THE STABILITY OF GPS CARRIER-PHASE RECEIVERS

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Abstract

GPS carrier-phase (CP) time and frequency transfer is a convenient and reliable method to compare distant ground clocks. Short- and long-baseline experiments were performed to ascertain whether CP receivers are sufficiently stable for use in the calibration of Two-Way Satellite Time and Frequency Transfer equipment and the comparison of primary frequency standards. The results were affirmative, demonstrating a time transfer precision of about 100 ps or better in a few days over short baselines and about 100 ps at 1 day and about 300 ps at 5 days over long baselines, provided the receivers hold their calibration, are operated under environmentally controlled conditions, and are connected to phase-stable antenna cable.

INTRODUCTION

GPS carrier-phase (CP) time and frequency transfer is a convenient and reliable method to compare distant ground clocks. The precision of this time transfer method is better than that of the GPS Common View method **[1]** and on short (sub-daily) timescales is also better than that of the Two-Way Satellite Time and Frequency Transfer (TWSTFT) method **[2]**. For both CP and TWSTFT, accuracy in time transfer is achieved through special calibration efforts that retain their validity over time only to the level of the precisions reported here. A frequency stability of 10^{15} or better permits precise comparison of atomic standards, e.g. **[3]**.

TECHNIQUE

In CP, satellite and receiver clocks are estimated at each data epoch relative to a reference receiver clock, in timing labs usually a receiver connected to a hydrogen maser. Geodetic (dual-frequency) time transfer receivers, like the Ashtech Z12-T, are frequency locked to an external high-performance clock, and are supplied a coherent external timing signal (usually 1 pulse-per-second) to facilitate generation of a traceable internal time reference on which to base all pseudorange measurements. The so-called ionosphere-free combination of the carrier-phase measurements made on the two frequencies L1 and L2 can be used to remove the effect of the ionosphere to first order, while the ionosphere-free code measurements do so by combining the codes at the P1 and P2 frequencies.

A separate issue for time transfer is that some receivers, such as the NovAtel T-Sync receiver, do not track the P1 code, but only the C/A (also known as C1) code. Hence, processing should apply measured C1-P1 biases.

In Bernese software **[4]**, non-clock parameters are first obtained from the double-differences between two simultaneous single-difference observations of two different satellites. This eliminates the clock dependencies so that other error sources (e.g., orbit error) can be solved for. Although GPS code (pseudorange) measurements are less accurate than the carrier-phase observations by a factor of about 100, they are necessary to resolve the carrier-phase ambiguity parameters. Timing differences derived from Precise Point Positioning are obtained from a combined pseudorange and phase fit for the local parameters (site clock, antenna position, and troposphere). The precision of the time differences are typically 50 ps for a 1-day observation **[5]**.

In recent years, many national timing laboratories have co-located geodetic GPS receivers together with their traditional GPS/GLONASS Common View (CV) receivers and TWSTFT equipment. Many of these geodetic receivers operate continuously within the International GNSS Service (IGS), and their RINEX-format data are regularly processed by IGS Analysis Centers. From its global network of over 350 stations and its Analysis Centers, the IGS generates GPS satellite ephemerides, and station and satellite clock time differences relative to the IGS Time Scale.

A postprocessing method called Precise Point Positioning (PPP) is in use in the geodetic community, allowing precise recovery of GPS antenna position, local tropospheric zenith delays, and clock phases by taking advantage of these IGS precise products. It requires RINEX files of phase measurement data from individual receivers (not necessarily in the IGS network), which are combined with precise information about the satellite ephemerides and clocks provided by the IGS. The time link between two stations can then be obtained by simple difference between the clock phases obtained for each station.

PPP solutions, providing a frequency stability (in terms of Allan deviation or ADEV) of 1×10^{-14} at 1 day, are twice as stable over the short/medium term than the GPS CV and GPS P3 **[6]** methods. PPP solutions are consistent with the IGS Final clock products at the sub-nanosecond level and at the 2-ns level with TWSTFT, GPS CV, and GPS P3. If ionosphere-free measurements are used in combination with nominally compensated tropospheric corrections, a frequency stability of 1 part in 10^{15} might be attainable with integration times of about 1 day. Further improvements can be made by reducing the day-boundary discontinuities that degrade the stability of concatenated daily solutions. This can be done by such procedures as multi-day averaging. In particular, a method called the sliding batch procedure has been developed **[7]**, in order to improve the continuity of solutions by minimizing the solution boundary discontinuities caused by colored noise in the pseudorange data.

