USING THE NAVSTAR GLOBAL POSITIONING SYSTEM
AS A GLOBAL TIMING SYSTEM

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ABSTRACT

The Navstar Global Positioning System (GPS), although primarily designed for three dimensional position and velocity determination, is uniquely capable of providing highly accurate and stable timing information to users. This capability is derived from the time delay pseudo ranging concept which forms the basis for GPS navigation. The combination of navigation and timing together in one system will make GPS the Precise Time and Time Interval (PTTI) source of choice for the forseeable future. Only GPS can supply continuous timing data world wide, in any weather, to a dynamically moving user at a previously unsurveyed site, with submicrosecond accuracy traceable to an established reference.

This paper discusses the application of Navstar GPS to the problems of PTTI dissemination. A short review of the GPS concept leads to a detailed description of the implementation of time transfer through Navstar GPS. Time is followed from the U.S. Naval Observatory (USNO) through the ground control, satellite, and receiving segments of GPS to the user's clock system. The three options by which a user's system can receive from the GPS receivers, currently under development by the DOD, are defined in detail. The electrical/digital/mechanical interface parameters along with suggested methods for their use are outlined for each option.

A detailed error model is also presented for the traceability of UTC (GPS) to UTC (USNO). Although absolute accuracy of UTC (GPS) provided to a user is specified to be slightly over 100 nanoseconds rms, substantially better accuracies can be easily achieved. By understanding and working around some of the GPS error uncertainties, real time synchronization between stationary users on the same continent can be controlled to within a few nanoseconds, and absolute post processed time offset with UTC (USNO) measured within 25 nanoseconds or better. A discussion of some of the potential work around techniques and their applications conclude this paper.

I. INTRODUCTION

The fundamental concepts of the Navstar Global Positioning System (GPS) have been well described in several excellent papers presented at recent Precise Time and Time Interval (PTTI) meetings, Frequency Control Symposia (FCS), and other conferences. The reader is referred to the bibliography at the end of the article for a short list of those papers available for a detailed definition of GPS <u>navigation</u> principles.

A. REVIEW

1. Operation in a Nutshell

GPS utilizes a constellation of satellites surrounding the earth in 10,900 nautical mile orbits. Each satellite transmits two "pseudorandom noise" (PRN) timing codes on each of two L-band carrier frequencies towards the earth. Because the frequencies and timing codes used in the transmission are coherently derived from an on-board highly stable atomic frequency standard, by observing the transmitted signals and correcting for path delays (i.e. line-of-sight distance atmospheric and relativistic effects, etc.) the on-board atomic frequency standard's phase and frequency may be accurately determined by a ground based observer. This determination of the satellite frequency standard phase and frequency is the responsibility of the GPS ground control and tracking network, known collectively as the Control Segment. The Control Segment's observation of satellite frequency standard "time" (timing code epoch time or T_Z) is compared against the GPS system time (T_{GPS}) as kept by the Control Segment. From this comparison, a "satellite clock state" (i.e. time bias, drift and drift rate between T_Z and T_{GPS}) is computed.

The clock state terms which relate the timing code epoch time to T_{GPS} (See Table 2, equations 1,4) as well as the position of the satellite as a function of T_{GPS} are uploaded into the satellite as digital data by the Control Segment. The uploaded information is then added onto the PRN codes as a 50 bit per second data stream by the satellite and the resulting satellite data, PRN timing codes, and carrier frequencies are transmitted towards the earth's surface as the satellite's useful navigation signals.

2. Satellite-Control Feedback Loop Operation

When both the satellite's frequency standard time (T_Z) and the satellite's position are unknown (as they are for the Control Segment) merely observing the satellite's transmitted frequencies and timing codes provide insufficient information to independently determine either of the two unknown quantities (e.g. is T_Z three nanoseconds ahead

of the observer or is the satellite one meter further away?). But if a fairly good initial estimate of the unknowns can be determined, detailed state and error models plus Kalman filtering can be used to separate and estimate the two unknown quantities based upon the one observation. This is exactly the method by which the Control Segment does it's determination of the satellite's clock and position values. The Control Segment uses extrapolated values of T_Z and satellite position from a previous time as current initial estimates of the unknown quantities and, in essence, the control segment - satellite system operates as a discreet cycle feedback loop (see Figure 1, Loop L_1).

During each nominally eight hour period (for example, the period P_o), the Control Segment uses it's Monitor Stations (MSs) to track the satellite as it moves through it's orbit. The tracking data during this period is sent to the Control Segment computation center where it is corrected for propagation delays, and coarsely modeled into satellite position and T_Z states. These states are then compared with the data being transmitted by the satellite during the period (which were based on the previous period, P_{-1}) to develop precise current error state estimates and filtered to predict the satellites future position and clock states. These predicted future states, known as ephemerides and space vehicle time (T_{SV}) state terms, are uploaded near the end of the current period for transmission by the satellite during the following period P_1. Thus, the process will repeat itself cyclicly, feeding forward a previous estimate to be used in determining current values. The satellite begins each period by transmitting the fresh ephemerides and T_{SV} terms uploaded from the Control Segment. As the period progresses, the satellite continues transmitting the same data with which it started. This data however has "aged" and become less accurate because of the time dependent growth of non-deterministic factors which affect the satellite's ephemeris and T_{SV} term accuracies. The satellite's data will continue to age throughout the period until it is replaced at the start of the next period with fresh data and the satellite's transmission accuracy is, in effect, reset to it's optimal value.

To provide continuous worldwide availability of sufficient satellites for users, there will be at least eighteen satellites in orbit at all times. The GPS Control Segment will continuously repeat the above feedback process with each of the on-orbit satellites to assure that every satellites' ephemeris and T_{SV} terms are updated on schedule so as to provide the specified accuracy to users. Thus, there will be eighteen simultaneous feedback loops operating, tied together by a common navigation time reference - T_{GPS}, and position reference - WGS-72.
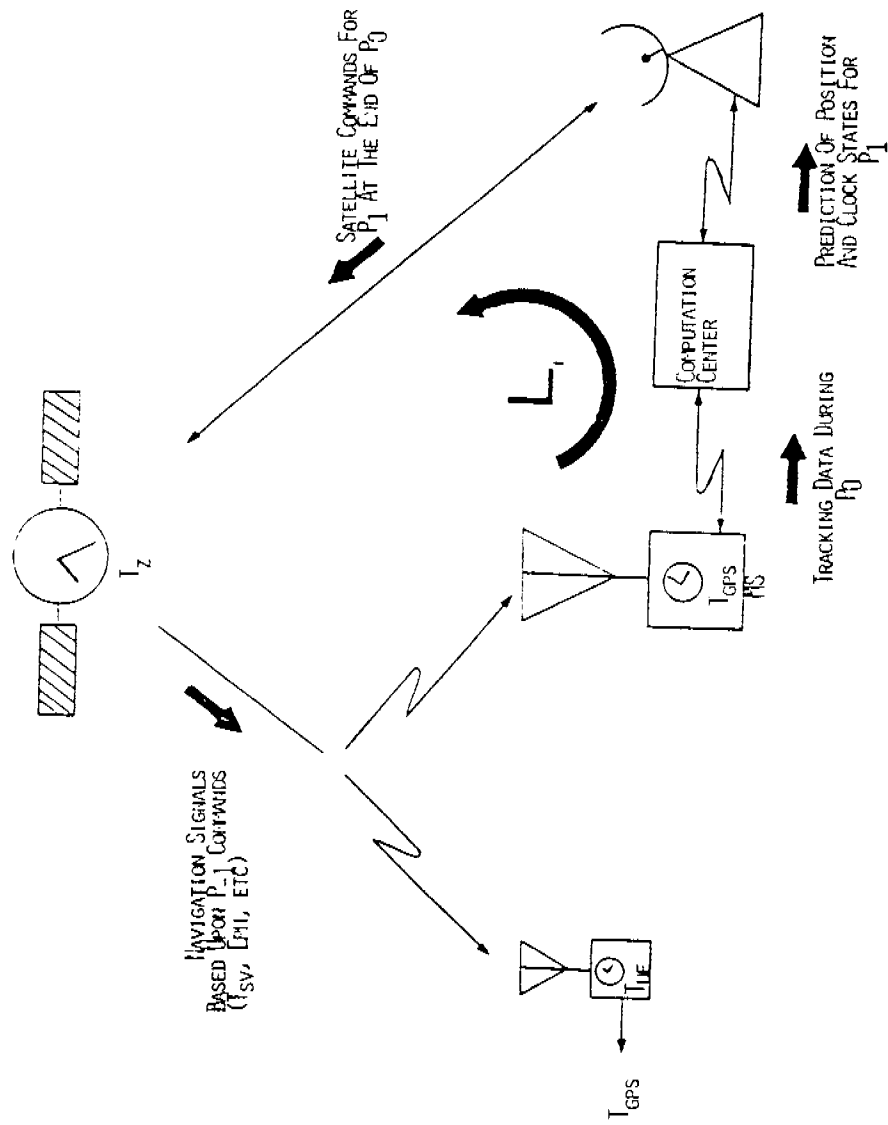
Fig. 1 - Navigation Time Feedback Loop

