1999 GPS TIME TRANSFER PERFORMANCE

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Abstract

In the 1990s, the number of military and civilian government agencies who've become dependent on GPS for accurate timing and navigation has consistently increased. The GPS Operational Control Segment (OCS), using information provided by the United States Naval Observatory (USNO), maintains the GPS timing signal well within specifications. This paper summarizes the 1999 performance of One-Way (Direct-Access) GPS time transfer for authorized users. Data from previous years will also be presented as a means of comparison. Additionally, the paper briefly covers some recent GPS Master Control Station (MCS) activities affecting the GPS signal.

INTRODUCTION

Time transfer performance is defined as a description of how accurately users can convert to Coordinated Universal Time (UTC) as maintained by the United States Naval Observatory (USNO), UTC(USNO), by tracking GPS satellites and using timing information found in the navigation message. Based on its low cost, accessibility, and global coverage, GPS serves as USNO's primary method for transferring precise time to Department of Defense (DoD) users [1].

Although many methods exist for utilizing GPS satellites in the time transfer process, this paper focuses on *direct access* GPS time transfer performance for authorized users. Since authorized users are able to correct for Selective Availability (SA) through keyed receiver sets, they achieve a more accurate measure of UTC(USNO) as compared to unauthorized users. Direct access has proven itself ideal for military systems since users can operate autonomously and in complete anonymity with only a single receiver.

Before providing statistics on performance, several key terms will be defined and a brief overview of the continuous USNO-GPS feedback loop will be discussed. Armed with this background information, Precise Positioning Service (PPS) users will truly appreciate the new level in GPS time transfer performance achieved in 1999. Finally, the last part of this paper deals with some interesting discoveries and improvements related to multipath, User Range Accuracy (URA), and Broadcast Interfrequency Bias (TgD) values which may be of interest to the Precise Time and Time Interval community. Hopefully, such information will lead to further improvements in time transfer performance in the coming years.

DEFINITIONS AND TERMS

GPS Time is defined by the GPS Composite Clock, an implicit ensemble of monitor station and satellite vehicle frequency standards. Currently, up to 18 individual satellites and 5 Air Force monitor station clocks contribute to the ensemble. This "paper clock" offers more stability and accuracy than any single clock and is not susceptible to a single point of failure. Figure 1 shows the composition of the Composite Clock for a random day in 1999. Authorized users obtain GPS Time by locking up on any broadcasting GPS satellite and correcting for the MCS Kalman filter's estimate of its offset from the Composite Clock. Only then can they make the transformation to UTC(GPS) by utilizing the information in Subframe 4, Page 18 of the GPS navigation message.

UTC(USNO), as maintained by USNO in Washington, D.C., utilizes a single hydrogen maser reference frequency for its Master Clock. USNO dynamically steers their Master Clock to an ensemble consisting of 6-12 hydrogen masers and over 30 Hewlett-Packard Cesium 5071 frequency standards. Each day, USNO provides the MCS with a least-squares fit estimate of the phase offset between GPS Time and UTC(USNO) [1]. The MCS uses this value to "steer" GPS Time to UTC(USNO), the official Department of Defense (DoD) time standard. ICD-GPS-202, which defines the interface between the OCS and USNO, requires this offset, known as *GPS-UTC(USNO)*, to be less than 1000 nanoseconds (ns) [2].

Along with GPS-UTC(USNO), USNO includes the previous day's *AVGERR*, *SIGMA*, and *TT RMS* to the 2 SOPS. AVGERR is a straight average of the UTC(GPS) – UTC(USNO) time difference for the entire GPS constellation based on USNO monitoring. SIGMA is the standard deviation from the AVGERR of the measurements used to determine the average. TT RMS is the Root Sum Square of the AVGERR and SIGMA for the applicable day. TT RMS is the single best indicator for whether or not GPS is meeting the ICD-GPS-202 time transfer specification of 28 ns RMS.

USNO-GPS FEEDBACK LOOP

Currently, USNO monitors the GPS dissemination of UTC(USNO) each day using a Stanford Telecommunications Inc. (STel) 5401C receiver. The 5401C is able to correct for the effects of Selective Availability since it is a keyed, dual-frequency receiver set. Through individual 13 minute single-satellite observations, USNO calculates time differences between the GPS broadcast of UTC(USNO) and official UTC(USNO) time derived from the USNO Master Clock. Time transfer data (including the GPS-UTC(USNO), AVGERR, and TT RMS values mentioned above) gathered and processed from USNO's receivers are then stored in a database for retrieval by MCS personnel.

