# 1998 GPS TIME TRANSFER PERFORMANCE

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*Abstract*

***Every year more and more government and civilian agencies rely on GPS for accurate timing and navigation. The GPS Operational Control Segment, using information provided by the United States Naval Observatory, maintains the GPS timing signal well within specifications. This paper summarizes 1998 GPS Time Transfer performance for authorized users and relates the results to the mechanics of the GPS time steering algorithm. Data from previous years will also be presented as a means of comparison.***

## INTRODUCTION

The term "GPS Time Transfer" has historically assumed multiple meanings. Many in the Precise Time and Time Interval community often associate this term with the specific GPS technique used predominantly for international ground laboratory clock comparison, namely, *common-view* GPS time transfer. As we know, common-view GPS time transfer involves the use of multiple (usually paired) ground receivers.

Often forgotten in the PTTI community is the other main GPS time transfer technique, *direct-access* GPS time transfer, which many also dub "standard" GPS time transfer. In the direct-access GPS technique, users can obtain the official Department of Defense (DoD) time reference, UTC(USNO), by employing only one receiver and taking advantage of the available information in the broadcast GPS navigation message [1].

Direct-access GPS time transfer offers advantages that are most useful, primarily, for military or military-related systems. Since direct-access GPS time transfer doesn't require station-to-station communications with other ground receivers, direct-access GPS users can operate autonomously, in anonymity.

The United States Naval Observatory (USNO) performs around-the-clock monitoring of GPS's timing broadcast. USNO monitors three main time signals: 1) individual satellite time, 2) GPS ensemble time (the GPS Composite Clock), and 3) GPS's broadcast of UTC(USNO), which we call UTC(GPS). USNO currently employs Stanford Telecom (STel) 5401C receivers to perform this monitoring. STel 5401C receivers are dual-channel, keyed sets, and thus, are dual-frequency (L1 and L2) receivers capable of tracking Y-Code and correcting for the effects of Selective Availability (SA). USNO forwards time transfer information, gathered and processed from these receivers, to the GPS control segment, which is operated by the 2d Space Operations Squadron (2 SOPS).

As we know, not all GPS time transfer receivers are key-able, and therefore, not all GPS receivers can correct for SA. These civilian, or "unauthorized," receivers do not realize the same accuracy that keyed, or "authorized," sets benefit from. Therefore, civilian direct-access users often must augment their systems with melting pot schemes, atomic reference clock supplementation, or other techniques. This paper exclusively reviews the recent performance of direct-access GPS time transfer for *authorized* users.

## CURRENT TIME TRANSFER PERFORMANCE

Figure 1 shows a plot of the daily UTC(GPS)-UTC(USNO) time transfer root-mean-square (RMS) and average (AVGERR) errors for 1997. The 1997 GPS time transfer RMS was 7.84 ns, significantly lower than previous years. Figure I depicts a visible drop in the RMS in the beginning of the year due, in part, to the Ephemeris Enhancement Endeavor (EEE). After the initial EEE process completed on 28 February 1997 (MJD 97059), the daily RMS value exceeded 10 ns on only eight occasions [2].

Figure 2 shows similar daily time transfer RMS and AVGERR data for 1998. From 1 January 1998 – 23 November 1998, the time transfer RMS was 6.88 ns, a 12% improvement over 1997. This year also saw a new record low of 4.44 ns set on 5 October 1998 (MJD 98278). Looking at both 1997 and 1998 plots reveals that each daily RMS has remained well below the UTC(GPS)-UTC(USNO) specification of 28 ns (RMS), defined in the USNO/2 SOPS interface control document, ICD-GPS-202 [1].

## GPS-UTC(USNO) PERFORMANCE

A critical element in the delivery of UTC(GPS) to users is the GPS timescale, called the GPS Composite Clock. Typically, direct-access GPS time transfer users obtain satellite time by locking onto a broadcasting GPS vehicle, subsequently obtain GPS time by correcting for satellite clock offsets, and finally obtain UTC(GPS) by applying GPS-UTC(USNO) corrections [3]. The performance of GPS-UTC(USNO) significantly affects the performance of UTC(GPS)-UTC(USNO), and usually serves as a second indication of how well GPS can deliver time.

