

Long-term Comparisons between Two Way Satellite and Geodetic Time Transfer Systems

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Abstract—GPS observations recorded in the United States and Europe were used to evaluate time transfer capabilities of GETT (geodetic time transfer). Timing estimates were compared with two-way satellite time and frequency transfer (TWSTFT) systems. A comparison of calibrated links at the US Naval Observatory (Washington D.C.) and Colorado Springs (Colorado) yields agreement of 2.17 ns over 6 months with a standard deviation of 0.73 ns. An uncalibrated link between NIST (Boulder, Colorado) and Physikalisch-Technische Bundesanstalt (Germany) has a standard deviation of 0.79 ns over the same time period.

I. INTRODUCTION

MULTIPLE requirements are needed to validate a geodetic time transfer (GETT) system. One crucial requirement is to develop a calibration technique for the hardware systems at both timing stations [1]. Secondly, candidate timing systems must be tested against other timing systems. In this paper we focus on comparing GETT with the two-way satellite time and frequency transfer system (TWSTFT). While TWSTFT is more expensive than GETT, it has the advantage that the timing community has been evaluating and improving its performance for many years. A long-term comparison of geodetic and two-way time transfer systems allows one to assess not only the long-term stability of the system but also provides valuable information about short-term instabilities in GETT that might not have been observed during the short-term calibration experiments [1].

II. GETT DATA ANALYSIS

GETT experiments were conducted between timing laboratories in the United States and in Europe from August 17, 2002 through March 1, 2003. The sites used in this study are shown in Figure 1. With the exception of NIS5, all sites are part of the IGS network [2]. Information about these sites, including some description of local timing links, can be found at the IGS website, <http://igs.cb.jpl.nasa.gov>. Data from the sites are also archived by the IGS. The NIS5 data are publically archived at <http://www.unavco.org>.

The $L1$ and $L2$ carrier phase and pseudorange data used in this study were all recorded at 30 second intervals. All analysis of the GPS observables was done with the GIPSY-OASIS II software [3], [4]. The first step is to detect, and repair if possible, cycle slips [5]. The carrier phase data are then decimated to 5 minute intervals, and pseudorange measurements are carrier-smoothed over a box window for that interval. Each pseudorange observation is carrier-smoothed over a window of ± 2 minutes (± 2.5 is not used to prevent

TABLE I
MODELS AND ESTIMATED PARAMETERS.

Parameter	Estimation	<i>a priori</i> σ
GPS Orbits	Fixed	IGS final
Ref. Frame	ITRF2000	[7]
Dry Troposphere Zenith	Modeled	hydrostatic
Wet Troposphere Zenith	Random Walk $\sigma_{RW} = 3 \frac{mm}{\sqrt{hr}}$	10 cm
Wet Troposphere Azimuth	Random Walk $\sigma_{RW} = 0.3 \frac{mm}{\sqrt{hr}}$ [10]	5 cm
Reference GPS Position	Constant	2 cm
Non-Reference GPS Position	Constant	500 m
Reference Clock	USNO	
Receiver and Satellite Clocks	White Noise	1 sec
Phase Bias	Constant	100 m
Elevation	Pseudorange	17 degrees
Angle Cutoff	Phase	7 degrees

using the end points twice) [6]. Single frequency carrier phase and pseudorange data are then converted into ionosphere-free observables.

Model and parameter estimation constraints are summarized in Table I. For GPS satellite orbits, the final (precise) orbits provided by the International GPS Service (IGS) are used [2]. These orbits are defined in International Terrestrial Reference Frame (ITRF) 2000 [7]. They have a radial accuracy of < 5 cm when compared with laser ranging techniques [8]; the radial precision of the orbits is ~ 3 cm [9]. In addition to fixing the orbits, we constrain the station coordinates of one site (USNO), also defined in ITRF 2000. All other station coordinates are estimated with very large (500 meter) *a priori* constraints. With the exception of the reference clock (USNO), we estimate a timing update for each geodetic receiver at every measurement epoch (5 minutes). A dry troposphere zenith delay is removed from the observables based on the assumption of hydrostatic equilibrium. We estimate both a zenith and azimuthal wet troposphere delay. This methodology has been shown to improve positioning [10] but was not used in our previous study [11].

