Towards Sub-10^{-16} Transcontinental GPS Carrier-Phase Frequency Transfer: a Simulation Study

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***Abstract*—A simulation study is performed using *GIPSY* software in order to determine the impact of site-based and satellite-based systematic errors on the accuracy of between-site GPS carrier-phase frequency comparisons. The data are analyzed using both the precise point positioning (ppp) and network methods: in the former, the time differences between the satellite clocks and system time are fixed to predetermined values. In the latter, the time differences of both the satellite clocks and the receiver clocks are estimated relative to some reference clock (usually a ground-based receiver clock). We also analyze data both with and without the added constraint of double-difference ambiguity fixing. We find that between-site frequency comparisons are largely unaffected by site-based and satellite-based systematic errors when 100% of the double-difference ambiguities are fixed. We also find that in the ppp method, although fixing ambiguities removes between-site frequency errors, it can cause errors in the values of the individual receiver clocks relative to system time. Finally, we find that when a network solution is performed and ambiguities are not fixed, an error made at site A may adversely affect frequency comparisons between sites B and C.**

I. Introduction

GPS carrier-phase frequency transfer (GPSCPFT) is estimated to have a frequency-comparison uncertainty of $4\text{-}5\cdot10^{-16}$ over transcontinental distances at averaging times of 10 d or more [1, 2]. However, cesium fountain primary frequency standards can now realize the SI second with uncertainties of $4\text{-}6\cdot10^{-16}$ (excluding dead time and transfer noise) [3]. We are therefore conducting a simulation study designed to find out how accurate the fixed input parameters (e.g., satellite ephemerides) and the estimates of the correlated parameters (e.g., zenith troposphere delay) must be if we wish to perform transcontinental GPSCPFT with an uncertainty of less than 10^{-16} (roughly 8.6 ps/d).

This paper summarizes what we have learned so far. While we will examine how systematic errors of size x cause frequency-transfer errors of size y, we will primarily address the differences in results obtained when the precise point positioning ("ppp," [4]) and "network" methods are used, and when the added constraints of double-difference ambiguity fixing [5] are or are not applied. (The terms "network method," "ppp method" and "double-difference ambiguity fixing" are defined in Section II.) Both double-difference ambiguity fixing and the use of the network method allow an error made at one site to propagate into the parameters estimated for other sites.

Our study is performed using the *GIPSY* analysis software[1] [6] created and provided by the Jet Propulsion Laboratory. Dach *et al.* [7] performed similar research on the network method using the *Bernese* [8] software.

II. Propagation of Errors

Let GPS satellite i transmit a signal that is received at site 1. The ionosphere-free [9] pseudorange and carrier-phase measurements $P3_1^i$ and $L3_1^i$ can be written in length units as

$$P3_1^i = \rho_1^i + T_1^i + c\cdot(dt_1 - dt^i) \qquad (1)$$

$$L3_1^i = \rho_1^i + T_1^i + c\cdot(dt_1 - dt^i) + B_1^i \qquad (2)$$

where ρ_1^i denotes the geometric distance between the receiver and the satellite, T_1^i denotes the excess delay of the signal through the troposphere, and dt_1 and dt^i denote the errors of the receiver and satellite clocks relative to system time. B_1^i denotes the phase bias, i.e., the unknown constant that exists for each set of receiver-satellite carrier-phase measurements because there is an integer number of carrier wavelengths initially lying between the satellite and the receiver that cannot be measured. We shall use the term "ambiguity-free" to refer to a solution in which the values of B_1^i are simply estimated as real-valued parameters. In contrast, we shall use the term "ambiguity-fixed" to refer to solutions obtained when the constraints of double-difference ambiguity fixing (described below) have been applied.

[1]A specific trade name is used for identification purposes only; no endorsement is implied.

In the ppp method, both the satellite orbits and the satellite clocks ($dt^i s$) are fixed to precise, predetermined values. Therefore, in a ppp ambiguity-free solution, the data from different receivers are not used to estimate any common parameters. In this case, an error made in the model at site 1, e.g., a position error, can only propagate back into the parameters estimated for site 1. However, in the network method, although the satellite orbits are still fixed, one of the clocks in the receiver-satellite system is denoted as the reference clock, and all of the remaining $dt_l s$ and $dt^i s$ are estimated relative to it. Because satellite i is usually visible to more than one receiver, data from more than one receiver are used to estimate dt^i. This creates an opportunity for the propagation of a site-based error even in the ambiguity-free solution. Suppose we make an error in the position at site 1, and suppose sites 1 and 2 observe satellite i. The error at 1 can propagate into the estimate of dt^i, but because i is also observed at 2, the error in dt^i can then propagate into the parameters estimated for site 2.

Double-difference ambiguity fixing provides another means by which errors can be propagated between sites, because in this optional procedure, we apply the following additional constraint to as many two-receiver-two-satellite pairs as possible:

$$B_{1,2}^{i,j} \equiv [B_1^i - B_1^j] - [B_2^i - B_2^j] = V_{1,2}^{i,j}, \quad (3)$$

where the values of $V_{1,2}^{i,j}$ are determined independently by an ambiguity-fixing algorithm. If we make a mistake at site 1 and if we insist that (3) be true, then we may incorrectly adjust the previously-correct parameter estimates for site 2 so that (3) continues to be true.

III. ANALYSIS METHOD

Ionosphere-free carrier-phase and pseudorange data were simulated in one-week batches for the stations shown in Fig. 1 using final orbits and "sinex" coordinates provided by the International GNSS Service [10] and earth-orientation parameters obtained from *IERS Bulletin B* [11]. Such a set of sites might be used to compare the frequency of clocks located at the National Institute of Standards and Technology (NIST) in Boulder, Colorado USA and at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. PTB and NIST lie approximately 7532 km apart.

