ONE-WAY GPS TIME TRANSFER: 2002 PERFORMANCE

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Abstract

The Global Positioning System (GPS), among other duties, serves countless worldwide precise time users. These users are both civilian and military, are located on ground, in air, at sea, and in space. The respective missions of these users span metrology & calibration, research & development, test & evaluation, communication synchronization, and surveillance. The vast majority of these users employ what is called "one-way" synchronization using GPS. One-way synchronization allows users to realize precise time, autonomously and anonymously, using the direct precise time broadcast of GPS. Using data collected, processed, and provided by the United States Naval Observatory (USNO), the authors present an analysis of one-way GPS time transfer performance for FY 2002, utilizing a metric in use since the Initial Operational Capability (IOC) of GPS. This metric describes how well a fixed (surveyed) location user, employing an authorized receiver, tracking one satellite at a time, can obtain precise time using GPS one-way synchronization, without any special augmentation. The performance one-way users experience will vary depending on the particular application. Though no one metric can possibly represent all types of users, the fixed-location analysis provides other types of users a baseline for deriving theoretical assessments of performance that can fairly represent their respectively unique applications.

INTRODUCTION

Many worldwide users of precise time utilize "one-way" GPS time transfer, also known as "direct-access" GPS time transfer. In the direct-access GPS technique, a user can access a globally available common time reference, UTC(GPS), by employing only one receiver and taking advantage of the available information in the broadcast GPS navigation message **[1]**. UTC(GPS)* is GPS's delivered prediction of UTC as maintained by the U.S. Naval Observatory [known as UTC(USNO)], and UTC(GPS) is traceable to UTC(USNO).

Direct-access GPS time transfer is mandated by the Master Positioning, Navigation and Timing Plan, [CJCSI 6130.01b] as the primary means for all Department of Defense (DoD) systems to access precise time **[2]**.

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*The acronym "UTC(GPS)" is not universally recognized in the PTTI community. The term "UTC(GPS)" is, however, used by the 2d Space Operations Squadron, to best represent a particular time scale within the Global Positioning System. Specifically, "UTC(GPS)" denotes the time scale that serves as GPS's delivered prediction of UTC(USNO). – The Authors.

Direct-access offers advantages, that are most useful for military or military-related systems, over point-to-point time transfer techniques (GPS common view and Two-Way Satellite Time Transfer). Though point-to-point techniques are suitable for high accuracy applications, direct-access GPS time transfer doesn't require station-to-station communications between users and other ground receiver systems. Thus, direct-access GPS users can operate autonomously, in anonymity. Direct-access GPS time transfer has become a significant service for a diverse array of both military and civilian applications.

The United States Naval Observatory (USNO) performs around-the-clock monitoring of the GPS broadcast of time relative to UTC(USNO). USNO monitors three main time scales/references: 1) individual satellite time, 2) GPS ensemble time (the GPS Composite Clock), and 3) UTC(GPS). USNO currently employs keyed dual-frequency (L1 and L2) receivers, capable of tracking P(Y)-Code, to perform this monitoring function. USNO forwards daily time transfer information, gathered and processed from these receivers, to the GPS control segment, operated by the 2d Space Operations Squadron (2 SOPS). 2 SOPS, in turn, uses this USNO data to, among other purposes, keep UTC(GPS) closely aligned with UTC(USNO).

As many know, not all GPS time transfer receivers are key-able, and therefore, not all GPS receivers can track P(Y)-Code. These civilian, or "unauthorized," receivers may not realize the same performance that keyed, or "authorized," sets benefit from.

In particular, since the granularity of the civilian C/A-Code is a factor of ten worse than P(Y)-Code, some civilian users may experience slightly less accuracy than military users; however, some manufacturers have, for the most part, overcome this accuracy reduction with digital tracking algorithms. Also, the inability to track P(Y)-Code can translate into the unavailability of dual-frequency ionosphere measurements; however, techniques, such as codeless dual-frequency, exist to produce ionospheric measurements that are almost as good as those produced by pure dual-frequency code tracking. Additionally, users who choose to augment GPS receiver systems with atomic frequency standards and all-in-view processing techniques can realize even further improved performance.

