FREQUENCY TRANSFER
USING PRECISE POINT POSITIONING[*]

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Abstract

Using Precise Point Positioning (PPP) we show the potential for comparing frequency standards with time stabilities of under 300 ps in flicker phase noise for time periods of 1 to 10 d. This leads to comparisons at 1 part in 10^{15} or better at 10 d. We compare short baseline PPP results with 2 hour data from the NIST Measurements System. We compare results from the NIST – USNO baseline with hourly Two-Way Satellite Time and Frequency Transfer results.

1 Introduction

The focus of this work is on aiding the comparison of state-of-the-art frequency standards. Current standards require comparisons at 1 part in 10^{15} or better. Frequency comparisons of such standards are needed across intercontinental baselines, such as between the National Institute of Standards and Technology (NIST) in Boulder, Colorado, USA and Europe. Currently, the best methods for comparison are Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GPS carrier-phase frequency transfer using a geodetic software. Such software packages have been designed for the best possible global positioning using GPS for applications such as tracking movement of continental plates. A comparison between the standards at NIST and PTB showed transfer noise was negligible after 15 d [8].

Another method was reported by Fenton et. al. [2] using the Wide Area Augmentation System (WAAS) satellite and high-gain dishes. They performed an experiment between the National Research Council (NRC) of Canada and the US Naval Observatory (USNO) in Washington DC, USA, using the code-carrier difference to estimate changes in the ionospheric delay. The Allan deviation of the time transfer using this method was less than 10^{-15} after an averaging time of 8 h.

Whereas previous studies of GPS carrier-phase frequency transfer have generally been done using a network of stations [3,5,6], in this case we compute for each single location separately. We accept the International GPS Service (IGS) post-processed estimates of satellite ephemerides and clocks [4,12], hold the receiver coordinates fixed, and estimate the local clock against the IGS time scale. We do this for two receivers, then difference the results to cancel the IGS time, obtaining the comparison of the clocks driving the receivers. We evaluate these results by comparing with independent measurement.

The receivers used in this experiment were all of the same manufacture and model, though with somewhat different firmware. The same company made the antennas that made the receivers. The antenna models were different, but of similar design. The antennas were not temperature-controlled at all. The receiver temperatures were controlled only in that they were inside laboratories.

We report data using two baselines: a short-baseline comparison at NIST, and comparisons between NIST and at USNO when hourly TWSTFT measurements were also available.

2 Precise Point Positioning

In Precise Point Positioning (PPP) we are able to estimate the clock driving a single receiver against the IGS Time Scale, typically with deviations across satellites at a common time of under 2 cm, about 67 ps. To do this we minimize the variables that we must estimate by fixing previously estimated values for antenna phase center position, satellite orbits, and satellite clocks. The software must estimate or obtain the usual parameters used for geodetic positioning: satellite antenna phase center, phase wind up, Earth tides, and C/A to P code offsets. Errors in these estimates are small compared to the instability of the results. The need to estimate ionospheric delay is eliminated by using the ionosphere-free combination of the phases at the two L-band frequencies, P1 and P2. The main sources of instability can be separated into hardware and software. Hardware

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instabilities in delay due to temperature dependence, multi-path interference, and impedance mismatch produce instabilities in the clock measurements. Likely candidates for instabilities from software include tropospheric delay estimates and effects due to the software design. In particular, the use of a continuous filter spanning many days is a significant departure from the more common use of independent 1-day arcs. The comparison of these two modes merits further study.

We report here two different software systems run in PPP mode. We estimated frequency-transfer results over all intervals discussed in this paper using a commercial software. This software was developed based on code from the Canadian Geodetic Survey Division, Geomatics Canada, Natural Resources Canada. The GIPSY software [11], developed by the Jet Propulsion Laboratory (JPL), was used on a 40 d run of the short-baseline experiment.

3 Short-Baseline Experiment

The short-baseline experiment at NIST involved a receiver driven by an H-maser and another driven by an OCXO in two comparisons, the first lasting 40 d and the second 254 d. Unfortunately, the OCXO receiver had no system in place for measuring or controlling phase changes upon reset. The H-maser receiver, however, had a 1 pps measurement system. The two receivers, of the same manufacture and model, though slightly different firmware versions, were located in separate rooms and different floors of the NIST laboratory in Boulder. Because of the resets in the OCXO-locked receiver, we analysed the data in segments. The two clocks were compared in the NIST measurement system every two hours with an accuracy better than 50 ps.