The daily GPS-UTC(USNO) offsets for 1997 and 1998 are displayed in Figures 3 and 4, respectively. 2 SOPS remains sufficiently safe from breaking ICD-GPS-202's specification for |GPS-UTC(USNO)|, 1000 ns [1]. In fact, the maximum daily GPS-UTC(USNO) offset in 1997 was –15.2 ns on 16 May (MJD 97136), and 1998's maximum was +8.7 ns, on both 18 and 19 June (MJDs 98169 and 98170).

Obviously, GPS-UTC(USNO) performance has far exceeded specifications; clearly, the GPS time steering algorithm superbly accomplishes the task of meeting the 1000 ns specification. So, how does the GPS time steering algorithm do it?

## THE GPS TIME STEERING ALGORITHM

As with many time scales, the stability of the GPS Composite Clock is largely dependent on how effectively its operators discipline it to its assumed "truth" source. Within the timing community exist several different types of steering algorithms, each fulfilling different requirements, and thus serving different purposes. Perhaps no other steering algorithm is more misunderstood than the often (and unfairly) maligned GPS Bang-Bang time steering algorithm.

Many steering algorithms are designed to optimize a cost equation. Usually such a cost equation takes counter-opposing requirements into consideration and provides the user/operator the mathematical vehicle for delicately balancing the given, often conflicting, requirements. Commonly, the conflicting requirements are, specifically, the need to minimize time offsets with respect to a truth source, and the need to ensure sufficient absolute stability.

In GPS, the analogous steering requirements are fairly straightforward. As mentioned earlier, the difference between the GPS time scale and UTC(USNO) must not exceed an absolute value of 1000 ns. Additionally, GPS operators must ensure that the steering doesn't excessively degrade the GPS time scale's stability, essential to GPS's navigation and time transfer missions.

The main reason |GPS-UTC(USNO)| never risks closely approaching tolerance is the impressive stability of the GPS Composite Clock. Ironically, and contrary to popular opinion, however, neither navigation nor time transfer users reap any benefits from tighter GPS-UTC(USNO) time synchronization performance. Many in the timing community have held misperceptions about this subject, usually because many are used to working with systems that offer improved performance as an inverse function of that system's timing offsets with respect to "truth" sources. However, in GPS, navigation users require real-time satellite-to-satellite stability, and not absolute "truth" synchronization, in order to operate optimally.

Likewise, large GPS-UTC(USNO) offsets do *not* degrade service to direct-access GPS time transfer users, either, as long as users appropriately apply the GPS-UTC(USNO) parameters broadcasted in subframe 4, page 18 of the GPS navigation message, to compensate for these offsets [3]. For instance, the GPS time scale could hypothetically be several hundred nanoseconds off from UTC(USNO), but as long as the broadcast corrections are of good quality, users can still obtain UTC(USNO) with excellent results, as indicated earlier.

Therefore, 2 SOPS operators have the freedom to choose time steering parameters designed to place the instability caused by GPS time steering below the noise level of GPS time itself. More importantly, 2 SOPS has the freedom to use a relatively simple steering algorithm to meet its performance objectives [4].

## The Mechanics of GPS Time Steering

Perhaps the most common general steering algorithm design involves the use of gain coefficients [or in inverse formulation, damping factors]. Second-order systems generally employ two coefficients, which, in particular, are the phase gain and the frequency gain. Designers usually derive these gain terms from simulations, or from cost equations. Simply stated, these algorithms generally input estimates of time and rate (or, respectively, phase and frequency) offsets, multiply each offset by its corresponding gain term, and add the two results together to calculate a steering value, in a recursive fashion.

Furthermore, many designers choose to impose upper and lower limits to the recursively-calculated steering value. In some systems, the calculated value will more often exceed the imposed limits than not, resulting in the predominant occurrence of "limiter value steers." When a steering system uses limits that are so tight that "limiter value steers" occur almost exclusively, the algorithm essentially behaves as having what is termed as a "bang-bang" characteristic.