This paper exclusively reviews the recent performance of direct-access GPS time transfer for *authorized* users in a fixed (surveyed) location, single-satellite tracking scenario.

CURRENT TIME TRANSFER PERFORMANCE

Figure 1 shows a plot of the daily UTC(GPS) - UTC(USNO) time transfer root-mean-square (RMS) and average (AVG) errors for October 2000 through September 2002. This metric essentially indicates how well GPS is predicting and delivering precise time for the DoD. During Fiscal Year 2002, the time transfer performance was 5.84 ns (RMS). That is, a fixed-location authorized user, tracking one satellite at a time, typically obtained DoD precise time with an accuracy of 5.84 ns, 1 sigma. These numbers will not necessarily represent typical error figures for all users, particularly if certain users operate unauthorized receivers, have significant surveyed location biases or calibration errors, or experience unusual problems with multipath, troposphere modeling, or environmental stability.

Numerous refinements over many years at both the GPS Master Control Station (MCS) and USNO have contributed to this level of performance, well below a somewhat dated UTC(GPS) - UTC(USNO) budget total of 28 ns (1 sigma), last listed in the USNO/2 SOPS interface control document, ICD-GPS-202, Rev A **[3]**. The GPS Program Office is currently assessing in which documentation this error budget may best reside in the future. In 2000, USNO agreed to reduce its Measurement calibration uncertainty allocation from 12 ns (1 sigma) down to 3 ns (1 sigma) **[4]**. Assuming the other contributing error budget components remain unchanged, this USNO change would drop the overall error budget from 28 ns (1 sigma) to 25.5 ns (1 sigma) **[5,6]**; see Figure 2.

The most recent major contribution towards improving GPS's time transfer performance has been the development of a new, 12-channel authorized receiver, which USNO began using operationally to generate daily data for 2 SOPS on 9 July 2002. More details on this USNO development are discussed in a paper presented at PTTI 2000 **[7]**.

GPS - UTC(USNO) PERFORMANCE

A critical element in the delivery of UTC(GPS) to users is the GPS timescale, also known as the GPS Composite Clock or GPS time, and labeled herein simply as GPS. 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 in subframe 1 of the navigation message, and finally obtain UTC(GPS) by applying GPS - UTC(USNO) predictions in subframe 4, page 18 of the navigation message **[1]**.

The fidelity of the GPS - UTC(USNO) predictions significantly affects the performance of UTC(GPS) - UTC(USNO), and usually serves as a second indication of how well GPS is delivering precise time. The daily GPS - UTC(USNO) offsets, corrected for leap seconds, for October 2000 through September 2002, are displayed in Figure 3. GPS remains well within ICD-GPS-200's specification for |GPS - UTC(USNO)|, 1000 ns, corrected for leap seconds **[1]**.

It is important to note that, contrary to popular opinion, GPS time *was never designed* to predict or represent the DoD's precise time source, UTC(USNO). Rather, GPS time serves as a stable timescale *internal* to GPS. For this reason, GPS time is *not* synchronized to UTC(USNO). Instead, the MCS steers GPS time only to keep its offset from UTC(USNO), *corrected for leap seconds*, within the limits of the 1000 ns specification. The effects of GPS time steering are currently significantly below the noise level of GPS time itself, over satellite upload prediction spans. With this level of steering, the MCS is easily able to meet the 1000 ns specification without significantly degrading the stability of GPS time. By the way, users who want GPS's closest prediction of UTC(USNO) should make use of UTC(GPS), obtained by using the timing information in subframe 4, page 18.

GPS TIMESCALE STABILITY

The stability of GPS - UTC(USNO), based on daily GPS - UTC(USNO) data points provided by USNO from October 2000 through September 2002, is presented in Figure 4. The 1-day stability for this period, $1.43 \cdot 10^{-14}$, is consistent with typical performance demonstrated in recent years.

Note how the Allan deviation slope gradually changes to –1 at a τ value of around 10 days, indicating the finite bounding of GPS - UTC(USNO). Additionally, note that the effective instability caused by GPS steering *never* approaches the inherent noise level of GPS - UTC(USNO) for $\tau = 1$ day. One-day stability is especially important, since 1 day is the nominal GPS navigation upload prediction span. These indicators again demonstrate the effectiveness of GPS's time steering algorithm—long-term synchronization at a relatively small sacrifice to short-term stability.