Every day at 1500z, the 2 SOPS on-duty Payload Systems Operator (PSO) performs the USNO download to retrieve the time transfer information from USNO. After ensuring the values meet minimum specifications, the PSO enters the GPS-UTC(USNO) value (in nanoseconds) into the MCS system via a display terminal. This value is used to produce the bias and drift predictions between GPS Time and UTC(USNO) found in Subframe 4, Page 18 of the navigation message. This portion of the nav message also contains the accumulated leap seconds between GPS and UTC and the effective date of a planned change in leap second count.

In addition to the information from USNO, the MCS also continuously receives ranging measurements from its five Air Force monitor stations. These ranging measurements serve as

input into the MCS Kalman filter to produce clock offset predictions from the Composite Clock for each satellite. Typically, the MCS transmits new navigation uploads to each satellite vehicle every 24 hours so users are able to obtain very accurate navigation and time transfer information. This continuous USNO-GPS feedback loop has proven very efficient in delivering precise time transfer to users around the world.

CURRENT TIME TRANSFER PERFORMANCE

Figure 2 shows a plot of the daily UTC(GPS)-UTC(USNO) time transfer root mean square (TT RMS) and average errors (AVGERR) for 1998 [3]. The 1998 GPS time transfer RMS was 6.94 ns, significantly lower than 1997's RMS of 7.84 ns. The TT RMS exceeded 10 ns on only three occasions in 1998, while its low mark was 4.44 ns on 5 October (Day 278 of 1998). There was only one other instance during 1998 when the TT RMS was below 5 ns.

Figure 3 shows the same TT RMS and AVGERR data plotted for 1999. From 1 January 1999 to 31 October 1999, the time transfer RMS was 6.63 ns, a 4.4 percent improvement over 1998. This slight drop in the RMS is attributed to the fact that 2 SOPS has been conducting "contingency" navigation uploads at a 3 meter Estimated Range Deviation (ERD) tolerance for the entire year. An ERD is the difference between the Kalman filter's current estimate of the apparent range to a satellite and the range to the satellite calculated from the satellite's navigation message. In August of 1998, 2 SOPS went from a 5-meter upload threshold to a 3-meter threshold. Thanks in part to the new upload strategy, the year saw six separate days where the TT RMS was below 5 ns, with a new record low of 4.43 ns set on 23 May 1999 (Day 143 of 1999).

The 1999 plot reveals two separate periods when the TT RMS rose above 10 ns. The first instance, occurring in mid January (Days 16-20 of 1999), was the result of a noisy USNO receiver and was not a true indicator of GPS time transfer performance. The second instance, occurring in mid September (Day 260 of 1999), was due to SVN 19's clock instability. SVN 19 was immediately set unhealthy upon recognition that the vehicle was contributing to higher time transfer errors and since then an on-board frequency standard swap has been accomplished. Despite these two instances, each daily RMS is well below the UTC(GPS)-UTC(USNO) Interface Control Document specification of 28 ns RMS.

GPS-UTC(USNO) PERFORMANCE

Figures 4 and 5 show the daily GPS-UTC(USNO) offsets for 1998 and 1999, respectively. 1998's maximum deviation of GPS-UTC(USNO), +8.7 ns, occurred on 19 June (Day 170 of 1998), while 1999's was −15.13 ns on 13 August (Day 225 of 1999). The MCS had not seen a GPS-UTC(USNO) value this high since 16 May 1997 (Day 136). This higher-than-normal offset value is attributed, as is the maximum TT RMS mentioned above, to SVN 19's clock instability. Despite the runoff in GPS-UTC(USNO) during this time frame, 2 SOPS is well within the 1000 ns specification for GPS-UTC(USNO) mandated by ICD-GPS-202. More importantly, because the USNO-MCS feedback loop continued to operate through this period, the TT RMS did not experience significant degradation as a result of this GPS-UTC(USNO) offset.

As illustrated in Figures 3 and 5, the clock instability on SVN 19 was apparent in the daily GPS-UTC(USNO) offset several weeks before being seen in the TT RMS values. In this instance, the larger-than-normal daily offsets were a good indication something was amiss with GPS Time.

This is a perfect example of how the performance of GPS-UTC(USNO) can often serve as a precursor to the performance of UTC(GPS)-UTC(USNO).

GPS TIMESCALE STABILITY

The stability of GPS-UTC(USNO) for 1998 and 1999, based on daily GPS-UTC(USNO) data points provided by USNO, is presented in Figure 6. The one-day stability for 1999, 1.55 E-14, is slightly better than 1998's one-day stability of 1.59 E-14. As illustrated in the plot, the long-term stability is not quite as good as that seen in 1998 [4]. The reason for this slight degradation rests with the instability of SVN 19 during a portion of the year. Take away the clock instability for this satellite and 1999's stability is roughly as good as exhibited for 1998.