3.1 A 40 Day Short-Baseline Experiment at NIST

As we see in Figure 1, the difference between the PPP results and the measurement system were peak-to-peak about 1 ns. The Time Deviation (TDEV) is a statistic useful for characterizing the time stability of time and frequency comparison systems [1]. Looking at TDEV of the longest segment in Figure 2, we see that the noise type was consistent with a flicker phase modulation (PM) model at 100 ps or less [9].

3.2 A 48-day interval without breaks

This interval was part of a 205 d interval of study. Again, the receiver locked to the OCXO had numerous resets. We were able to obtain a 48 d interval without breaks to compare the commercial PPP results to the NIST measurement system. The difference between these two data sets is shown below in Figure 5. The TDEV of these data is shown in Figure 6. The very short term here shows a much higher noise level. But from 1 d on, the data are consistent with a flicker PM model under 300 ps.
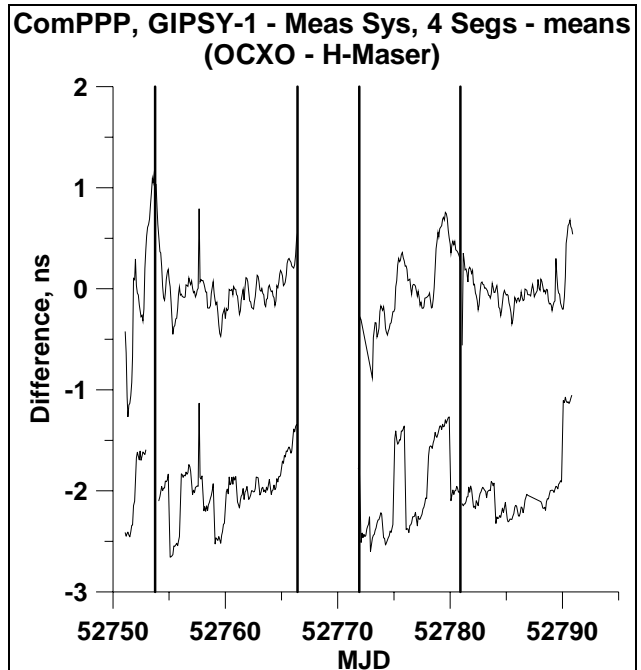

Figure 1: The difference of two PPP estimates, a commercial software and GIPSY, minus data from the local NIST measurement system 2-hour points. The GIPSY results were offset by –2 ns. The data were analyzed in four segments. The vertical lines mark the segments.
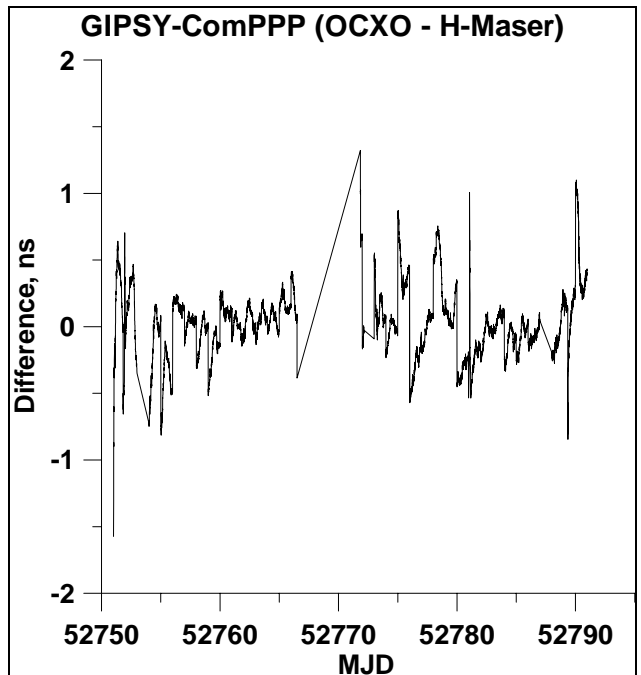

