# 1996 GPS TIME TRANSFER PERFORMANCE

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**Abstract**

***The requirements for GPS time transfer accuracy are more demanding than ever before. The Operational Control Segment has responded, providing a consistently accurate signal to the user community. This paper presents a summary of GPS Time Transfer performance for 1996 and offers several theories for the continued improved performance. Refined techniques in the areas of MCS satellite clock estimation and monitor station clock performance assessment are two areas with significant impact to GPS time. As historical perspective, 1995 time transfer performance is compared to the current year's data.***

## INTRODUCTION

Time transfer performance is a description of how accurately users can obtain Coordinated Universal Time (UTC) by tracking GPS satellites and using the timing information found in subframe 4, page 18 of the navigation message.[1] This timing information includes:

- the accumulated leap seconds between GPS and UTC
- the effective date of a planned change in leap second count
- the GPS-UTC bias and drift estimates.

In accordance with a recent revision of ICD-GPS-202, the time transfer error of UTC(GPS) must be less than 28 nanoseconds (1 $\sigma$).[2] In other words, any authorized (PPS) user of the GPS navigation message must be able to correct to UTC to within 28 nanoseconds. Furthermore, the GPS time scale must be maintained to within 1 microsecond of UTC time, once the correction for leap seconds has been made.[1] The data presented below will illustrate that GPS time transfer in 1996 performed well within these limits.

## THE YEAR IN REVIEW

The United States Naval Observatory (USNO) provides daily timing information to the 2d Space Operations Squadron (2 SOPS), located at Falcon AFB, CO. Included in this information is the previous day's time transfer performance. This performance is represented by several values. First is the GPS-UTC AVGERR, a daily average of the UTC(GPS) - UTC(USNO) time difference for the GPS constellation. This value is obtained from up to 84 thirteen-minute, single-satellite tracks by the operational USNO STel receiver. Associated with this value is the standard deviation from the AVGERR of the measurements used to determine the average. This value is labeled SIGMA. The RSS of the AVGERR and SIGMA produces the time transfer RMS for the previous day. This value is essentially an RMS of all of the UTC(GPS) - UTC(USNO) time difference errors for the previous day, and is the most reliable available indication of whether or not GPS is meeting the ICD-GPS-202 specification of 28 ns time transfer error.

Figure 1 shows a plot of the daily time transfer RMS and the associated AVGERR. The performance for 1996 marks a new milestone in the GPS program. For the first time ever, the GPS time transfer RMS for the year is below 10 ns. From 1 January 1996 - 1 November 1996, the time transfer RMS was an impressive 9.58 ns. At no point did errors exceed 20 ns, a testament to the dedication of, and the coordination between, the 2 SOPS operations crews and USNO Time Service personnel. The reader will note that Figure 1 includes four highlighted points of interest that will be explained below.

The year's highest daily time transfer RMS, 19.65 ns, occurred on 15 January 1996 (96015). On that date, SVN20/PRN 20 experienced a failure of its operational frequency standard. This failure was preceded by an abrupt change in phase and frequency which resulted in erratic ranging errors and degraded time transfer. The USNO receiver happened to track SVN 20/PRN 20 during this anomaly, and as a result the time transfer values for that day were unusually large.

There are three other points of interest in the Figure shown, labeled with the dates of occurrence. On 18 May 1996 (96139) the time transfer RMS was 12.21 ns. Under most circumstances, a time transfer value of this magnitude causes little concern. At the time of occurrence, however, the RMS had remained consistently below 10 ns for more than 20 days, and had reached as low as 7 ns on three separate occasions. Further investigation revealed that problems with an environmental chamber had caused a 2 to 3 ns/day runoff in UTC(USNO). Once detected and corrected, time transfer again returned to its sub-10-ns performance.

The spikes labeled on 4 August 1996 (96217) and 28 August 1996 (96241) were each due to single satellite anomalies concurrent with USNO receiver set tracking times. In the first instance, SVN 16/PRN 16 experienced platform stability problems. In the case of SVN 40/PRN 10, the newly activated rubidium frequency standard exhibited instability characteristic of a new rubidium clock.[3] The instability on SVN 40 eventually required 2 SOPS analysts to set the navigation signal unhealthy for almost 3 days.

Despite the four instances outlined above, time transfer for 1996 set a new standard. For historical perspective, the same performance statistics are plotted for 1995 in Figure 2. The time transfer RMS for the time period 1 January 1995–1 November 1995 was 10.60 ns.