MULTIPATH

Colorado Springs Monitor Station (COSPM), located at Schriever AFB, CO, is one of five operational Air Force monitor stations which provide ranging data on all GPS satellites to the MCS. Since the ranging measurements from each Air Force station are input into the MCS Kalman filter to produce each satellite's ephemeris and clock estimates, it is important these measurements be as accurate as possible. However, unknown to many in the GPS community is the long-standing mystery surrounding high range residuals at COSPM. Based on National Imagery and Mapping Agency (NIMA) post-fit residual statistics, COSPM's RMS residuals are three times those of a mean consisting of ten other Air Force and NIMA monitor stations. The severe multipath at this site had been a topic for wide speculation until a recent study pinpointed the source of the problem.

The Tiger Team tasked with getting to the bottom of this issue consisted of members from 2 SOPS, NIMA, Lockheed-Martin, and Aerospace. Speculation on the multipath source centered on three main areas: a lightning rod located next to the antenna, the protective radome surrounding the antenna, and the "busy environment" at which the monitor station is located. The lightning rod was quickly dismissed since every Air Force station has a similar device within close proximity to each antenna with no apparent multipath effects. The radome was another matter, however. COSPM is the only Air Force station with a protective radome surrounding the antenna. In order to shield the antenna from snow and ice, a bubble-shaped fiberglass radome has surrounded COSPM's antenna since it became operational in November 1985. The busy environment theory was also considered since the activity at Schriever AFB is magnitudes greater than the remote sites located at Ascension Island, Diego Garcia, Kwajalein Atoll, and Hawaii.

To test the radome theory, 2 SOPS used an Ashtech Z(Y)-12 receiver along with a Dorn Margolin choke-ring antenna mounted on a tripod to collect data from both inside and outside the radome in various configurations. The first configuration collected three days of 15-second data with the Ashtech/Dorn Margolin combination inside the radome. The second configuration collected three days of 15-second data with the Ashtech/Dorn Margolin outside the radome. Finally, three days of data were collected with the Ashtech receiver connected to the operational Vega antenna. By extracting the binary data from the Ashtech receiver and evaluating the L1/L2 ADR second differences, L1/L2 multipath, and L1/L2 Signal-to-Noise (SNR) under all receiver/antenna configurations, it was obvious that the source of the multipath at COSPM was the radome. The Ashtech/Dorn Margolin configuration outside the radome produced 20 cm RMS residuals compared to 55 cm RMS residuals inside the radome.

Based on the results of this study, efforts are underway to consider elimination of the radome at COSPM and consequently receive more accurate ranging measurements from this station. Since COSPM is the single biggest contributor to the GPS Composite Clock (as illustrated in Figure 1), the stability and accuracy of GPS Time should easily improve by reducing the measurement noise at this site.

USER RANGE ACCURACY (URA) IMPROVEMENT

URA, as defined in ICD-GPS-200, is a statistical indicator of the ranging accuracy obtainable from satellites [5]. It represents the one-sigma estimate of space and control segment errors users may see. URA is broadcast in the navigation message as an index value that corresponds to the maximum URA value predicted over a given fit interval. For authorized users it provides a useful indication of satellite performance. This index value represents errors as indicated in the following table:

URA INDEX	URA (meters)		
0	0.00	< URA ≤	2.40
1	2.40	< URA ≤	3.40
2	3.40	< URA ≤	4.85
3	4.85	< URA ≤	6.85
4	6.85	< URA ≤	9.65
5	9.65	< URA ≤	13.65
6	13.65	< URA ≤	24.00
7	24.00	< URA ≤	48.00
8	48.00	< URA ≤	96.00
9	96.00	< URA ≤	192.00
10	192.00	< URA ≤	384.00
11	384.00	< URA ≤	768.00
12	768.00	< URA ≤	1536.00
13	1536.00	< URA ≤	3072.00
14	3072.00	< URA ≤	6144.00
15	6144.00	< URA ≤	Use at own risk

Although URA was designed to perform this function, 2 SOPS noticed the index did not provide much differentiation between satellites. After further analysis, it was discovered that the MCS database included an unusually large general modeling error that significantly skewed URA. This general modeling error was originally included to account for modeling errors not represented in the Kalman filter process noise budget. Because URA is calculated by adding general modeling error to ephemeris and clock errors, any overestimation distorts URA. Originally, this value was conservatively set to 3 meters. But because 2 SOPS had undertaken Kalman filter tuning to minimize modeling error, this value had become obsolete. In fact, further investigation revealed that space and control segment errors, under current operational procedures, were already being sufficiently modeled by the inherent noise present in ephemeris and clock predictions.

