# Precision and Accuracy of USNO GPS Carrier Phase Time Transfer: 2012 Update

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*Abstract*— **The United States Naval Observatory (USNO) produces GPS carrier-phase time-transfer (GPSCPTT) estimates for approximately 100 receiver clocks daily. All estimates are available with 16-h latency; a subset of approximately 34 are available every 6 h with 3-h latency plus 24 h of predictions. The once-per-day post-processed estimates are referred to as "rapids" (USR); the four-times-per/day estimates/predictions are referred to as "ultra-rapids" (USU). The ultra-rapids are suitable for real-time applications. We investigate the uncertainty of USR and the first 6 h of USU predictions by comparing them to four weeks of IGS Final Clock solutions along 4-6 timing links. No day-boundary discontinuities (DBDs) were removed. USR exhibited a 60-100 ps RMS difference and a few to tens of picoseconds time stability with respect to the IGS Finals, supporting an estimate of 125 ps USR standalone time stability. White FM characterized the USR-IGS difference for most averaging times observed, with USR-IGS frequency stabilities of 0.9-2.1·10$^{-15}$ at averaging time $\tau$ = 1 d. DBD removal would likely improve that value. USU clock predictions exhibited bi-modal performance with respect to IGS Finals, with links to site WES2 exhibiting noticeably worse behavior than links not utilizing it. USU-IGS differences were 139-220 and 470-584 ps RMS. USU-IGS time stabilities of 133 ps or better were observed for non-WES2 links, supporting an estimate of 153 ps time stability for USU clock predictions. Non-WES2 USU-IGS frequency stabilities exhibited 8·10$^{-14}$ – 8·10$^{-15}$ frequency stabilities for $\tau$ < 6 h (the prediction length).**

## I. INTRODUCTION

The GPS Analysis Division, part of the Earth Orientation Department at the United States Naval Observatory (USNO), produces GPS carrier-phase time-transfer (GPSCPTT) estimates for approximately 100 GPS-receiver clocks daily in its service as an associate analysis center of the International GNSS Service (IGS) [1]. Clock estimates are produced in both "rapid" and "ultra-rapid" operations, each of which creates time-transfer estimates spaced at 5-minute intervals. The processing is conducted using *Bernese 5.0 GPS Analysis Software* [2] in tandem with automation routines developed in-house, with each product set containing estimates of GPS satellite orbits and earth-orientation parameters in addition to GPSCPTT values.

"Rapid" processing is conducted once/day using 24 h of measurements collected the previous UTC day. Solutions for approximately 100 clocks are obtained using either network or precise point positioning (PPP) [3] algorithms and are available with 16-h latency. USNO has missed only one rapid-processing deadline since September 2007. "Ultra-rapid" processing is conducted every six hours for 0000, 0600, 1200 and 1800 UTC using the most-recent 24 h of data available. Solutions for approximately 34 clocks are obtained using a network algorithm. Because these solutions provide 24 h of post-processed estimates and 24 h of predictions, and are available with 3 h latency, they are useful for real-time applications. USNO maintains a 99% on-time rate for these products. All products can be downloaded immediately after completion from [4].

We evaluate the performance of USNO rapid solutions (USR) and ultra-rapid clock predictions (USU) by comparing them to IGS Final Clock Estimates [1].

## II. METHOD

Time-transfer links between six BIPM timing laboratories were compared to examine USR quality: Alternate Master Clock (AMC2; Colorado Springs, Colorado, USA), National Institute of Standards and Technology (NIST; Boulder, Colorado, USA), United States Naval Observatory (USN3; Washington, DC, USA), Physikalisch-Technische Bundesanstalt (PTBB; Braunschweig, Germany), Istituto Nazionale di Recerca Metrologica (IENG; Torino, Italy) and (Swiss) Federal Office of Metrology (WAB2; Wabern, Switzerland). The links studied were AMC2-NIST (147 km), PTBB-WAB2 (635 km), PTBB-IENG (835 km), USN3-AMC2 (2361 km), USN3-PTBB (6275 km) and PTBB-NIST (7532 km).