Accordingly, PPP offers the opportunity to calibrate TWSTFT hardware with co-located geodetic GPS receivers without incurring the cost and labor of transporting calibration equipment from one TWSTFT site to another, the validation of which is one objective of this paper. TWSTFT equipment can be kept within 0.4 ns rms of a given calibration over a time period of years if properly maintained **[8]**, though long-term variations of up to 3 ns have been observed.

The long-term stability of CP receiver calibrations is on the order of 1 ns over 1 year **[1]**. The stability solutions in this paper include not only that of the hardware, but also the modelling errors inherent in the processing software, and so characterize all the errors that one would expect in using the CP/PPP method.

EQUIPMENT

This study uses receivers *AMC2* at the Alternate Master Clock facility in Colorado, *NIST* at NIST in Colorado, *PTBB* at PTB in Germany, and *NOV1*, *USNO*, and *USN3* at the U.S. Naval Observatory (USNO) in Washington, D.C. All are Ashtech Z-12T geodetic receivers, except *NOV1*, which is a NovAtel geodetic receiver. All use hydrogen masers as external time references. All but *NOV1* are on the IGS network, from which the data are publicly available.

The PPP processing was performed using PPP Release 1087 developed by National Resources Canada **[9]**, with IGS Final 15-minute satellite orbit and 5-minute satellite clock products. Smoothing (backwards filtering) was done both daily and, to minimize day-boundary discontinuities, with the sliding-batch technique, using the 4th of every 7-day interval overlapped daily.

ZERO-BASELINE SOLUTIONS

Over short baselines, most geodetic parameters, including clocks, are insensitive to orbit error. This is also true of atmospheric conditions, which are common to both antennas for a short baseline. Multipath is usually the dominant observational error, but other local factors include receiver noise due to temperature sensitivities, RF interference, internal impedance mismatches, etc. **[10]**

For zero-baseline measurements, many error sources are identical for each receiver and, therefore, cancel out in the clock solutions. For example, the multipath reception errors will completely cancel out for each receiver, assuming they are the same model (so their rejection algorithms would be the same). Delays due to the troposphere are also identical. Therefore, analysis of a zero-baseline experiment will result in the most precise solution possible, given the equipment setup. The main limitations are hardware delay variations due to the changes in ambient conditions.

To approach a long-term stability of 100 ps in a CP time/frequency transfer system, minimizing the thermal sensitivities in the receiver and associated hardware is required. Use of phase-stable antenna cable is necessary if more than a few meters are exposed to outdoor temperature changes, as is use of either thermally controlled antenna enclosures or antenna electronics designed to be thermally stable over wide temperature ranges.

At USNO, short- and zero-baseline time transfer is conducted routinely between devices referenced to the master clocks. Receivers *USN3* and *NOV1* share a common antenna and are operated in the same temperature-controlled (to within ±0.5 deg C) room, while receiver *USNO*, at a distance of 174 m from the others, is also in a temperature-controlled (to within ±1 deg C) chamber (suboptimal for a chamber). The AOA Dorne Margolin choke-ring antennas are not temperature stabilized, but the antenna cabling is passive phase-stabilized.

Segments of simultaneous clock differences over 97 days (MJD 55371-55468) from all three co-located USNO receivers, shown in Figure 1, have been used to determine their individual absolute time and frequency stabilities through a three-cornered-hat approach. Application to 7-day batch-smoothed data results in significant improvement over daily solutions (averaging 30% in the ADEVs). Figure 2 compares segments of *USN3* data from the daily and 7-day solutions, exhibiting the smoothing of the day-boundary discontinuities between the two.

The results for frequency stability (ADEV) and time deviation (TDEV) are shown in Figures 3 and 4 plotted vs. sampling time (tau) and are listed in Table 1. The ADEVs were solved for using a method designed to minimize cross-correlations **[11]**. The TDEVs were not so solved, since that method has yet been published for TDEVs, so they do not exactly relate to the corresponding ADEVs.

