PRELIMINARY COMPARISON OF TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER AND GPS COMMON-VIEW TIME TRANSFER DURING THE INTELSAT FIELD TRIAL

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Abstract

For a decade and a half GPS Common-View time transfer has greatly served the needs of primary timing laboratories for regular intercomparisons of remote atomic clocks. However, GPS as a one-way technique has natural limits and may not meet all challenges of the comparison of the coming new generations of atomic clocks. Two-Way Satellite Time and Frequency Transfer (TWSTFT) is a promising technique which may successfully complement GPS. For two years, regular TWSTFT's have been performed between eight laboratories situated in both Europe and North America, using INTELSAT satellites. This has enabled an extensive direct comparison to be made between these two high performance time-transfer methods. The performance of the TWSTFT and GPS Common-View methods are compared over a number of time-transfer links. These links use a variety of time-transfer hardware and atomic clocks and have baselines of substantially different lengths. The relative merits of the two time-transfer systems are discussed.

INTRODUCTION

The performance of atomic clocks maintained at primary timing laboratories have improved considerably in recent years. There is now a challenge to develop suitable time and frequency transfer methods to exploit this improved performance. The standard method of intercomparing clocks contributing to International Atomic Time (TAI) is by common-view of Global Positioning System (GPS) satellites[1]. Two-Way Satellite Time and Frequency Transfer (TWSTFT) has in recent years been developed as an alternative time and frequency transfer method[2]. TWSTFT as a two-way time-transfer method, offers many potential advantages over the existing one-way methods. Due to the symmetrical nature of the TWSTFT method, several sources of systematic errors are either eliminated or greatly reduced. These include errors associated with Earth station and satellite positions along with ionospheric and tropospheric delay errors. The use of directional antennas and high frequency transmissions enables low power transmissions to be made with relatively high carrier-to-noise ratios, resulting in high precision measurements. The downside is that TWSTFT instrumentation is somewhat more expensive. Satellite time must also be purchased on a commercial geostationary satellite.

In this paper, a detailed study is presented of the comparison between regular TWSTFT and GPS common-view measurements. Measurements have been included from five European laboratories recorded over a period of two years. The (TWSTFT-GPS) differences obtained from each link were examined. Values of σ_y were calculated from the TWSTFT and GPS time transfers and also from the (TWSTFT-GPS) differences. Comparisons were made against σ_y values calculated from co-located atomic clock comparisons performed at NPL. Finally, discrepancies between the TWSTFT and GPS time transfers are explained in terms of changes in both instrumentation and environmental conditions at each laboratory.

METHOD

The international TWSTFT field trial experiment has been performed during the last two years using an INTELSAT satellite at 307°E[3]. Six European and two North American laboratories have been participating in this experiment. The instrumentation used at each location has been described previously[4,5]. The results presented in this paper have been obtained from intercomparisons of data from five of the European Laboratories. These were the Technical University Graz, Graz, Austria (TUG), National Physical Laboratory, Teddington, UK (NPL), Van Swinden Laboratorium, Delft, the Netherlands (VSL), Forschungs- und Technologiezentrum, Deutsche Telekom, Darmstadt, Germany (FTZ), and Physikalisch-Technische Bundesanstalt, Braunschweig, Germany (PTB). The atomic clocks and TWSTFT Earth station instrumentation used at each location are summarized in Table 1. The provision of cost-free time by INTELSAT enabled the TWSTFT measurements to take place. Initially the INTELSAT (VA-F13) satellite at 307°E was used, but this was replaced by the INTELSAT (VII-F6) satellite. A schedule of TWSTFT measurements has been performed three times per week, with each individual time transfer lasting for five minutes. GPS measurements were made according to the BIPM International GPS common-view schedules 22, 23, 24, and 25. All GPS time receivers involved in this study are single-channel, C/A code, NBS-type.

DATA ANALYSIS

The TWSTFT and GPS data sets are fundamentally different. The TWSTFT data consist of spot measurements of five minutes duration made every two or three days. In contrast, the GPS readings are obtained from the mean of a series of up to 60 thirteen-minute measurements, spread throughout two days. The noise within a five-minute TWSTFT time time transfer is substantially lower than the noise within a block of 13-minute GPS data. Underlying both sets of measurements are the variations of the atomic clocks. These short- and medium-term clock variations are small in the case of the hydrogen maser, but significantly larger in the case of commercial cesium clocks.