3. User Operation

The beneficiary of the eighteen Control Segment/satellite feedback loops is the GPS navigation user. Unlike the Control Segment tracking stations, the user is not at a known location nor does he have with him an atomic clock to independently keep T_{GPS}, but he is able to take the satellite's navigation data as truth for T_{SV} and satellite position. The User Equipment (UE) receiver on the ground has four unknown quantities it must determine to provide a navigation solution; the UE's position vector components (x, y, and z) and it's local clock offset from each T_{SV} (Since each T_{SV} is approximately equal to T_{GPS} (modulo one week), the UE need only determine one satellite's T_{SV} to establish the clock offset). This then is the classical problem; faced with four unknown quantities, the UE must track four satellites (e.g. "eavesdrop" on four of the Control Segment/Satellite feedback loops) simultaneously to obtain the four independent range equations necessary for a position solution.

As widely reported in the literature, the GPS UE receiver does this solution process well. Accuracies of 2 to 3 meters in x, y, and z have been achieved and 16 meters spherical error probable (SEP) worldwide is promised operational users against the reference truth, WGS-72 . But these are only three dimensional position accuracies, what about the fourth dimension of the solution - the dimension of time?

B. TIMES IN GPS.

1. Navigation Time

The GPS UE, in computing its four dimensional navigation solution, treats it's unknown time coordinate just as it treats it's position coordinates. The Geometric Dilution of Precision (GDOP), which effects navigation accuracy due to non-orthogonality of the satellite-user ranging vectors, also affects the navigation time accuracy (See Section III.B). If the time and three position errors are normalized for geometric effects, the resulting Control/Satellite -UE ranging errors are found to be approximately equal in magnitude and uncorrelated. The ranging error between each satellite and the UE has been demonstrated to be within 5.3 meters or 17.5 nanoseconds (1σ), with the units being used interchangably. These control/satellite -UE ranging errors are known as User Equivalent Ranging Errors (UERE) and more about them will be said later.

The value of the time error as defined above is critical to the understanding of GPS's PTTI applications. The error of 17.5 nanoseconds is (neglecting amplification due to GDOP) the error the UE experiences in determining its local clock's offset from T_{GPS} averaged over some period of time and averaged over a number of satellites

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(i.e., the error the UE has in determining the navigation time). This navigation time, T_{GPS}, is of little value to most PTTI users however. It is not necessarily stable nor tied to any accepted standard. T_{GPS} need only be continuous and without major steps in phase or frequency to maintain navigation performance of the system. The way that the GPS Control Segment determines T_{GPS} (as a paper clock based upon the ensemble of all monitor station frequency standards and driven by one of the MS standard's reference frequency (the GPS Master Clock)) satisfies the requirements for continuity and being without steps, but carries any and all Master Clock frequency instabilities throughout the entire system as instabilities in T_{GPS}. Thus, T_{GPS} is quite insufficient for many timing applications but, for the purposes of a navigation time, T_{GPS} serves it's function well.

2. "Time Dissemination" Time.

To solve the problem of supplying a useful time (in the PTTI sense of the word) to using systems when all that is necessarily available from GPS is T_{GPS}, the designers of GPS have also included terms in the 50 bit per second navigation data message to relate T_{GPS} to UTC. These terms accompany those for T_{SV} and the ephemerides as functions of T_{GPS}. They will be located in page 18 of subframe 4 of each satellite's message and include; time bias and drift rate terms between T_{GPS} and T_{UTC}, an accumulative integral second offset term to account for leap seconds, and a future impending leap second change value as well as the UTC time of applicability of the future leap second value change (See Table 2, equations 4,5,6).

The reader should note that this is a major change in GPS approach to the problems of time transfer. The original concept, as widely reported, was to steer T_{GPS} into direct synchronization with UTC. Repetitive leaps in T_{GPS} or step changes in the GPS Master Clock's frequency to achieve synchronization with UTC were found to have major, although transient, effects on the quality of GPS user's navigation solutions. Thus the decision was made to allow GPS time to be semi-free running (within an operational bound of 1 microsecond (modulo one second)) relative to UTC and accomplish precise time dissemination with a correction algorithm operating much the same way as the correction from T_Z to T_{SV} (T_{GPS}).

This time dissemination technique may be similarly viewed as a discreet cycle feedback loop (L_2) as shown in Figure 2. A GPS UE set has been selected in lieu of a monitor station for location at USNO because of it's lower cost and ease of maintenance. This loop operates at a nominal one week cycle period. During each period (e.g. P_0) the UE set will track a series of single satellites. The UE set's computed UTC (based upon T_Z, T_{SV} terms, $T_{GPS-UTC}$ terms, etc., being transmitted by each satellite during P_0) will be compared to UTC as kept by USNO (UTC(USNO)). The resulting array of measured UTC(GPS)-UTC (USNO)