Time-transfer links between four laboratories equipped with hydrogen masers were compared to examine the USU prediction quality: Alternate Master Clock (AMC2; Colorado Springs, Colorado, USA), United States Naval Observatory (USNO; Washington, DC, USA), Westford (WES2; Westford, MA, USA) and Onsala (ONSA; Onsala, Sweden) The links

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studied were USN3-WES2 (624 km), USN3-AMC2 (2361 km), WES2-ONSA (5601 km) and USN3-ONSA (6150 km).

The IGS Final, USR and USU solutions are spaced at five-minute intervals. A point-by-point subtraction was performed between the USNO and IGS Final solutions for each of the links listed above over dates 25 March – 21 April 2012 (MJD 56011-38). All 24 h of the USR solutions were studied, but only the first six hours of USU predictions were studied. Day-boundary discontinuities (DBDs) were not removed. A five-sigma filter was applied to remove outliers.

USNO clock estimates are not included in the IGS final combination. Although USNO GPSCPTT results are thus independent of those obtained by the IGS, both estimate sets are obtained by processing largely the same GPS measurements. (Different data windowing may be involved.) Subtracting USNO and IGS GPSCPTT estimates may therefore remove parts of the (a) hardware instabilities and (b) hardware-and-software-based DBDs.

## III. RESULTS & DISCUSSION

Fig. 1 shows the USR-IGS double differences for the six clock pairs studied. Neither mean nor trend was removed from the double differences. The five-sigma filter removed 5/5383 and 15/7198 points from the NIST-AMC2 and USN3-AMC2 double-differences, respectively; no points were removed from the other four data sets. Large gaps in the double-difference plots (e.g., 56014) are due to data non-availability at the time of processing. A least-squares line fit to each month-long set of double-differences yielded slopes (absolute values) of 0.1 – 2.2 ps/d.

The standard deviation of the double differences was considerably larger than the mean in all links except for PTBB-WAB2, indicating that USR results were unbiased relative to IGS finals. RMS values ranged from 60-100 ps, with no apparent correlation between link distance and quality.

Fig. 2 shows the DBDs associated with the double differences shown in Fig. 1, as well as those associated with the IGS and USR solutions. (The IGS and USR solutions were not five-sigma filtered, revealing some of the outliers in Fig. 2.) The USR-IGS DBD RMSs were 80-125 ps. There is some correlation between IGS and USR DBD estimates (e.g., USN3-AMC2 MJD 56020) which means that a USNO-IGS double-difference might underestimate the size of DBDs that users of IGS or USR solutions would have to tolerate. On the other hand, Fig. 2 shows that on many days, the size of the DBDs in the USR or IGS solutions are the same order of magnitude of that in the USR-IGS double difference, meaning that DBD estimates obtained from double differences have some predictive value.

Fig. 3 shows the time/frequency stability of the double differences shown in Fig. 1. The best time stability occurs at $\tau$ = 20 min, increasing after that at an approximately white FM (WFM) rate, with WFM [5] visible in the frequency stability plot as well.

As Fig. 3 shows, USR time-transfer estimates have a few to tens of ps noise with respect to the IGS Final estimates, which in turn have approximately 75 ps noise [1]. The time stability could be converging on a single value less than 100 ps in Fig. 3; [6] studied a year's worth of comparison between USR and IGS rapid estimates in which the time stability remained nearly constant out to $\tau$ = 14-28 d. If the double-difference time stability indeed remains less than 100 ps and the time stability of the IGS estimates is 75 ps, then the time stability of the USR estimates could be estimated to be 125 ps. There could be systematic errors common to the USNO and IGS estimates untreated by this computation, but at present, few means exist to quantify them.

Fig. 3 also shows that PTBB-WAB2 excepted, the USR time-transfer estimates have $0.9\text{-}2.1\cdot10^{-15}$ frequency stability at $\tau$ = 1 d with respect to the IGS Final estimates. Removing DBDs should improve that value [7]. All time/frequency stability estimates were computed using *Stable32* software [8] which provides error bars; though not shown, the uncertainty values associated with the PTBB-WAB2 frequency stability estimates are not large enough to make the difference between its and the other links' stability insignificant.