Also shown within the same figure is a plot of the stability of UTC(GPS) - UTC(USNO), showing the inferior short-term ($\tau \leq \sim 2$ days), but superior long-term ($\tau > \sim 2$ days) stability of UTC(GPS) as compared to GPS time, highlighting a fundamental difference between the respective purposes of GPS time and UTC(GPS). GPS time is designed for stability over nominal satellite upload prediction spans; UTC(GPS) is designed to deliver a prediction of UTC(USNO). The differences between the respective stability profiles are a by-product of this design. UTC(GPS) exhibits inferior shorter-term stability essentially as a result of the additional uncertainty of the subframe 4, page 18 time transfer parameters.

IONOSPHERE COEFFICIENT ERROR (28 May – 2 June 2002)

Dual-frequency GPS users enjoy the advantage of being able to measure ionosphere delay. Most single-frequency users don't reap this benefit. Instead, single-frequency users can access eight ionosphere coefficients, located in subframe 4, page 18 in the navigation message. The MCS uploads these coefficients based on the current Day of Year (DoY), and the current solar flux value, in solar flux units (*sfu*s), as measured in Penticton, Canada **[8]**. The data base table, based on a model by Jack Klobuchar **[9]**, contains 2960 entries.

On 30 May 2002, a USNO representative located at Schriever AFB brought to the attention of 2 SOPS a strange pattern appearing in plots of single-frequency corrections as output by USNO receivers. After analysis of 2 SOPS operations event logs, as well as MCS software and data base files, on 31 May 2002, 2 SOPS concluded that two of the 2960 entries in the database file had erroneous exponents, resulting in values off by a factor of $1 \cdot 10^{12}$. One of these erroneous exponents caused the broadcast Alpha Zero ionosphere coefficient to default to a value of zero, causing the strange pattern USNO personnel had observed. MCS database management personnel changed these two values, and 2 SOPS operations crews began updating subframe 4, page 18 parameters. By 2200z, 2 June 2002, 2 SOPS had mitigated all broadcast traces of the erroneous coefficient. From 28 May to 2 June 2002, single frequency users may have experienced as much as 16 meters of error due to the erroneous Alpha Zero coefficient.

Further analysis in the GPS community suggests that these erroneous exponents may have resided in the MCS database file as far back as the 1980s. Representatives from the GPS Program Office recently scrubbed the remaining 2958 coefficients to check for additional errors, and found none.

AN AGING SATELLITE CONSTELLATION

The global, around-the-clock availability of navigation and precise time transfer provided by GPS of course rests largely on the mission capability of the NAVSTAR satellites. As the legacy of GPS ages, so do many of these satellites. The constellation of (currently) 27 operational GPS satellites consists of three different generations, or block types. Specifically, the current constellation includes 3 Block II, 18 Block IIA, and 6 Block IIR vehicles.

At press time, of the 21 older II/IIA satellites, 20 are past their contracted mean mission duration of 6 years, and 17 are past their design life of 7.5 years; see Figure 5. Moreover, of all the satellites, 13 are one component away from mission failure, and nine are one component away from bus failure. Figure 5 shows one additional vehicle, SVN21, which recently failed and is awaiting disposal. As the community charts the future of our satellite constellation, in terms of modernization and GPS III, the overall age of the constellation unavoidably forces program managers into tough decisions related to balancing the long-term goals of system enhancement with the short-term needs of mission sustenance.

CONCLUSION

Worldwide civil and military applications depend greatly on the worldwide availability of GPS for one-way synchronization. 2 SOPS and USNO, along with other agencies, have sustained the outstanding performance of UTC(GPS) and remain committed to improving one-way GPS time transfer in the future. The steady-state performance of UTC(GPS) is far better than requirements, though outliers can be large, especially when unexpected problems occur. User programs must assess their own needs for integrity monitoring and robustness in general, and design and procure accordingly.