Figure 2: The difference between the two curves in Figure 1. The upper curve, the commercial PPP data, was subtracted from the lower curve, the GIPSY data.
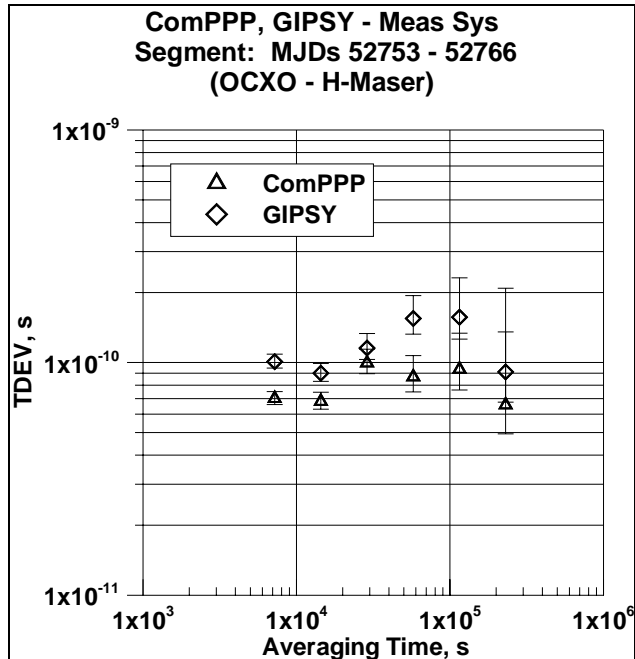
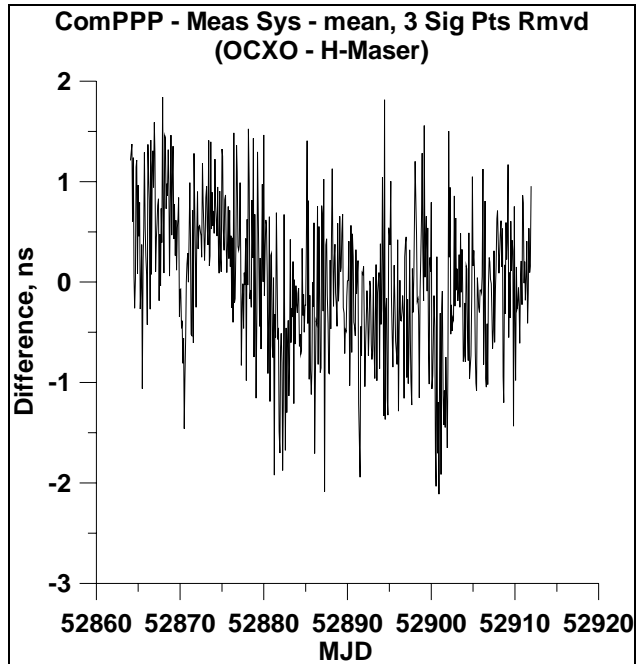**Figure 3**: TDEV of the longest segment of the data in Figure 1.

Figure 5: Data as in Figure 1, but for a different interval without resets. A commercial software's clock difference estimates, minus data from the local NIST Measurement System's 2 hour points. The clocks estimated were an OCXO minus an H-Maser. Nine points have been removed that exceeded three standard deviations from the data mean.
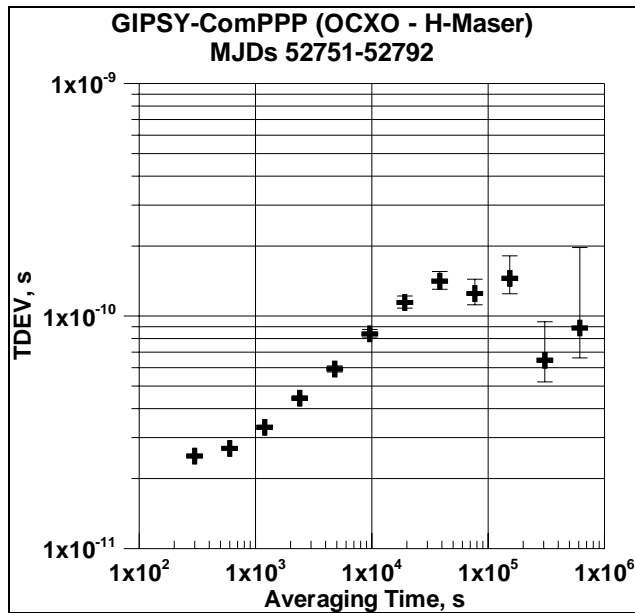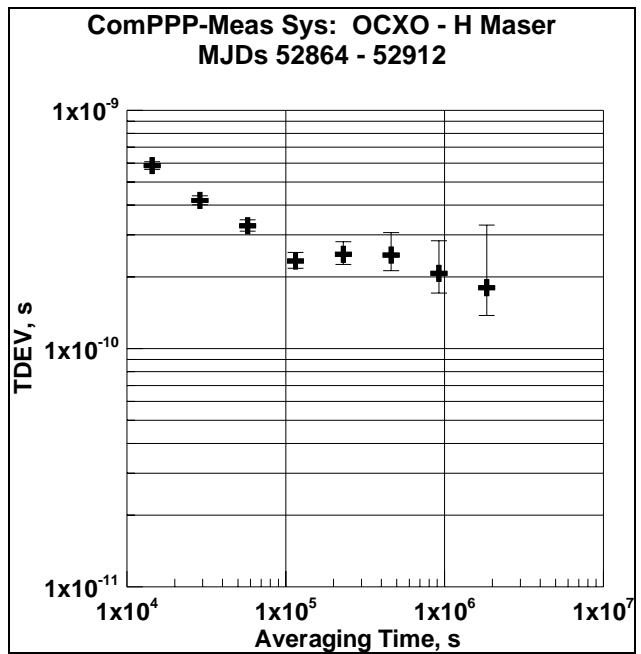