Table 1. Results for the absolute frequency stabilities and time deviations of the USNO receivers.

	ADEV		TDEV	
Receivers	τ = 1 day	τ = 14 days	τ = 1 day	τ = 14 days
USN3	9.4×10^{-16}	1.1×10^{-16}	2.0×10^{-11}	2.4×10^{-11}
NOV1	2.3×10^{-16}	3.2×10^{-17}	2.9×10^{-11}	2.7×10^{-11}
USNO	2.2×10^{-15}	2.8×10^{-16}	7.9×10^{-11}	7.8×10^{-11}

Thus, time transfer of about 100 ps or better was accomplished in a few days. The measured frequency stability of *USNO* is worse than that of *USN3* and *NOV1* in large part because of its separate antenna and the correction necessary to reduce it to common clock. On the other hand, the stabilities of *USN3* and *NOV1* are actually a bit worse than their measurements indicate because of the intercorrelations arising from their common location.

Use of IGS Rapid Orbits rather than Final Orbits show insignificant degradation (a few percent in the ADEVs), which is not enough to appreciably detract from the method's ability to perform precise calibration of TWSTFT hardware. Also, the shorter latency of the Rapid Orbit results permits the derivation of precise calibrations more quickly than waiting for the availability of the Final Orbits from the IGS.

No statistically significant correlation with room temperature was found to the limit of 1 ps/deg C for either receiver in the temperature-controlled room.

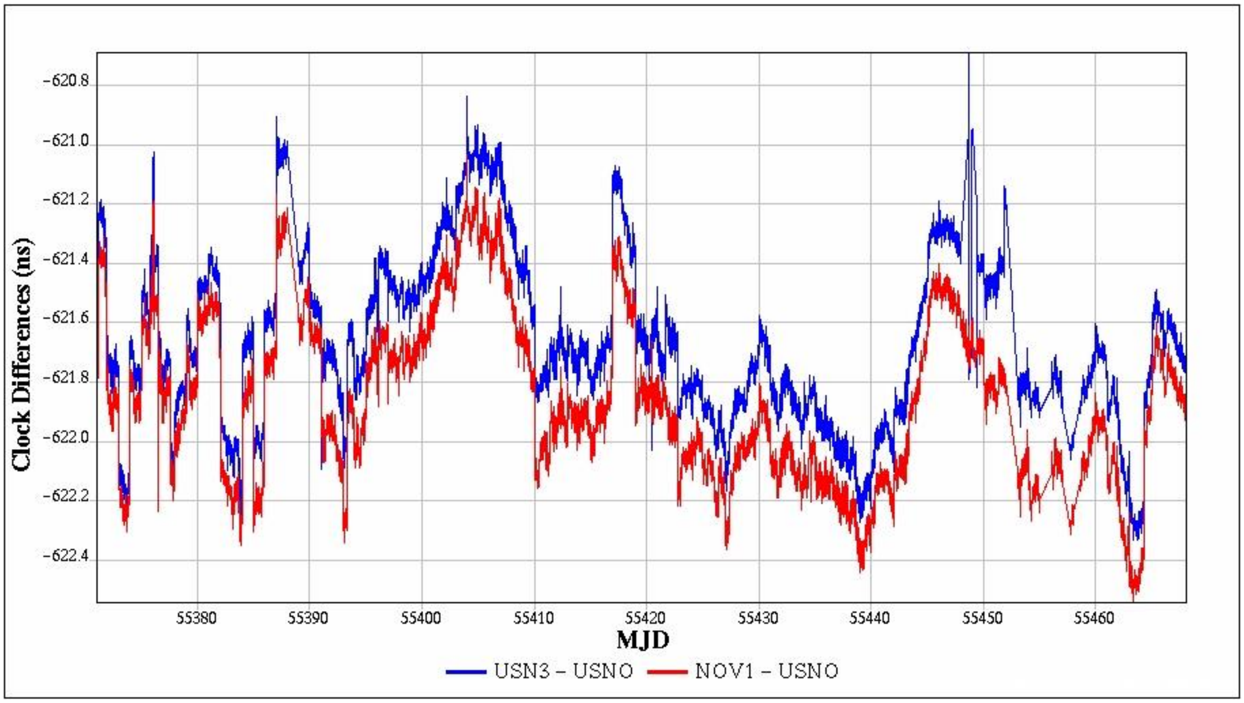

Figure 1. Clock differences for the receivers at USNO.