The GIPSY-OASIS II software uses a Square Root Information Filter (SRIF) for parameter estimation [12]. *A priori* values are designated and for this study the carrier phase and pseudorange data are weighted at 1 cm and 100 cm, respectively. For ambiguity resolution, the pseudorange widelaning method is used [13].

The GPS data were analyzed in three-day batches with 24-hour overlaps used to remove discontinuities at the day

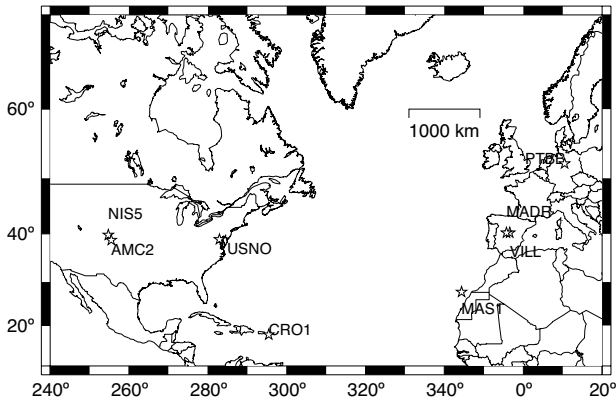


Fig. 1. GPS sites used in this study.

boundaries [14]. Recent studies suggest that the "day boundary" discontinuities should be left in the GETT time series. This recommendation is based on the fact that removing the discontinuities will result in accumulated error which is random walk [15]. A better approach than the one we used here would be to compare the time series with and without day boundary discontinuities so that this accumulated error could be bounded.

Both GETT and TWSTFT had occasional gaps in their data. If a GETT receiver problem caused a gap in the recorded observations, a new series was started when the receiver resumed tracking. Because of power transient behavior, the first several hours were removed from the data when a receiver came back on-line. We also removed several days of NIS5 observations related to temperature excursions [1].

III. COMPARISONS WITH TWSTFT

Our timing comparisons use GETT sites USNO, NIS5, AMC2, and PTBB (Figure 1). In order to compare these sites with TWSTFT links, local corrections are often required. Table II shows the timing source used for GETT and TWSTFT at each location. Of the 4 GETT sites, three receivers were calibrated using the methodology of *Plumb et al.* [1]. Unfortunately the calibrated receiver at the U.S. Naval Observatory (USN1) had many more data gaps than the alternate GETT site USNO. In order to use the USN1 receiver calibration, we computed a multi-day local clock tie between USNO and USN1 using GETT. A conservative estimate of the tie accuracy is 0.2 ns [14]. For calculations of ADEV and TDEV at USNO, AMC2, and NIST, we converted timing estimates to maser ensembles. At USNO and AMC2 these ensembles are called the USNO and AMC Maser Means [16], [17]; at NIST it is called AT1 [18]. The variability of these individual corrections is shown in Figure 2. The links from USNO are available by anonymous ftp at tycho.usno.navy.mil. In all cases, ADEV and TDEV will have greatest uncertainties at longer averaging times, particularly for $\tau > 1E+6$ seconds.

A. USNO - AMC2

The TWSTFT link between USNO and AMC2 has been calibrated using a portable two-way system. The accuracy of

TABLE II
GETT-TWSTFT LINKS

GETT ID	GETT Reference	TWSTFT Reference	Final Reference
NIS5	UTC(NIST)	UTC(NIST)	AT1 [18]
PTBB	H2	H2	H2
AMC2	AMC(MC1)	AMC(MC1)	AMC (Maser Mean) [16]
USNO	USNO(MC3)	USNO(MC2)	USNO (Maser Mean) [16], [17]