Figure 3 also illustrates the improved performance of time transfer from 1995 to 1996. This composite plot of the GPS-UTC values from 1 January 1995–1 November 1996 shows that 2 SOPS has remained well within the one microsecond requirement mandated by ICD-GPS-200.[1] The large offset at the beginning of 1995 was due to a timing anomaly with the Colorado Springs Monitor Station (COSPM). This event was explained in detail in Capt. Steven T. Hutsell's 1995 PTTI paper, *"Ideas for future GPS timing improvements."*[4]

## THEORIES FOR IMPROVED PERFORMANCE

The operation of the GPS constellation is a very dynamic process. The operators and analysts of the 2 SOPS and outside agencies are constantly trying to improve upon the accuracy of the system. Their efforts include not only improving upon existing processes, but also establishing new operating principles based on lessons learned from anomalous conditions. This section will present examples of both refined techniques and new processes that have contributed to the improvement of GPS time transfer.

One of the most significant areas of recent improvement is the tuning of satellite clock estimation in the MCS Kalman filter. This process was presented to the community in December 1994 by Capt. Steven T. Hutsell in his paper, *"Fine tuning GPS clock estimation in the MCS."*[5] The process of reviewing and updating process noise values for each of the operational on-orbit frequency standards continues on a quarterly basis. The result has been a significant improvement on the stability of GPS time. Figure 4 shows the Allan deviation plot for GPS time in 1995 and 1996. The efforts of the Naval Research Laboratory and the 2 SOPS deserve much of the credit for this improvement in stability.

In addition to the efforts to optimize satellite clock performance, analysts have taken measures to ensure that Monitor Station clock performance is also optimized. A series of hardware problems at the remote sites forced analysts to explore methods to minimize the impact of adverse conditions on the GPS time scale. The challenges presented themselves in the form of failed air conditioning units, which caused rapid fluctuations in both temperature and humidity. The effects of these changes have been shown to severely destabilize the HP 5061 cesium frequency standard.[6] All four remote Air Force Monitor Stations use the HP 5061 cesium frequency standard. Since each Monitor Station clock is weighted roughly 10% (long-term) in the GPS composite clock, the effects of such conditions must be mitigated to protect the integrity of the GPS time scale. Analysts now have developed a knowledge base of how to detect and react to such conditions in such a way as to minimize the effect of substandard environmental conditions. The result has been a more robust and dynamic time scale, and improved time transfer performance.

One of the most recent timing improvements was the addition of the USNO Alternate Master Clock (AMC). The AMC is co-located with the MCS at Falcon AFB. This facility utilizes up to 12 HP 5071A Cesium frequency standards and up to three Sigma Tau hydrogen masers, and two "master clocks," AMC #1 and AMC #2, respectively. AMC #1, the operational reference, is steered to the DoD Master Clock at USNO via two-way time transfer. More importantly to the 2 SOPS, however, AMC #1 also provides the 5 MHz timing signal to the Colorado Springs Monitor Station (COSPM). COSPM now has an even more stable and more accurate signal than any of the other four Air Force Monitor Stations. Consequently, COSPM receives approximately 20% long-term weighting in the GPS composite clock. The connection of the AMC to COSPM was completed on 12 September 1996, so only preliminary data are available as of this writing.

Another improvement is the active pursuit of an optimum partitioning strategy. The disposal of the last Block I satellite and the successful launches of three new Block IIA satellites have required a constant review of the Kalman filter's estimating partitions. Following guidelines established in July 1993 by 2 SOPS analysts Capt. Dave Malinowski and 1Lt Bill Witwicki, system experts have ensured partitions are optimized for stability and monitor station visibility.[7] This process will continue as GPS enters a new era with the first of several Block IIR satellite launches, scheduled to begin in January 1997.

Thanks to the efforts of both 2 SOPS and USNO personnel, the download of daily timing data is a much more reliable process. Prior to 20 Oct 95, 2 SOPS operators would obtain the daily GPS-UTC offset and the previous day's time transfer performance via a Zenith Z-248 PC connected to a modem and a Guardsman encryption/decryption device. This setup was often unreliable, and the download was often delayed several hours.[4] Since that time, however, the download hardware has been upgraded to a 486 Zenith PC connected to a keyed Secure Telephone Unit (STU-III). A PROCOMM PLUS© script automates the dialing and file transfer, greatly improving the reliability of the download. The result is a more consistent daily input of the GPS-UTC data.