Fig. 4 shows the USU-IGS double differences for the four USU clock pairs studied. Again, only the first six hours of USU clock predictions are considered. Neither mean nor trend was removed from the double differences. The five-sigma filter removed 237/7190, 286/7189 and 144/7252 points from the USN3-WES2, WES2-ONSA and USN3-ONSA double differences, with no points removed from USN3-AMC2. All means were well less than the standard deviations, indicating unbiased predictions.

The statistics of the USN3-AMC2 and USN3-ONSA links are very promising, with RMS differences of 139 and 220 ps with respect to the IGS Finals implying USU prediction standalone RMS of 158-232 ps. However, the USN3-WES2 and WES2-ONSA links have larger USU-IGS RMS values of 470 and 584 ps. We believe this is associated with WES2: the USN3-WES2 and WES2-ONSA double-difference plots are nearly mirror images. We do not know whether the WES2 problem lies in the processing of its data or the prediction algorithm used: all clocks are predicted as a simple linear trend, which might not adequately describe WES2 even over six hours. In any case, the link distribution is bi-modal: either 139-220 ps or 470-584 ps RMS with respect to IGS Finals.

Fig. 5 shows the DBDs associated with the double differences shown in Fig. 4. We again see a bi-modal distribution, with 154-243 ps and 735-928 ps RMS USU-IGS DBDs for the non-WES2 and WES2 links. Large frequency differences between the clocks under study prevent us from using simple subtraction to estimate the DBDs from the standalone IGS and USU solutions except in the USN3-