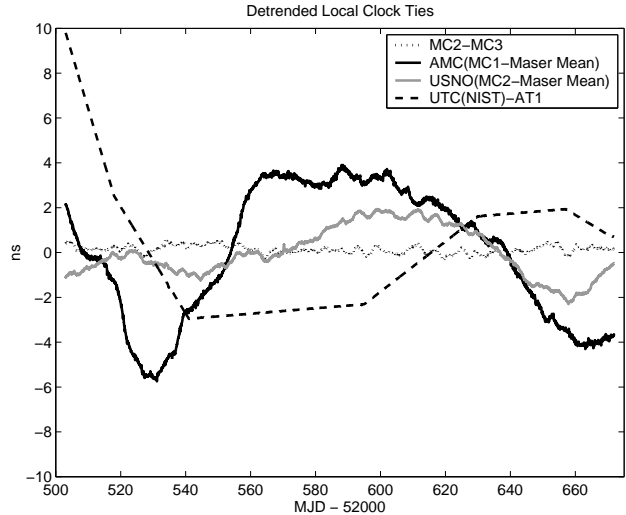


Fig. 2. Local clock corrections for GETT-TWSTFT comparisons. Frequency offsets of -2.5, -40.5, and -62.2 ns/day have been removed from AMC-Maser Mean, AT1-USNO(NIST), and MC2-Maser Mean corrections, respectively.

the link is believed to be on the order of 1 ns [16], [19]. A TWSTFT observation is generated every 5 minutes on this link. This is a significantly higher sampling-rate than was used in a previous comparison of the USNO-AMC2 link [11]. The GETT receivers have been calibrated against a GPS simulator [1]. Since TWSTFT at USNO is linked to USNO(MC2), the GETT site, which uses USNO(MC3), must be tied using local measurements [16]. At AMC2 no local corrections are required to compare TWSTFT and GETT.

The two time transfer series for USNO(MC2)-AMC(MC1) are shown in Figure 3. Changes in the calibration constants for the TWSTFT link - typically due to equipment changes - are shown as an alternating dark and light line. While overall there is good agreement between the two techniques, there is significant misfit during calibration periods C2-C3. The good agreement between MC2 and MC1 is due to steering of MC1. The short-term noise of the two systems can be evaluated in the time domain in Figure 4. Both measurement series include real clock behavior. The standard deviations for the TWSTFT and GETT time series are 0.34 and 0.09 ns, respectively.

In Figure 5 we tie the two series to their respective Maser Means and remove a common frequency offset. Removing the C2-C3 period, the mean difference in the two solutions is -2.11 ± 0.73 ns. This is well within the absolute calibration budget of the GETT system and the uncertainty in the two-way calibration.

Total ADEV and TDEV [20] for the GETT and TWSTFT

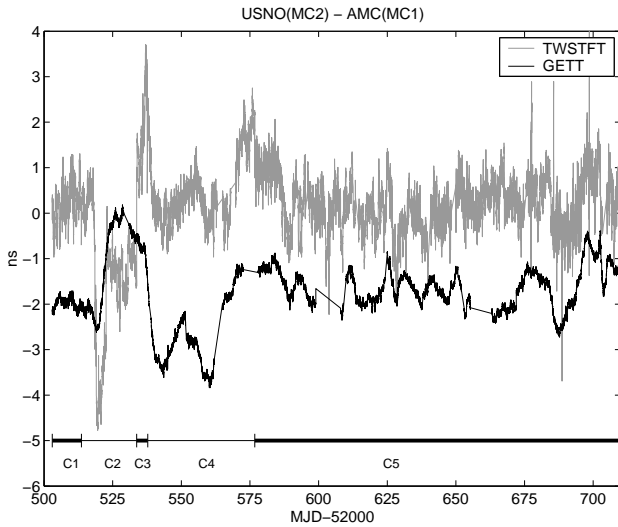


Fig. 3. Calibrated time transfer solutions, USNO(MC2)-AMC(MC1). The alternating dark and light line shows when TWSTFT calibration constants were changed.