TWSTFT measurements were made on Mondays, Wednesdays, and Fridays. This measurement schedule resulted in a regular but unevenly spaced data set. A simple algorithm has been developed to calculate a good approximation to σ_y[6] under these conditions. This algorithm has been successfully implemented.

Time transfers were computed using the GPS common-view method for the period MJD (49354-49950). During this period the Block II satellites were permanently subjected to Selective Availability (SA), so strict common-views were required to remove the effect of the SA clock dither. All common views retained for this study fulfilled the following conditions: 15 s common-view tolerance, 765 s minimum duration of the track, 20° minimum elevation angle for satellites. The 15 s tolerance for common-views was necessitated by a fault in the NBS type receivers which begin observations 15 s later than scheduled. There were between 25 to 40 common-view tracks per day fulfilling these conditions. Values of the common-views were computed for the midpoints of the tracks. The coordinates of the GPS ground antenna were expressed in the ITRF88 reference frame with uncertainty ranging from 10 cm to 30 cm[7]. The coordinates for NPL, VSL, and FTZ were newly determined and the GPS data were corrected in post-processing. The distances between European time laboratories range from a few hundred kilometers to about one thousand kilometers. During the GPS common-view time transfer the errors due to broadcast satellite ephemerides, ionospheric, and tropospheric delays, are reduced to the level of 1 ns or lower[8,9]. Therefore, there is no need to use post-processed precise ephemerides and measurements of ionosphere and troposphere[10]. For each link, a Vondrak smoothing was performed on the values UTC(Lab1)-UTC(Lab2), which acts as a low-pass filter with a cut-off period ranging from 0.5 day to 2 days depending on the pair of laboratories[11]. Those cut-off periods have been chosen as being approximately the limit between the short time intervals, where the measurement noise is dominant, and the longer intervals where the clock noise prevails. Finally, the smoothed values were interpolated for the occurrence of the TWSTFT measurements. The Vondrak smoothing method is illustrated in Figure 1. The "cloud" of GPS data points are shown, along with the curve resulting from the smoothing. The GPS links were differentially calibrated with an uncertainty of about 2 ns[12].

RESULTS

Curves of the (PTB-NPL) time transfer made over a two-year period are shown in Figure 2. The offset between the two curves is due in part to the delay asymmetries of the TWSTFT instrumentation not being calibrated, and in part to an offset of 150 ns being added to clearly separate the two curves. Curves of the (TWSTFT-GPS) differences are shown in Figures 3, 4, and 5. Values of σ_y calculated for both the TWSTFT and GPS Common-View time transfers and (TWSTFT-GPS) differences are shown in Table 2. σ_y values were calculated with averaging times (τ) of 2.3, 4.7, and 7 days.

Several trends emerged. There is good agreement in the shape of the time-transfer curves obtained using the TWSTFT and GPS common-view methods. Values of the standard deviation calculated from the (TWSTFT-GPS) differences are shown in Table 3, both for the complete data set and for a sub-section. Outlying points that deviated substantially from the mean value were removed before calculating the standard deviation using the points shown in Figures 3-5. The NPL-TUG differences exhibited the lowest standard deviation when calculated over the whole period. In order to compare (TWSTFT-GPS) differences over shorter periods, standard deviations have been calculated from subsets of the data which are free from rapid delay changes. The results obtained were encouraging. Standard deviations of between 1.4 ns and 2.7 ns were obtained over periods ranging from 70 to over 300 days. The most stable operation occurred on the (PTB-NPL) link, where a standard deviation of 1.4 ns was obtained for the (TWSTFT-GPS) differences over a period of 350 days.

Values of σ_y were calculated from TWSTFT, GPS, and (TWSTFT-GPS) data sets that contained only data collected on the same MJDs. When data were missing from one data set, the corresponding data were removed from the other data sets before processing. Any discrete delay steps occurring due to known instrumentation changes were removed before the σ_y values were calculated. Large discrete delay steps of amplitude 20 ns and 30 ns were removed from the FTZ data sets before calculating σ_y. These steps occurred only occasionally within a data set and were not typical of the data scatter. Values of σ_y varied considerably between the TWSTFT links. The (PTB-NPL) time transfer was the most stable link. These results were attributed to the use of an active Sigma Tau hydrogen maser at NPL and the Primary Cesium clock (CS2) at PTB compared with the use of commercial HP5071A cesium clocks at the other laboratories. With averaging times (τ) of 2.3 days or longer, the principal instability contributing to the σ_y values was clock noise. This is explained below.