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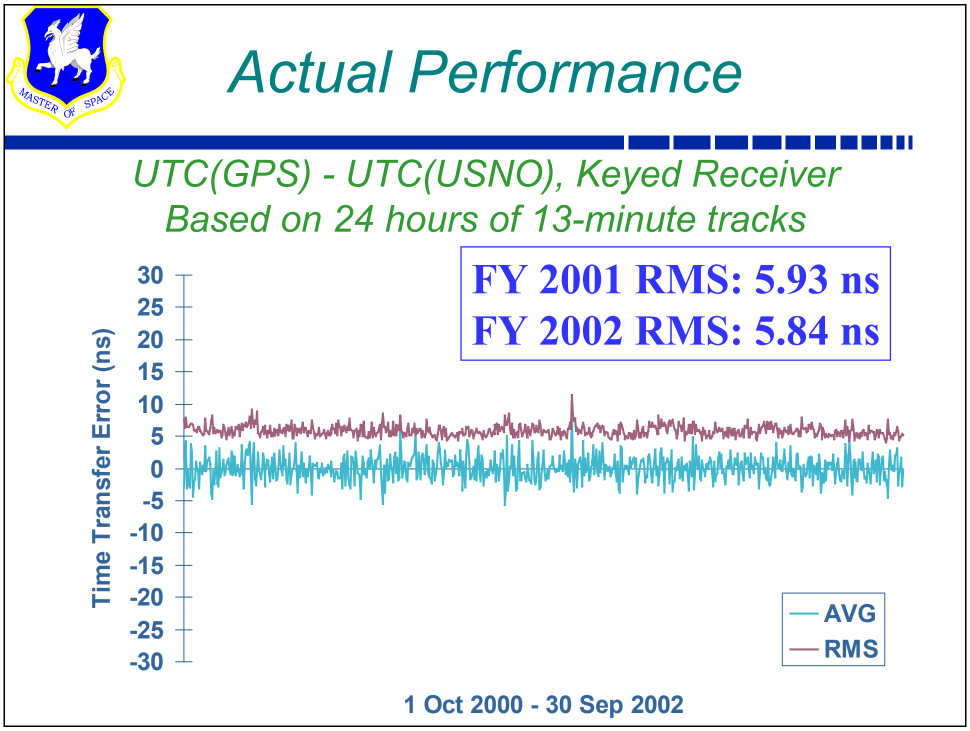
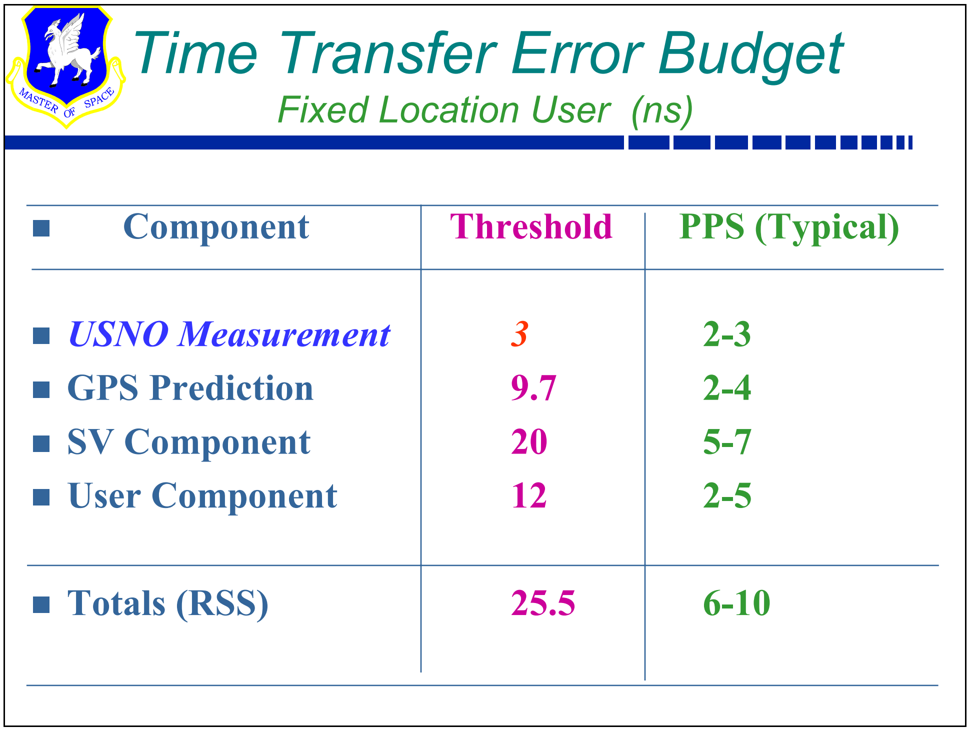


Actual Performance

UTC(GPS) - UTC(USNO), Keyed Receiver
Based on 24 hours of 13-minute tracks

FY 2001 RMS: 5.93 ns
FY 2002 RMS: 5.84 ns

Figure 1. UTC(GPS) – UTC(USNO) root-mean-square and average errors.