Setting general modeling errors to zero for all satellites was the simple solution to this problem. 2 SOPS, however, was concerned that URAs would no longer reflect one-sigma errors for all satellites. But after comparing specific satellite URA predictions to observed measurements, it

was determined that URA with general modeling errors set to zero accurately depicts one-sigma error. As a result, the database change was implemented in May 1999.

Before this change, broadcast URAs seldom differed between satellites. A satellite with predictable clock or ephemeris states and a new navigation upload would broadcast the same URA index as a satellite with noisy ephemeris or clock states and a day old upload. After the change, authorized users can differentiate between satellites whose uploads are new versus old or between satellites whose states are more versus less predictable.

BROADCAST INTER-FREQUENCY BIAS (T_{GD}) IMPROVEMENT

Single-frequency users require knowledge of differential group delays (T_{GD}) between L1 and L2 frequencies in order to precisely utilize clock offsets broadcast in the navigation message. In the past, broadcast T_{GD} values were derived from factory calibrations performed prior to satellite launch. In time, though, members of the ionospheric science community and other institutions recognized that these broadcast values were not sufficiently accurate representations of actual inter-frequency bias. Because of this, a joint effort between the Air Force, the Jet Propulsion Laboratory (JPL) and other members of the GPS community was formed to come up with more accurate estimations of T_{GD} values [6].

Although 2 SOPS was not involved with the derivation of new T_{GD} values, the squadron was crucial to the coordination and implementation of the use of new T_{GD} values. First, 2 SOPS created the process to evaluate and update new T_{GD} values on an ongoing basis. Second, 2 SOPS helped resolve bureaucratic concerns so all organizations involved were satisfied with the process and the inter-organizational agreement. Once this approval was gained, 2 SOPS implemented and verified the first set of new T_{GD} values in April 1999. Since this time, the values have been updated quarterly.

In the future, 2 SOPS will continue to update T_{GD} values on a quarterly basis. To do this, JPL will provide these values, upon request, at the same time that 2 SOPS updates monitor station and satellite clock noise parameters. To prevent unnecessary work, changes to broadcast T_{GD} values will only be made when new T_{GD} values would result in changes to the index broadcast in the navigation message (which is quantized in 2^{-31} second increments). Additionally, JPL will provide T_{GD} values, upon request from 2 SOPS, when new satellites are launched or if a satellite's hardware configuration is changed. This ongoing process will ensure that single frequency users will be able to correctly implement the clock offsets broadcast in GPS navigation messages.

CONCLUSION

Although GPS performed significantly better than specifications, this year showed how time transfer performance can easily be impacted by aging equipment. It should be noted that the continued use of old satellites and ground systems will make further time transfer improvements challenging. Despite this, 2 SOPS and USNO, with help from JPL and several other agencies, have found new ways to improve GPS time transfer. Through database refinements, as well as the ongoing monitoring and expedient recognition/resolution of satellite and ground system anomalies, 2 SOPS and USNO have continued to maintain GPS as a reliable and stable time transfer distributor.

ACKNOWLEDGMENTS

REFERENCES

[1]   2 SOPS Mission Support Document 3-11, UTC Time Transfer

[2]   ICD-GPS-202, Revision A, 13 December 1996

[3]   Huser, Stacy Jo, Lt. and Hutsell, Steven T., *1998 GPS Time Transfer Performance*, Proceedings of the 30th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 1-3 December 1998, Reston, VA, USA, pp. 125-134.