T_{SV_1}

T_{SV_3}

T_{SV_4}

T_{SV_2}

T_{SV} TERMS, EPH, T_{GPS}-UTC(GPS), LS INFO, ETC. FOR P_1 UPLOADED AT END OF P_0

L_1

GPS CONTROL SEGMENT

L_2

UTC(GPS)-UTC(USNO), LS INFORMATION DURING P_0

UTC USNO

T_{SV} TERMS, EPH, T_{GPS}-UTC (GPS), LS INFO, ETC. BASED UPON P_{-1}
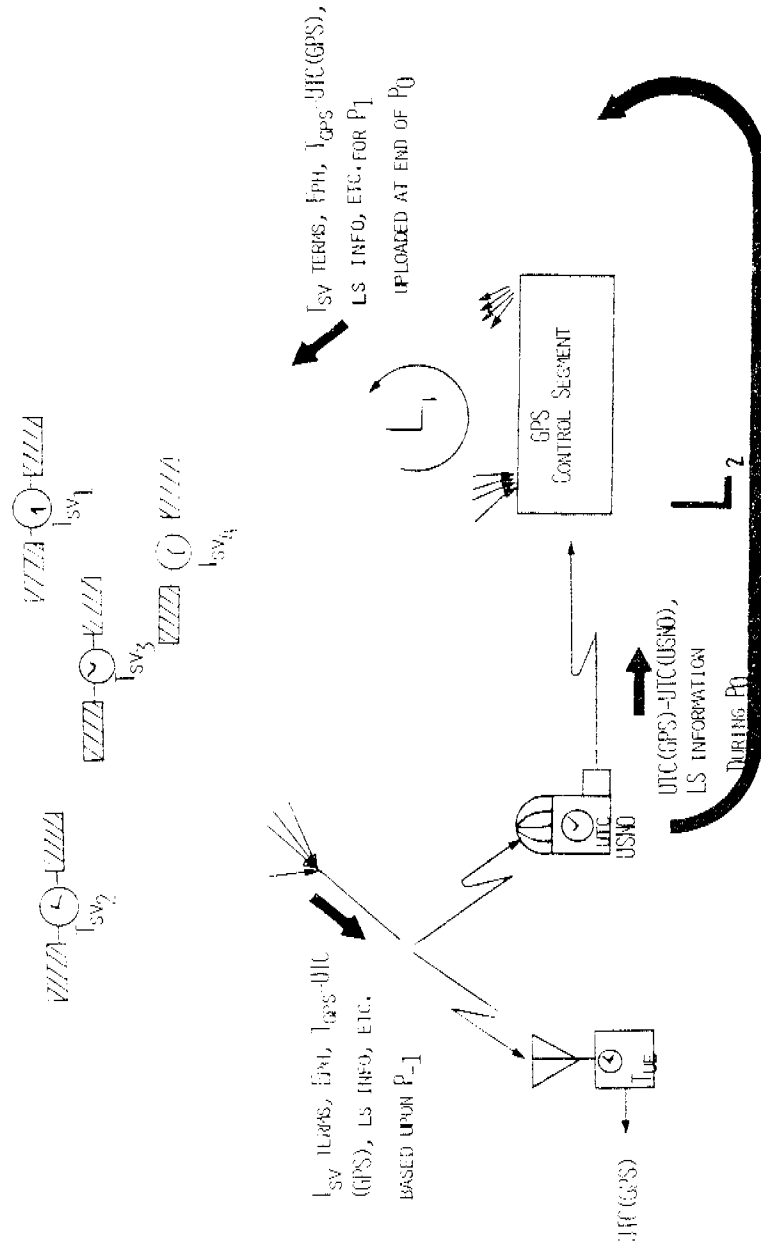
T_{UE}

UTC(GPS)

Fig. 2 – "Time Dissemination" Time Feedback Loop

differences for the tracking period will be transmitted during the period to the Control Segment computation center for modeling the drifts and offsets in UTC(GPS) and T_{GPS} versus UTC(USNO) as well as computing the new T_{GPS} to UTC (GPS) correction terms. At the start of the next one week period (P_1), these new terms will be uploaded into the satellites for transmission to precise time users during P_1; and so, as for T_{SV}, the closed cycle feedback loop repeats ad infinitum.

C. Summary.

        In summary, the definitions of the types of "time" used in GPS are given in Table 1. The equations used to get from time to time are summarized in Table 2, and applied as follows:

        a. T_{Z_i} is the PRN code phase time as it leaves the ith satellite.

        b. Each T_{SV} is T_Z plus correction terms (eqs 1,2) from the navigation data message. T_{SV} is approximately T_{GPS} modulo one week.

        c. The UE calculates T_{GPS} as the average T_{SV} plus accumulated weeks since midnight 5/6 January 1980 (eq 3).

        d. The UE calculates UTC based on the average satellite's T_{GPS} (eqs 4,5). Note that this UTC is a 24 hour count only and is corrected for leap second adjustments. (See ICD-GPS-200 for additional details).

II. TIME FROM GPS USER EQUIPMENT

A user of GPS fits in one of two categories; (a) those who will design and build their own equipment to receive the satellite signals and process navigation/time data to their own specifications, and (b) those who will utilize the DOD procured User Equipment (UE) receivers to obtain navigation and time data in a readily useable format. The first section of this paper addressed how the first category of user can recover UTC from the GPS satellite signals. This section deals with the second category - users who can use UE as a black box source of precise navigation and time for their own system or application and how they can directly receive UTC from the UE.

A. User Equipment Program

        The GPS UE is presently in it's Full Scale Engineering Development (FSED) cycle or Phase II of a three phase program. During Phase I, four U.S. contractors developed and demonstrated UE sets to validate the GPS concept. Most of the UE testing was conducted at Yuma Proving Ground in Arizona utilizing limited satellite coverage from a maximum of four Navigation Development Satellites (Block I type). This

Symbol	Definition	LSB	Modulus	Limit of Resolution	Absolute Reference
T_{z_i}	i^{th} Satellite frequency standard time represented by the PRN code phase or carrier phase.	1 P chip =97.75 nSec	1 week (604,800 sec)	0.05 P chip=5 nSec or 0.1 carrier cycle=0.6 nSec	None
T_{SV_i}	T_{z_i} plus navigation message clock state correction terms ($\approx T_{GPS}$ Modulo one week)	2^{-31} seconds	1 week	Same as above	GPS time
T_{GPS}	Time as kept by GPS Control Segment	2^{-31} seconds	20 years	N/A	UTC (USNO) at midnight 5/6 Jan 80
UTC(GPS)	GPS's estimate of UTC	2^{-30} seconds	24 hours	N/A	UTC(USNO)
T_{UE}	UE Clock Time	N/A	N/A	500 pSec	None

TABLE 1 TIMES IN GPS

A. From T_{Z_i} to T_{SV_i}:

$$T_{SV_i} = T_{Z_i} - \Delta T_{SV_i} \tag{1}$$

$$\Delta T_{SV_i} = a_{f0} + a_{f1} (T_{GPS} - T_{OC_i}) + a_{f2} (T_{GPS} - T_{OC_i})^2 + \Delta t_{r_i} \tag{2}$$

Where: a. a_{f0}, a_{f1}, a_{f2} = clock correction coefficients contained in the navigation data message.

b. T_{OC_i} = clock data reference time for the ith satellite contained in the navigation data message.

c. $\Delta t_{r_i} = Fe_i (A_i)^{\frac{1}{2}} \sin E_{K_i}$ = relativistic correction (e, A, and E_K are orbital parameters contained in the navigation data message, F is a constant equal to -4.443 E-10 sec/(meter)$^{\frac{1}{2}}$).

B. From T_{SV_i} to T_{GPS}:

$$T_{GPS} = (1/n \sum_{i=1}^{n} T_{SV_i}) + WN + \text{(midnight 5/6 Jan 80)} \tag{3}$$

Where: a. n=number of GPS satellites being averaged by the UE.

b. WN = week number (contained in the navigation message).

c. (midnight 5/6 Jan 80) = the GPS-UTC zero reference time.

C. From T_{GPS} to UTC (GPS): UTC (GPS) = $(T_{GPS} - \Delta t_{UTC})$ $\left[\text{MOD } 86400 \right]$ (4)

$$\Delta t_{UTC} = \Delta t_{LS} + A_o + A_1 (T_{GPS} - t_{ot} + 604800 (WN-WN_t)) \tag{5}$$

Where: a. Δt_{LS} = a value for future for leap second corrections to be applied at UTC zero hour of the effectivity date indicated by the Week Number (WN_{LSF}) and Day Number (DN) (Δt_{LS}, WN_{LSF}, DN are contained in the navigation data message).

b. A_o, A_1 = UTC correction coefficients contained in the navigation data message.

c. t_{ot} = reference GPS time for time data, WN_t=the week number for time data (both in navigation data message).