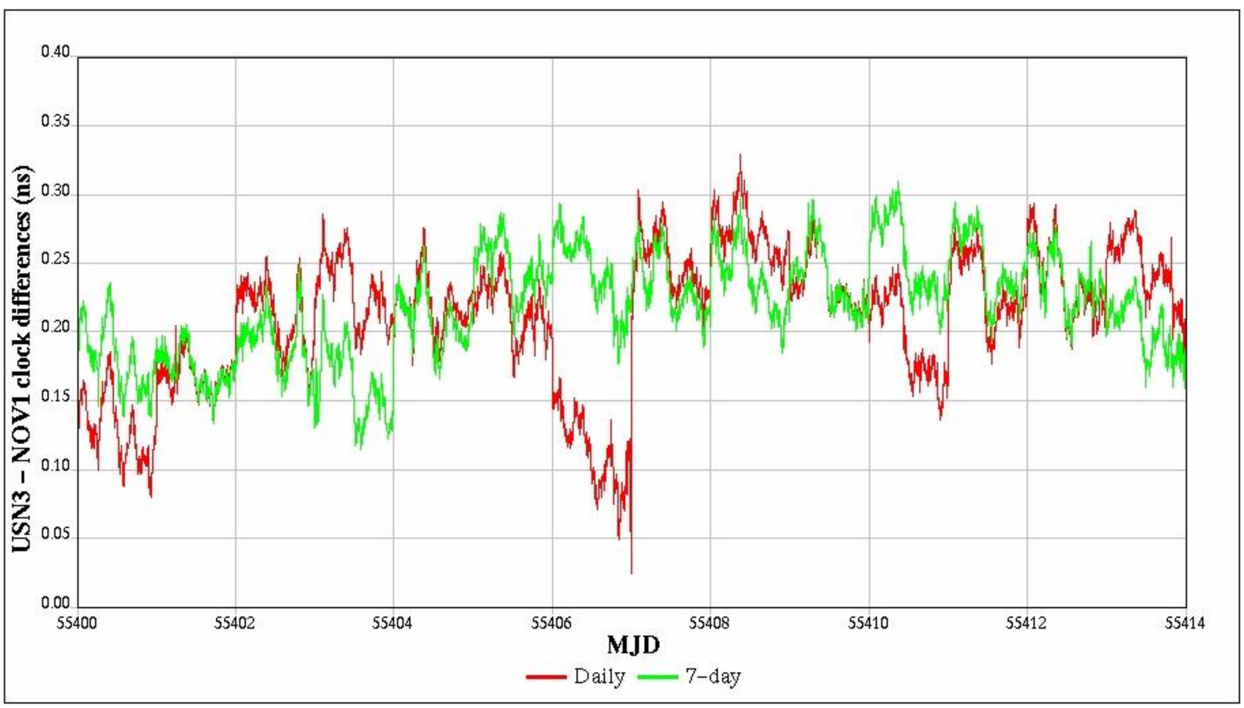

Figure 2. Close-up of *USN3* data from the daily and 7-day solutions.