For a given time transfer, values of σ_y were in almost all examples lower for the GPS common-view measurements when compared against the TWSTFT measurements. In most cases, the difference in σ_y values was quite small, but clearly significant. This difference was particularly noticeable on the most stable (PTB-NPL) link, with an averaging time (τ) of 2.3 days. In almost all examples, the values of σ_y obtained from the (TWSTFT-GPS) difference were significantly lower than the σ_y values obtained from the individual time transfers. This again indicated that the major contribution to the time transfer σ_y values is from clock noise. A significant proportion of this noise cancels in the (TWSTFT-GPS) differences, due to the partial elimination of noise from the clocks.

Despite the lower σ_y values obtained from the GPS time transfers, the conclusion should not be drawn that the GPS common-view method offers the best technique for clock comparison. The lower σ_y values may be due to the choice of TWSTFT and GPS measurement schedules, rather than to an intrinsically higher accuracy of the GPS method. The σ_y values obtained from a TWSTFT are calculated from "spot" five-minute readings, made either two or three days apart. In contrast, the σ_y values obtained from a GPS common-view time transfer are calculated from "weighted means" of up to two days' data, with approximately thirty satellite readings contributing to each day's data. σ_y values calculated from these mean values will be lower even in the case where two perfect time-transfer systems are used.

To illustrate the above point further, co-located clock comparisons have been made between two HP5071A commercial cesium clocks and an active hydrogen maser at NPL. One hundred days of measurements have been examined. Values of σ_y obtained from the comparisons are shown in Table 4, using averaging times (τ) of 2, 4, and 8 days. The σ_y values were calculated from single readings, from the mean of 48-readings taken over the two days, and from the (single reading - mean readings) differences. The results show the advantage of taking measurements throughout the 48-hour period. With a two-day averaging time, the σ_y values calculated from the mean readings were substantially lower than the σ_y values calculated from the single readings. The values of σ_y obtained from the co-located measurements were comparable with, and only slightly lower than, the σ_y values obtained from the TWSTFT and GPS time transfers. These results suggest that a large fraction of each time transfer σ_y value is due to clock noise. These results also show that the differences between the σ_y values obtained from the TWSTFT and GPS common-view systems is most likely to be due to the choice of measurement schedule, rather than any intrinsically better delay stability of the GPS system.

Plots of (TWSTFT-GPS) differences show several trends. There are delay steps of several nanoseconds occurring within some of the instrumentation. Several, but not all, of these delay changes are associated with known delay changes of either the GPS or the TWSTFT instrumentation due to hardware replacement. Periodic delay changes with an annual period occur within the (VSL-NPL) differences. Temperature-dependent delay changes have been observed in previous studies of (TWSTFT-GPS) differences[13].

DISCUSSION

There are several possible improvements that may be made to both the TWSTFT and GPS common-view time-transfer systems used in this experiment. Neither the TWSTFT system nor the GPS system are presently operating using optimum hardware. The GPS system may benefit from the use of dual-frequency multichannel receivers, which make optimum use of the available GPS signals. Work has already been performed to improve the use of the GPS system for time transfer by, for example, better satellite ephemeris determination, improved Earth station coordinate determination, ionospheric measurement, and tropospheric modelling. The main limitation to the performance of the common-view GPS method is the delay stability of the receiver instrumentation. The TWSTFT system may benefit from the use of more recently designed modems. Further improvements may be obtained from the optimization of the Earth station instrumentation to minimize the delay instabilities. Satellite simulators may be used to measure the Earth station delay asymmetries during a TWSTFT measurement session.

The values of σ_y obtained using both the TWSTFT and GPS systems have been limited by the performance of the cesium atomic clocks at most locations. A parallel TWSTFT experiment has been taking place between Europe and North America. The combination of longer baseline time transfers and the possibility of operating with active hydrogen masers at both locations should make the study of these links of considerable interest. It will be of particular interest to examine the effects of ionospheric corrections, and precise ephemeris corrections applied to the GPS measurements, made over these relatively long links.