TABLE 2 TIME EQUATIONS

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testing included some limited testing of the time transfer capabilities of GPS. Those test results showed that $\pm$ 25 nanosecond (1σ) real-time time transfer accuracy was achievable using GPS in a benign field test environment, and that the operational GPS should definitely include time transfer as one of its goals.

The present Phase II began after a favorable Defense Systems Acquisition Council decision on GPS was reached in June 1979. Two UE contractors (Magnavox and Rockwell Collins) were selected out of the original four to develop preproduction prototype UE sets and further demonstrate the mililtary utility and mission enhancing capability of GPS. The competitive environment established between the two contractors during Phase II is expected to produce the most effective UE set designs. But because of the competition between the two designs, this paper is restricted in it's discussion of the UE design details to standardized or non competition sensitive characteristics.

Development Test and Evaluation (DT&E) and Initial Operational Test and Evaluation (IOT&E) will be conducted on the two families of equipment from 1982 through 1984. These contractor and government test activities will be conducted at a number of text facilities on land, sea, and airborne test platforms. Five of the Block II type satellites (new navigation message structure) are expected to be available to support this testing. This new type of satellite navigation message will allow testing of the time dissemination procedures discussed in Section 1, including the UTC synchronization parameters which were not present in the Block I navigation message.

Production of GPS UE sets will occur during the Phase III portion of the Navstar program beginning in 1985. Full system capability will be achieved in 1987 when 18 operational satellites will be deployed in orbit. Integration of production UE into military host vehicles and availability of UE for operational time dissemination will begin in 1985 and continue through the 1990's.

B.   User Equipment Functional Characteristics

The application of GPS UE to various types of military missions under a wide variety of operational conditions has led to the development of three types of UE sets - low dynamic (single satellite channel), medium dynamic (two channel), and high dynamic (five channel) units. The following discussion focuses on the high dynamic (HD) UE set since it is of most interest to a precise time user. Deviations of the low dynamic (LD) and medium dynamic (MD) sets from the HD sets exist primarily in size and in range of host platform dynamic tracking ability and are not further discussed here.

The HD UE set has been designed for operation in the most severe avionic environments and for rigorous shipboard operation. Part of the

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IOT&E test program will be to unconditionally qualify the equipment for service use aboard virtually any manned military platform. This is a significant point, in that the performance specifications cited herein apply throughout the entire military environment range. Unlike some of the non DOD utilizer designed equipment whose performance is defined only for laboratory conditions, the GPS UE will perform to specification over any combination of the stated environmental conditions - a significant advantage for the military field user.

Typical functional characteristics of the HD user set are defined in Table 3. The weight and power values include the required antennas, mounts, operator control/display units, interface units, power supplies, etc.

C.   Time Interface Characteristics

If, say, a user has one of these UE sets and it is supposed to provide him with position/navigation and time data - how does he access the data?   For position/navigation data, the manner is straight forward: if the user wants the data sent to the operator - the UE's control/display unit displays the requested data "real time" (i.e., real time enough for a man/machine interface) or the UE set will drive the operator's flight instruments directly. For the data to be sent to the host platform's computer - a digital data link (e.g., NTDS or MIL-STD-1553) along with a time tagging scheme (e.g., "real time", 64 mSec counter, "slow strobe") is used. For either of these two approaches, the senescence of data is not particularly critical. A delay of 64 mSec in making the position data available to the using system only induces 7.7 cm worth of transmission uncertainty into the perceived position accuracy (at a host vehicle velocity of 1200 m/Sec).   This is a negligible error source when compared with a 15 m SEP.

Senescence of time data is another story however.   A time uncertainty of 64 mSec across a digital data bus, will produce a transmission uncertainty of 64 m/Sec at the receiving device -certainly a significant error when compared with 0.1 mSec potential accuracy. Thusly, a separate analog signal is the only way to communicate time to precision levels.   The designers of GPS have recognized this and have included three primary analog signal methods to accomplish time dissemination/communication to a using system.   These are in order of their accuracy:

   (A)   Time Mark Signal
   (B)   Reset Pulse (limited implementation)
   (C)   Data Capture Pulse

The frst two are output analogs from the UE, the last is an input analog to the UE.   Digital data is required for all three to resolve modulus and definition uncertainties.   These signals are

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Size:	7.62 x 7.5 x 19.52 inches (Receiver, etc)
	6 x 5.75 x 8 inches (Control display Unit)
	14 x 14 x 2 inches (Antenna)
Total Weight;	≤ 66 lbs
Total Power:	< 300 watts, MIL-STD-704A
	115 Vac 60/400Hz or 28 Vac
Environmental Characteristics:	MIL-E-5400, MIL-E-16400, MIL-E-4158, etc. (F-16, Surface/subsurface ship typical)
Mean Time Between Maintenance:	1500 hr
Dynamic Range:	Velocity = 1200 m/sec
	Acceleration = 90 m/sec^2
	Jerk = 100 m/sec^3
Time from Power On Until First Fix:	7 minutes
Rate of Subsequent Fixes:	Once per second
Threat Survivability:	Very High
Accuracies*:	Position (3 dimensional) = 15m (SEP)
	Velocity (3 dimensional)= 0.1 m/Sec(RMS)
	Time (to UTC) = 0.1 μSec (1σ)

(*worst case environment, average satellite visibility)

TABLE 3 - Typical HD UE Set Characteristics

further defined in the following paragraphs.

1.   Time Mark Signal (TMS)

The Time Mark Signal is a very sharp rise time discreet pulse which coincides with the precise moment in UTC of applicability of each Time Mark Data Block (TMDB). It is the most accurate signal available from the UE to allow the host vehicle's GPS utilizing subsystems to maintain UTC. The TMS occurs at a nominal once per second rate, but does not, itself, represent UTC one-second rollovers!

This analog TMS signal should be construed to be only half of the most precise time interface from the UE. The other half is a simple unidirectional data link which supplies data (the TMDB) to identify the meaning of the analog pulse. This data link is known as the GPS instrumentation port. Each GPS UE has an instrumentation port (IP), and each provides time in this combinational manner. An error of less than 111 nSec (1σ) true accuracy to UTC (USNO) is promised to the user of these signals under any/all combinations of UE design environments (accuracy of the LD UE set's TMS is somewhat less however).