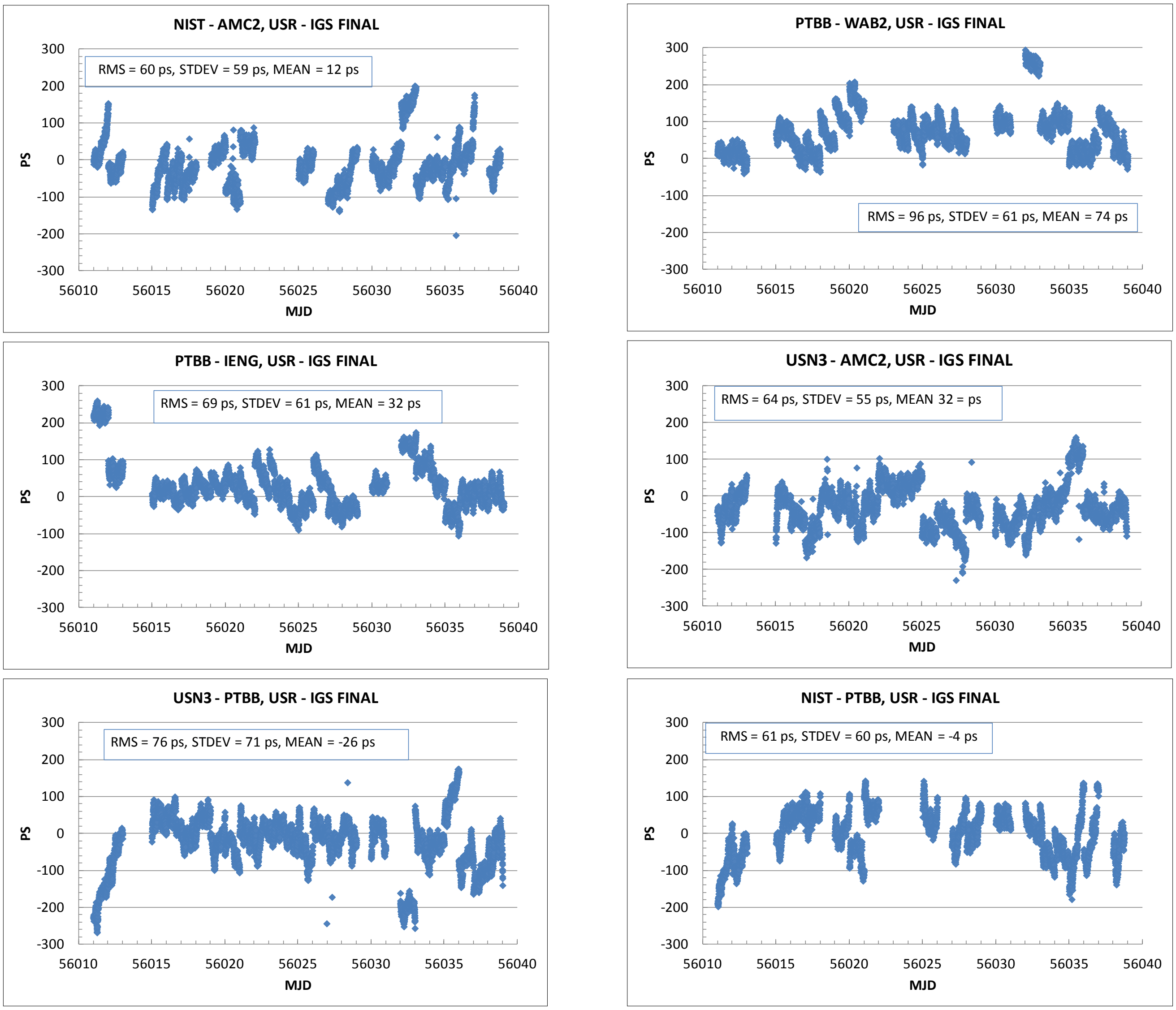

Figure 1. Difference of USNO rapid and IGS final time-transfer estimates. Day-boundary discontinuities were not removed. “STDEV” = standard deviation.

AMC2 link. On that link, the RMS DBDs are 154, 141 and 175 ps for the USU-IGS, USU and IGS values, respectively. The USU-IGS and USU DBDs are correlated; in fact, this is expected because the USU solutions have DBDs every six hours while the IGS solutions have one per day, meaning ¾ of the Fig. 5 DBDs (all links) come only from the USU solutions: no USU-IGS DBD cancellation can occur. So, though on three of the Fig. 5 links we do not have DBDs from the standalone USU/IGS solutions, the RMS of the DBDs in the double-differences are a reasonable predictor of the DBDs to be tolerated when using a USU prediction, because lowering of the RMS through USU-IGS DBD cancellation can only occur 25% of the time. Conclusion: the DBDs in the USU clock predictions show (thus far) a bi-modal size distribution of 154-243 ps and 735-928 ps.

Fig. 6 shows the time/frequency stability of the double differences shown in Fig. 4. The time stability of the USU-IGS differences is roughly 10 times worse than that of the USR-IGS differences. However, the maximum TDEV value of the USN3-AMC2 and USN3-ONSA links is 133 ps, with many values well below 100 ps. WFM dominates until $\tau = 21$ h 20 min, at which point the time stability begins to improve. The reason for this is unknown: perhaps the long-term agreement of the IGS Final and USU predicted time-transfer estimates is better than the short-term agreement. This would be the case if the IGS Final estimates more accurately reflect the five-minute point-to-point (or other short-term) behavior of the clocks under study than do the USU predictions. The USU predictions will over-smooth the clock noise, but several IGS values must be averaged to reduce solution noise

Figure 2. Day boundary discontinuities in double-difference, USNO rapid and IGS final time-transfer estimates.