Figure 4: TDEV of the data in Figure 2.

Figure 6: TDEV of the data in Figure 5.

4 NIST-USNO Experiment

We compared H-masers between NIST and USNO using the commercial PPP software in three intervals when there were hourly two-way time transfer data. The signals from these H-masers were steered to time and frequency of each lab's UTC. We computed the difference between the two transfer techniques: two-way minus PPP.

There were two relatively short intervals: MJDs 52556 – 52566 (October 9 – 19, 2002), and MJDs 52642-52657 (January 3 – 16, 2003). Finally, we look at the 252 d interval from June 2003 – January 2004.

4.1 Short interval experiments comparing UTC(USNO) and UTC(NIST)

In the October 2002 experiment, we can see significant intervals with missing two-way data in Figure 7, making it difficult to draw conclusions. For example, we have not computed any variances.

In the second experiment, there were again periods of missing two-way data. However, we were able to find a 13 d interval without gaps. Figure 8 shows the two-way minus PPP data for the entire interval. Figure 9 shows TDEV for the interval without breaks. The noise type of the difference between the commercial PPP and TWSTFT systems was consistent with a flicker PM model at 300 ps or less.
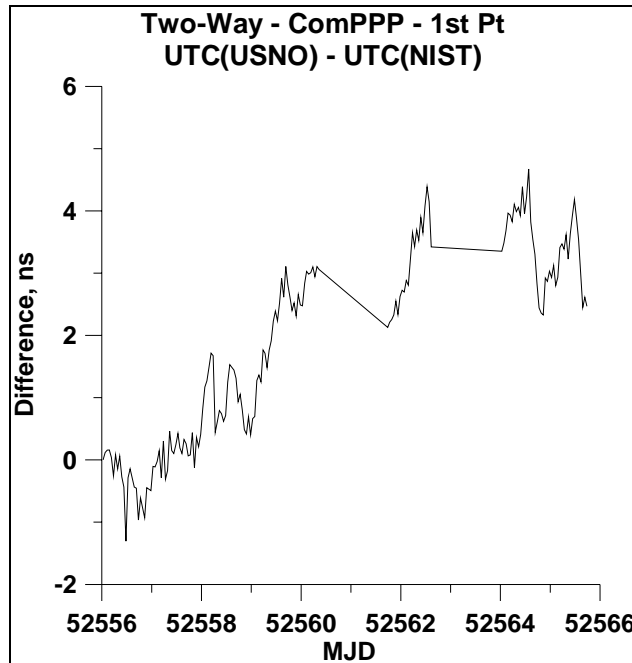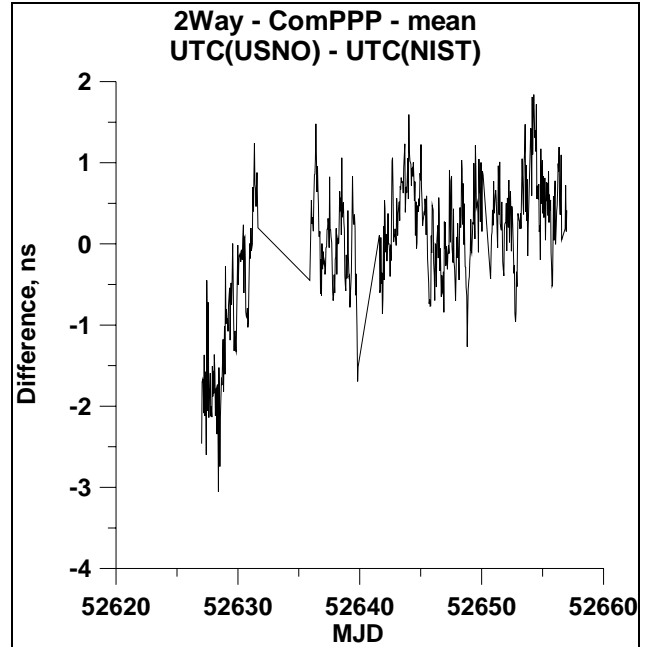