TMS Operational Use

The operational manner in which this approach works is as shown in Figure 3. A using system will first detect the incoming TMS and will time tag the TMS leading edge against its own internal clock (T_{us}). Within 450 mSec, the UE set will transmit the TMDB across the IP. The using system will read this data and parse the CUT Time into two pieces, one for integer number of UTC one second rollovers and one for the fraction of seconds after the last UTC one second rollover that the TMS was issued by the UE set. The using system can now compute its internal clock offset from UTC (USNO) by using the following equations:
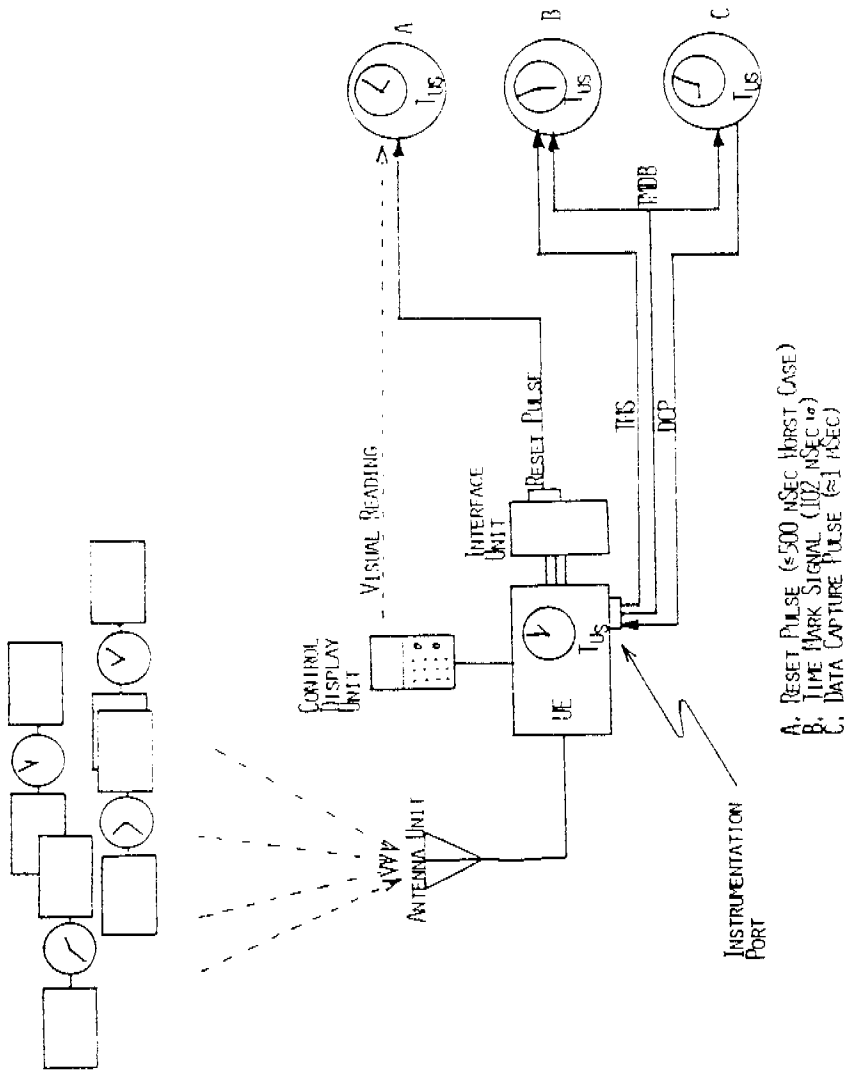
$$T_{us} @ \text{ TMS issuance} = T_{us}(\text{TMS}) = T_{us}(\text{TMS}) \text{ integer} + T_{us}(\text{TMS})_{\text{fraction}} \tag{7}$$

$$\text{UTC}_{\text{TMDB}} = \text{UTC integer} + \text{UTC fraction} \tag{8}$$

$$\text{UTC integer} - T_{us}(\text{TMS}) \text{ integer} = \text{leap second or integral second} \\ \text{offset between UTC and } T_{us} @ T_{us}(\text{TMS}) \tag{9}$$

$$\text{UTC fraction} - T_{us}(\text{TMS}) \text{ fraction} = \text{fractional second offset} \\ \text{between UTC and } T_{us} @ T_{us}(\text{TMS}) \tag{10}$$

Note though, that the offsets computed above are valid only at T_{us}(TMS). The reason for this is that although the TMS occurs at a nominal 1 Hz rate, there is substantial noise about that 1 Hz between subsequent TMS's and the UTC fractions reflect the magnitude and sign of that noise.

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A. RESET PULSE (≤500 NSEC WORST CASE)
B. TIME MARK SIGNAL (102 NSEC ₁ₑ)
C. DATA CAPTURE PULSE (≈1 μSEC)

Fig. 3 – Time Interfacing Methods

Analog Signal Characteristics

Functionally, the TMS is essentially the UE set's own internal time strobe used for keeping T_{UE} and strobing the internal navigation processing. It is a countdown of the set's Master Reference Oscillator (MRO) frequency and so is coherent with all frequencies (e.g. L_1, L_2, IF Lo, etc.) used internal to the set. Although the set's MRO is a high precision ($\sigma_y(t)=10^{-12}$, t = 1 sec) ovenized quartz oscillator, it is not itself tuned operationally to a precision nominal frequency. For signal tracking-VCO's and DCO's are used, and for processing tasks - the precise frequency is not important since as long as the deviation is known it can be accounted for with software corrections. This and the environmental effects (acceleration sensitivity of 6 x 10^{-10}/g, temperature sensitivity over +71°C to -54°C of 1 x 10^{-9}/range, etc.) on the MRO frequency are the cause of (a) TMS to TMS noise, (b) the non-alignment of the TMS with the UTC one second rollover, (c) non-alignment of TMS's between UE sets, and (d) the reason GPS UE provides only Time-of-Day and not frequency to using systems. See Table 4 for definition of the electrical characteristics of the time mark signal.

TMDB Digital Characteristics

The instrumentation port is a bidirectional Universal Asynchronous Receiver/Transmitter (UART) device used in a simplex mode for time dissemination purposes. The UE transmits the TMS time data to any listener using this device as an asynchronous serial stream using an RS-422 electrical structure operating at 76.8 Kilobaud (maximum). The UART has been chosen for the data link because of the low cost, high reliability and simplicity of the technique.

The data in the TMDB comes to the using system as a 70 sixteen bit word data block. The 64 words of data are shown in Figure 4 (message headers and checks are omitted). As can be seen, there is quite a bit more in this data block than just time information. All the data is valid exactly at the rise time of the immediately preceeding TMS. For additional details of this data block and how to use the IP, refer to ICD-GPS-204, Navstar GPS Instrumentation and Connector standards available from the GPS Program Office. This document defines the UE design details and also specifies how a MIL-STD-1553 data bus can be alternatively used by a using system to receive the TMDB.

2.   Reset Pulse

While the Time Mark Signal is the most accurate method of receiving time out of the UE set, not all using systems are sophisticated enough to utilize that method (e.g. a stand alone atomic clock). As an alternative for those systems, some GPS UE have built-in interface modules to provide a direct reset pulse to be used for clock synchronization (currently only submarine type UE incorporate this

a.	Amplitude:	3 volt minimum into 50 ohm load

		5 volt maximum into an open circuit

b.	Width:	20 microseconds $\pm$ 20%

c.	Rise-time:	$\leq$ 20 nanoseconds nominal (ambient

		temperature), 50 nanoseconds maximum

d.	Fall-time:	< 1 microsecond

e.	Connector Type:	MIL-C-38994/201B35PN (13 PIN)

f.	Wire Type:	COAX

g.	Pin Assignment:	See ICD-GPS-204

TABLE 4 - Time Mark Signal Interface Characteristics

a.	Signal Type	Positive Going Pulse

b.	Frequency	1 Pulse Per Minute

c.	Amplitude	10 v $\pm$ 10%

d.	Width	20 mSec $\pm$ 10%

e.	Risetime	$\approx$ 20 nSec

f.	Falltime	< 1μSec

TABLE 5 - Typical Reset Pulse Interface Characteristics

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Data Item	No. of Parameters	Data Type	No. of Words	Units
GPS Time	1	DPFP*	4	seconds
➤ CCT Time	1	DPFP	4	seconds
Δ T from GPS Time	1	Integer	1	10 milliseconds
Time Mark Counter	1	Integer	1	NA
Position (Lat, Lon)	2	FP	4	radians
Position (x,y,z)	3	FP	6	meters
Altitude (MSL & absolute)	2	FP	4	meters
Velocity	3	FP	6	meters/seconds
Acceleration (E,N,Up)	3	FP	6	meters/sec/sec
Attitude (Pitch, Roll)	2	FP	4	radians
True Heading	1	FP	2	radians
Magnetic Variation	1	FP	2	radians
Measurement Channel Status	5	Binary	10	NA
Position Error Std. Dev. (N,E,Up)	3	FP	6	meters
RSS (N,E,Up) Pos. Error of Std. Dev.	1	FP	2	meters
Equipment Configuration	1	Binary	2	NA

*Double Precision Floating point

Fig. 4 - Time Mark Data Block

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feature since they are the only types of vehicles which have an on-board installed atomic clock).