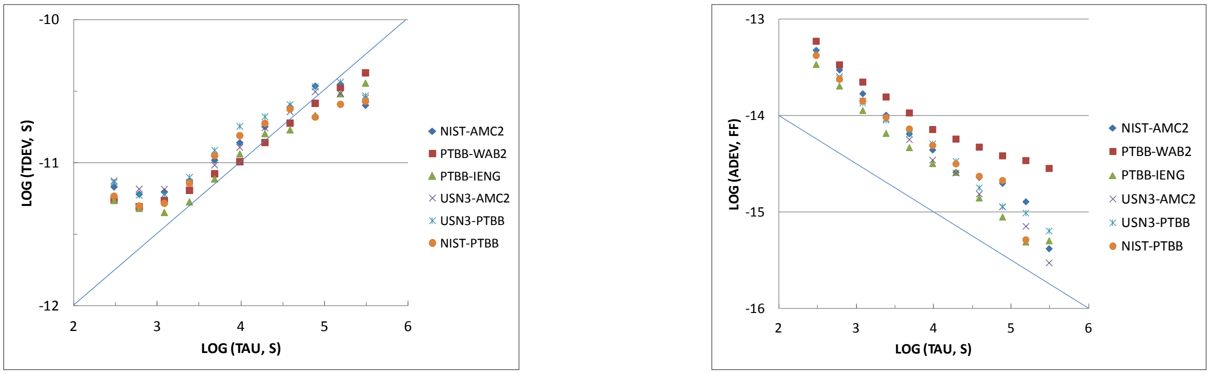

Figure 3. Time and frequency stability (time deviation TDEV; Allan deviation ADEV; [5]) of the Fig. 1 USNO rapid – IGS final clock double-differences. Blue lines indicate 0.5 slope associated with white FM noise.

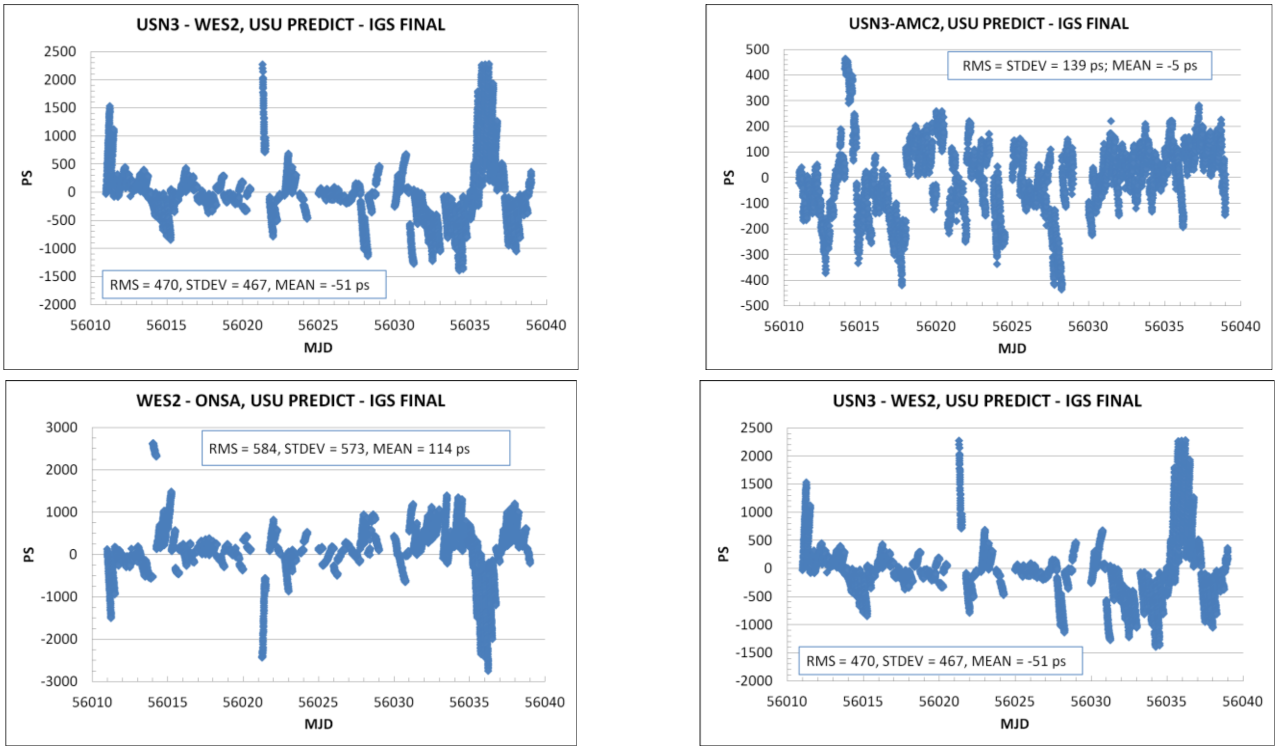

Figure 4. Difference between first 6 h of USNO ultra-rapid predicted and IGS final time-transfer estimates. Day-boundary discontinuities were not removed.