The simulated data points were spaced at 300-s intervals. The zenith troposphere delay associated with each site was modeled using a wet value z_{wet} of 0.1 m and a hydrostatic value z_{dry} of

$$z_{dry}(meters) = 1.013 \cdot 2.27 e^{-0.116 \cdot 10^{-3} h}, \quad (4)$$

where h is the height of the site above the ellipsoid in meters. The Niell mapping function [12] was then used to compute the troposphere delay appropriate for each satellite given its elevation angle. No stochastic noise was added to the models. The differences between the receiver clocks and system time ("SYST"), as well as the differences between the satellite clocks and SYST were set to zero.

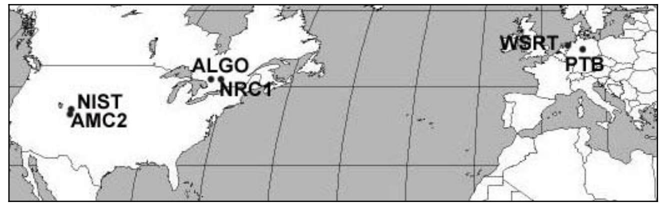

Figure 1. Simulated-data sites. "NIST" is located at the National Institute of Standards and Technology in Boulder, Colorado, USA. "AMC2" is located in Colorado Springs, Colorado, USA, "ALGO" in Algonquin Park, Canada, "NRC1" in Ottawa, Canada, "WSRT" at Westerbork, Netherlands, and "PTB" at the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany.

The simulated data were then analyzed in one-week segments, with the data from all of the sites processed together in one batch, but with one of the model parameters fixed to a value different than that used in simulating the data. For example, if the data at ALGO had been simulated using a height of 200.914 m, we might process the data using an ALGO height of 200.924 m. Carrier-phase and pseudorange measurements were assigned one-sigma data-noise values of 1 cm and 1 m, as is customary [13, 14].

When performing a ppp solution, the only parameters estimated were the values of the receiver clocks with respect to (wrt.) SYST and the phase biases. We did not let the site or satellite positions vary even if that would have been the correct way to account for the mismodeling. This forced the mismodeling to be expressed as a receiver-clock or phase-bias error. When performing a network solution, we chose NIST to be the reference clock, and estimated the values of the other receiver clocks and the satellite clocks wrt. NIST. The phase biases were estimated as well.

Once the time-transfer results had been obtained using either the ppp or network method (the "ambiguity-free" solutions), the data were further processed by applying double-difference ambiguity fixing. This yielded an additional set of "ambiguity-fixed" results.

We examine the effect of changing the east (E), north (N), height (h) and z_{wet} values for intermediate station ALGO by 1 cm. This allows us to determine how an error in the modeling of an intermediate site impacts the frequency transfer between two sites of interest (e.g., NIST and PTB). We also examine the effect of perturbing the satellite clock values by 100 ps, and of perturbing the satellite ephemerides by 5 cm in the earth-centered-earth-fixed (ECEF) x, y, and z directions. (The orientation of the ECEF frame is described in "Results.") We show results from GPS week 1342 (Sep 25 - Oct 1, 2005; MJDs 53638-44) and discuss similarities to the results obtained for other weeks when appropriate.

IV. RESULTS

Fig. 2 shows the results of making a 1-cm error in the E, N, h or z_{wet} value for ALGO during GPS week 1342 when