GPS uses an *explicit* "Bang-Bang" steering algorithm. The simple mechanics of the GPS Bang-Bang steering algorithm are as follows. These mechanics occur in the GPS Master Control Station (MCS) every 15 minutes:

1. To begin, the algorithm receives MCS-calculated estimates of the time and rate offsets of GPS time with respect to UTC(USNO). These estimates are based on data points downloaded daily from USNO.

2. The algorithm then calculates a so-called "Discriminant," based on the respective time and rate offsets. In layman's terms, the Discriminant is essentially the predicted time (or phase) offset value at which the rate (or frequency) will reach zero, as a result of theoretical steering in the direction opposite to the current rate offset estimate.

3. Finally, the algorithm sets the steer sign to the opposite of the Discriminant sign.

The GPS steering magnitude is a fixed value located in a MCS database file. Currently, the steering magnitude is 1.0 E-19 s/s$^2$. Over 15 minutes, this translates into a frequency change of only 9 E-17 s/s and a time change of only *40.5 femtoseconds*. Were the algorithm to steer with the same sign for 24 straight hours, this magnitude would translate into a frequency change of 8.64 E-15 s/s, and a time change of only 373 picoseconds. Since GPS users depend on predictions from navigation messages which are typically not older than 24 hours, such small time changes are always insignificant compared to other subcomponents of direct-access GPS time transfer error, which, depending on the subcomponent, can be several nanoseconds. For that matter, 373 picoseconds is actually smaller than the granularity of the broadcast terms for satellite clock offset (465 picoseconds)!

Such changes induced by steering are well into the noise level of GPS [5]. Though 2 SOPS operators will, over time, modify this steering magnitude to appropriately match the ongoing improvements to GPS time performance, currently, the steering magnitude of 1.0 E-19 s/s$^2$ quite sufficiently meets GPS time steering requirements, with no significant degradation to GPS time stability. A corollary of this conclusion is the assertion that the current GPS time steering algorithm, by itself, tuned properly, is more than sufficient for GPS's steering requirements.

Figure 5 shows a visual example of how the GPS Bang-Bang steering algorithm generally works. The example begins with a scenario whereby GPS time is off from UTC(USNO) by -7.0 ns in time, and 0.0 ns/day in rate. The algorithm steers with a positive rate (of 1.0 E-19 $s/s^2$) until the GPS-UTC(USNO) plot reaches a point of inflection—when the time offset is –3.5 ns, and the rate offset is +2.29 ns/day. At this point of inflection, the Discriminant is zero, and the algorithm therefore begins to steer negatively (at –1.0 E-19 $s/s^2$) until the GPS-UTC(USNO) time and rate offsets are both near zero. This example shows how the algorithm would remove a –7.0 ns GPS-UTC(USNO) time offset, *in theory*. In reality, however, 2 SOPS receives updates from USNO *daily*, and, therefore, the MCS recalculates its time and rate offset estimates daily, as well. As a result, a theoretical steering strategy projected for, say, six days in the future, will usually change well before the strategy can be fully executed. As in the shown example, the effective "time constant" for steering is usually longer than one day, meaning that one day's worth of steering will usually remove only a *portion* of the estimated GPS-UTC(USNO) error. The result is a day-by-day, continuous drive to *gradually* remove GPS-UTC(USNO) time errors, and, if applicable, rate errors. This strategy proves to work exceptionally well.

## GPS TIMESCALE STABILITY

The stability of |GPS-UTC(USNO)| for 1997 and 1998, based on daily GPS-UTC(USNO) data points provided by USNO, is presented in Figure 6. The one-day stability for 1998, 1.61 E-14, is roughly as good as 1997's one-day stability of 1.77 E-14. Perhaps more important to note is the significant improvement in long-term stability for essentially all tau values greater than one day. Several likely factors accounting for the improved GPS timescale stability include the better operational performance of GPS ground [monitor] stations, the inclusion of more rubidium frequency standards in the GPS Composite Clock [6], and, generally stated, an overall improvement in the quality and efficiency of operations at 2 SOPS.