[4]   2 SOPS Mission Support Document 3-16, Timing Stability

[5]   ICD-GPS-202, Revision C, 10 October 1993, IRN-200C-002, 25 September 1997

[6]   Wilson, Brian D.; Yinger, Colleen H.; Fees, William A.; and Shank, Chris, Capt., *New and Improved: The Broadcast Interfrequency Biases*, GPS World, September 1999, pp. 56-66.
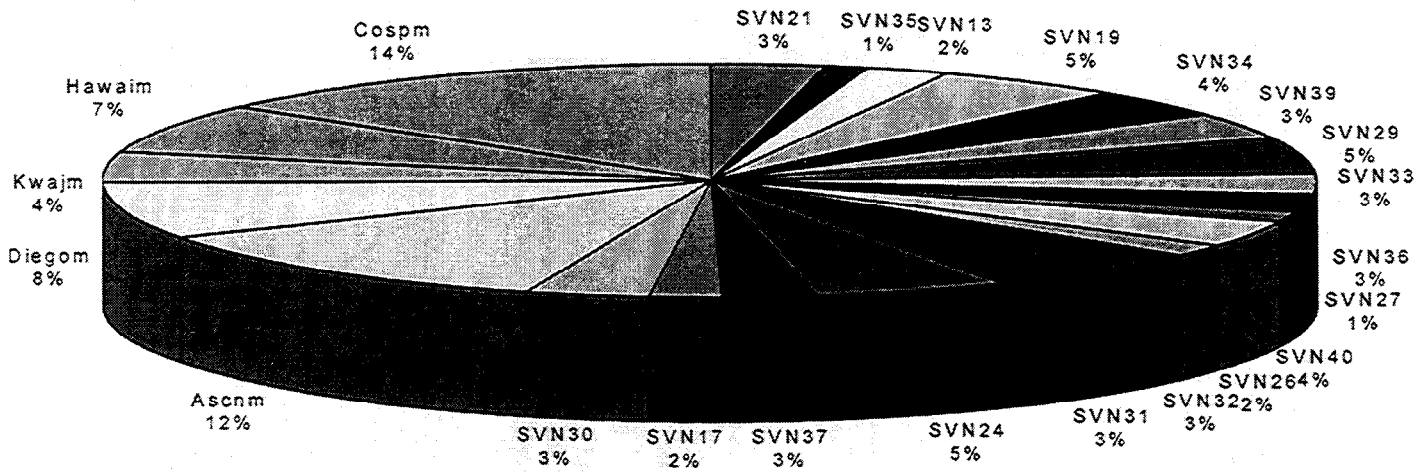
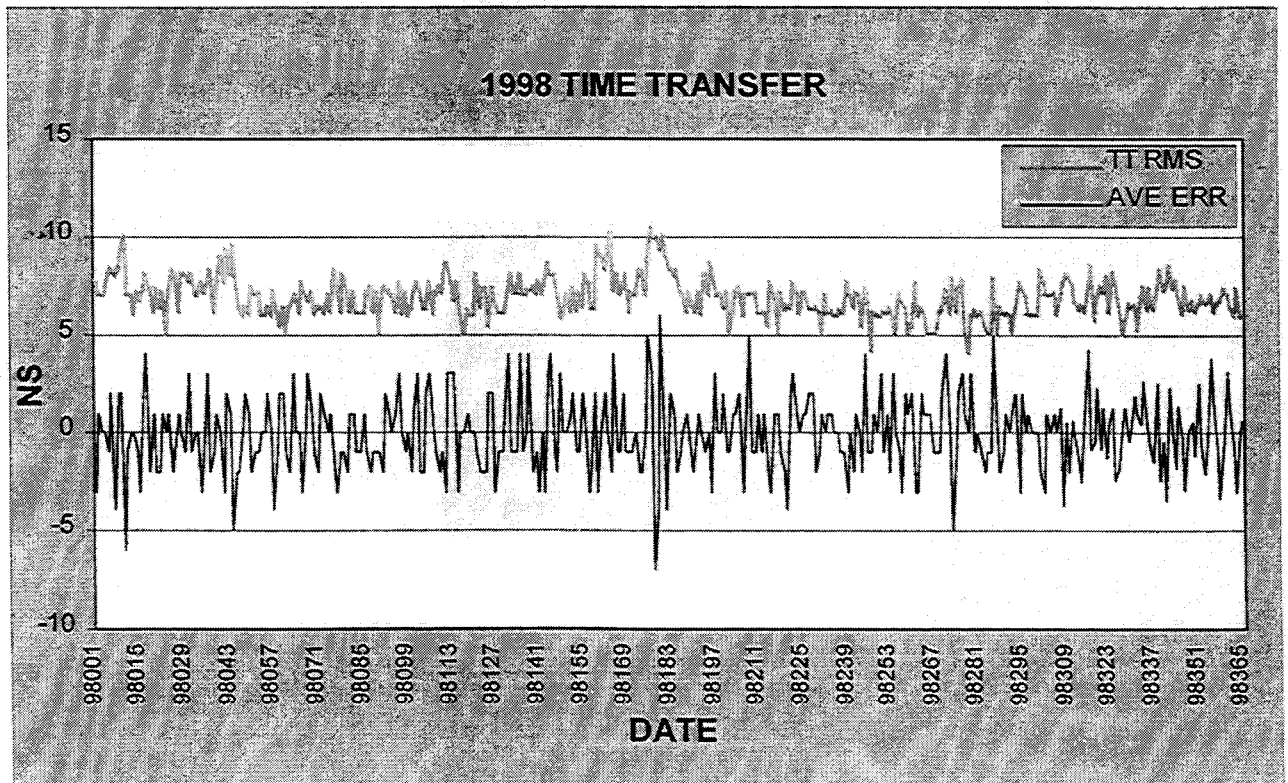FIGURE I. GPS Composite Clock Weighting for a random day in 1999