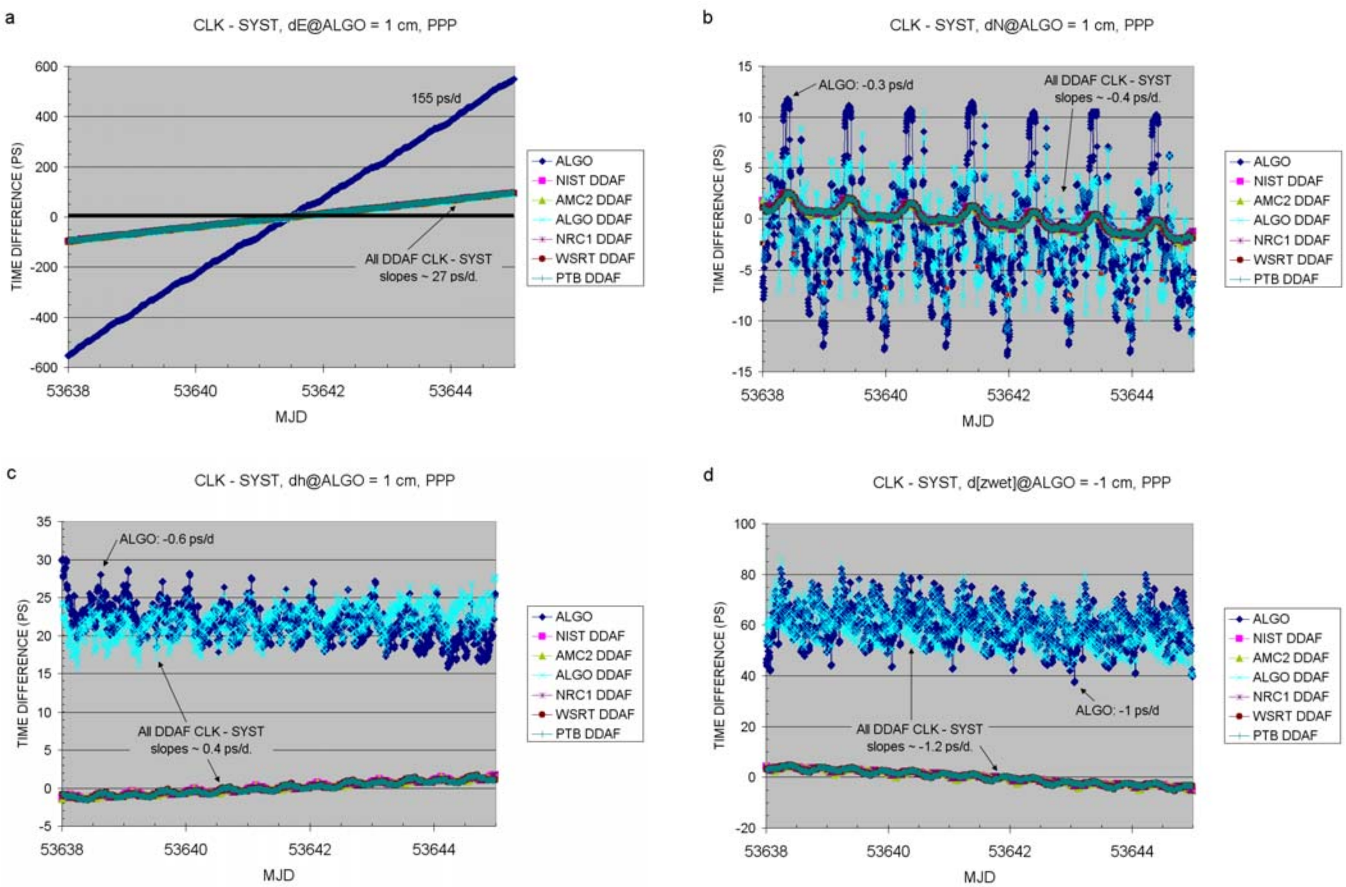

Figure 2. Effect of making a 1-cm error in position or zenith troposphere delay at ALGO when the ppp method is used. "DDAF" denotes a solution in which double-difference ambiguities have been fixed. Prior to ambiguity fixing, all values of CLK – SYST for clocks other than ALGO are zero. These values are not shown; however, the heavy black line along the x axis in 2a serves as a reminder.

the ppp method is used. The ambiguity-free values of ALGO – SYST exhibit frequency errors of 155, -0.3, -0.6 and -1 ps/d for *dE*, *dN*, *dH* and dz_{wet} respectively. The ambiguity-free values of all of the other receiver clocks remain (correctly) zero, because, prior to ambiguity fixing, the error at ALGO cannot propagate into the parameters estimated at any other site. (Frequency values were computed using a linear least-squares fit to the values of either CLK – SYST or CLK – NIST, as appropriate, and have uncertainties of a few hundredths of a picosecond/day.) Fig. 2 also shows that after ambiguity fixing has been performed, all of the clocks incur the same, approximately-equal frequency error wrt. SYST, with values of 27, -0.4, 0.4 and -1.2 ps/d for *dE*, *dN*, *dH* and dz_{wet} respectively. This implies that although double-difference ambiguity fixing creates frequency errors in CLK – SYST, it removes frequency errors in CLK(A) – CLK(B). This is confirmed in Fig. 3, which shows the values of CLK – NIST obtained by subtracting the values of CLK – SYST shown in Fig 2. All of the values of CLK – NIST obtained from the ambiguity-fixed solution exhibit frequency errors of less than 0.1 ps/d. Even after ambiguities have been fixed, a constant time error remains in the values of ALGO – NIST (or ALGO – any other clock) if the mismodeling was in *h* or z_{wet}; we cannot observe satellites below the horizon.

As Fig 2a shows, when the ambiguity-free frequency error in ALGO – SYST is large compared to the satellite-geometry noise, the ambiguity-fixed values of CLK – SYST are nearly equal to $\Sigma[\text{CLK} - \text{SYST}]_{\text{ambiguity-free}}$/(number of stations). A similar effect was observed in other weeks analyzed and will be seen again in Figs. 5-7.

In GPS week 1342, mismodeling ALGO in the *N*, *h*, and z_{wet} components caused only small (~ 1 ps/d) frequency errors in the ambiguity-free values of CLK – SYST when the ppp method was used. However, this same mismodeling sometimes caused frequency errors of up to 15 ps/d when simulations were performed for other GPS weeks. The large frequency errors caused by mismodeling ALGO in the east direction are examined further in "Discussion."

Fig. 4 shows the results of making a 1-cm error in the *E*, *N*, *h* or z_{wet} value for ALGO during GPS week 1342 when the network method is used. NIST is used as the reference clock, so all plots show CLK – NIST. We first consider the