Note how the Allan deviation slope gradually changes to –1 at a tau value of around ten days, indicating the finite bounding of GPS-UTC(USNO). Additionally, note that the effective instability caused by GPS steering, at most, *never* approaches the inherent noise level of GPS-UTC(USNO) for tau = 1 day. Again, one-day stability is especially important, since one day is the nominal GPS navigation upload prediction span. These indicators clearly demonstrate the effectiveness of GPS's Bang-Bang steering algorithm—long-term synchronization at a very small sacrifice to short-term stability.

## CONCLUSION

Every year GPS has set new records in direct-access time transfer performance and stability—1998 was no exception. 2 SOPS, USNO, and other agencies will always push to find ways to improve GPS time. Through refinements in the receipt and processing of USNO data, the inclusion of more rubidium frequency standards into the GPS Composite Clock, and the acquisition of better GPS monitor station hardware (and more monitor stations), among other endeavors, GPS can continue its trend of improving stability and time transfer performance for 1999 and beyond.

## ACKNOWLEDGMENTS

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The men and women of 2 SOPS
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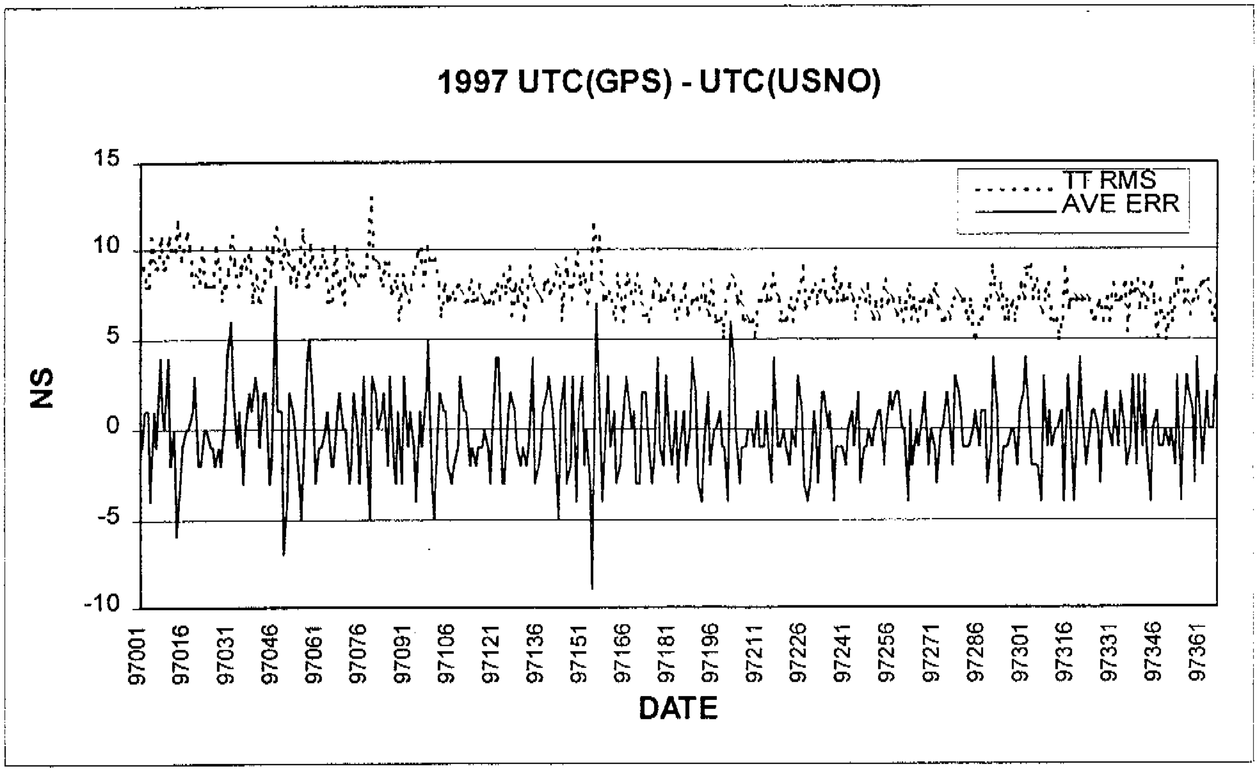