FIGURE II. 1998 UTC(GPS) - UTC(USNO) Root Mean Square and Average Error
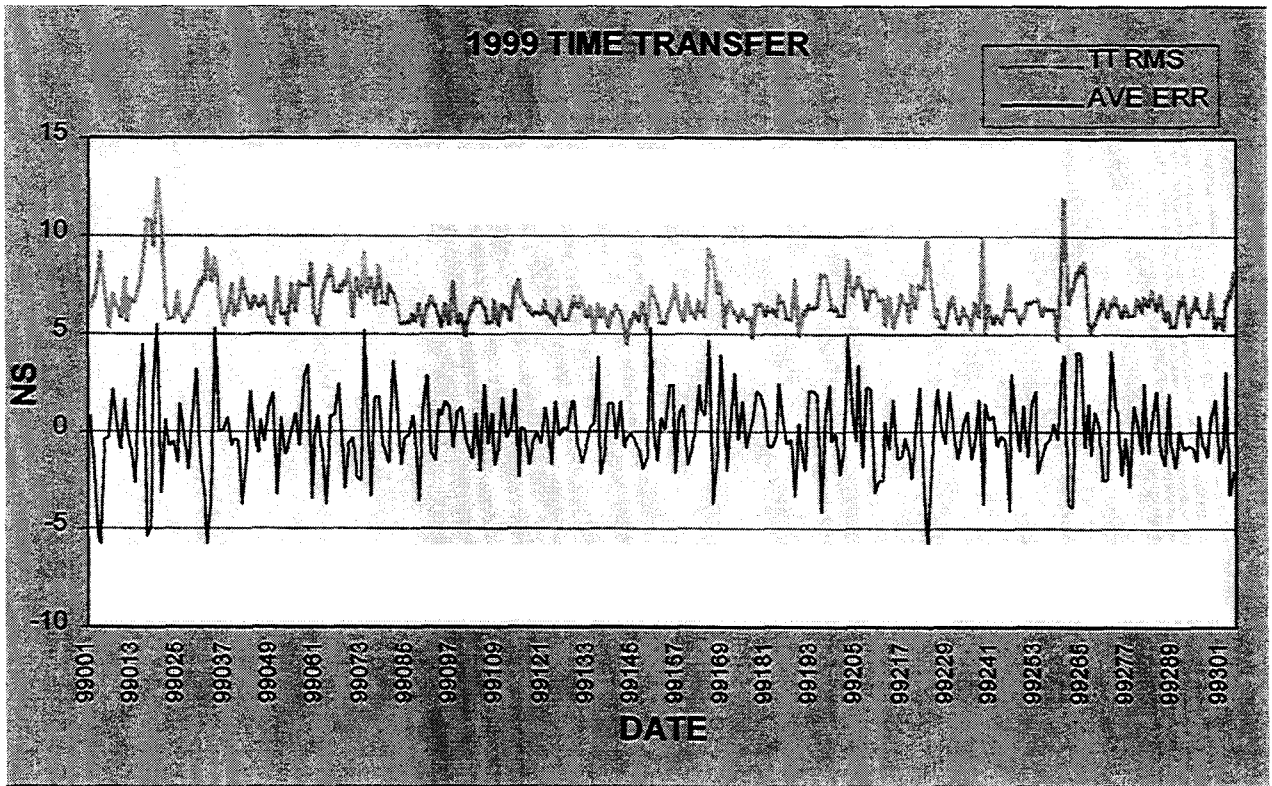
FIGURE III. Jan through Oct 