CONCLUSIONS

TWSTFT and GPS common-view methods have been shown to be capable of providing high-precision time transfers. Values of $\sigma_y(\tau = 2.3 \text{ days})$ as low as 1.3×10^{-14} and 1.8×10^{-14} have been reported for GPS common-view and TWSTFT respectively. This difference in σ_y values has been attributed to the behavior of the clocks when interrogated using the different measurement periods used by the two systems. Periodic delay changes of period one year were also observed. These changes correlated with outdoor temperature variations. Further work is required to obtain the optimum performance from both systems.

ACKNOWLEDGEMENTS

This work has been supported under the UK National Measurement System Program for Time and Frequency. The work has also been funded by grants from the Austrian Academy of Science and the Jubilee fund of the Austrian National Bank.

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Table 1 Atomic clocks and TWSTFT instrumentation.

Laboratory	TUG	NPL	VSL	FTZ	PTB
Clock	HP5071A	Hydrogen Maser	HP5071A	HP5071A	CS2 Primary Caesium
TWSTFT Antenna	1.8m	2.4m	3.0m	1.8m	1.8m
TWSTFT Modem	MITREX 2500	MITREX 2500	MITREX 2500	MITREX 2500A	MITREX 2500A

Table 2 Values of σ_y calculated from TWSTFT and GPS time transfer and (TWSTFT-GPS) differences.

LINK	TWSTFT Time Transfer σ_y x10 [14]			GPS Time Transfer σ_yx10 [14]			(TWSTFT - GPS) Difference σ_yx10 [14]		
	τ=2.3 days	τ=4.7 days	τ=7.0 days	τ=2.3 days	τ=4.7 days	τ=7.0 days	τ=2.3 days	τ=4.7 days	τ=7.0 days
NPL-TUG	2.4	1.5	1.2	2.3	1.4	1.2	1.3	0.6	0.5
VSL-NPL	5.1	5.5	4.5	4.8	5.3	4.4	2.8	1.7	0.9
VSL-TUG	5.8	4.5	4.8	5.6	4.0	4.4	2.0	1.3	1.0
FTZ-VSL	5.1	5.3	4.7	4.4	4.9	4.6	4.6	4.7	1.7
FTZ-NPL	3.6	2.7	2.5	3.0	2.5	2.4	2.0	1.3	1.1
FTZ-TUG	4.3	2.7	2.6	4.0	2.7	2.5	2.3	1.4	1.1
PTB-FTZ	3.8	2.7	2.4	3.6	2.4	2.3	0.9	0.7	1.2
PTB-VSL	4.3	3.6	3.4	4.2	3.1	3.2	2.6	1.6	1.0
PTB-NPL	1.8	1.0	1.0	1.3	0.8	0.9	1.7	0.8	0.6
PTB-TUG	2.9	1.6	1.3	2.6	1.6	1.4	1.5	0.9	0.8

Table 3 Standard deviations calculated from the (TWSTFT-GPS Common-View) differences.

LINK	Standard Deviation (Complete Period)	Duration of subset (MJDs)	Standard Deviation (subset)
NPL-TUG	2.4 ns	49471-49840	1.5 ns
VSL-NPL	4.1 ns	49707-49805	1.4 ns
VSL-TUG	4.6 ns	49590-49709	2.7 ns
FTZ-VSL	14.5 ns	49670-49754	2.9 ns
FTZ-NPL	7.4 ns	49670-49805	1.6 ns
FTZ-TUG	9.1 ns	49635-49805	1.5 ns
PTB-FTZ	11.7 ns	49657-49805	1.6 ns
PTB-VSL	4.3 ns	49670-49840	2.4 ns
PTB-NPL	2.5 ns	49600-49950	1.4 ns
PTB-TUG	3.4 ns	49567-49950	2.3 ns

Table 4 σ_y values calculated from co-located measurements made at NPL

	Single Readings σ_y x10 ^{14}			Mean Readings σ_yx10 ^{14}			Difference σ_yx10 ^{14}		
	τ=2.0 days	τ=4.0 days	τ=8.0 days	τ=2.0 days	τ=4.0 days	τ=8.0 days	τ=2.0 days	τ=4.0 days	τ=8.0 days
Maser-123	1.8	1.4	0.7	1.3	1.3	0.6	1.7	0.4	0.3
Maser-404	3.2	1.8	0.9	2.2	1.4	1.0	1.6	0.8	0.3
123-404	3.6	2.3	1.0	2.6	1.9	1.0	1.8	0.9	0.3

Maser = Sigma Tau Hydrogen Maser
123 = HP5071A High performance clock
404 = HP5071A Standard clock.