Figure 8: A second PPP comparison with hourly TWSTFT data between UTC(USNO) and UTC(NIST). There is a 13 d interval without gaps from MJD 52642 to 52657.
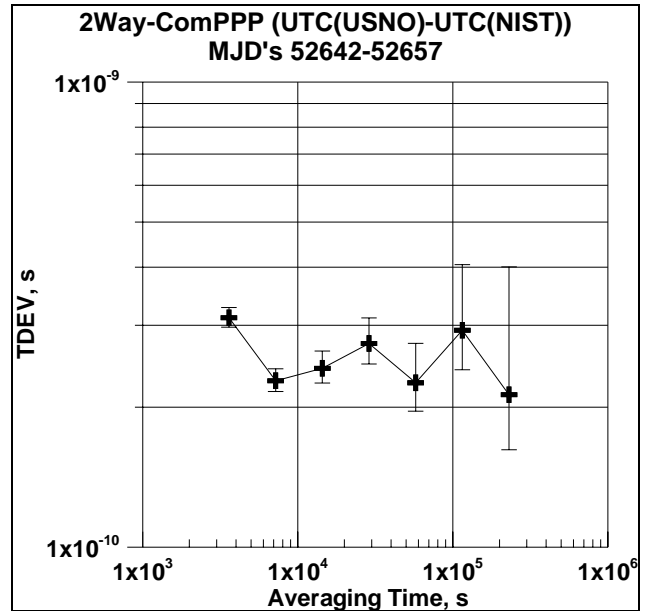

Figure 9: TDEV of the interval in Figure 8 without gaps in the data. The noise type is consistent with a flicker PM model at 300 ps or less.

Figure 7: A first PPP comparison with hourly TWSTFT data between UTC(USNO) and UTC(NIST).

4.2 A 205 day comparison between PPP and TWSTFT

We were able to obtain both commercial PPP results without uncorrectable resets and hourly TWSTFT data with no significant gaps from MJD 52802 to 53007, June 12, 2003 – January 3, 2004. The comparison, in Figure 10 below, shows a drift in the offset between the two systems, particularly in the months of November and December when the weather is colder. The slope during this latter interval is about 35 ps/d or $4 \cdot 10^{-16}$. This may indicate a temperature dependence on the delay through one or both of the systems.

We do not know whether the cause is in the GPS receivers or the TWSTFT hardware. We looked at the code common-view time transfer to see if it could offer a third vote. That method is much noisier, and varied between the results of the PPP and the TWSTFT data, yielding no preference for agreement with the bias of either PPP or TWSTFT.

We compute the TDEV of the data in Figure 10 to characterize the transfer systems. The commercial PPP results are best in short-term out to 1 d. The TWSTFT results are somewhat better after 1 d to where the clock noise dominates. The differential transfer after 1 d is again consistent with a flicker PM model of under 300 ps. This is shown in Figure 11, along with the TDEV values of the transfer data. Figure 12 is the modified Allan deviation (MDEV) of these data [9]. This allows us to see the capabilities for frequency transfer in a second-difference variance. It appears that frequency transfer at 1 part in 10^{15} is possible at 10 d of averaging.