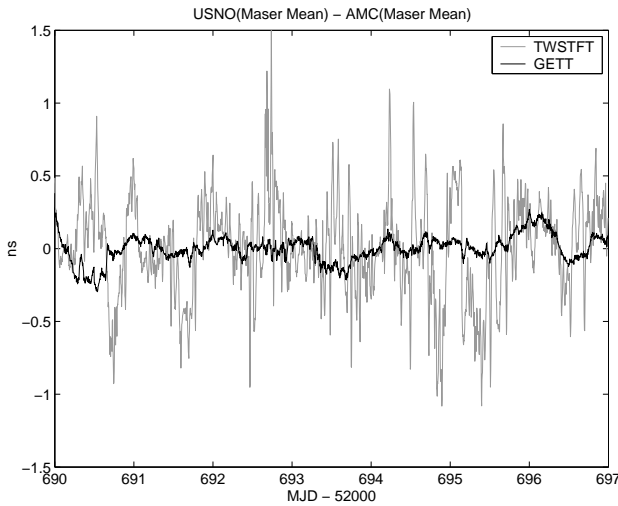


Fig. 4. One week of TWSTFT and GETT estimates for USNO(Maser Mean)-AMC(Maser Mean). A mean has been removed from each series.

series and their differences are shown in Figure 6. For τ less than $1E+6$ seconds the TWSTFT solution exhibits a combination of flicker phase modulation and white frequency modulation noise; after $1E+6$ seconds it trends towards flicker frequency modulation noise. The GETT solution exhibits white frequency modulation noise until $\tau \sim 2E+5$ seconds (2.3 days), after which it trends towards flicker frequency modulation noise. Both ADEV and TDEV of GETT-TWSTFT are dominated by TWSTFT noise until $\sim 3-5$ days. The difference of GETT and TWSTFT achieves an ADEV of $1.9E-16$ at $7.0E+6$ seconds (81 days). TDEV of the difference does not exceed 0.4 ns for any value of τ ; the highest TDEV achieved is 0.34 ns at $7.0E+6$ seconds.

B. USNO - NIST

The TWSTFT link between NIST and USNO is not calibrated. A constant offset will be removed from each time

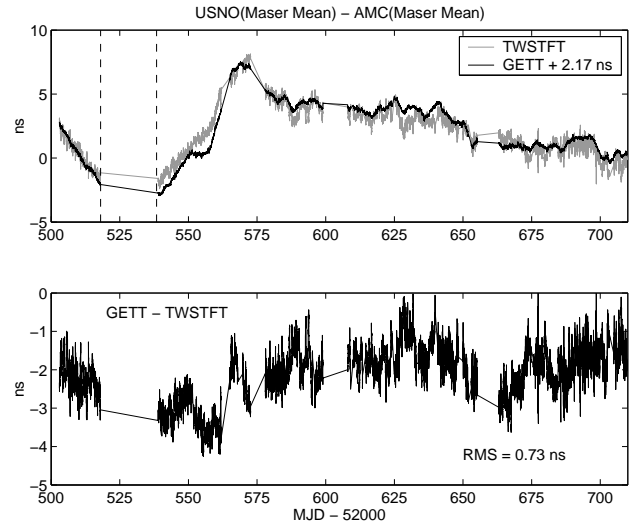


Fig. 5. USNO(Maser Mean) - AMC(Maser Mean) with TWSTFT outliers removed. The difference between GETT and TWSTFT is plotted in the lower panel.