Figure 1

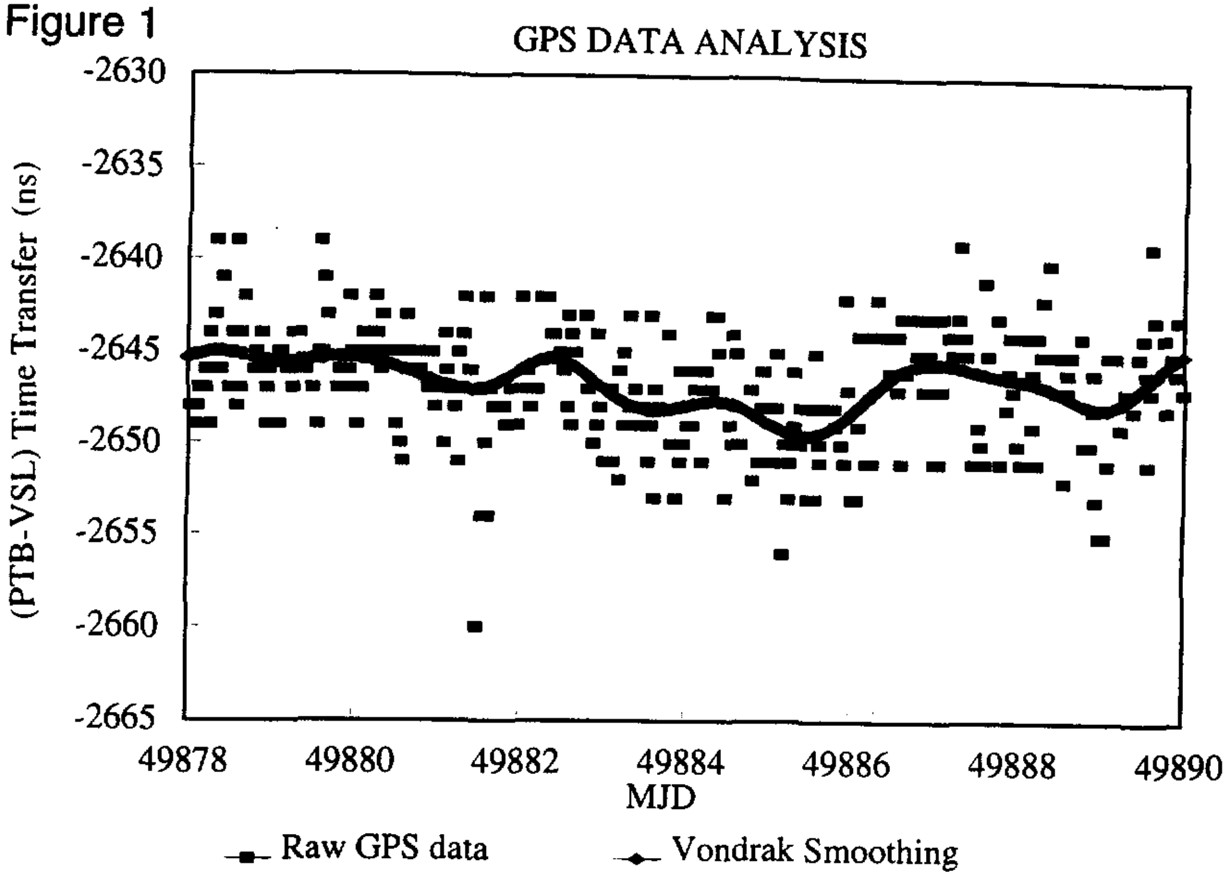


Figure 2

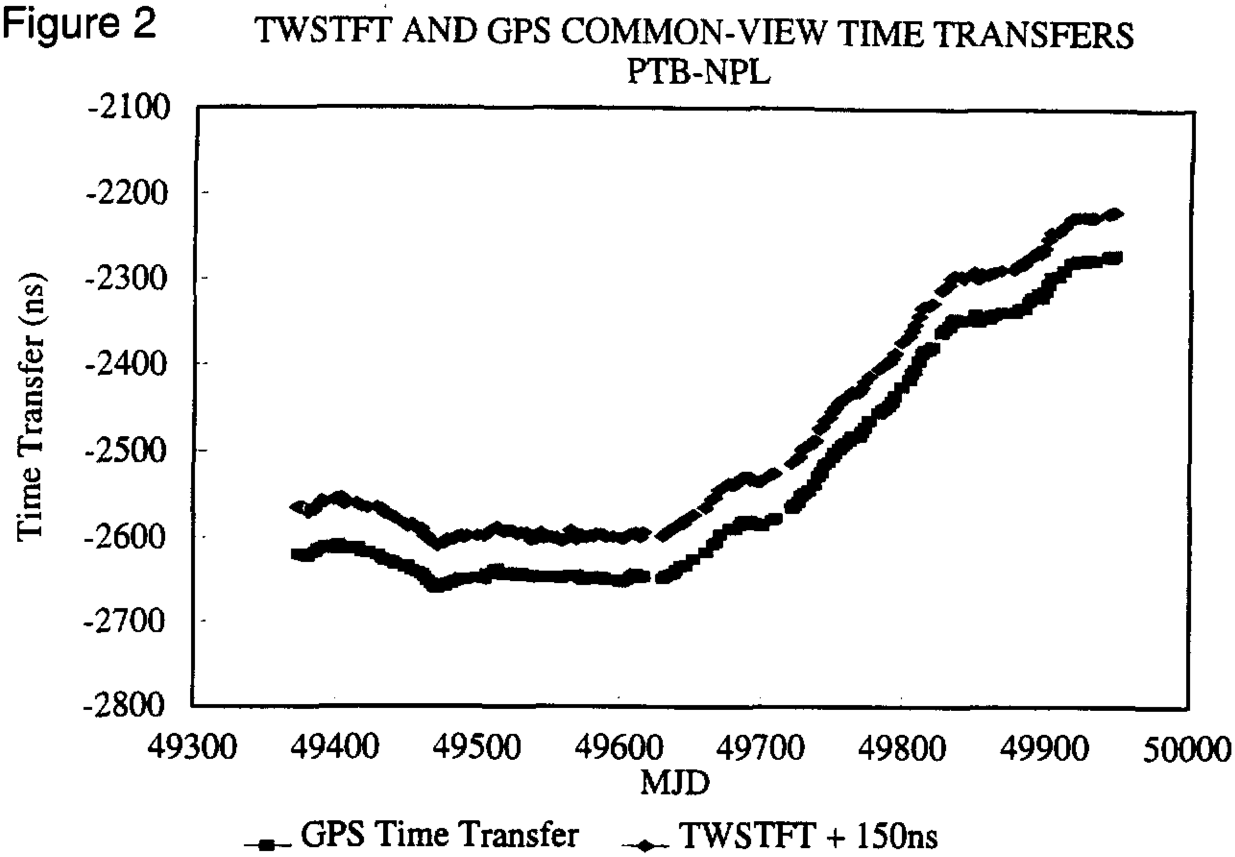