This reset pulse is a very fast rise time analog signal which occurs nearly (within approximately 500 nSec worst case) on the UTC (USNO) one minute rollovers. Utilizing this signal and the integer second UTC data displayed on the control/display unit, an operator can utilize the synchronization circuitry in an atomic cesium/rubidium clock to reset the clock to UTC. Details of this signal are shown in Table 5.

3. Data Capture Pulse

The Data Capture Pulse (DCP) is the least precise method of receiving time out of the UE set - accurate only to 1 mSec of UTC. It's primary use is in test instrumentation applications of GPS where time and location of "significant events" aboard a platform are to be instrumented. The using system supplies a 28 v positive going pulse to the UE instrumentation port at a maximum rate of 2Hz to mark the significant events (See Figure 3). The UE responds with the time and location of the "significant event" over the IP data link (the UART device). The format and content of the data block thus returned to the using system is identical to that used for the Time Mark Signal (Figure 4) except that it's time of applicability is the "significant event" of interest (the significant event may also be a clock pulse). ICD-GPS-204 contains additional details of this UE function.

III. Error Model Specification

The error sources which effect a using system's reception of UTC (GPS) from UE are many. They are both deterministic and random, geometrically independent and highly geometric dependent, constant and time varying, independent of environment and environmentally sensitive. This section characterizes some of these factors (UERE, GDOP), shows how they combine, and ultimately how they can be managed for higher accuracy UTC (GPS) reception by the using system.

A. System Error Budget - UERE

The GPS system error budget has been widely cited in prior analyses of the time accuracy of GPS. It serves as a convenient starting point in this analysis as well. The budget, as shown in Table 6, is divided into system segment allocations and totals up to a 5.3 meter (1σ) User Equivalent Ranging Error (UERE). This total UERE can be interpreted to be the average error a using system would perceive in the spherical loci of potential location points resulting from a single satellite ranging operation as output by the GPS UE against the absolute reference frame, WGS-72 ("average" as used here means averaged over using systems uniformly distributed in both time and space).

SEGMENT	ERROR SOURCES	SYSTEM BUDGET (METERS 1σ)
SPACE	Clock & Navigation Subsystem Stability	2.7
	Predictability of SV Perturbations	1.0
	Other	0.5
	Total Segment	2.9
CONTROL	Ephemeris Prediction and Model Implementation	2.5
	Other	0.5
	Total Segment	2.6
USER	Ionospheric Delay Compensation	2.3
	Tropospheric Delay Compensation	2.0
	Receiver Noise and Resolution	1.5
	Multipath	1.2
	Other	0.5
	Total Segment	3.6
SYSTEM	Total 1σ UERE =	5.3

GPS System Error Budget

TABLE 6

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1. Satellite Segment

The GPS Space Segment contributions to UERE are primarily due to stability limits in the on board atomic frequency standards. Both rubidium and cesium standards are in use aboard the space vehicles and, despite some early hardware failures, the satellite clocks are performing quite well and have generally exceeded their performance specifications. It is difficult to say however, just how well the onboard clock/navigation subsystems are behaving. It is extraordinarily difficult to separate the effects of the clock/navigation subsystem from the second error source allocated to the satellite - the perturbations about the nominal orbit/ephemeris due to solar pressure variations, satellite outgassing, and attitude control activities on-board the satellite.

Both sources of error have the same net effect as perceived by the ground based observers (the control segment and the users): the apparent line-of-sight difference between the signal tracking derived range and the satellite ephemeris minus user location computed range as was also discussed in the first section of this paper. The definition of exactly which source is the major contributor to the induced UERE has been a hotly debated topic, but the question is moot from the using systems point of view. The user still perceives a total error attributable to the satellite of 2.9 meters (RSS of the three errors including "other"). This total error has some significant characteristics which are worthy of note:

    a.   The error value specified is the total induced error bound at the end of an upload applicability period. Immediately after a new upload the error is near zero and grows as a function of time towards the specified limit at the end of the period.

    b.   The error of one satellite is uncorrelated with the error of another satellite (except some small coupling due to common solar pressure effects and other environmental factors)

    c.   The error is random and is a zero mean process in the long term. All deterministic effects are accounted for in the Control Segment's ephemeris and clock correction models. The remaining errors are random and all biases are accounted for.

2. Control Segment

The GPS Control Segment Errors are characteristically much like the Satellite Segment errors although they stem from imprecise modeling as opposed to physical factors in and on the satellite. The Control Segment cannot physically track the satellite across the heavens, but instead must rely on navigation signal tracking of the satellites. This

fact imposes two fundamental characteristics on the quality of the derived ephemerides uploaded to the satellites: a) the Control Segment corrects the navigation signals for net effect -exactly the same net effect the UE will see in the field, thus resulting in the combined satellite derived ranging signals/Control Segment derived ephemerides being optimally corrected for the field user, and b) the Control Segment cannot precisely predict future satellite ephemerides because the input satellite position tracking data has residual SV clock/navigation subsystem, SV perturbation, and signal path delay model noise imposed on it (as was seen in section one of this paper). In summary, the Control Segment errors can be said to have the following characteristics:

   a. The 2.6 meter (total) error value specified for the control segment is the total induced error bound at the end of the upload period. The error has the same time dependent characteristics as the space segment errors.

   b. The ephemeris errors for one satellite are partially correlated with those for another satellite. Each satellite is modeled independently but residual effects of the tracking and estimation process induce some small correlation.

   c. The errors are generally not random due to the imprecise modeling processes. As GPS matures and additional refinements are made to the models, the deterministic effects should decrease in size. Steady state biases are definitely part of the modeling process and affect all satellites uniformly. The biases discovered so far have been minor and have been related to tracking station location errors.

3. User Segment

   The GPS User Segment error sources are quite unlike the Space and Control segment errors. They do not depend on the upload period nor are they otherwise time dependent. The UE UERE contributions are due to either path delay uncertainties or hardware noise, both of which are environmentally dependent.

Hardware - The hardware noise specification value of 1.6 meters (includes "other") is sized for code tracking in an operational, high threat, jammed environment. It is a random zero mean process noise and, between different tracking channels in the receiver, is uncorrelated.

Path Delays _ The path delays that the satellite's navigation signal experiences before reaching the user's antenna are determined by the earth's atmosphere and by reflective surfaces in the vicinity of the user's antenna (multipath). The UE use a dual frequency (L_1/L_2) correction algorithm to correct for

ionospheric delays, a geometric correction algorithm for the tropospheric delays, and a combination of search algorithm and judicious antenna placement to minimize multipath errors. The specified values for each of these error sources are the residual errors after making the corrections and reflect on the accuracy of the algorithms used. These errors are generally quite correlated among visible satellites and have both random and bias components.