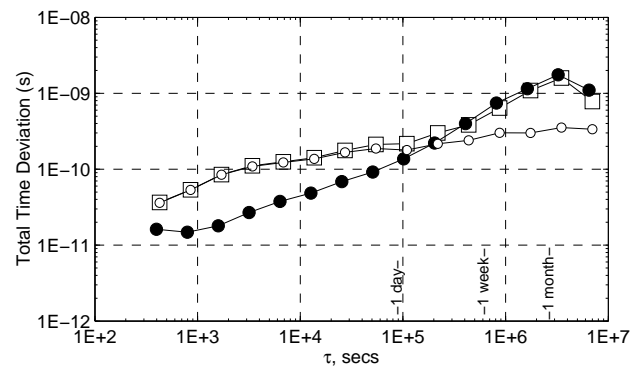
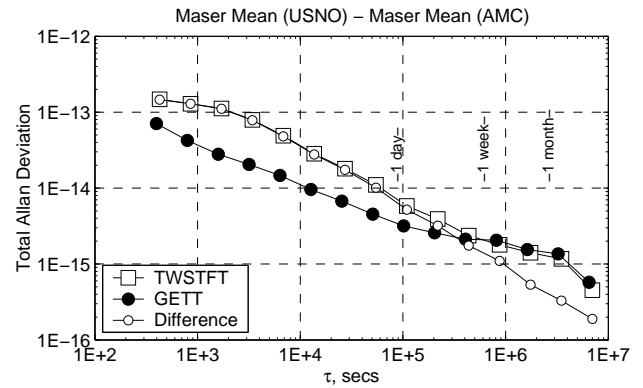


Fig. 6. Maser Mean (USNO) - Maser Mean (AMC): Total ADEV and TDEV for GETT, TWSTFT and their difference.

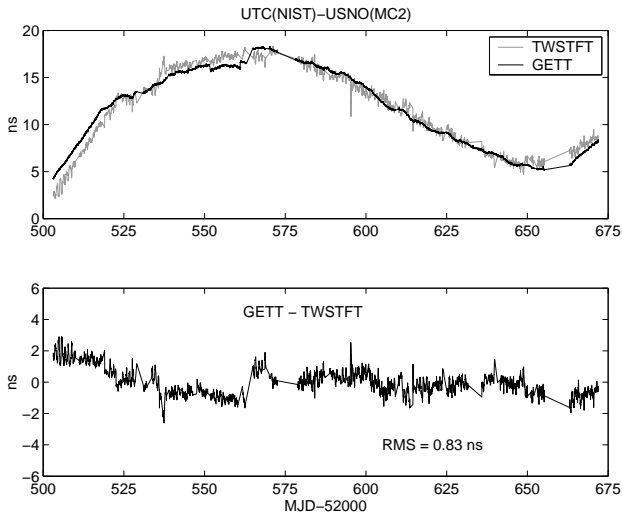


Fig. 7. Upper panel: USNO(MC2)-UTC(NIST) for TWSTFT and GETT. Lower panel: the difference between GETT and TWSTFT.

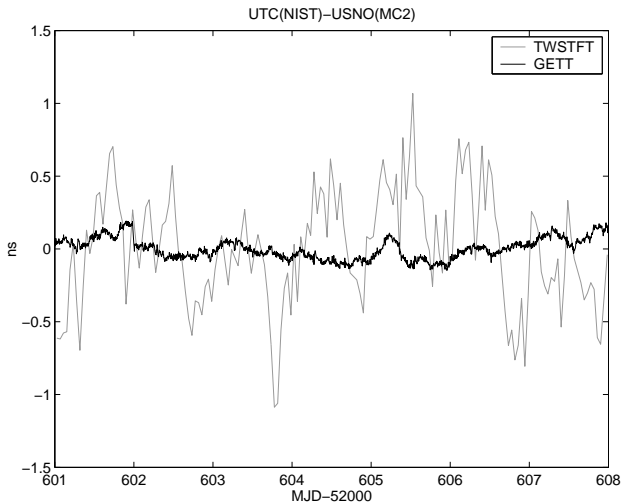


Fig. 8. One week of TWSTFT and GETT estimates for UTC(NIST)-USNO(MC2).

series for comparisons with GETT. The TWSTFT link was run once per hour during this period as an experiment. Each reported hourly TWSTFT observation is actually an average over 13 minutes of two-way communications (T. Parker, private communication, 2003). Results for the TWSTFT and GETT measurements for UTC(NIST)-USNO(MC2) are shown in Figure 7. The standard deviation of the GETT-TWSTFT difference is 0.83 ns. The TWSTFT estimates on this link have a significant diurnal component an order of magnitude greater than the GETT estimates (Figure 8). The standard deviations for the TWSTFT and GETT estimates for the week shown in Figure 8 are 0.39 and 0.07 ns, respectively. Overall these values agree qualitatively with the corresponding USNO-AMC2 values of 0.34 and 0.09 ns.