## CONTINUED IMPROVEMENTS

For the past several years, the focus of most efforts to improve GPS accuracy has been related to timing. As methods such as the ones outlined above have been implemented, errors that were once in the noise level have begun to emerge. Several presentations at the Performance Analysis Working Group (PAWG) in August 1996 highlighted periodic errors affecting GPS performance.[8,9,10,11] Since ephemeris and clock state estimation are intrinsically linked within the MCS Kalman filter process, the removal of these periodics should further improve time transfer. An effort is currently underway to identify possible error sources and remove them in a safe and efficient manner.

The Block IIR program will introduce the latest technology in GPS timing. Ground testing of the EG&G rubidium frequency standard, the primary timing source for all Block IIR satellites, has produced some impressive results. The Naval Research Lab has provided Hadamard deviation plots for the EG&G Block IIR Engineering Design Model rubidium oscillator Serial No. 4 which show that the stability for a sample time of one day was $2 \cdot 10^{-14}$.[12] Such performance is encouraging and could signal the breakthrough to the next level of GPS time transfer performance.

## CONCLUSION

GPS time transfer for 1996 has established a new standard in performance. The analysts of the 2 SOPS and the outside agencies that support the mission will continue to strive for a more stable and accurate signal. The improvements summarized above will spawn new ideas for ways to safely contribute to the most stable and accurate GPS timing signal ever.

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The men and women of the 2 SOPS.

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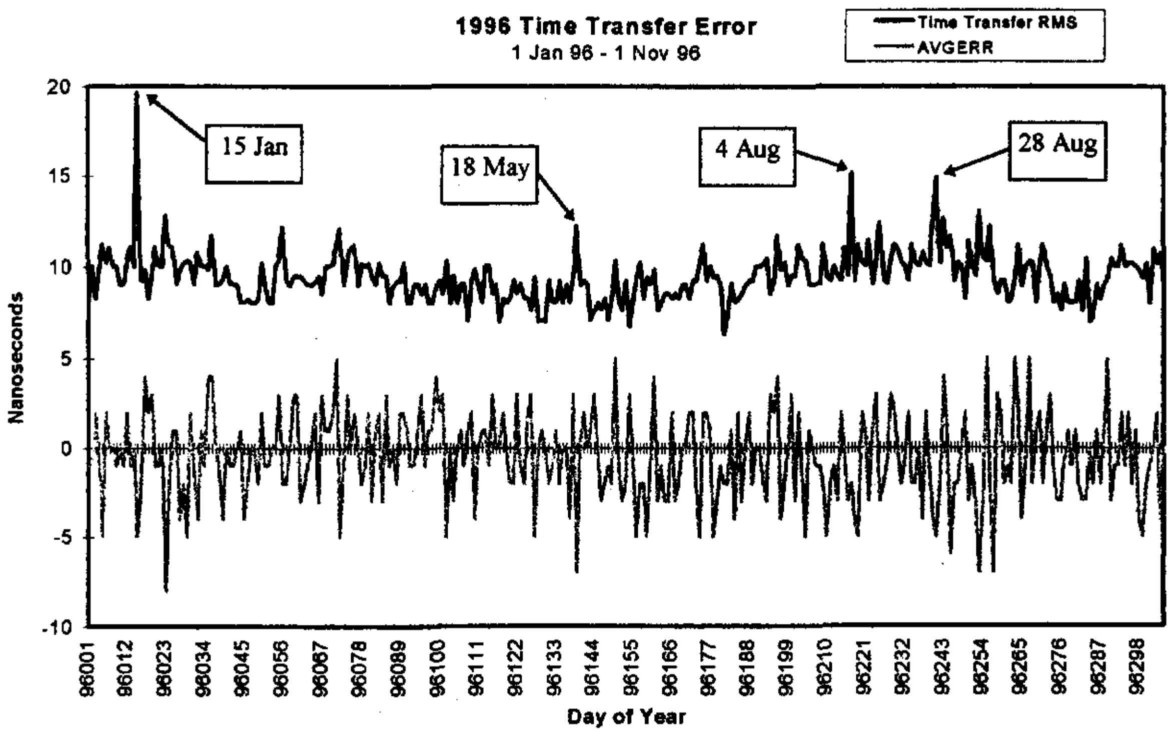