Figure 3

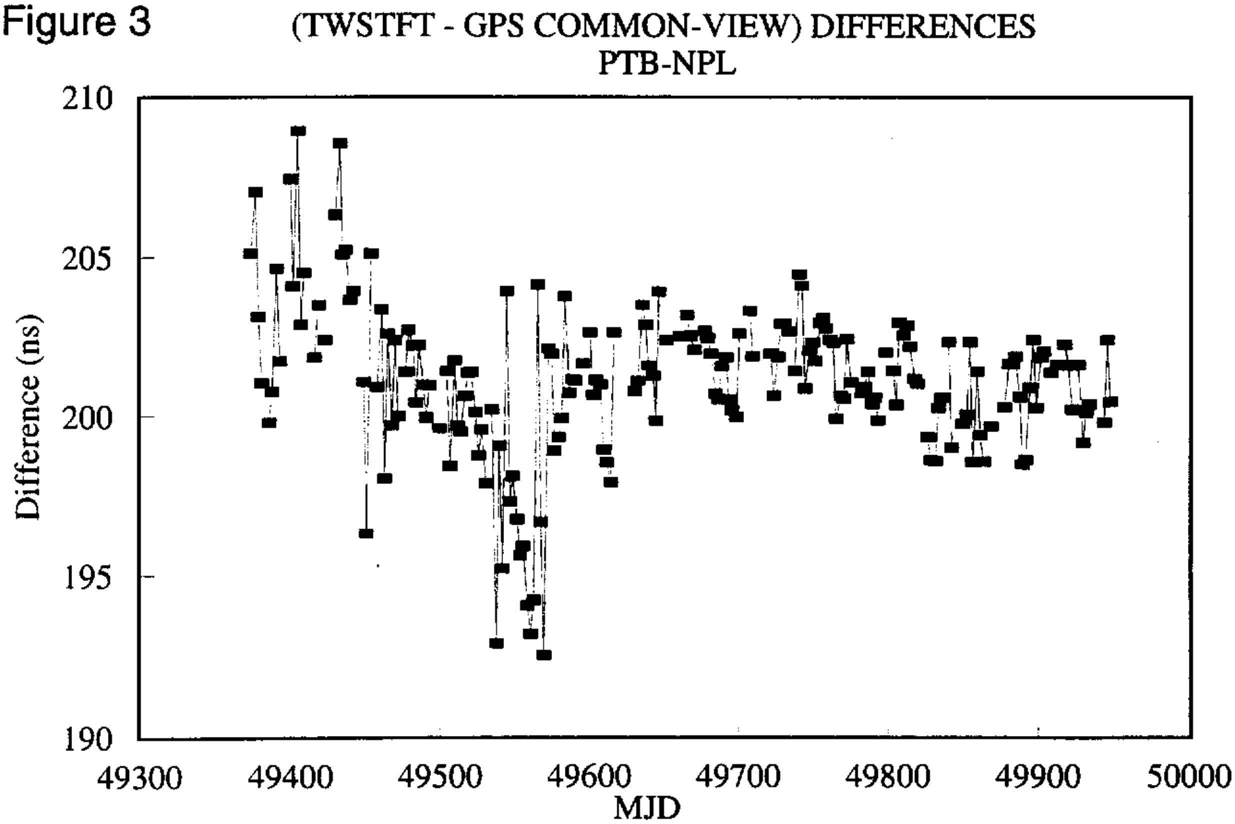


Figure 4

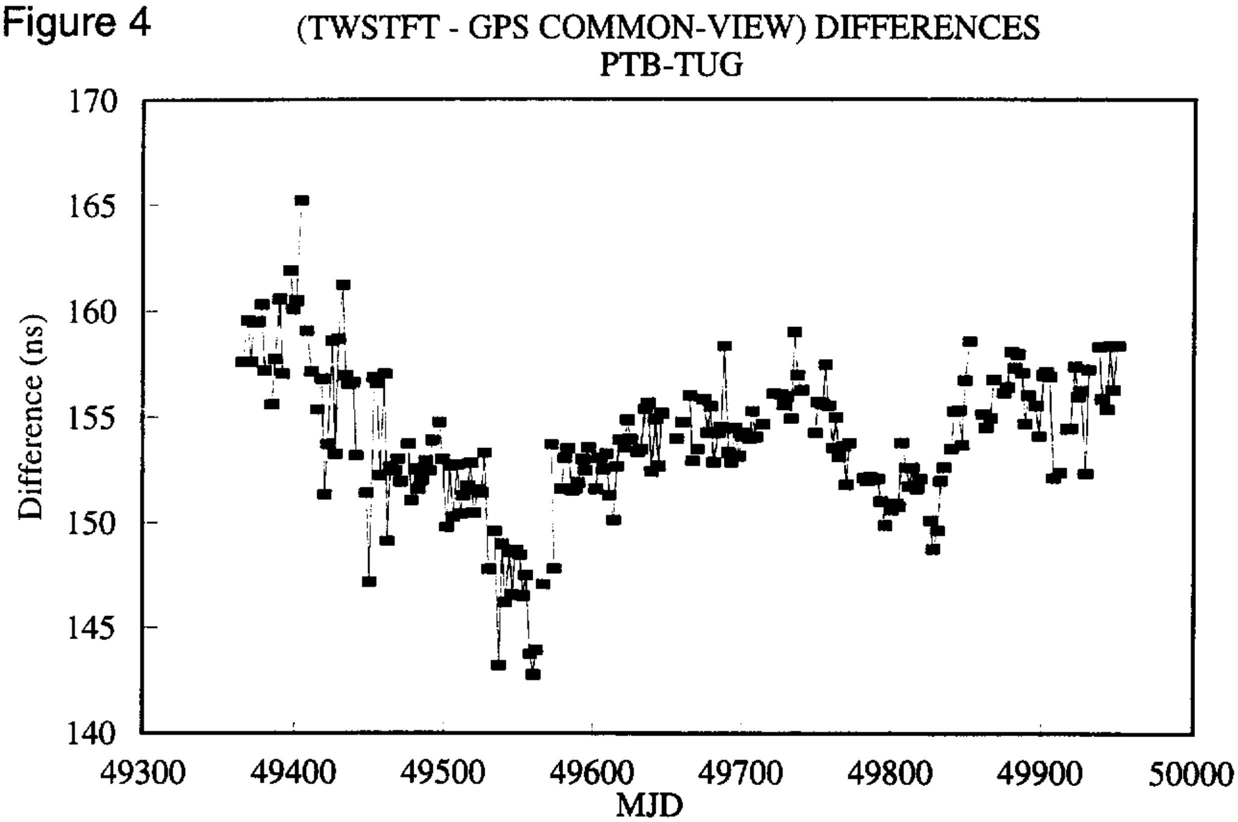