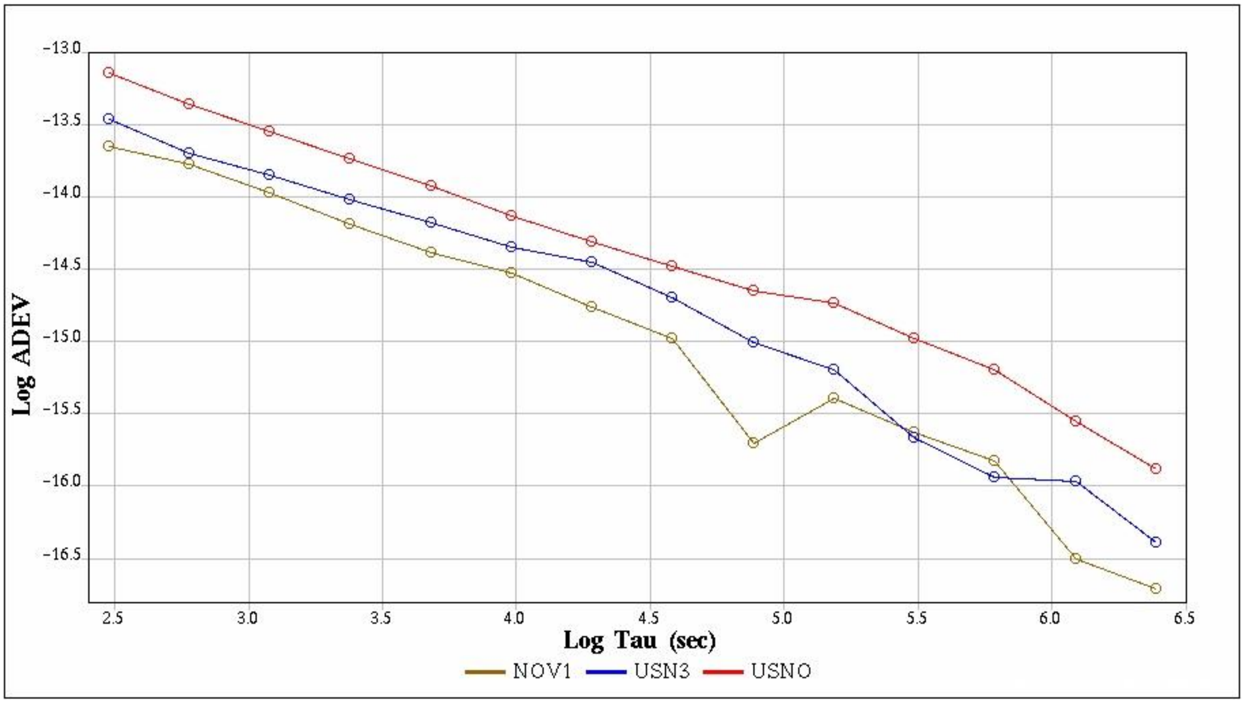

Figure 3. Frequency stabilities of the receivers at USNO.