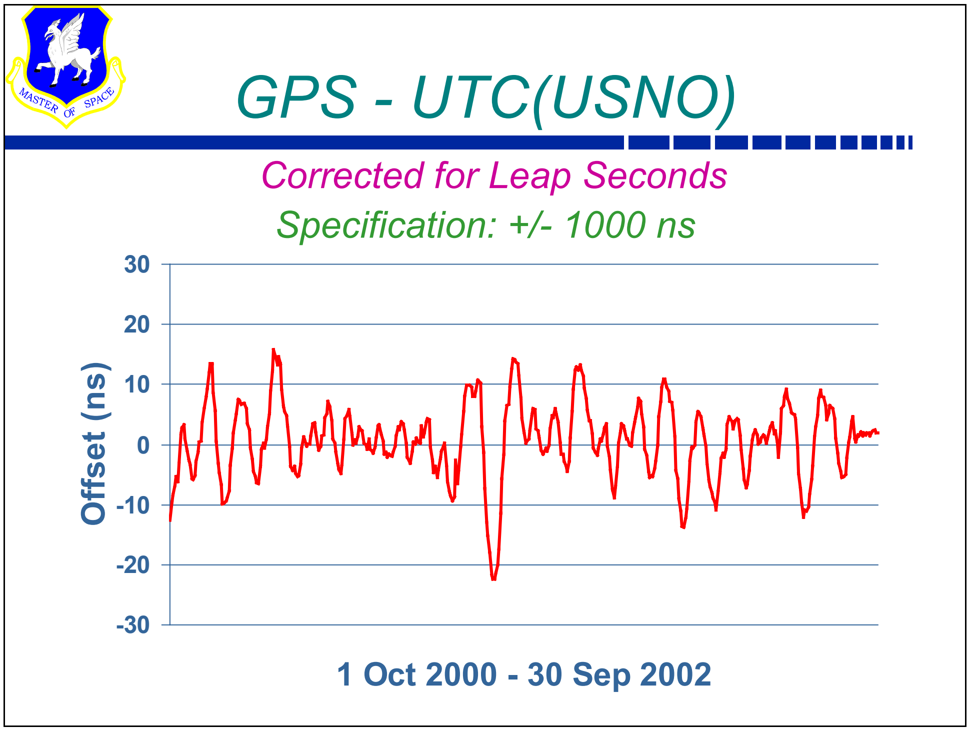


Time Transfer Error Budget

Fixed Location User (ns)

Component	Threshold	PPS (Typical)
USNO Measurement	3	2-3
GPS Prediction	9.7	2-4
SV Component	20	5-7
User Component	12	2-5
Totals (RSS)	25.5	6-10

Figure 2. A 2002 GPS time transfer error budget.