Before computing total ADEV and TDEV statistics, the GETT and TWSTFT measurements are linked to maser ensembles (AT1 at NIST, the Maser Mean at USNO) and a common frequency offset is removed. The ADEV and TDEV

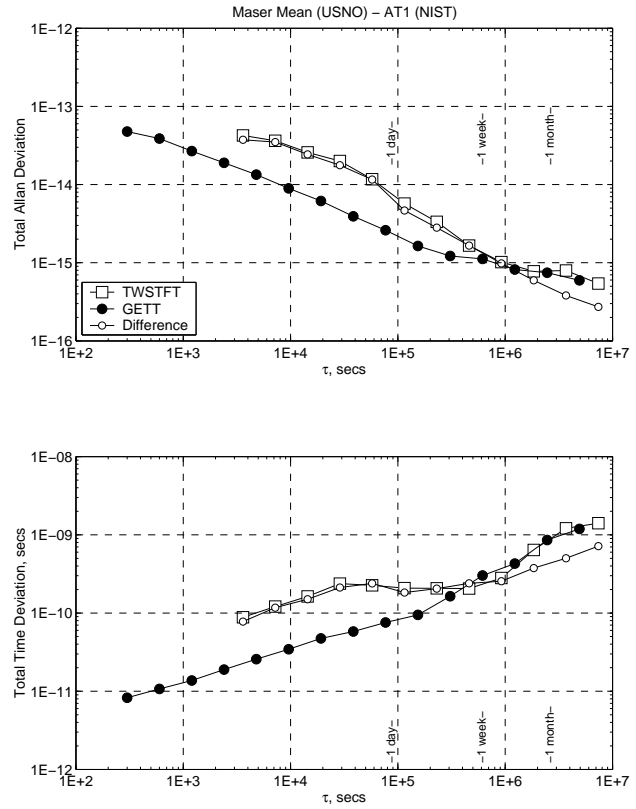


Fig. 9. Total ADEV and TDEV, USNO (Maser Mean) - NIST(AT1), for GETT, TWSTFT, and GETT-TWSTFT.

statistics for GETT, TWSTFT, and their difference are shown in Figure 9. Up until $\tau \sim 1E+6$ seconds, the TWSTFT solution exhibits a combination of flicker phase modulation and white frequency modulation noise; after $1E+6$ seconds it trends towards flicker frequency modulation noise. GETT exhibits white frequency modulation noise until $\tau \sim 2E+5$ seconds (2.3 days), after which it trends towards flicker frequency modulation noise. ADEV and TDEV for the differenced estimates are dominated by TWSTFT noise until $\tau = 5-7$ days. Without the masers masking the time transfer effects, the differenced estimates continue to exhibit a combination of flicker phase modulation and white frequency modulation noise. The differenced estimates achieve an ADEV of $2.7E-16$ at $\tau = 7.4E6$ seconds (86 days); the corresponding maximum TDEV is 0.72 ns at $\tau = 7.4E6$ seconds.

C. PTB - NIST

An uncalibrated TWSTFT link between NIST and Physikalisch-Technische Bundesanstalt (PTB) is operated for ~ 15 minutes on Monday, Wednesday, and Friday of each week. Although the NIST(NIS5) GETT receiver is calibrated, the PTB GPS receiver is not. Therefore, a constant offset will be removed from each time series for comparisons. Both the TWSTFT station and the GETT receiver at PTB use maser H2 as their reference clock; both transfer systems at NIST are referenced to UTC(NIST).