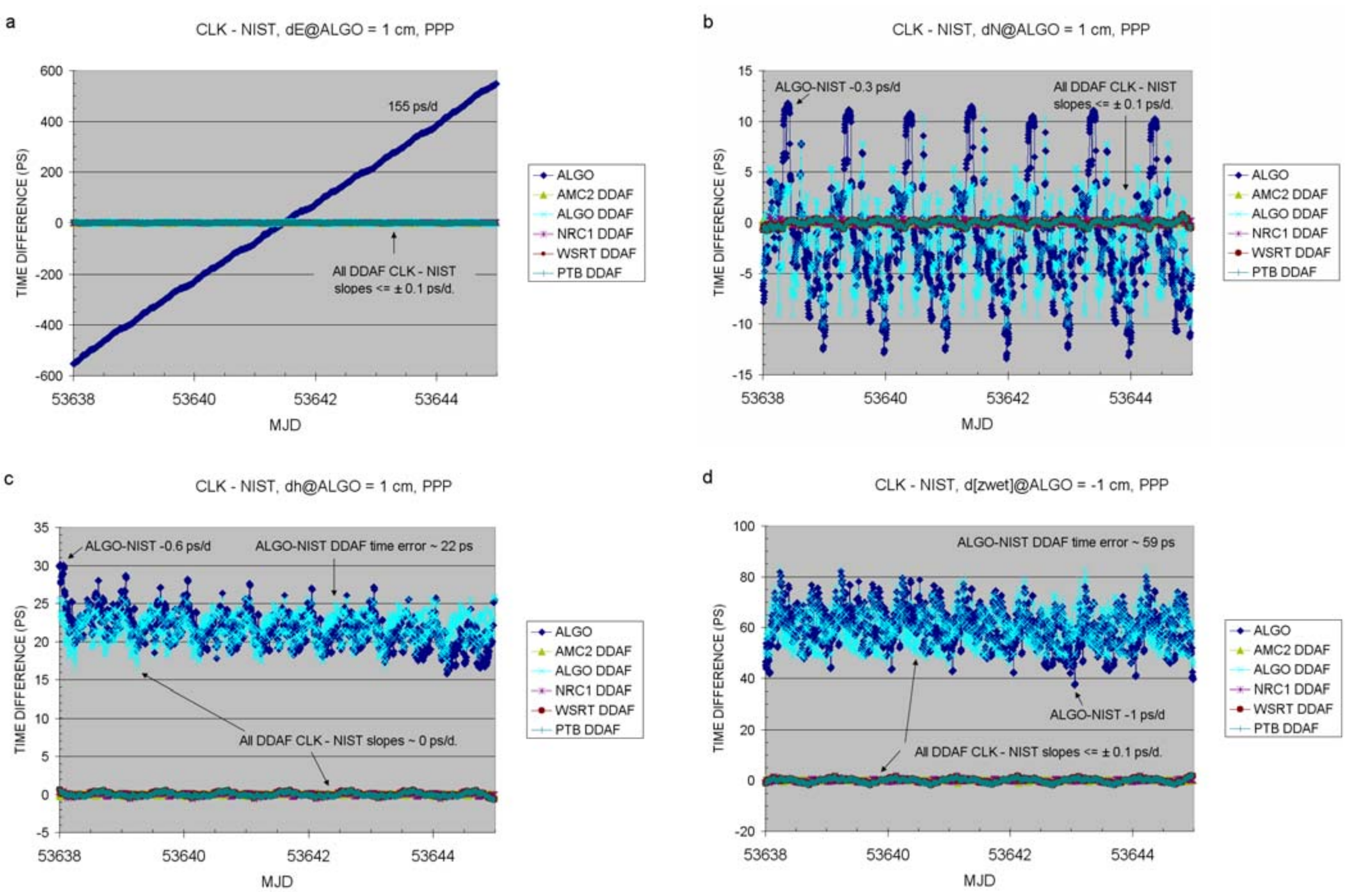

Figure 3. Effect on CLK – NIST of making a 1-cm error in position or zenith troposphere delay at ALGO when the ppp method is used. "DDAF" denotes a solution in which double-difference ambiguities have been fixed; if not marked with a DDAF, the solution is "ambiguity-free" (see text). Mismodeling *h* or z_{wet} causes constant time errors in the ambiguity-fixed values of ALGO – NIST; the values of these time errors are shown on the plots.

values obtained when ambiguities have not been fixed. A 1-cm *dE* at ALGO causes an ALGO – NIST frequency error of 153 ps/d (Fig. 4a), similar to that which occurred in the ambiguity-free ppp solution (Fig. 3a). However (Fig. 4a), it also causes frequency errors in the ambiguity-free solutions for WSRT – NIST and PTB – NIST of about 11 ps/d. A 1-cm *dN* at ALGO (Fig. 4b) causes ALGO – and NRC1 – NIST frequency errors of about -12 ps/d, and WSRT – and PTB – NIST errors of approximately -38 ps/d. A 1-cm *dH* at ALGO (Fig. 4c) causes ALGO – NIST and NRC1 – NIST errors of 12-14 ps/d and WSRT – NIST and PTB – NIST errors of approximately 40 ps/d. And a 1-cm dz_{wet} at ALGO (Fig. 4d) causes ALGO – NIST and NRC1 – NIST frequency errors of approximately -43 ps/d, as well as PTB – NIST and WSRT – NIST errors of approximately -118 ps/d.

A 1-cm mismodeling error at ALGO appears to cause a frequency error in PTB-NIST of up to $1.4{\cdot}10^{-15}$ when satellite clocks are estimated and when the double-difference ambiguities are not fixed. However, Figs. 4a-d also show that when double-difference ambiguities are fixed, all of the between-site frequency errors collapse back to zero, just as they did for the ambiguity-fixed between-site frequency comparisons in the ppp method.

Figs. 2-4 showed that fixing double-difference ambiguities removes the effect of site-based modeling errors when the frequency of one receiver clock is compared to that of another. We now show that this is also true when the mismodeling originates at the satellite.

Figs. 5-7 show the effect of moving all of the satellites +5 cm in the ECEF x, y, and z directions. The origin of the ECEF frame lies at the earth's center, with the x axis projecting out of the intersection of Greenwich meridian and the equator, the z axis projecting out of the North Pole, and the y axis projecting out of the equator in the Indian Ocean. PTB and WSRT lie nearly along the x axis, ALGO and NRC1 along the -y axis, and NIST/AMC2 about 15° west of the -y axis.

As Fig. 5a shows, in the ppp ambiguity-free solution, an orbital error in the x direction causes large frequency errors