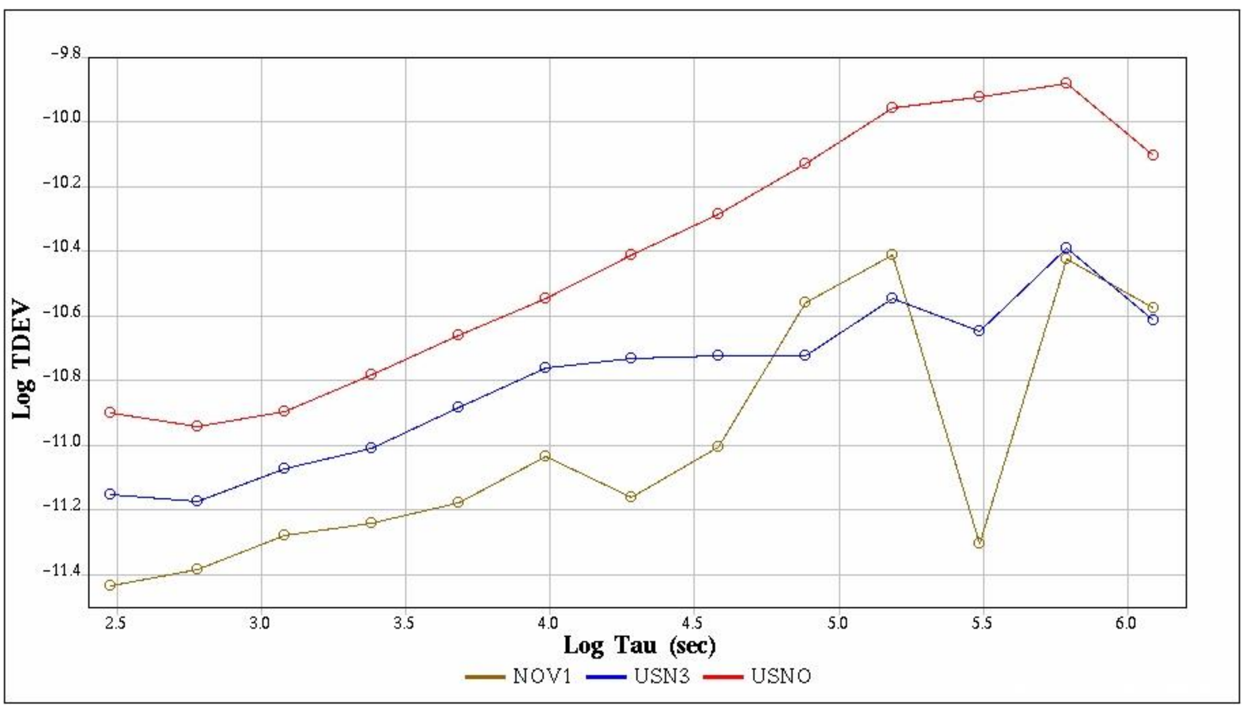

Figure 4. Time deviations of the receivers at USNO.

LONG-BASELINE SOLUTIONS

The dominant errors for long-baseline solutions are multipath, troposphere mismodelling, satellite orbital errors, and differences between and variations in the hardware setups.

Segments of simultaneous clock differences over 149 days (MJD 55224-55373) from the receivers *AMC2*, *NIST*, *PTBB*, and *USN3*, shown in Figure 5, have been used to determine their individual absolute time and frequency stabilities through an n-cornered-hat approach, as above. These pairs of receivers do not share a common clock, so the movements between their clocks are incorporated into these stabilities, which are therefore only upper limits.

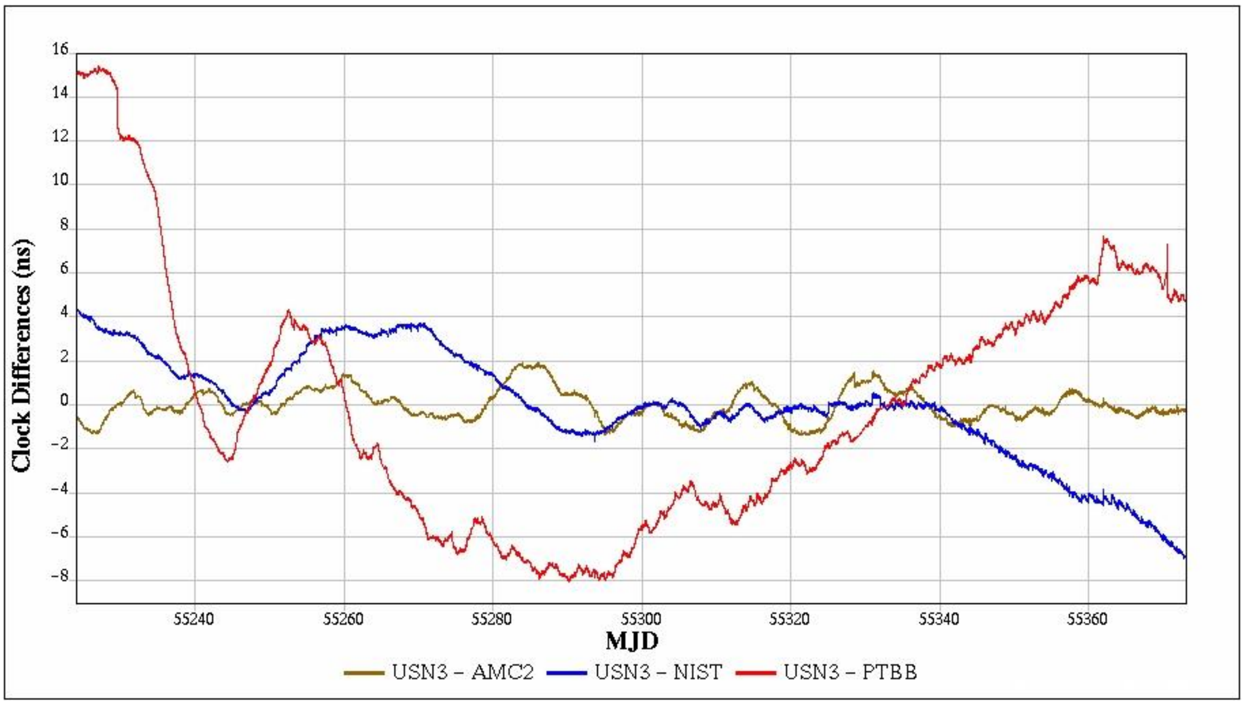

Figure 5. Clock differences for the international timing lab receiver/clock combinations, normalized to a mean of zero.