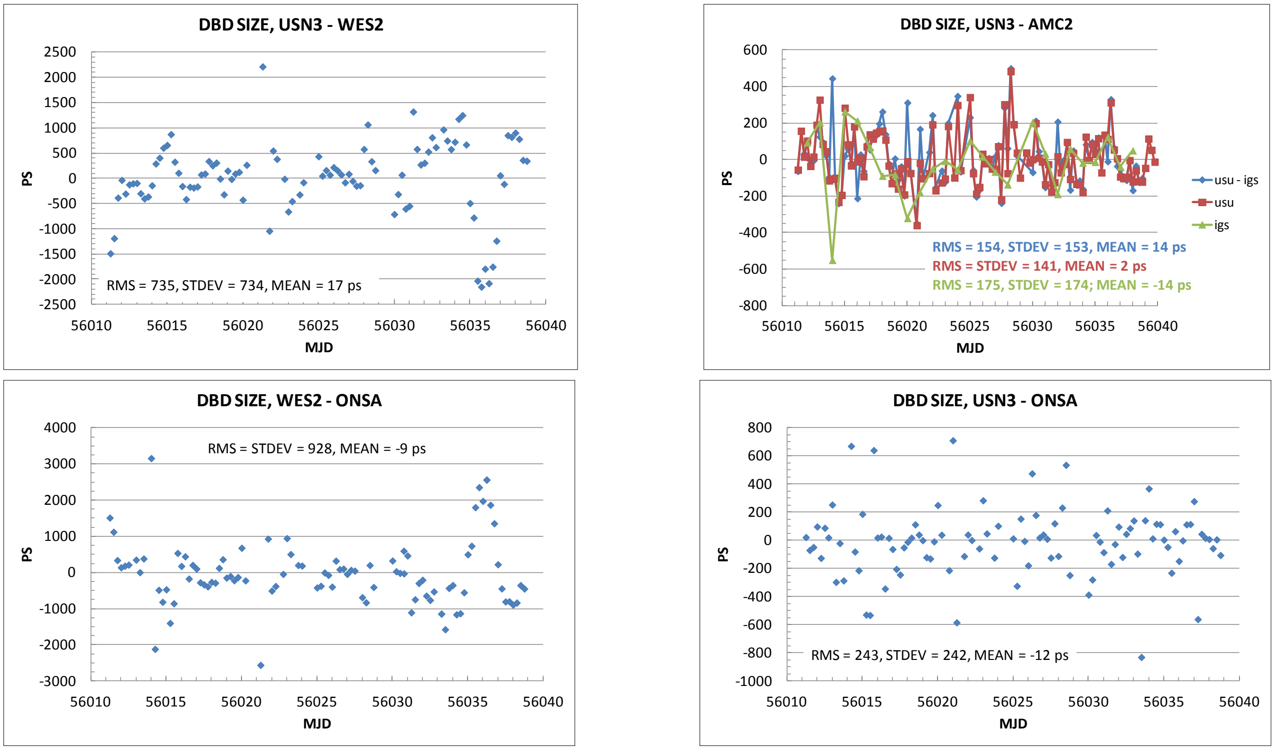

Figure 5. Day boundary discontinuities in USNO ultra-rapid 6h predict – IGS final double differences. USN3-AMC2 plot also shows day boundary discontinuities in IGS and USNO ultra-rapid predict solutions.

