary receiver are of three different manufacturers. *NIS2*, *NISY*, *NIF1* are Novatel receivers, with the *NIS2* and *NISY* model being OEMV also called OEM5, and *NIF1* model OEM6. *NISS* is a Septentrio PolaRx3eTR, and *NISJ* is a Javad Delta receiver. We also have a Javad Sigma receiver which is the actual Javad receiver, that is a candidate, but data from that receiver are not available here. Again, please note that we identify manufacturers and models for research purposes only.

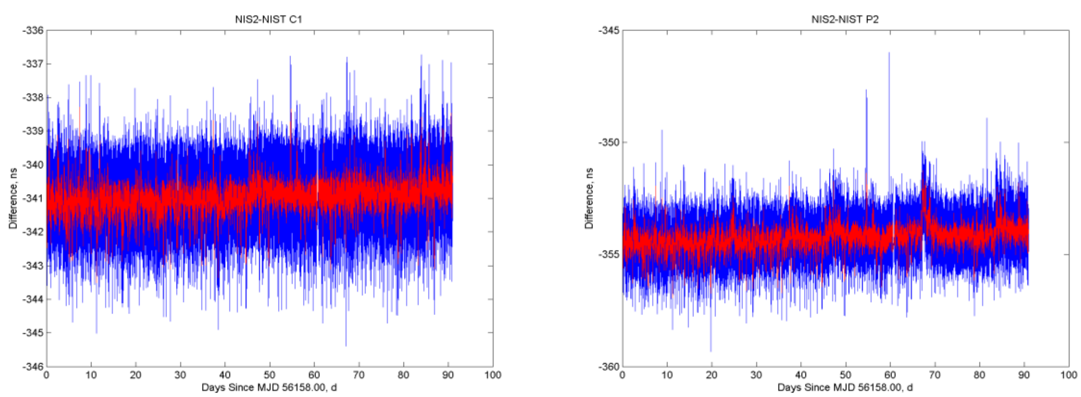

Figure 6. *NIS2-NIST* common-clock short-baseline differences using C1 data (left) and P2 data (right) every 30 s. The red plots are 16 minute averages. *NIS2* is a Novatel OEM5, and *NIST* is a Novatel OEM4 receiver.

We show the data themselves in Figure 6 for this particular case to illustrate the consistency of the results. Since TDEV gives the root-mean-squared stability of the data, it may smooth out some effects. The plot of the data themselves can reveal peak variations and other effects. We see in Figure 6 occasional excursions in the receiver differences over 90 days of data. These reveal some of the effects in time transfer that might be attributed incorrectly to clock differences. We also note an apparent slope overall in these data. These are both receiver effects that can be seen locally by monitoring multiple receivers, but that cannot be seen in the TDEV plots.

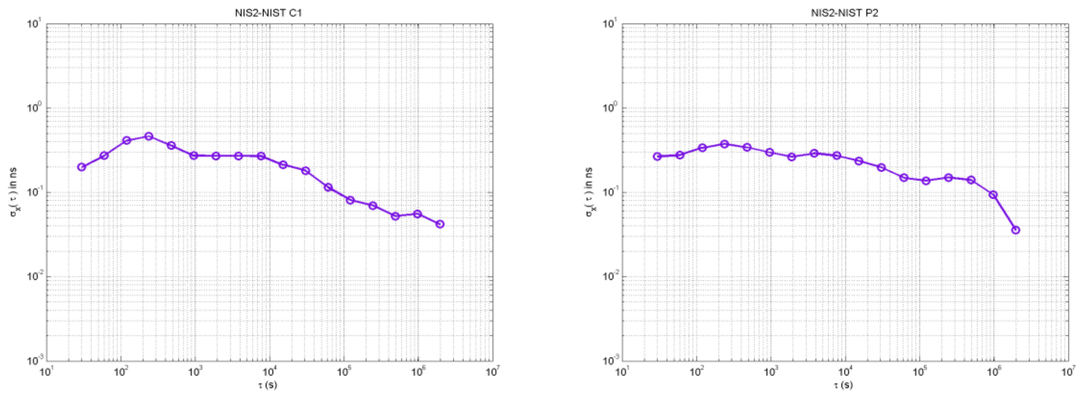

Figure 7. TDEV of the data in Figures 6. *NIS2* is a Novatel OEM5, and *NIST* is a Novatel OEM4 receiver.