The absolute receiver frequency stability limits obtained for the receiver/satellite clock combinations are shown in Figure 6. At 1 day, they ranged from 1.4×10^{-15} (for *AMC2*) to 4.5×10^{-15} (for *PTBB*) and, at 28 days, they ranged from 1.7×10^{-16} (*USN3*) to 1.8×10^{-15} (*PTBB*). The slope of the log ADEVs out to 1 day (where time transfer noise still dominates the clock noise) is -0.6, about what is expected for random-walk phase noise. This noise is probably the result of temporal correlations introduced by the carrier-phase smoothing **[10]** via backwards-filtering and perhaps some of the random-walk noise in the tropospheric estimates, which are correlated with the clock estimates.

The time deviations are plotted in Figure 7. At 1 day, they ranged from 8.4×10^{-11} (for *AMC2*) to 1.9×10^{-10} (for *PTBB*) and, at 28 days, they ranged from 3.2×10^{-10} (*USN3*) to 2.7×10^{-9} (*PTBB*). Thus, intercontinental time transfer capabilities of about 100 ps at 1 day and about 300 ps at 5 days have been demonstrated. The results for USN3 and AMC2 suffer least from the lack of a common clock because the AMC master clock is steered toward the USNO Master Clock (hence, *AMC2* is steered toward *USN3*) based on TWSTFT, effectively giving them a common clock on long timescales.