Figure 11: TDEV of the transfer data using TWSTFT and PPP, and of the difference. The commercial PPP results are best in short-term out to 1 d. The TWSTFT results are somewhat better after 1 d. The differential transfer is again consistent with a flicker PM model of under 300 ps.
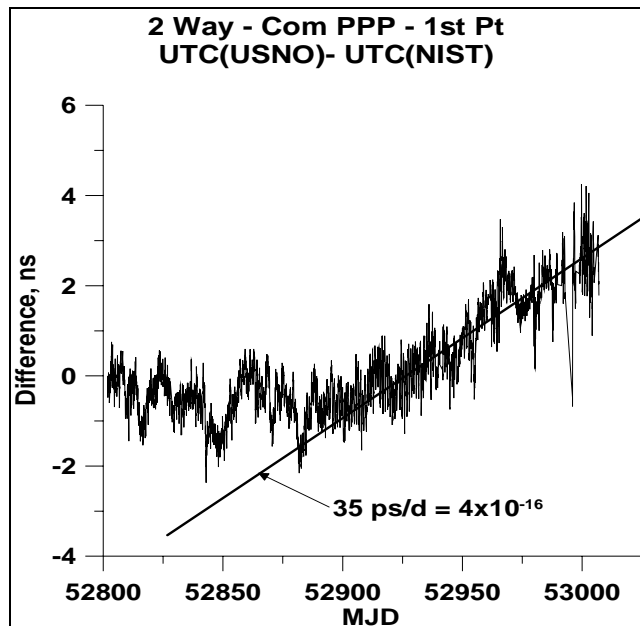

Figure 10: A 205 d comparison of hourly TWSTFT data with the commercial PPP results, between UTC(NIST) and UTC(USNO). We see a change in delay between the two systems over the colder months of November and December of 35 ps/d or $4 \cdot 10^{-16}$.
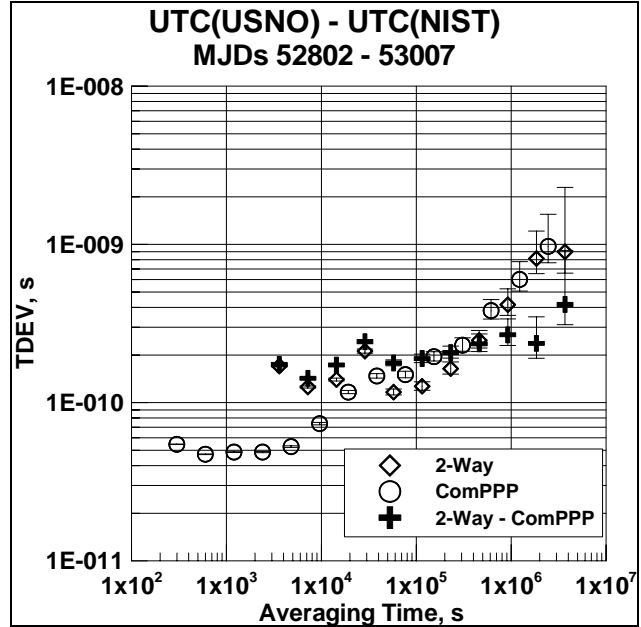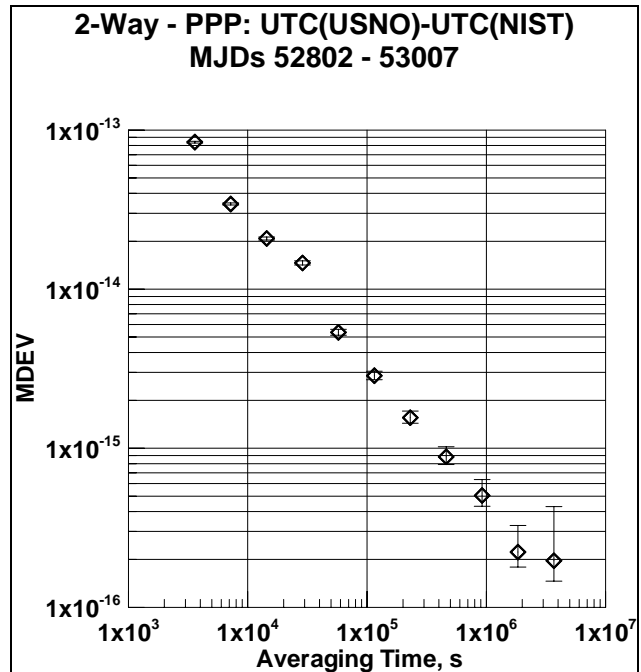

Figure 12: MDEV of the data in Figure 10. It appears that frequency transfer of 1 part in 10^{15} is possible after 10 d of averaging.