B.   GDOP

Given that each segment of GPS is performing within its system error budget allocation, the navigation accuracy available to a using system from the GPS UE can be determined by the instantaneous UERE's of the four control/satellite - UE receiver links being used and the Geometric Dilution of Precision (GDOP) between the satellites and the user. This GDOP is a measure of how the satellite geometry affects user accuracy. It's mathematical development and interpretation have been rigorously described several times in recent literature and do not bear repeating here. Suffice it to say that GDOP and its related HDOP (Horizontal Dilution of Precision) act as amplification factors of UERE to give the resulting navigational errors due to the effect of the three dimensional geometry of the satellites and user position as well those due to the four dimensional navigation solution. As a result of this definition and its underlying assumptions the following relationships can be shown to hold:

$$GDOP^2 = HDOP^2 + VDOP^2 + TDOP^2$$

Horizontal Position Error = UERE x HDOP
Vertical Position Error = UERE x VDOP
Navigation Time Error = UERE x TDOP

For specification purposes, for UE solving the four dimensional navigation equations (four equations, four unknowns), the following values of the GDOPs are used (based on the 50th percentile values for a nominal constellation of satellites):

GDOP = 3.56
HDOP = 1.58
VDOP = 2.71
TDOP = 1.68

And thus, the specified value for average time error for GPS UE is:

$$UERE \times TDOP = (5.3m)(3.3nSec/m)(1.68) = 27.9 \ nSec(1\sigma) \qquad (11)$$

or the accuracy of navigation time in the GPS UE is $T_{GPS} \pm 27.9$ nSec(1σ).

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C. **UTC Accuracy**

The time error induced in the UE due to UERE and TDOP of ±29.7 nSec (1σ) is only part of the error which a using system will perceive in the time it receives from the UE. Superimposed on the navigation time error are errors due to the T_{GPS} to UTC (USNO) correction model and errors due to the UE hardware in handling it's analog time signals. Both these errors are independent of geometry and so GDOP or TDOP do not affect them. Each can be characterized as follows:

1. **T_{GPS} to UTC (USNO) model**

As described in section I.B.2, the Control Segment will be cooperating with USNO in operating a specially calibrated UE set at USNO to receive UTC(GPS) and communicate time differences to the Control Segment on a twenty-four hour cycle. The Control Segment will model these errors and upload the correction terms on a weekly basis into the satellites. The choice of upload periods strongly influences the accuracy provided to users at the end of the weekly upload period. The GPS system specification only calls for this value to be within 100 nSec(1σ). It is this value which has dictated the upload cycle period. Substantially better accuracies could be achieved with more rapid updates -but as yet, no military using command has expressed a requirement which would necessitate a more rapid update cycle. Thus, the current GPS baseline is weekly time uploads.

This time upload procedure error budget at the end of each prediction period has been allocated among the various sources as follows:

(UTC(GPS)-UTC(USNO)) @ USNO (measurement):	31 Nanoseconds (1σ)
$(T_{SVi}-T_{GPS})$ at Control Segment (measurement):	14 Nanoseconds(1σ)
RSS of Measurement Errors:	34 Nanoseconds (1σ)
Projection/Extrapolation of Previous Measurements 6 days into future:	x 5
UTC (USNO) - T_{GPS} error:	76 Nanoseconds (1σ)
Stability of T_{GPS} versus UTC(USNO):	47 Nanoseconds (1σ)
Total Error of UTC(GPS) versus UTC (USNO):	90 Nanoseconds (1σ)

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2. UE hardware time handling errors

The GPS UE has been optimized for navigation computation and not specifically for absolute time synchronization. As a result, a rather large error tolerance has been specified for the total UE induced error in time dissemination: 38 nSec (1σ). This is the additional hardware error the UE can allow to be induced in the final time accuracy output to a using system for its most accurate time interface, the Time Mark Signal. The specified tolerances for the other time interfaces, the Reset Pulse and the Data Capture Pulse, are higher as previously mentioned (primarily due to the additional hardware uncertainties associated with additional analog signal handling).

The major limiting factors which causes such a large error in the UE handling of timing are the acceleration and other environmental sensitivities of the UE Master Reference Oscillator. The value of 38 nSec(1σ) is specified over the environment of the UE and this environment includes up to 9 g's steady state and 15 g transient accelerations, +71°C to -54° C temperature range and transient power excursions. Other hardware delays (such as the temperature dependent amplifier and antenna delays, installation peculiar cable delays, and short term electromagnetic interference noise) as well as software (Kalman filter transient response) effects are also included in the factors which limit the UE's ability to provide a well regulated analog signal to a using system.

D. Combination of errors

Thusly, the final UTC(GPS) provided to a using system using the TMS in the field at an unknown location and operating in a severe military environment is accurate to UTC (USNO) within the following bound:

T_{GPS} Errors:	29.7 Nanoseconds (1σ)
T_{GPS} to UTC (USNO) Errors:	90.0 Nanoseconds (1σ)
UE Interface/Hardware Time Handling Errors to using system:	37.9 Nanoseconds (1σ)
Total UTC (GPS) Error Bound Estimated:	102 Nanoseconds (1σ)
Specified UTC (GPS) Error Bound:	111 Nanosecond (1σ)

IV. What If 102 nSec Isn't Good Enough?

There are several techniques one may apply to the operation of the GPS UE to achieve much better time dissemination performance. Each technique makes use of particular characteristics of the error inducing sources to either have the errors cancel out with a common mode

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technique or make the error source irrelevant to the problem at hand. A few of these techniques are described below along with their effect on the error sources. These techniques are also applied to two specific using system cases as examples of what can be achieved using GPS in a realistic scenario rather than the preceeding worst case specification value discussion.

A.   Error Source Reduction Techniques

1.   Multipath error reduction:

The Multipath error allocation can be eliminated by judicious placement of the GPS UE antenna to avoid hard surface reflections of satellite signals.

2.   Receiver noise reduction:

The receiver noise value of 5 nSec (1.5m) can be reduced to 0.6 nSec by operating in a less jammed environment (i.e. not operating in the middle of a high power jammer field). The lesser levels of jamming will allow precision carrier phase tracking of the signal rather than just P-code tracking and so a corresponding decrease in receiver noise can be achieved.

3.   Operate the UE in a stationary mode:

This technique includes both true stationary (velocity of the UE=0) and receiver velocity aiding with minimal acceleration modes. Utilization of either of these modes allows the UE to reduce it's own UERE components (and it's time estimation errors), by approximately $1/\sqrt{2}$. These modes also allow reduction of the acceleration induced errors in the master reference oscillator to zero with a corresponding increase in the precision control of the analog time signal output (depending on design peculiarities this can reduce the analog handling error by about $1/\sqrt{2}$ or more).

4.   Operate the User Equipment at a known location:

Utilizing a surveyed location can reduce the UE's perceived TDOP to unity. This results from the fact that only the UE's time is an unknown and only one satellite need be tracked - so geometry has no effect. A previously determined GPS navigation solution is sufficiently precise to enable this technique to work.

5.   Average over several satellites in view at known location.

This will reduce the independent and uncorrelated error contributions to UERE and T_{GPS}-UTC (USNO) by approximately $1/\sqrt{4} = \frac{1}{2}$.

6. Calibrate the user hardware errors and operate in a stable environment:

This technique is applicable to all types of using systems. It requires a one time calibration with an independent UTC (USNO) source and can be done prior to fielding of the UE. The improvement is design dependent but can potentially reduce the analog signal handling errors to the order of a few nanoseconds.