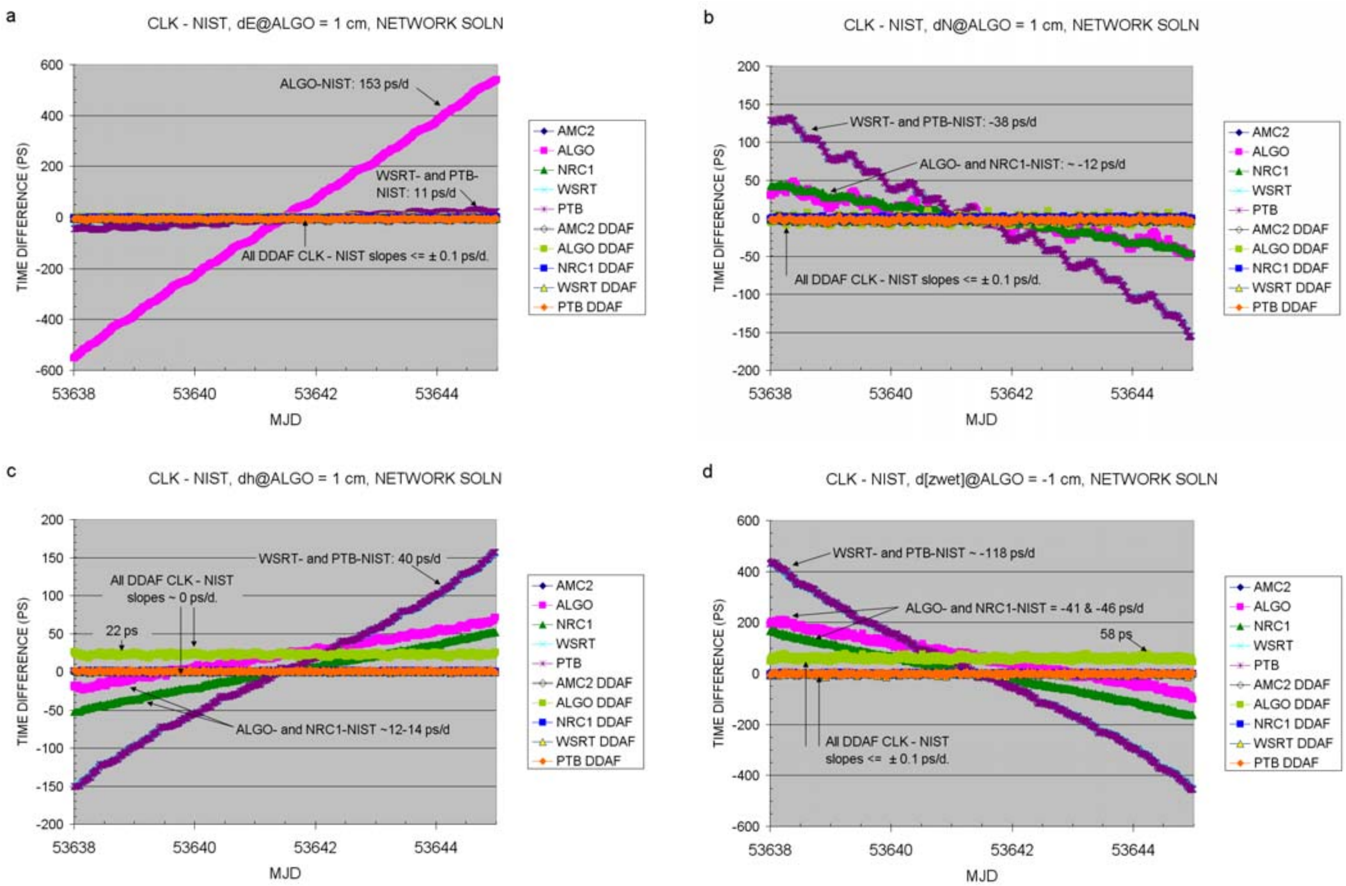

Figure 4. Effect on CLK – NIST of making a 1-cm error in position or zenith troposphere delay at ALGO when the network method is used. "DDAF" denotes a solution in which double-difference ambiguities have been fixed; if not marked with a DDAF, the solution is "ambiguity-free" (see text). Mismodeling h or z_{wet} causes constant time errors in the ambiguity-fixed values of ALGO – NIST; the values of these time errors are shown on the plots.

(-730 to -760 ps/d) for the North American stations, all of which lie in the vicinity of the -y axis, and smaller frequency errors (approximately +100 ps/d) for WSRT and PTB, which lie near the x axis. As Fig. 5b shows, this in turn causes the ppp ambiguity-free values of WSRT – and PTB – NIST to be very large: 800 to 860 ps/d. However, Fig. 5a shows that when double-difference ambiguities are fixed, all values of CLK – SYST "rotate" to the same frequency value, -495 to -493 ps/d, which is reasonably close to the average (-461 ps/d) of the ambiguity-free values of CLK – SYST. Because all ambiguity-fixed values of CLK – SYST have approximately the same frequency error, the frequency errors in the ambiguity-fixed values of CLK(A) – CLK(B) become less than or equal to 2 ps/d, as is shown in Fig. 5b. Figs. 6a-b show that analogous results are obtained when an orbital error is made in the y direction.

Fig. 5c shows the effect of making a 5-cm orbital error in the ECEF x direction when the network method is used. The satellite-clock estimates apparently absorb much of the orbit error: the frequency errors in the ambiguity-free values of (receiver) CLK – NIST are nearly ten times smaller than they were in the ppp method. For example, the ppp ambiguity-free values of PTB – NIST had a frequency error of 857 ps/d (Fig. 5b), whereas the network solution ambiguity-free values of PTB – NIST have a frequency error of -78 ps/d (Fig. 5c). (We do not know why the ppp and network answers have opposite signs.) Fig. 5c also shows that double-difference ambiguity fixing removes the between-site frequency errors caused by the orbit mismodeling. Analogous results were obtained for the network method when the orbit error was made in the +y direction (Fig. 6c).