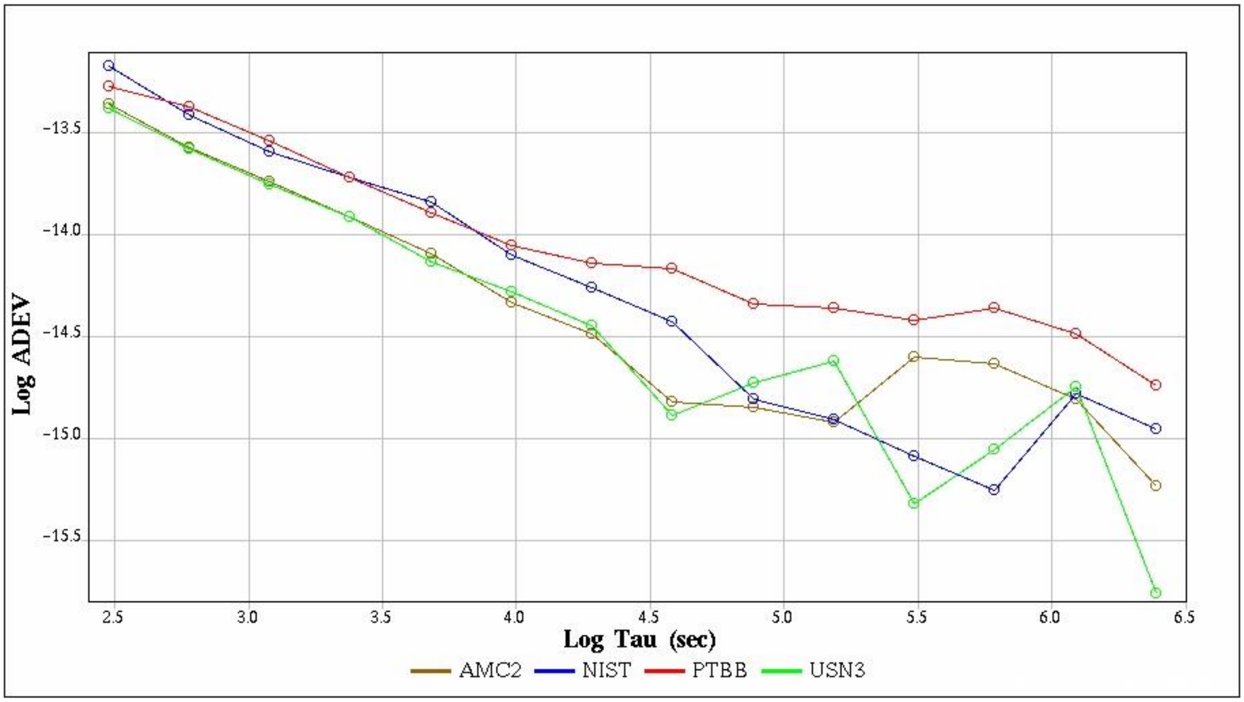

Figure 6. Absolute frequency stability limits of the timing lab receiver/satellite clock combinations.

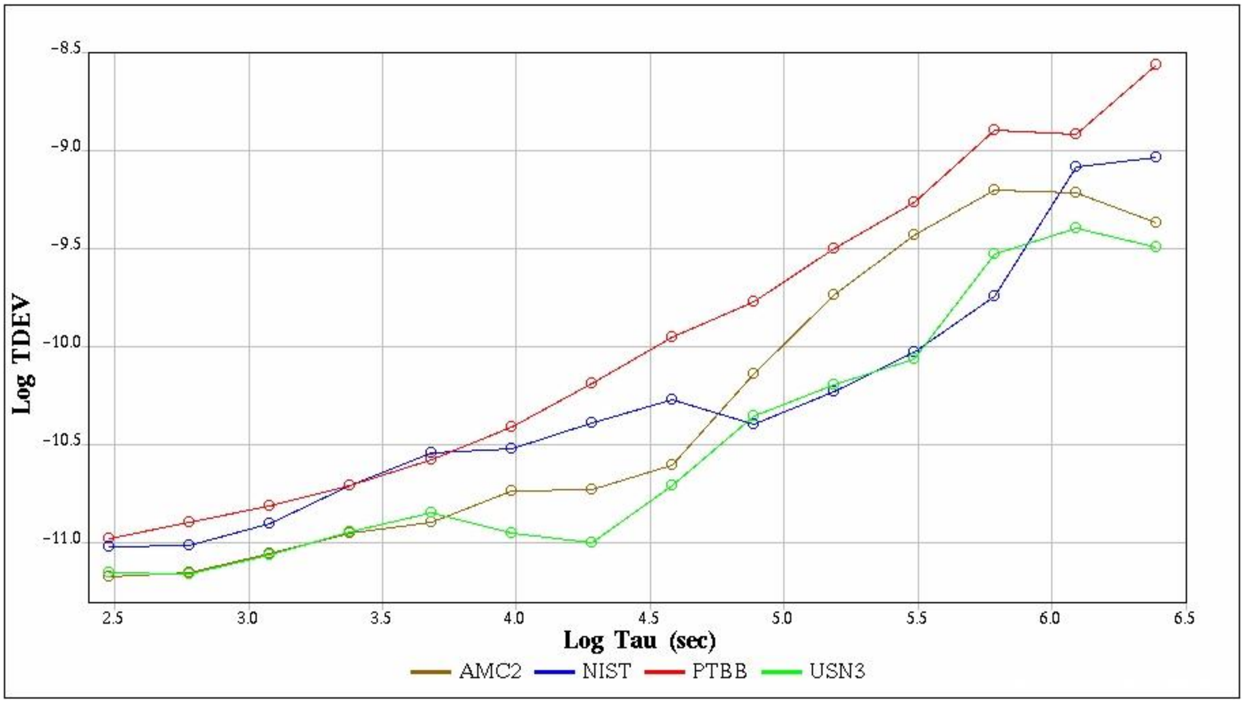

Figure 7. Absolute time deviation limits of the timing lab receiver/satellite clock combinations.

CONCLUSIONS

Carrier-phase receivers, when properly calibrated, operated under environmentally controlled conditions, and connected to phase-stable antenna cable, are sufficiently precise and stable to be utilized to calibrate TWSTFT equipment and to compare primary frequency standards. Short-baseline experiments at USNO have shown a time transfer performance of about 100 ps in a few days. Long-baseline solutions yield time transfer precisions of about 100 ps at 1 day and about 300 ps at 5 days.

DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, USNO does not endorse any commercial product, nor does USNO permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

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