**Figure 1. 1997 UTC(GPS) – UTC(USNO) Root-Mean-Square and Average Error**

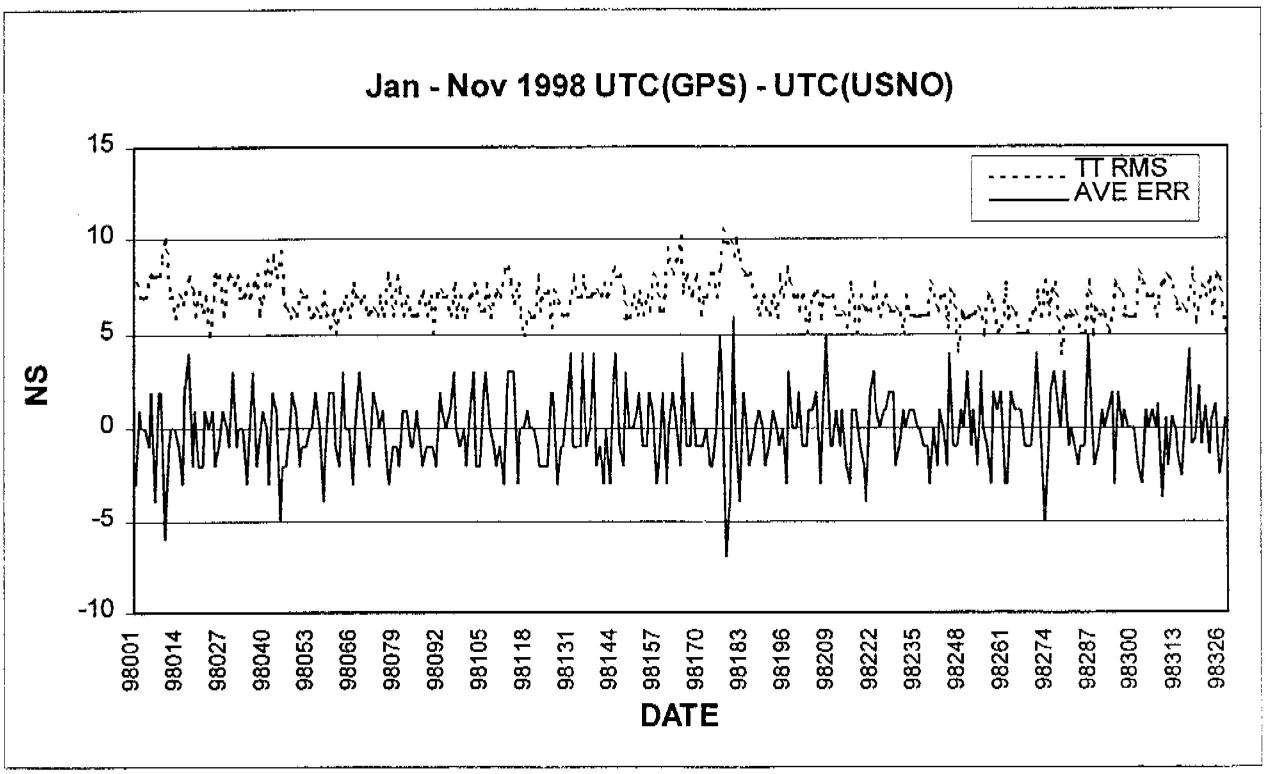


**Figure 2. Jan through Nov 1998 UTC(GPS) – UTC(USNO) Root-Mean-Square and Average Error**

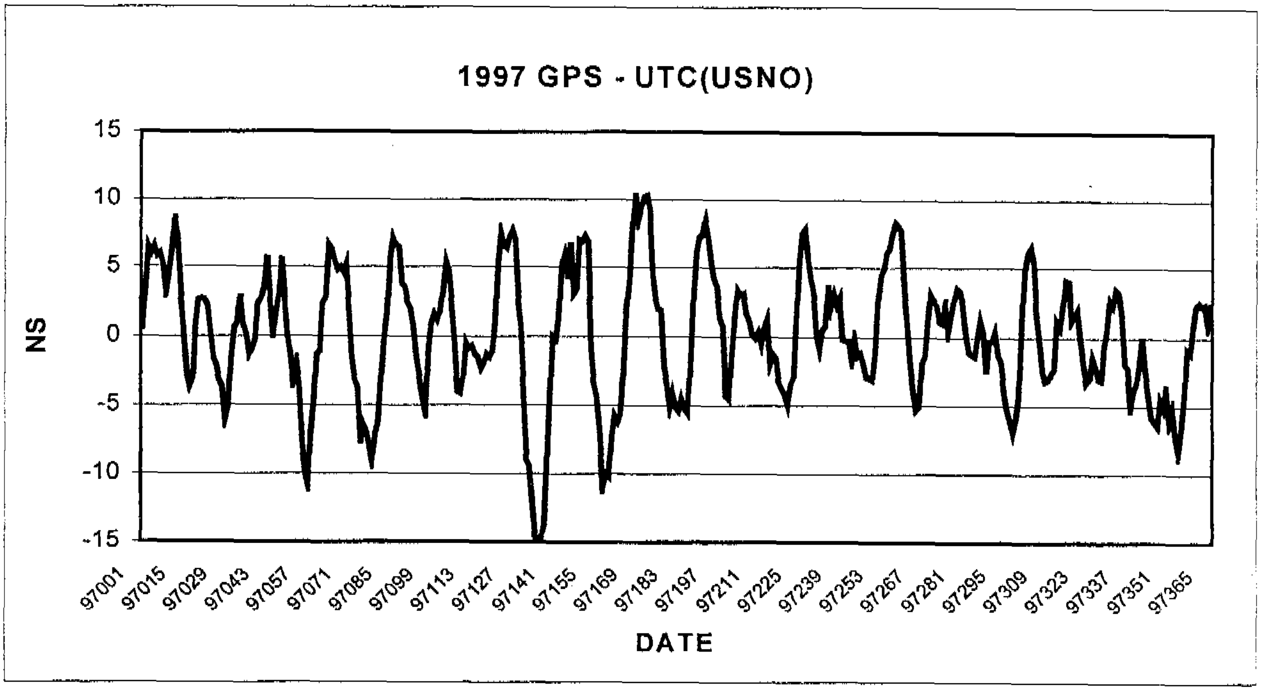


Figure 3. 1997 Daily GPS – UTC(USNO) Offset

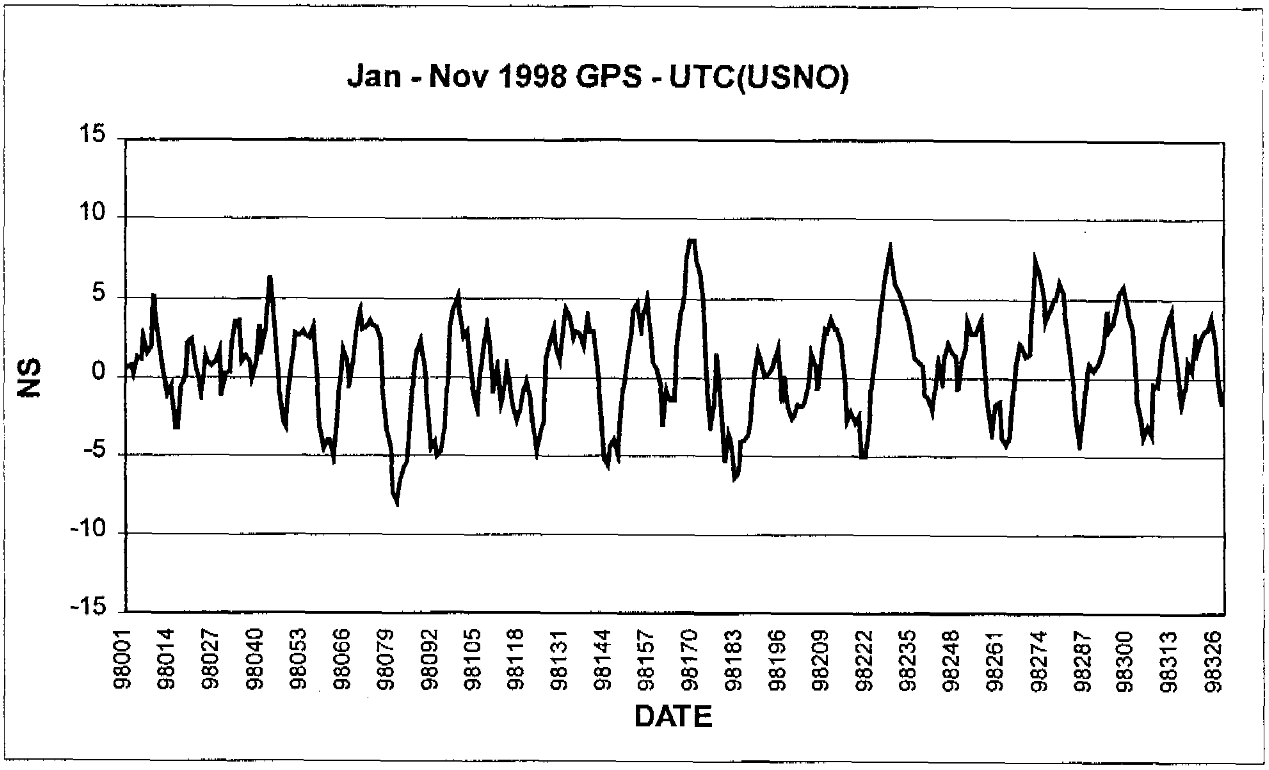