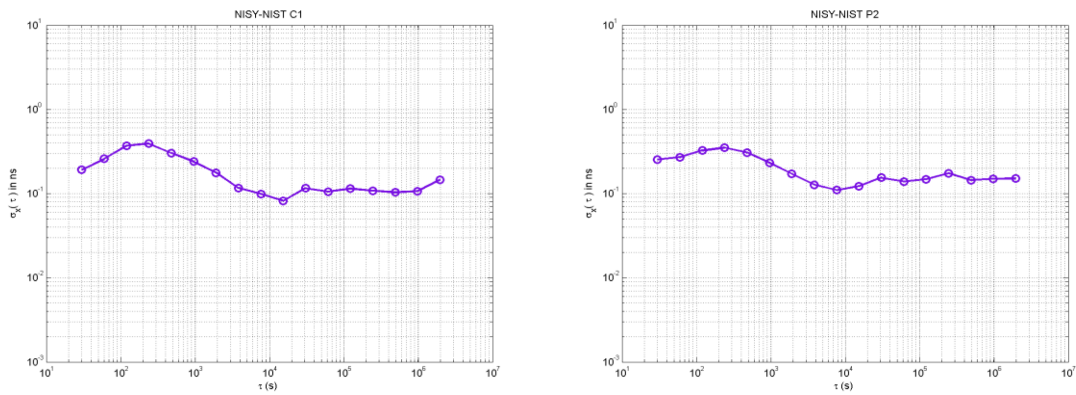

Figure 8. TDEV of *NISY-NIST* common-clock short-baseline differences using C1 data (left) and P2 data (right) every 30 s. *NISY* is a Novatel OEM5, and *NIST* is a Novatel OEM4 receiver.

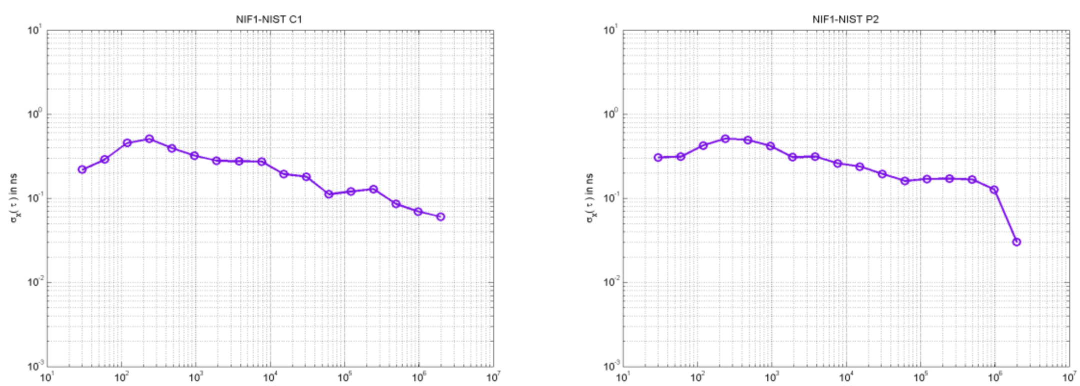

Figure 9. TDEV of *NIF1-NIST* common-clock short-baseline differences using C1 data (left) and P2 data (right) every 30 s. *NIF* is a Novatel OEM6, and *NIST* is a Novatel OEM4 receiver.

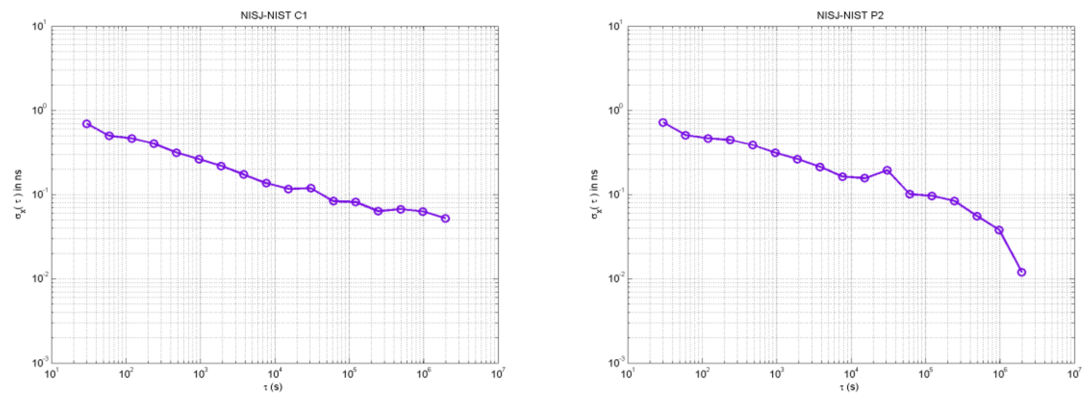

Figure 10. TDEV of *NISJ-NIST* common-clock short-baseline differences using C1 data (left) and P2 data (right) every 30 s. *NISJ* is a Septentrio Delta, and *NIST* is a Novatel OEM4 receiver.