7. Post processing:

Post processing of field data for using system applications which do not require real time synchronization with USNO can effectively eliminate the much of the 90 nSec of the UTC(GPS)-UTC(USNO) error source. The necessary data could be had by accessing a planned USNO data bank which will contain the satellite UTC(GPS)-UTC(USNO) data or the using system could use independently measured UTC(GPS) -UTC (using system) data collected at a laboratory site with a second UE and the using system's reference clock (which may or may not be synchronized with UTC (USNO)).

8. Co-regional operation (Common Mode):

With this technique, relative synchronization of two using systems can be improved. Common mode effects (e.g. both UE's tracking the same satellites and both experiencing approximately the same satellite ephemeris, ionospheric, etc. error sources) can be canceled or reduced between the two using systems if relative synchronization between the two is the desired effect.

9. Net Time Synchronization:

If synchronization between two using systems (net time) is all that is desired and absolute UTC traceability is relatively unimportant, then T_{GPS} can be used in lieu of UTC(GPS) and synchronization between the systems can be within the T_{GPS} plus UE hardware/analog signal errors.

B. Practical Examples

The foregoing techniques are in general non-exclusive and can be applied independently or in combination (depending on exact circumstance and user application). Two examples of user applications are given below to demonstrate the power of these techniques.

Example 1: Joint Tactical Information Distribution System (JTIDS) type of net synchronization. In this example, two using systems wish to real time control the absolute time bias between their clocks. Assumptions:

a. An F-16 type aircraft and ground terminal are the two systems.
b. The F-16 can partially velocity aid his GPS UE, the Ground Terminal is stationary and is at known site.
c. Moderate jamming environment.
d. Co-regional operation.

In this case the error reduction techniques that can be applied are: numbers 1,2,3,4,6,8,9. The resulting errors between the two user clocks can be conservatively estimated as 26 nSec (1σ) as shown by Table 7.

Example 2: A forward observer near a protected target is acquiring data which must be related to UTC (USNO) for subsequent analysis. For this example the following assumptions apply:

a. The observer is in a highly jammed environment.
b. He is stationary but at a unknown location.
c. He has a very precisely calibrated UE.
d. Post processing reference data is available.
e. The user utilizes GPS to determine his position.

In this example the following error reduction techniques may be applied: Numbers 1,3,4,5,6,7. Applying these techniques to this example, the UTC (USNO) time accuracy of the collected data would be within approximately 16 nSec (1σ) as given by Table 8.

V. Conclusion

The Navstar Global Positioning System has been shown to be a truly integrated timing system. Although some user may choose to build their own satellite timing receivers because of availabiity constraints or unusual applications, the majority of users can utilize the DOD developed User Equipment and the applicable techniques described in this paper to satisfy their current and future system time-of-day requirements.

In addition, GPS also supplies it's utilizing systems with precise position information. This is a key point in that precise time without precise position information is useless for many military and civilian applications (e.g., time-of-arrival locating, net synchronization, code validity interval communication security, etc.). GPS is unique in supplying both time and position to the same order of accuracy (102 nSec at the speed of light equals 31 meters) real time, anywhere, and in an operational environment.

TABLE 7

Practical Example 1

Error Value with Applied Techniques (nSec, 1σ)

Error Source	Nominal Error Value (nSec,1σ)	Ground Terminal	Aircraft
Space Segment Errors	9.6	$(0)^8$	$(0)^8$
Control Segment Errors	8.6	$(0)^8$	$(0)^8$
User Errors:			
Ionospheric	7.6	$7.6 \times (\frac{1}{2})^3 \times (\frac{1}{4})^8$	$7.6 \times (\frac{1}{4})^8$
Tropospheric	6.6	$6.6 \times_2 (\frac{1}{4})^3 \times (\frac{1}{4})^8$	$6.6 \times_2 (\frac{1}{4})^8$
Receiver Noise	5	$(0.6)^2$	$(0.6)^2$
Multipath	4	$(0)^1$	$(0)^1$
Other	1.7	1.7	1.7
UERE (RSS of above)	17.7	5.3	7.3
x TDOP	x1.68	$x (1.0)^4$	x 1.68
T_{GPS} Error	29.7	5.3	12.3
T_{GPS} to UTC (USNO)	90.0	$(0)^9$	$(0)^9$
UE Hardware Errors	37.9	$(10)^6$	$(20)^6$
Total Time Error (RSS of Above)	102	11.3	23.5

Synchronization error between Ground Terminal and Aircraft = $\sqrt{11.3^2 + 13.5^2}$

= 26 nSec (1σ)

Note: $(x)^n$ = value of error when technique n is applied

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TABLE 8

Practical Example 2

Error Source	Nominal Error Value (nSec, 1σ)	Error Value with Applied Technique(nSec, 1σ)
Space Segment Errors	9.6	$9.6 \, (\frac{1}{2})^5$
Control Segment Errors	8.6	$8.6 \, (\frac{1}{2})^5$
User Errors:		
Ionospheric	7.6	$7.6 \times (\frac{1}{2})^3$
Tropospheric	6.6	$6.6 \times (\frac{1}{2})^3$
Receiver Noise	5	$5 \times (\frac{1}{2})^3$
Multipath	4	$(0)^1$
Other	1.7	$1.7 \times (\frac{1}{2})^3$
UERE (RSS of Above)	17.7	10.3
x TDOP	x 1.68	$x \, (1)^4$
T_{GPS} Error	29.7	10.3
T_{GPS} to UTC (USNO)	90.0	$(6)^7$
UE Hardware Errors	37.9	$(10)^6$
Total Time Error (RSS of above)	102	16 (1σ)

Note: $(x)^n$ = value of error when technique n is applied

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QUESTIONS AND ANSWERS

MR. EDMUND CHRISTY, Offshore Navigation

Lieutenant, you mentioned that something was going to happen next week or so, and it sounded like "launch", could you repeat that?

LT. KOVACH:

December 10th, NAVSTAR 7 is scheduled to be launched, that's next Thursday. And if we are lucky, everything will go all right.

DR. VICTOR REINHARDT, NASA/Goddard

Just a comment, Councilman at M.I.T. has been building VLBI devices using the GPS signal as noise sources and has been able to do multi-path experiments on the picosecond level and he is finding out that the multipath problem is much less than people think due to nearby cars or towers, or things like that. I just wanted to mention that.

LT. KOVACH:

Multipath is typical on a very small level, although in a lot of our tests when we set up the inverted range, which real time com-putes the net satellite accuracy at Yuma, we found that we had a guide wire holding up one of the posts for the tower. And that was producing three to four meters worth of error, just from that one guide wire. It is kind of a black art situation, you really can't analyze it, you just have to try it and see how it works.

MR. KUHNLE:

When he was here last year, Capt. Doug. Tennant, said something about possibly the CA code might not be available to us sometime in the future, is that really true at this time?

LT. KOVACH:

The Federal Navigation Plan which came out early or late last year, calls for that CA code to be always available to all users. It might not be as accurate as some people would like, but they are like 200 meters CEP.

MR. NORM HOULDING, MITRE

What do you mean by jamming environment? Numerically?

LT. KOVACH:

That value is classified, but let me give you a practical example
that you might find enlightening in this regard. It turns out that
flying against a jamming field, the power necessary to run that
jamming field tells how big the plant would necessarily be, either
a hydro-electric plant, or a nuclear power plant. It turns out
that the power you need to protect the size of the plant that is
needed to produce the power that you are protecting it with, it
turns out to be pretty linear. I mean, you have got to go to the
big plant just to protect itself, so it can output the power to pro-
tect itself, you don't have any surplus power you can use anywhere
else.

GPS is very jam resistant especially when combined with a con-
trolled reception pattern antenna, one is able to null jammers and
interial navigation systems which provide good benefits.