Figure 4. Jan through Nov Daily GPS – UTC(USNO) Offset

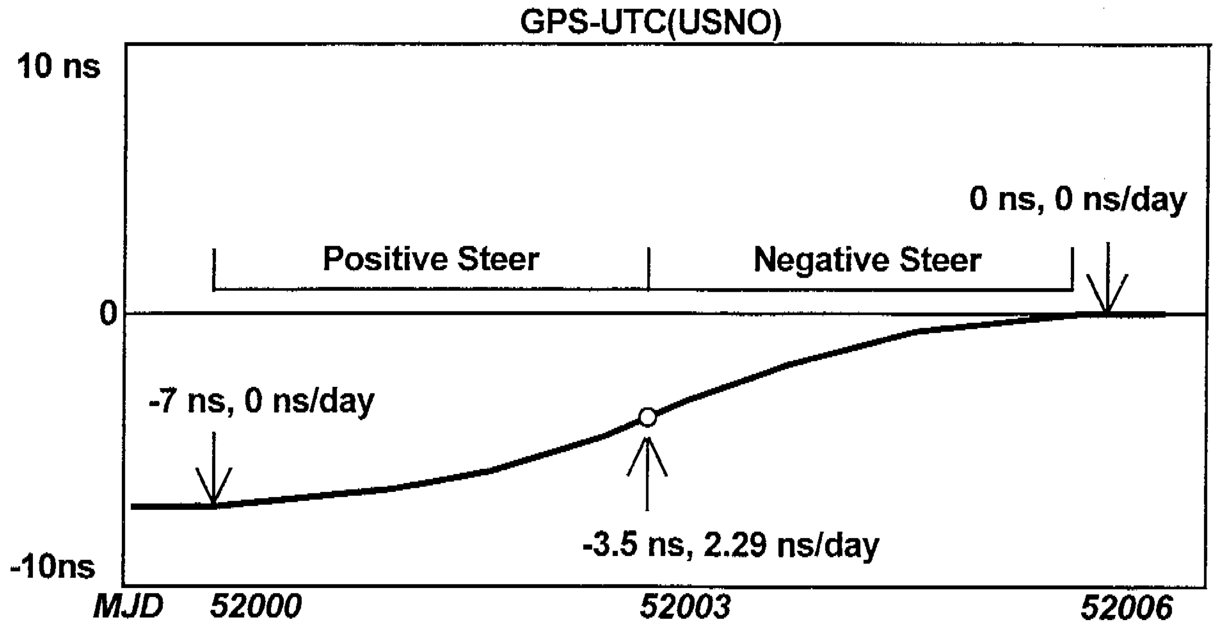


**Figure 5.** A visual example showing the functionality of the GPS Bang-Bang time steering algorithm.

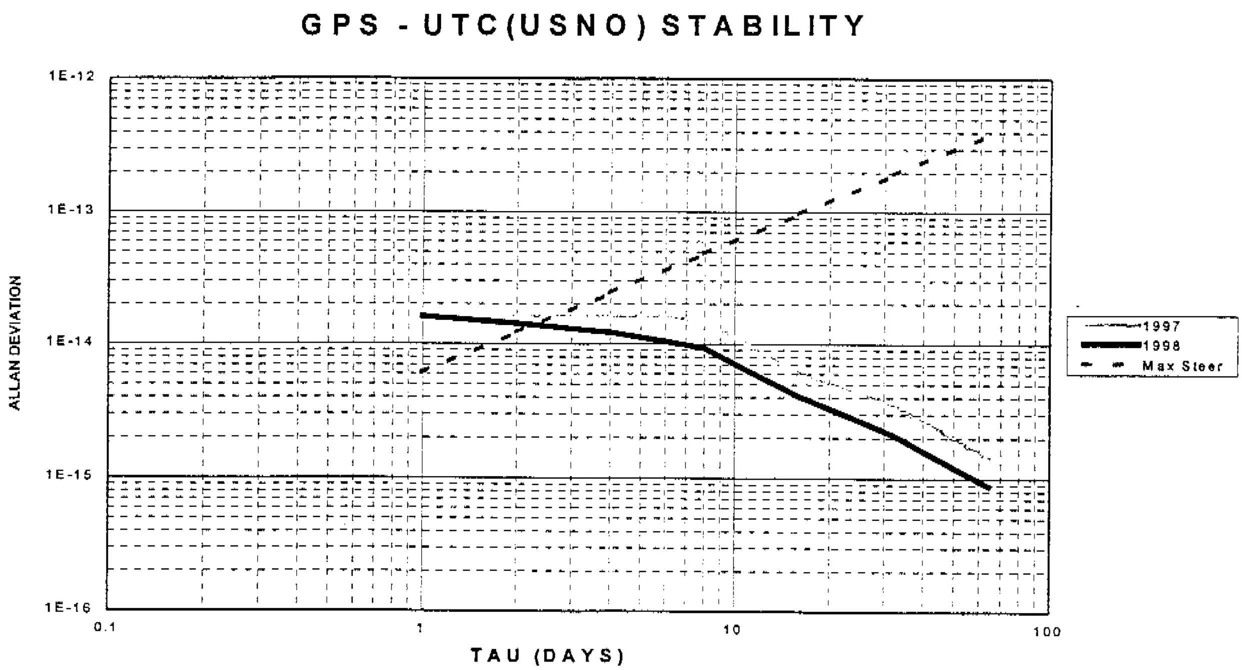


**Figure 6.** 1997 versus 1998 GPS – UTC(USNO) Stability

## Questions and Answers

DIETER KIRCHNER (TUG): In the first part of your talk, you were speaking about UTC GPS, and in the second part, you simply said "GPS" time. Is this identical?

STEVEN HUTSELL (USNO): No. If you want to get as close an approximation to what USNO is providing to DoD users by the GPS direct access signal, you would want this value here. When we are plotting the stability of GPS time versus UTC, we are comparing GPS to UTC - USNO. So, the answer to your question is GPS is sort of a free-wheeling time scale that users use primarily for navigation; and if they want to get as close to UTC - USNO as possible, they apply the Sub-Frame 4, page 18 correction.