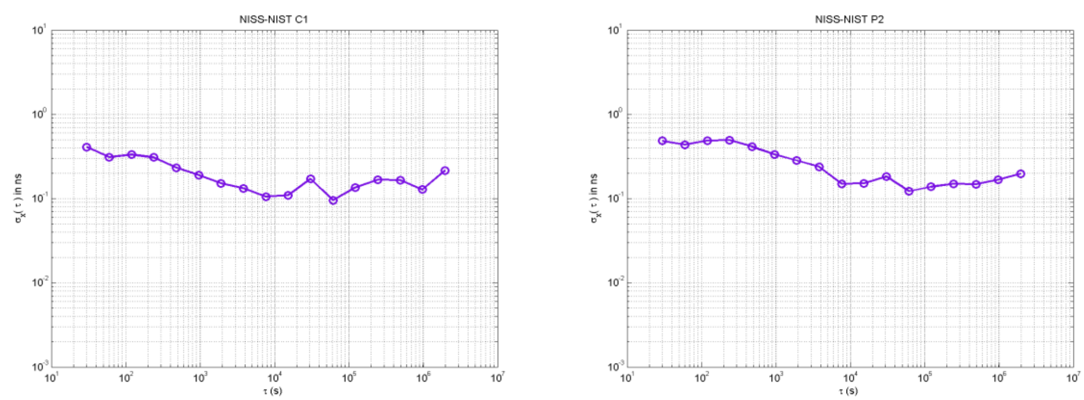

Figure 11. TDEV of *NISS-NIST* common-clock short-baseline differences using C1 data (left) and P2 data (right) every 30 s. *NISS* is a Septentrio PolaRx3eTR, and *NIST* is a Novatel OEM4 receiver.

III. Discussion and Conclusions

The receiver *NIST* appears to be among the most stable, based on comparing these plots to TDEV pair-wise plots without *NIST*. It is possible there are common-mode cancellations that make things look too good, since these receivers are all in a similar environment, e.g., they are all in Boulder Colorado, though they are not in the same room. Our immediate goal for the GPS receiver is to be able to compare active hydrogen masers, which could require stabilities of order 100 ps at 1 d. Thus, TDEV values are desired below 10^{-1} ns at integration times τ of 10^5 s.

The candidates for a new primary receiver are *NISY* or *NIS2*, among the Novatel OMEV (OEM5) generation, or *NIF1* for the Novatel OEM6. In addition we consider the Septentrio, *NISS*, and the Javad, *NISJ*. All of these receivers seem to not exhibit the anomaly of *NIST*. The overlap values do not seem to have a particularly systematic bias, though more data are needed to confirm this for both the *NISJ* and *NISS* receivers.

The differences in stability among the candidates are not large. There are different effects causing instability in the different integration times shown in these plots. The very short term, from 30 s, is generally dominated by the receiver stability. The instability in intermediate integration times, from 10^2 s out to about 10^4 s is generally dominated by multipath effects in the environment of the antenna, as well as residual code correlations among the satellite signals [3]. A differential diurnal variation, a common effect, appears in the TDEV plot as an increase in deviation at an integration time of ½ day, or about 4.3 x 10^4 s. TDEV values beyond 1 day, or beyond 10^5 s are mostly due to the stability of the individual receiver delays themselves. With *NIST* as the reference receiver, probably anything greater than 10^{-1} ns for TDEV past 1 day is due to the receiver under test.

With these considerations, *NISY* and *NISS* seem to exhibit the best stability, though their advantages are not very significant. Hence, other considerations may be more important in deciding the winner. Two such considerations lead to contradictory implications. One is that it is desirable for our primary receiver to provide P1 code data, since IGS products reference that code-phase. This is the code result sometimes called "pseudo-code," because it involves a technique of obtaining the code phase of the secure P(Y) code without knowledge of the code itself. Full code tracking of the P(Y) code can only be done by authorized users, such as the U.S. military and its allies. Among the receiver candidates here, only *NISS* and *NISJ* provide P1 "pseudo-code" data. The Novatel receivers provide only the clear access code data (C/A), referred to as C1, hence an estimate of the C1 to P1 bias for each satellite is required when using carrier-phase techniques. This would tend to lead us away from the Novatel models. However, NIST has developed an enclosure for the Novatel receivers that enables a simpler and perhaps more effective estimate of the reference clock delay, the so-called REF DELAY. See details on this enclosure and the reference delay estimates in [4]. This would tend to push toward using a Novatel model, perhaps *NISY*.

It is worth noting that all of these receivers have potential for tracking all of the new GNSS satellites, though perhaps with requiring firmware upgrades.

In conclusion, we have clarified the anomaly previously reported in the receiver *NIST*, and we have a few strong candidates for a new primary receiver. However, we are not yet ready to finally choose a new primary GNSS receiver.

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