Fig. 7 shows the effect of making a 5-cm orbital error in the +z ECEF direction. An error in this direction causes much smaller frequency errors in the ppp ambiguity-free values of CLK – SYST (Fig. 7a) and hence in those of CLK – NIST (Fig. 7b), with the ppp ambiguity-free values of CLK – NIST exhibiting maximum frequency errors of ~ 40 ps/d. Fixing double-difference ambiguities gives all of the ppp estimates of CLK – SYST approximately the same frequency

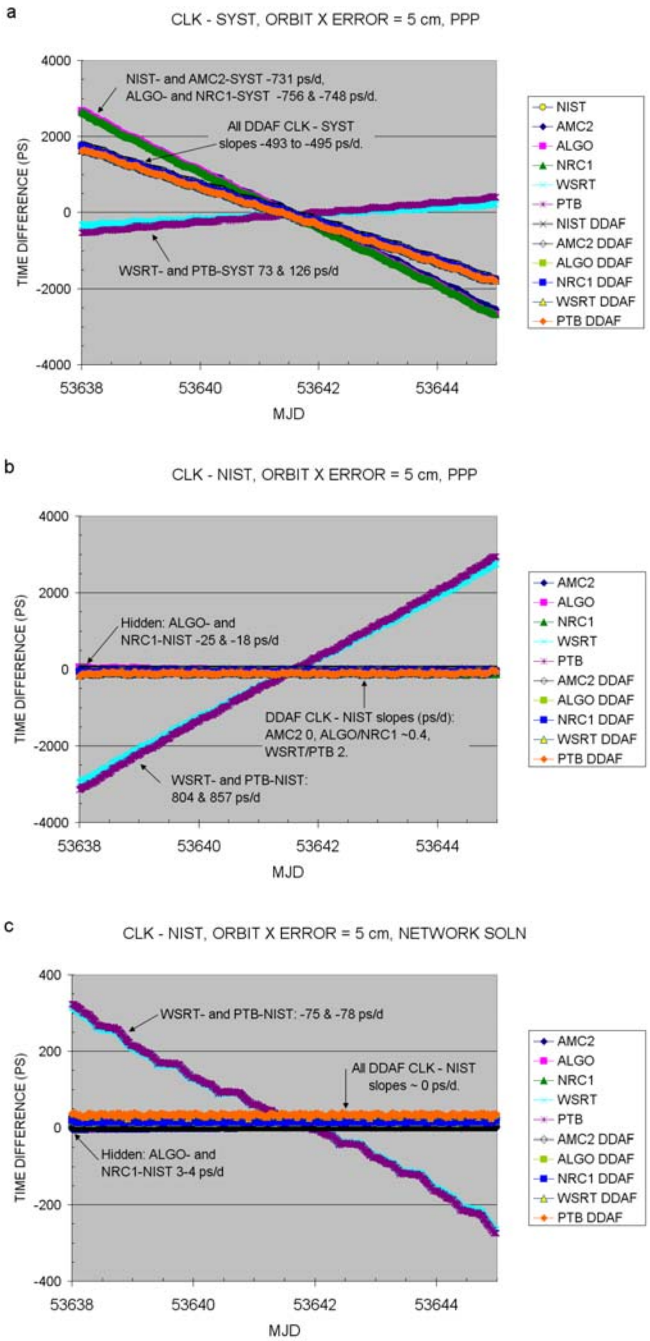

Figure 5. Effect of moving all satellites +5 cm along the ECEF x axis in ppp and network methods. "DDAF" denotes an "ambiguity-fixed" solution; if not marked with a DDAF, the solution is "ambiguity-free" (see text).

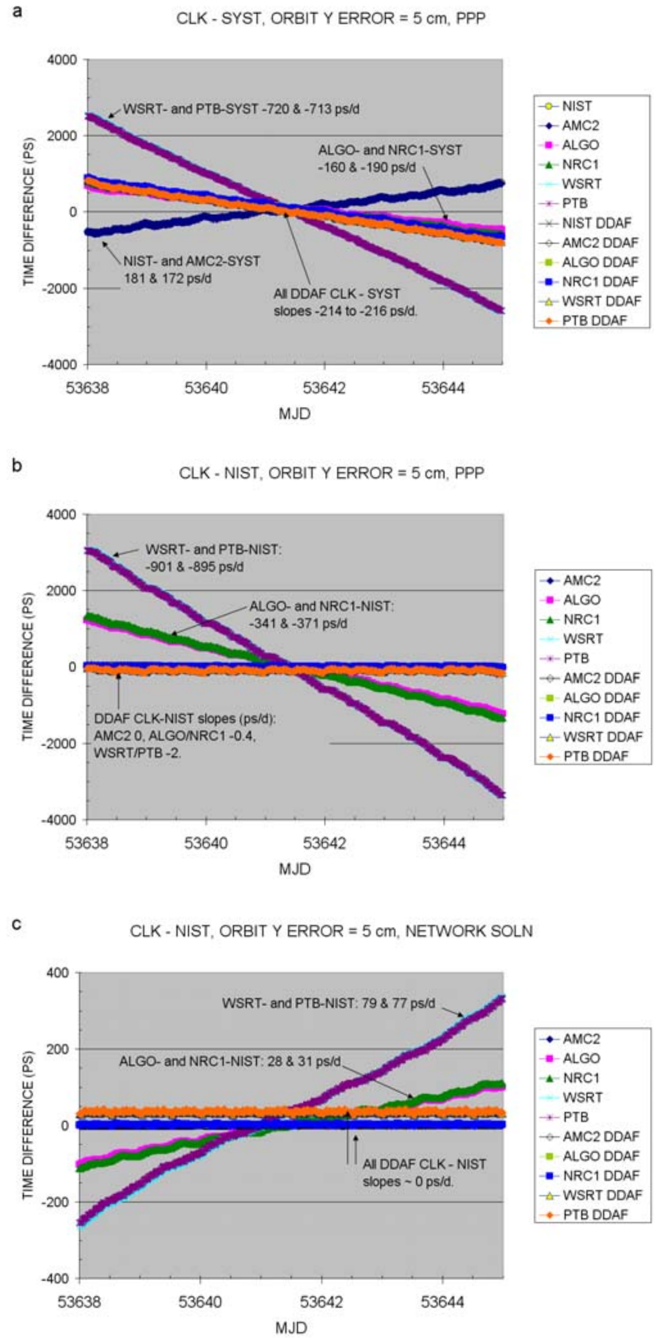

Figure 6. Effect of moving all satellites +5 cm along the ECEF y axis in ppp and network methods. Labeling is the same as in Fig. 5.

error of -4 ps/d (Fig. 7a); thus, the ppp ambiguity-fixed values of CLK – NIST are correct to within 1 ps/d (Fig. 7b).