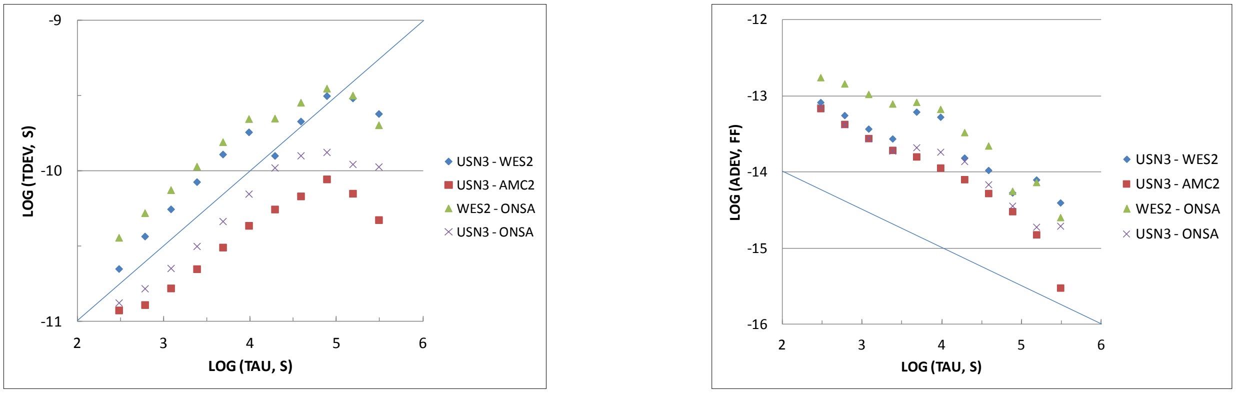

Figure 6. Time and frequency stability (time deviation TDEV; Allan deviation ADEV) of the Fig. 4 USNO ultra-rapid predict – IGS final clock double-differences. Blue lines indicate 0.5 slope associated with white FM noise.

adequately to detect the clock noise. Finally, the WES2 solutions exhibit a strange feature at $\tau$ = 5 h 20 min, perhaps related to the 6-h prediction refresh rate, that the *Stable32* error bars aren't large enough to negate.

The USU-IGS frequency stability is again WFM, with most links exhibiting $8{\cdot}10^{-14} - 8{\cdot}10^{-15}$ stability for $\tau < 6$ h, i.e., during the prediction interval, and continuing to decrease with increased averaging time. Odd features are again visible for WES2 links at $\tau$ = 80-160 min and 1 d 18 h 40 min.

## IV. CONCLUSIONS & FUTURE WORK

USNO "rapid" GPS carrier phase time-transfer clock estimates (USR) exhibited a 60-100 ps RMS difference with respect to the IGS Final clock estimates. No mean bias was observed on five out of six links studied. The USR-IGS double differences exhibited day-boundary-discontinuities (DBDs) with RMS range 80-125 ps. 70-250 ps RMS covers the range of most USR and IGS standalone DBDs observed, with more study needed due to inadequate filtering. USR solutions exhibited a few to tens of ps time stability wrt IGS solutions which could indicate approximately 125 ps USR standalone time stability. White FM characterized the USR-IGS difference for most averaging times observed, with USR-IGS frequency stabilities of $0.9\text{-}2.1{\cdot}10^{-15}$ at $\tau$ = 1 d. DBD removal would likely improve that value.

USNO "ultra-rapid" (USU) clock predictions exhibited bi-modal performance wrt IGS Final estimates, with links to WES2 exhibiting noticeably worse behavior. USU-IGS differences were 139-220 and 470-584 ps RMS, again with no mean bias observed. Double-difference (USU-IGS) DBDs had RMSs of 154-243 and 735-928 ps; the USU-IGS DBDs are reasonable estimators of the DBDs encountered by USU users because USU DBDs can only be canceled by IGS DBDs every one out of four points. USU-IGS time stabilities of 133 ps or better were observed for non-WES2 links, indicating 153 ps time stability for USU clock predictions. Non-WES2 USU-IGS frequency stabilities exhibited $8{\cdot}10^{-14} - 8{\cdot}10^{-15}$ frequency stabilities for $\tau < 6$ h (the prediction length).

More study is needed to determine whether the bi-modal USU performance exhibited was a fluke or a real shortcoming in the prediction technique. Examining the performance of 3-9 h clock predictions (as opposed to 0-6 h) would allow more exact characterization of the user experience, as USU predictions have 3 h latency. USU DBD size could be assessed more exactly by assessing only DBDs associated with the 0600, 1200 and 1800 UTC releases.

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