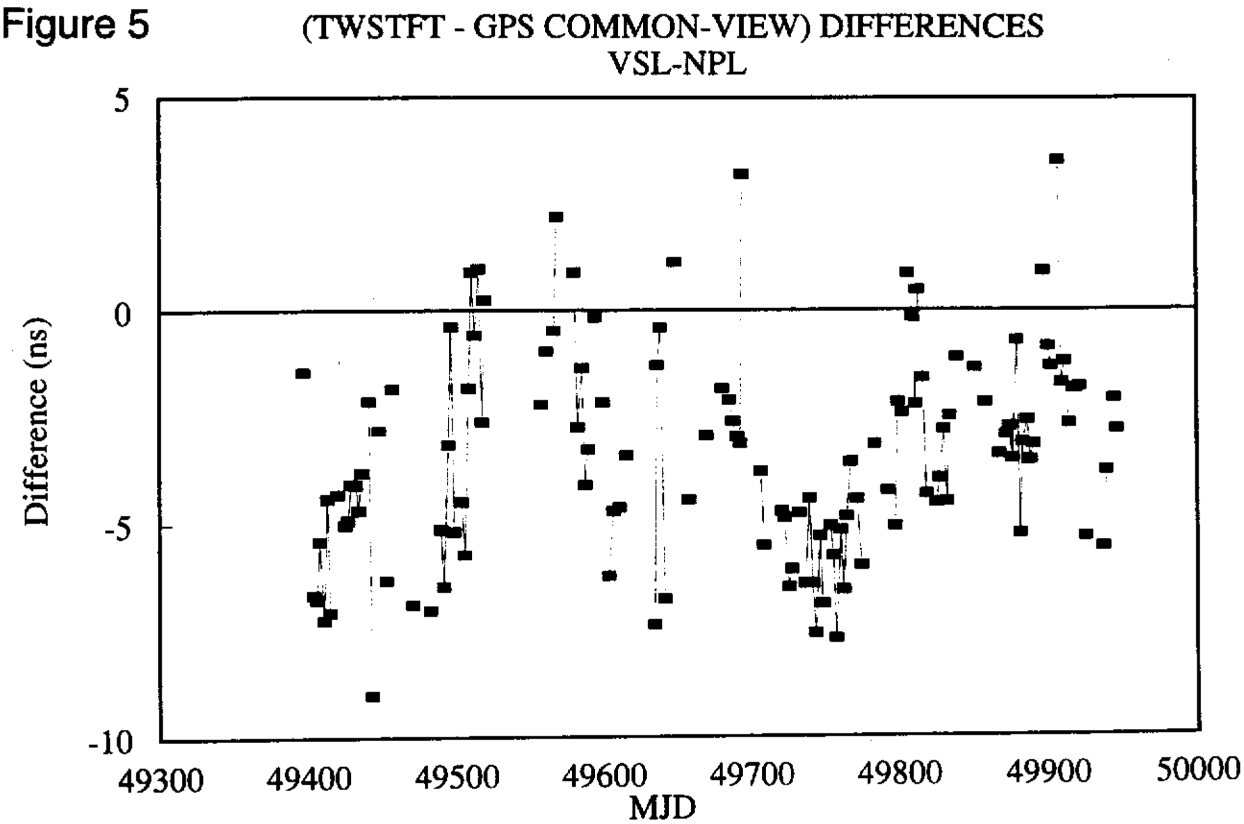


Figure 5


(TWSTFT - GPS COMMON-VIEW) DIFFERENCES
VSL-NPL
Difference (ns)
5
0
-5
-10
49300
49400
49500
49600
49700
49800
49900
50000
MJD