Estimating satellite clocks (i.e., performing a network solution) mitigated the effects of an orbit error when the error was made in the x or y ECEF direction. However, this is not true when the orbit error is made in the z direction. As Fig. 7c shows, the values of PTB – NIST obtained from a network solution in which the ambiguities have not been fixed have a frequency error of -164 ps/d, rather than the +33 ps/d they had in the ppp ambiguity-free solution (Fig. 7b). Despite this, as Fig. 7c shows, fixing double-difference

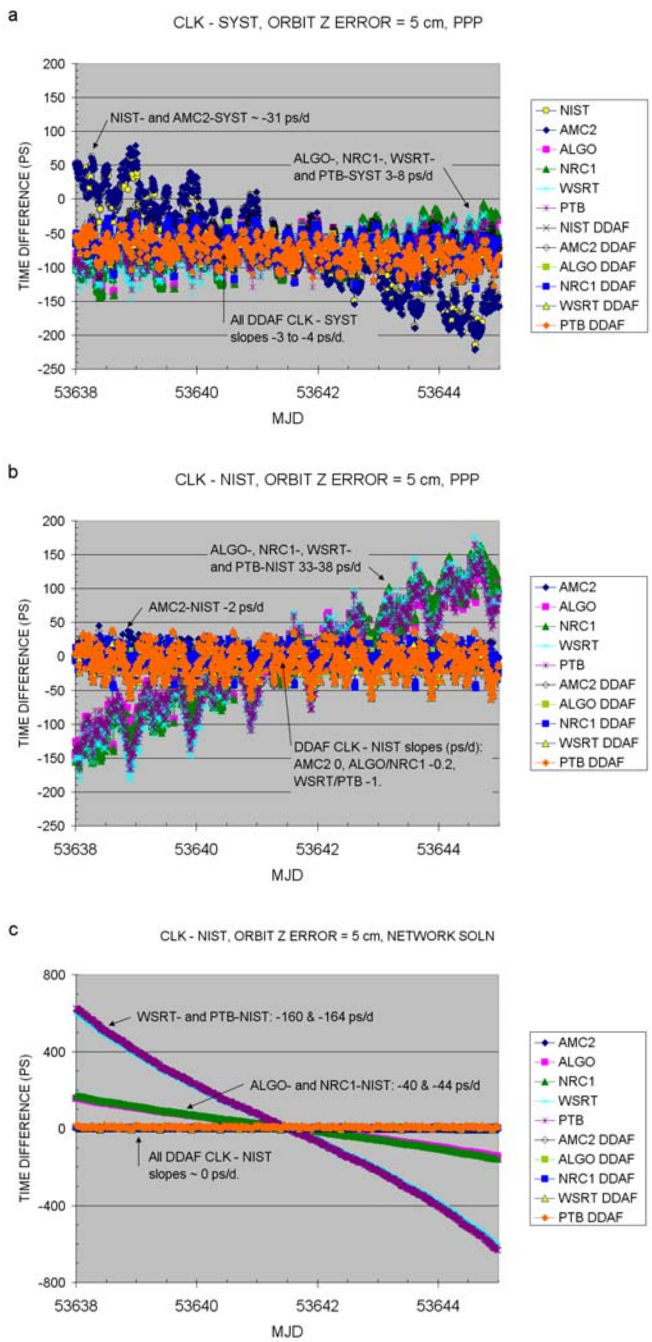

Figure 7. Effect of moving all satellites +5 cm along the ECEF z axis in ppp and network methods. Labeling is the same as in Fig. 5.

ambiguities still corrects all values of CLK – NIST to the proper frequency value of 0 ps/d.

Mismodeling all values of satellite clock – SYST by +100 ps caused insignificant between-site frequency changes. When the ppp method was used, each value of CLK – SYST changed by a constant value of +100 ps, with a maximum variation of ± 8 fs. When the network method was used, the satellite-clock mismodeling was absorbed into the satellite-clock estimates; all values of receiver clock – NIST were zero to within a maximum excursion of ± 0.025 fs.

V. Discussion

The results obtained thus far indicate that we can perform nearly perfect *between-site* frequency comparisons in the presence of systematic errors when double-difference ambiguities are fixed. This raises three questions. In this simulation study, we were able to fix 100% of the double-difference ambiguities, i.e., we were able to apply an extra constraint such as that shown in (3) to every independent value of $B_{1,2}^{i,j}$. However, when analyzing real data, we are rarely able to apply such constraints to more than 90% of the $B_{1,2}^{i,j}$s. (The ability to apply such constraints depends on the quality of receiver data, the number of overlapping observations between sites 1 and 2 of satellites i and j, and sometimes on the spatial smoothness of ionospheric conditions.) So, the first question is: how much of the impact of a systematic error remains when only a fraction of the ambiguities have been fixed? The second is: why does systematic error *x* cause frequency error *y* in solutions in which ambiguities have not been fixed? And the third is: in a network solution, what determines the amount by which an error propagates between sites?