1999 UTC(GPS) - UTC(USNO) Root Mean Square and Average Error
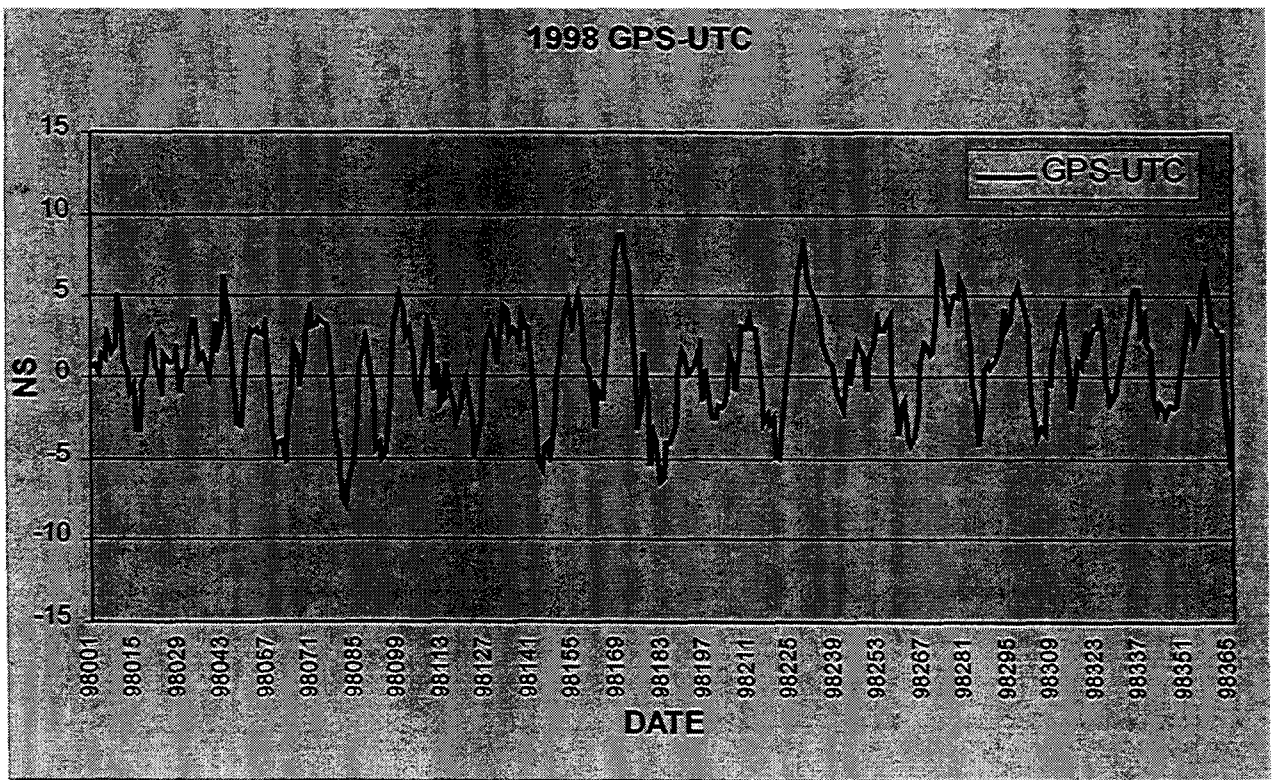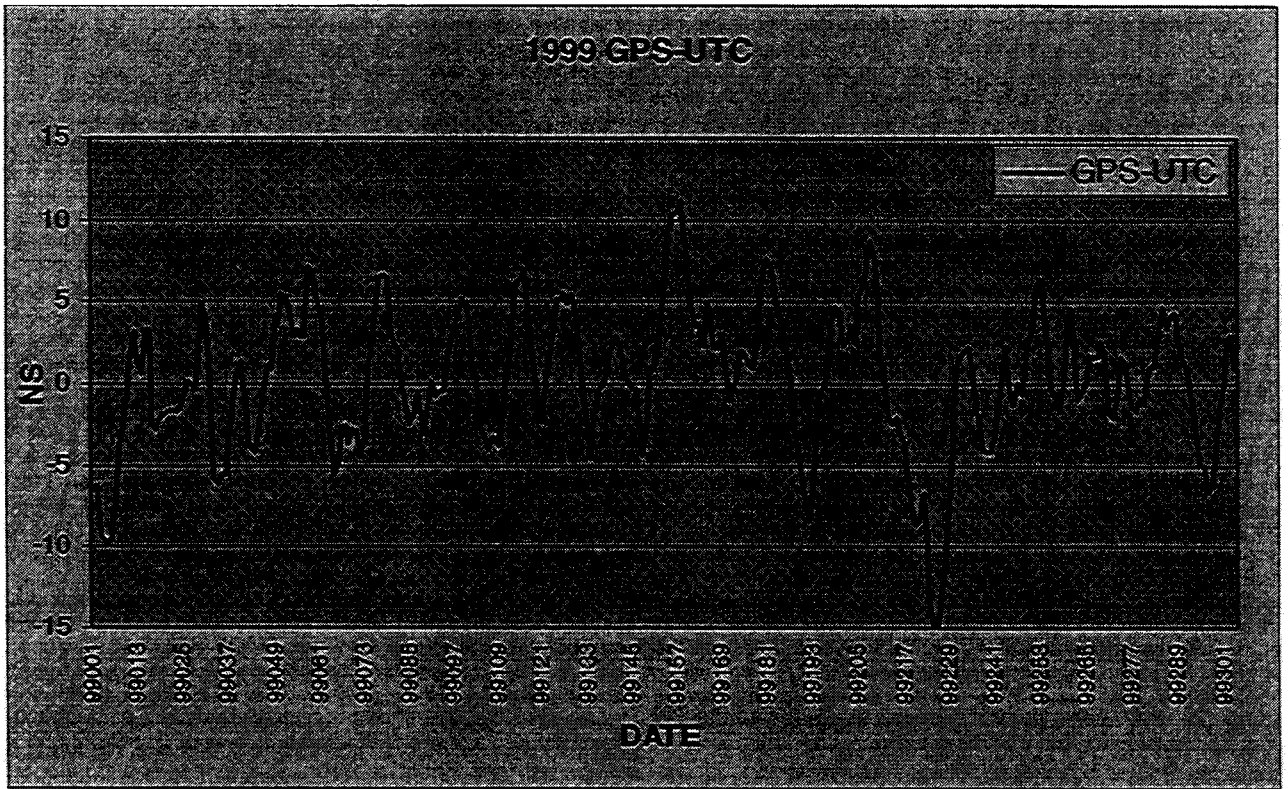