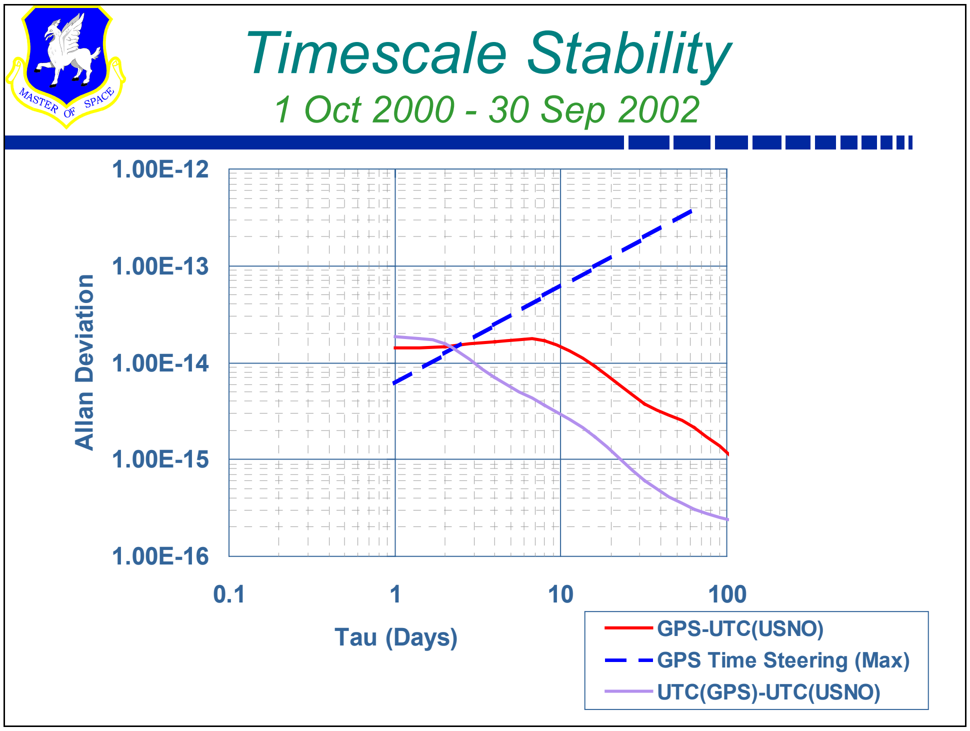


GPS - UTC(USNO)

Corrected for Leap Seconds

Specification: +/- 1000 ns

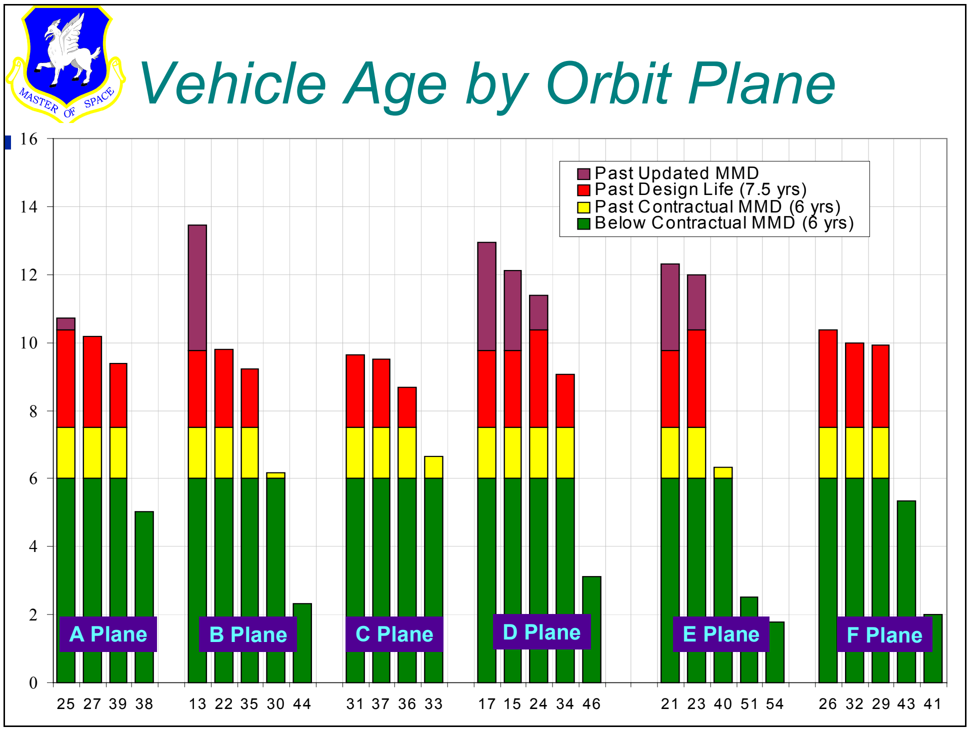
Figure 3. Daily GPS – UTC(USNO) phase offset.



Timescale Stability

1 Oct 2000 - 30 Sep 2002

Figure 4. Timescale stability: GPS time vs. UTC(GPS).



Vehicle Age by Orbit Plane

Figure 5. The current ages (in years) of the individual GPS satellites.