Figs. 2-4 showed that a 1-cm *dE* in ALGO's position caused a frequency error of $1.8 \cdot 10^{-15}$ in the values of ALGO – (any other clock) when ambiguities had not been fixed. We see a similar effect when we make 1-cm *dE*s at the other sites shown in Fig. 1, and in data simulated for GPS weeks 1305, 1318 and 1331. We believe this is caused by a combination of two factors. The first is that the pseudorange (P3) measurements are weighted very lightly compared to the carrier-phase (L3) measurements. (Recall that the P3 and L3 measurements were assigned data-noise values of 1 m and 1 cm, respectively.) The second is that at mid-latitude sites in the northern hemisphere, satellites almost always travel from west to east overhead, rather than there being an even balance of west-to-east and east-to-west tracks.

dR_1^i, the difference between a simulated (correct) $L3_1^i$ or $P3_1^i$ measurement and that predicted by a processing model with east position error dE_1, can be written as

$$dR_1^i = dE_1 \sin(az_1^i)\cos(el_1^i)\,, \tag{5}$$

where az_1^i and el_1^i denote the azimuth and elevation angles of satellite i as observed at site 1. If dE_1 is positive, then as a satellite travels from west to east, dR_1^i will change in a positive direction. If dR_1^i changes in a positive direction, and if the change in dR_1^i drives a change in receiver-clock value, then this change in dR_1^i contributes a positive frequency error to the receiver clock. If the majority of satellites travel in this direction, then each satellite contributes such a frequency error. If the P3 measurements are adequately weighted, this ought not to cause a cumulative frequency error because the *time* errors contributed by the satellites to the west will be negative, those contributed by the satellites to the east will be positive, and the combination will average to zero. However, if the P3 measurements are insufficiently weighted, the jumps in clock values that normally occur every time a new satellite rises – and that correctly serve to keep the overall average centered on zero – are improperly absorbed by the phase-bias estimates. In this case, there is nothing to mitigate the positive-frequency-bias contribution of each of the satellites, and we obtain a net frequency error.

If the above is true, then a 1-cm *dE* should cause a smaller frequency error if it is made at a polar (high-latitude) site, because such sites have an even distribution of west-to-east and east-to-west moving satellites. To test this, we simulated data for a fictional station named POLE. POLE has the same longitude and height as ALGO, but is located at 87° N. The satellites travel predominantly from west-to-east at ALGO, but both west-to-east and east-to-west at POLE. As Fig. 8a shows, while a 1-cm *dE* at ALGO causes a 155 ps/d error in ALGO – SYST, a 1-cm *dE* at POLE causes only a 20 ps/d error in POLE – SYST. This is consistent with the above assertion.

Another implication of the above is that higher weighting of the P3 measurements ought to reduce the effect of an east error at a mid-latitude site. That is because the P3 measurements have no phase biases to incorrectly absorb the time jumps (1), and hence estimates of CLK – SYST based only on P3 measurements remain correctly centered around zero. Thus, we tested the impact of decreasing the data-noise values of the P3 measurements while maintaining the data-noise values of the L3 measurements at 1 cm. This increased the relative weight of the P3 measurements. Fig. 8b shows that using P3 data-noise values of 10 cm, 2 cm and 1 cm reduces the effect of a 1-cm *dE* at ALGO from 155 ps/d (default weighting) to 12, 0.5 and 0 ps/d, respectively. In real life, no one would use such small data-noise values for P3 measurements; they are too noisy and subject to multipath. However, this does suggest that rather than discarding P3 measurements altogether [15], perhaps we should weight them more heavily for frequency-transfer applications.

VI. CONCLUSIONS

We examine the impact of systematic errors on our ability to compare the frequencies of clocks located continents apart. We find that between-site frequency comparisons are largely unaffected by site-based and satellite-based systematic errors when 100% of the double-difference ambiguities are fixed. We also find that in the ppp method, although fixing ambiguities removes between-site frequency errors, it can cause errors in the values of the individual receiver clocks relative to system time. Finally, we find that when a network solution is performed and ambiguities are not fixed, an error made at site A may adversely affect frequency comparisons between sites B and C. We plan to investigate the effect of fixing fewer than 100% of the ambiguities, and to further examine the size and propagation of errors in solutions in which ambiguities have not been fixed.

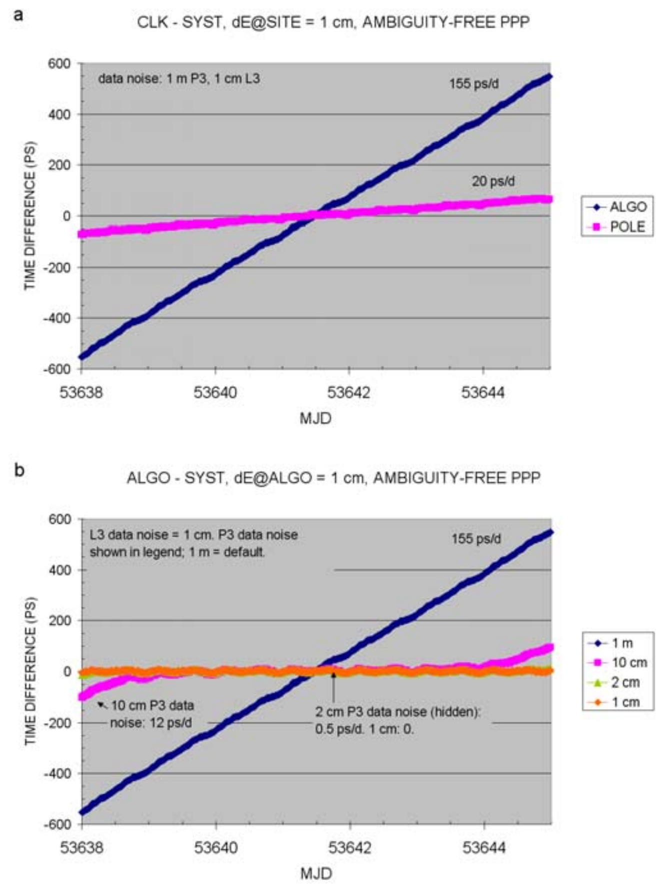

Figure 8. (a) Effect of more-even distribution of east-to-west and west-to-east-tracking satellites on impact of 1-cm east error. POLE has the same longitude and height as ALGO, but is located at 87° N. (b) Effect of increased pseudorange weighting on impact of 1-cm east error at ALGO.

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