TWSTFT and GETT time transfer estimates for H2(PTB) - UTC(NIST) are shown in Figure 10. There is a gap in the

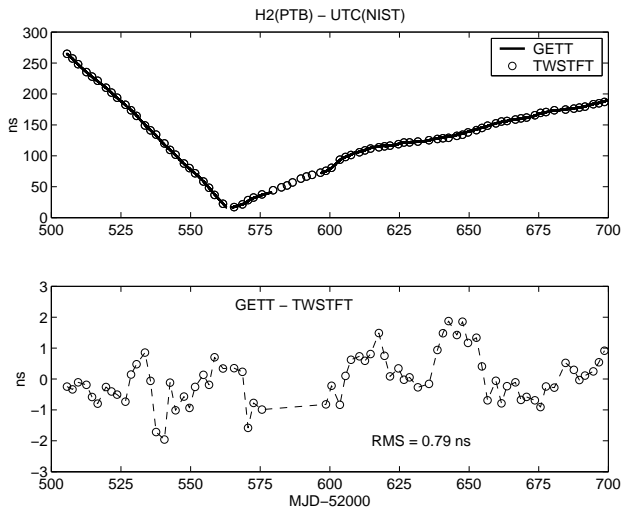


Fig. 10. Top panel: GETT and TWSTFT results for H2(PTB)-UTC(NIST). The large frequency shift on day 52564 is due to maser H2(PTB) being steered; bottom panel: the difference of the GETT and TWSTFT estimates shown above.

GETT estimates from MJD 52579-52596; this was due to software errors at PTB’s GETT site. The abrupt change in frequency offset on MJD 52564 is due to H2(PTB) undergoing an active frequency steer at that time. Coincidentally, this corresponds with the temperature excursion problem experienced by the NIST receiver, which causes the data gap from MJD 52564-52565. The difference between the two timing systems has a standard deviation of 0.79 ns (Figure 10).

Due to the large frequency change after H2 (PTB) was steered, the time series must be detrended in two separate sections. First, the frequency offset before (-4.3 ns/day) and after (1.3 ns/day) the steer are removed. Next, the two detrended series are matched at the point of the steer, and the values on either side of the GETT observation gap are matched.

Total ADEV and TDEV for these time series are shown in Figure 11. GETT noise characteristics are flicker phase modulation for $\tau < 1000$ seconds, white frequency modulation until $\tau \sim 1E+5$ seconds, followed by flicker frequency modulation. The TWSTFT results are dominated by flicker frequency modulation noise. The difference between the estimates demonstrates flicker phase modulation. The difference in the estimates achieves an ADEV of $1.9E-16$ at $\tau = 7.5E+6$ seconds (87 days). TDEV at the same τ is 0.24 ns.

IV. DISCUSSION

In order to evaluate GETT precision, we have summarized our measurements as follows. For $\tau < 1E+5$ seconds, total ADEV is computed for our three GETT baselines. This statistic will include clock noise but it will be dominated by transfer noise; for $\tau > 4E+5$ seconds, we assume that ADEV is driven by clock noise and thus we use GETT - TWSTFT. At these longer periods both TWSTFT and GETT transfer noise will influence the ADEV. Also shown in Figure 12 are previously published GETT values for AMC2-USNO [11] and a stable IGS site with a hydrogen maser, WSRT [15]. In all cases we normalize the ADEV values to correspond to a single