4.3 A frequency transfer statistic

Parker, Howe and Weiss discussed the use of a statistic that may be more appropriate for characterizing frequency transfer than MDEV and TDEV which are second-difference variances [8]. A more direct way to estimate frequency transfer uncertainty is using a first difference of averaged time data. This frequency transfer statistic averages the frequency transfer squared for different transfer intervals. T is the total time for the transfer experiment. We average measured time differences over equal intervals, A, at the beginning and end of the test time T. This gives us a frequency average over a running time of $\tau = T - A$. The definition is

$$\sigma^2{}_{tt}(T,\tau) = \frac{\left\langle \left(\overline{x}_{t+\tau} - \overline{x}_t\right)^2 \right\rangle}{\tau^2}. \qquad (1)$$

This is just the mean-squared fractional frequency of the time transfer data set. The definition is illustrated in Figure 13, where A is the averaging time for each of the end-points,

$$A = T - \tau.$$

Figure 14 gives this statistic for the data in Figure 10. This is a combined uncertainty due to frequency transfer error both in TWSTFT and PPP. From Figure 14 we see that frequency transfer at 1 part in 10^{15} is possible after 10 d.
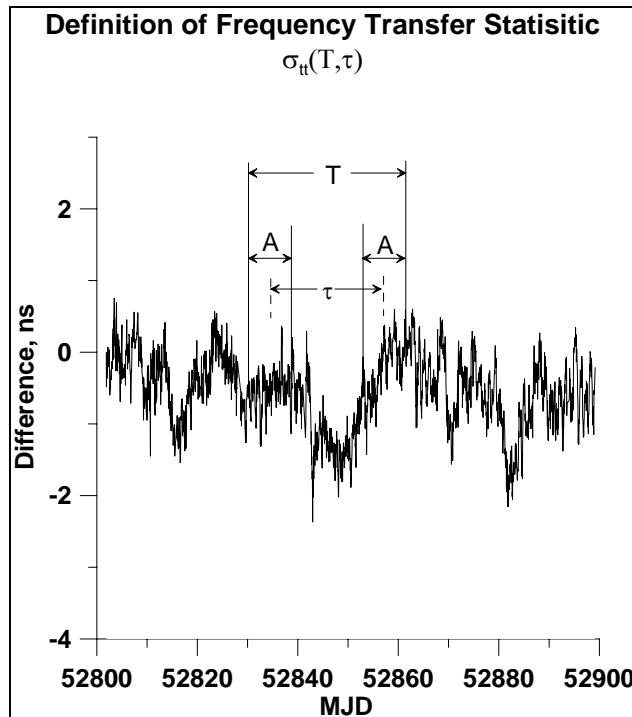

Figure 14: Frequency transfer uncertainty, as defined in eqution (1), for the data of Figure 10.

Figure 13: Parameters used for the definition of a frequency transfer statistic, $\sigma_{tt}(T,\tau)$. *A* is the averaging time for each of the end-points, $A = T - \tau$.
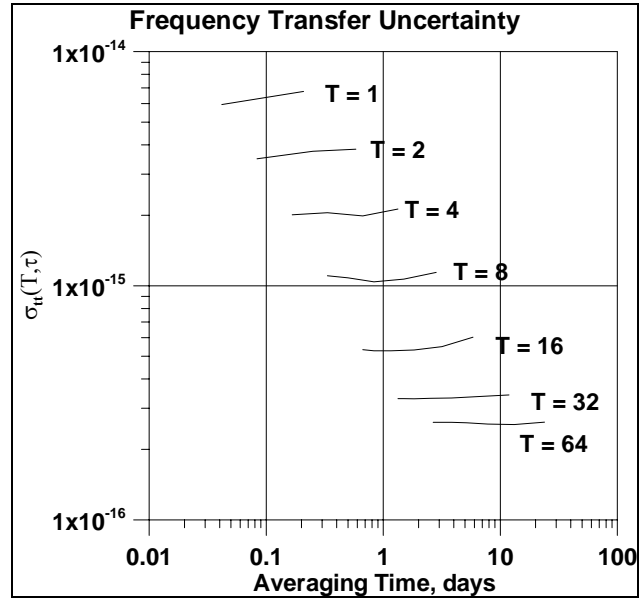
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