FIGURE IV. 1998 Daily GPS - UTC(USNO) Offset

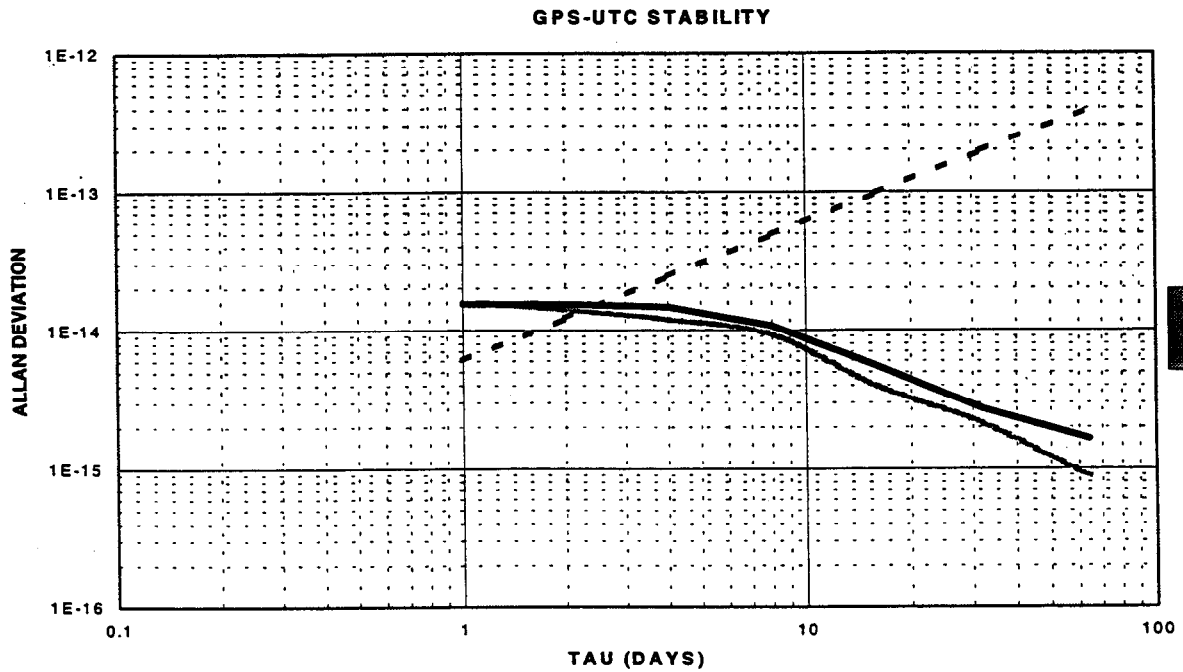FIGURE V. Jan through Oct 1999 Daily GPS - UTC(USNO) Offset

FIGURE VI. 1998 versus 1999 GPS - UTC(USNO) Stability

Questions and Answers

BILL REID (SFA at NRL): I'm fascinated by this measurement noise reduction by removing the radome. What is the physical setup at the other monitor sites? Do they have radomes or not?

CAPTAIN MICHAEL RIVERS (USAF 2SOPS): No, they do not. Essentially — you can correct me if I'm wrong on this, Steve — as far as I know it was put at Colorado Springs because of the snow and ice that are there in Colorado Springs. It simply isn't that way at most of those equatorial-type locations.

WLODZIMIERZ LEWANDOWSKI (BIPM): I would like to stress a point that what you call UTC (GPS) in fact should be called UTC (USNO) as broadcasted by GPS. Because, in fact, UTC (GPS) does not exist. So, this is one point. The other one is of less importance. On your viewgraphs, you are using the difference UTC (GPS) minus UTC (USNO). But usually UTC (GPS) — this operation is misleading, if I'm right. But I think I am.

RIVERS: That's correct.