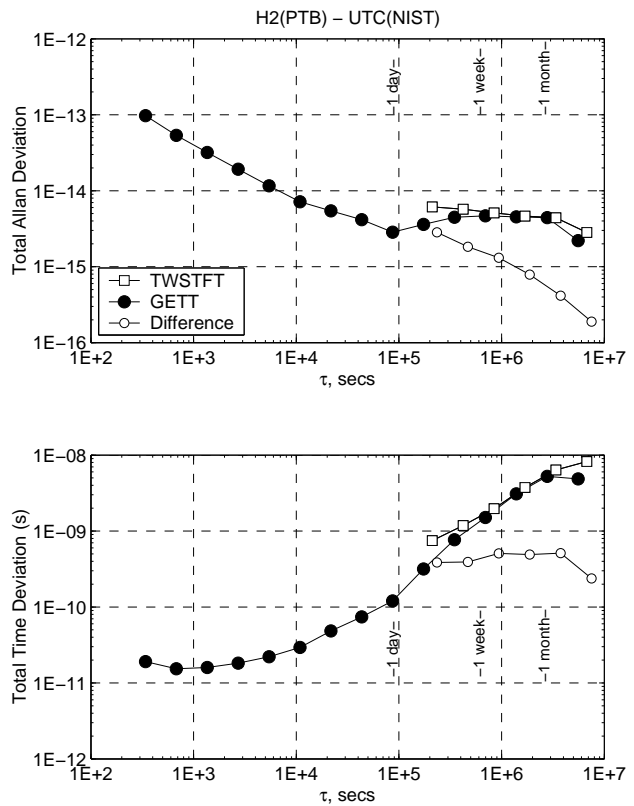


Fig. 11. Total ADEV and TDEV for TWSTFT, GETT, and TWSTFT-GETT for H2(PTB) - UTC(NIST).

GETT site. Also shown for comparison is a recent estimate of the GETT stability floor [15]. For times less than a day, the floor is determined to be $2.01E-13 \tau^{-0.44}$. For longer times, they assume stability is driven by white phase noise of $1.15E-10 \tau^{-1}$

A cesium fountain’s accuracy is on the order of 1-1.5E-15 [21]. GETT total ADEV reaches this level at 2-3 days. For additional discussion of the difficulties in evaluating frequency transfer accuracy, the reader is directed to [22].

V. CONCLUSIONS

With the development of cesium fountains and timing experiments in space, there is an increased need for reliable, inexpensive, and accurate time transfer systems. Existing time transfer systems such as TWSTFT and GPS common-view are reliable but have significant limitations. TWSTFT is very accurate and has demonstrated long-term stability. Unfortunately, satellite time is expensive, and the measurement schedules for most links are shorter than would be most useful. GPS common-view is inexpensive and improvements continue to be made in using this technique. Nevertheless, common-view data spanning from 20-40 days would likely be required to reach the accuracy level of the cesium fountains [22]. In this paper we demonstrate that for a period of ~ 6 months, calibrated GETT systems at USNO and AMC2 agreed with TWSTFT within ~ 2 ns. This is consistent with a previous study of uncalibrated links [11] although that study was limited by receiver clock resets. Although there is a wide variety in

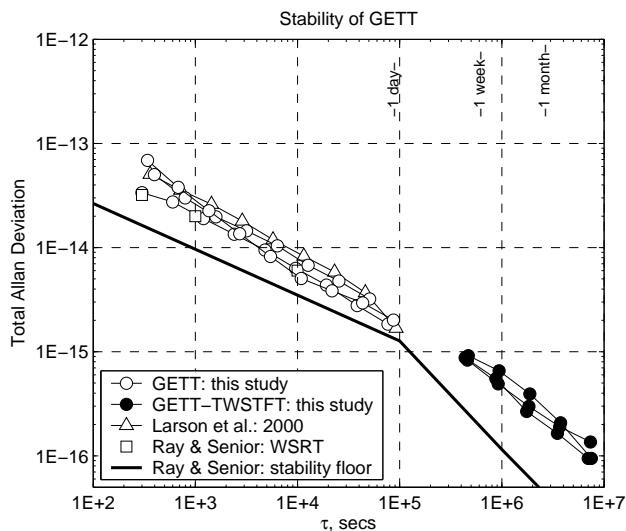


Fig. 12. Stability for a single GETT site based on this study and recent published analyses. For $\tau > 4E+5$, the difference of GETT and TWSTFT is used.

the precision of GETT sites, our results and those of others [15] indicate that GETT is an accurate and reliable time and frequency transfer technique.

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