*Figure 1: GPS Time Transfer: 1 Jan 96 - 1 Nov 96*

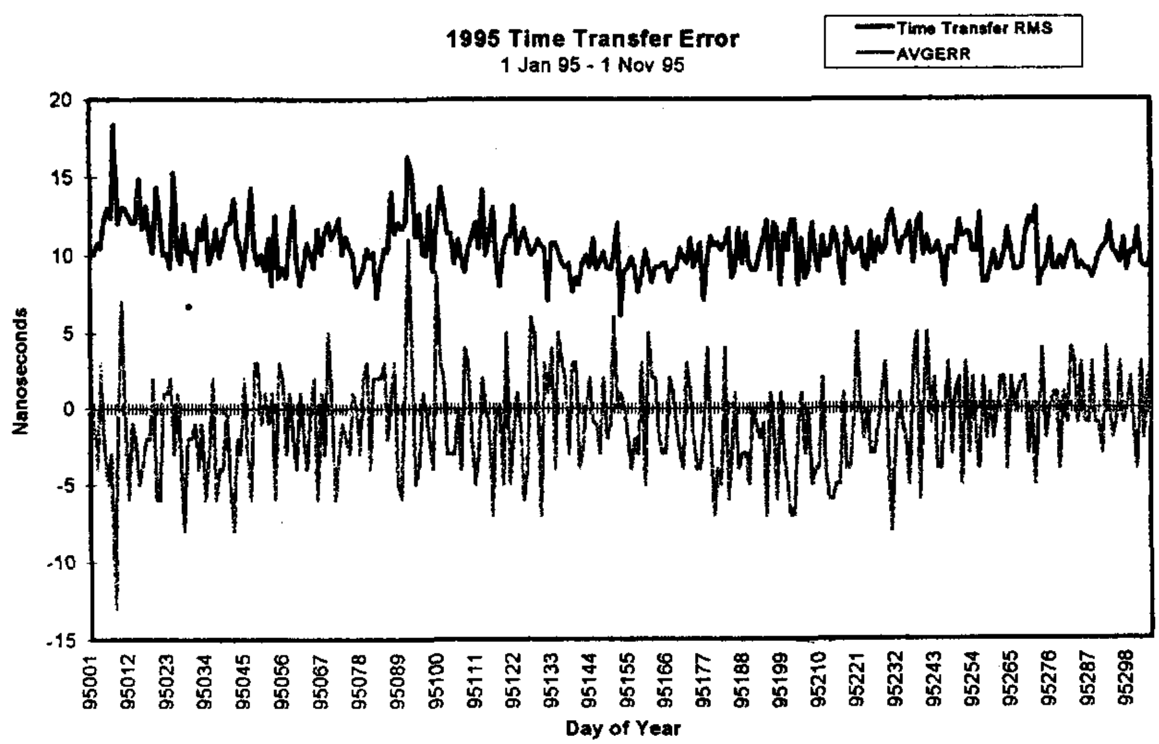


*Figure 2: GPS Time Transfer: 1 Jan 95 - 1 Nov 95*

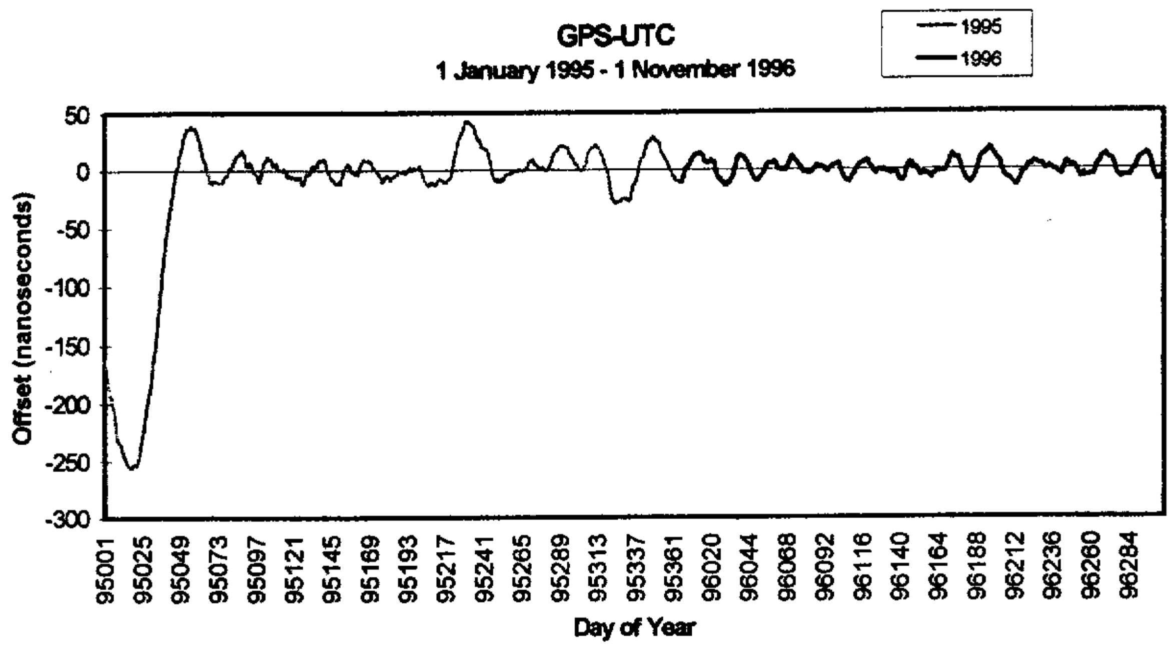


*Figure 3: GPS-UTC, 1 Jan 95 - 1 Nov 96*

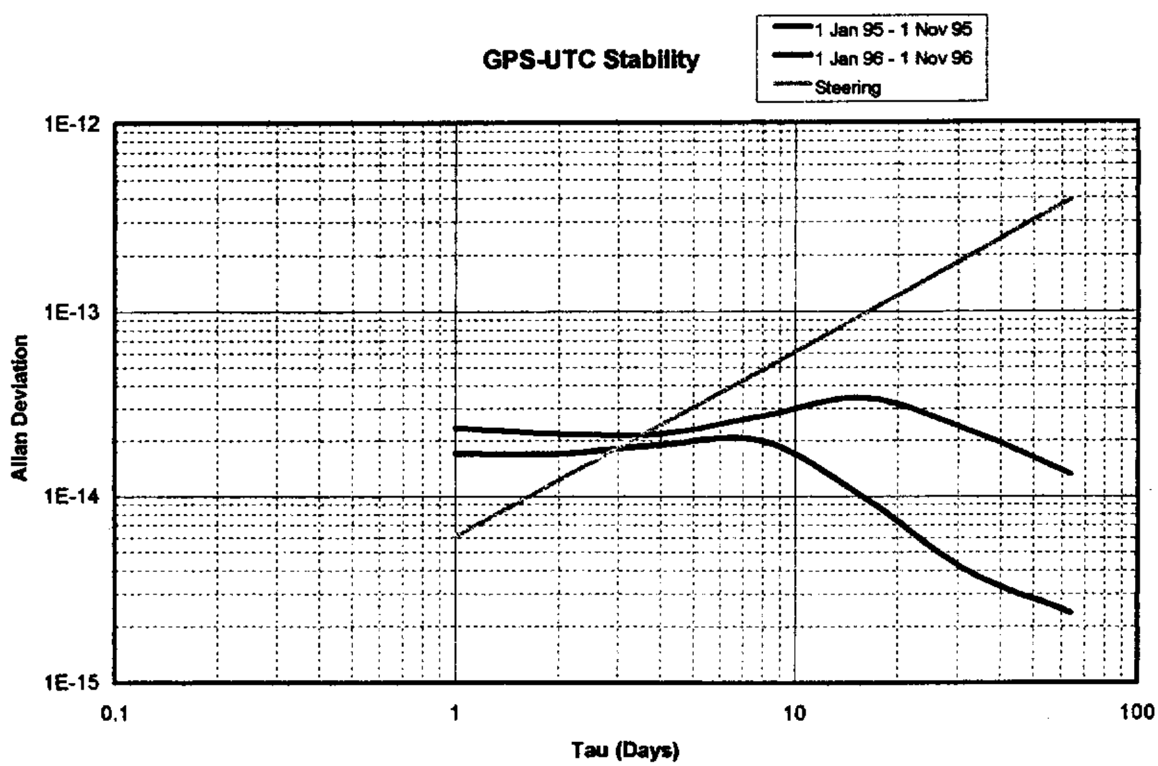


*Figure 4: GPS Time Stability*

## Questions and Answers

RICHARD GRIFFIN (TEXAS INSTRUMENTS): You had mentioned the working group had had some errors. Not having an opportunity to attend that, could you just give a quick summary of what the top three or four major error sources are?

JEFFREY CRUM: Well, actually, that's one of the challenges facing us right now. We had probably at least five independent studies that were presented at the POG that identified kind of a periodic error affecting GPS performance. And yet at the same time, we didn't really have too many suggestions as to where that error was coming from or how we can help remove it.

So certainly if people have suggestions for places that we can start looking, we have an effort underway with some possible suggestions primarily dealing the ephemeris queuing on trying to mitigate the impact of that periodic. But we're certainly open to suggestions, and I think this is probably the right forum to ask for help.

DAVID ALLAN (ALLAN'S TIME): The 28-nanosecond sigma for UTC accuracy, is that a two-sigma accuracy number?

JEFFREY CRUM: That's just one sigma.