



# **The use of Global Positioning System Time for Spacecraft Navigation**

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**ESA Technical Note**

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## Configuration Control

Version	Date	Changes
0	14 January 2000	Creation of Document
0.5	15 April 2000	Modification of all pages
0.6	2 May 2000	SA off for NAVSTAR

## 1 Scope and Background

This Technical Note is raised to study the possibility to acquire and disseminate GPS system time on-board a spacecraft.

This technical note (TN) deals with the use of GPS time for navigation (spacecraft platform) purposes. Other time signals on-board a spacecraft for other purposes are not considered (payload).

The purpose of this document is to establish a base for discussion about the use of global positioning system time on-board of a spacecraft in a consolidated manner, perhaps being a future recommendation for a new CCSDS standard.

## 2 Nomenclature

GPS stands for Global Positioning System, no matter which system either NAVSTAR, GLONASS or GalileoSAT. NAVSTAR stands for the USA GPS system. GLONASS is the Russian GPS system. GalileoSAT is the flight segment of the European GPS system (GNSS-2 extension).

## 3 Introduction

The Global Positioning System (GPS) is a system to accurately determine the position of a user receiver. It is based on the old navigation principle of triangulation [8].

## 4 GPS Constellations

The two active GPS constellations for global positioning are the US NAVSTAR system and the Russian GLONASS system. To these two, in the year 2010 the European GalileoSAT will join.

At present the NAVSTAR constellation is composed of 27 satellites deployed at 26.600 Km in elliptical orbits around the Earth. The satellites are located in 4 orbital planes where each orbital plane contains 6 satellites.

Each NAVSTAR satellite is called a space vehicle (SV). The NAVSTAR satellites are numbered sequentially after the space vehicle number (SVN). The SVs are classified in blocks depending on the construction time.

The NAVSTAR Block I satellites were constructed in early 70s, and launched between 1978 and 1985. The last block I satellite was deorbited in 1995. A modern block II and IIA satellites were constructed during the 90s. Now, the nominal NAVSTAR constellation is composed of nine block II satellites plus fifteen block IIA satellites. Block IIA satellites represent an upgrade to block II satellites. Replacements are on its way for the last part of the 90s and the beginning of the next century with blocks IIR and IIF. R for replenishment and F for follow-on series.

The payload of the blocks II and IIA do carry more than GPS hardware. Among others, NAVSTAR satellites can detect remote nuclear explosions, for instance [3].

The Russian GLONASS system is similar to the American NAVSTAR. GLONASS stands for the Global Orbiting Navigation Satellite System [9]. It is a satellite constellation initiated by the former Soviet Union and now under the control of the Russian Federation. GLONASS is formed also of 24 satellites having 3 orbital planes, with 8 satellites per plane at an altitude of about 19,100 km..

Unlike NAVSTAR, GLONASS uses the Frequency Division Multiple Access (FDMA) technique to broadcast the data. To date, only 14 satellites are in use [7] [11].

The GLONASS satellites transmit signals on two frequencies (L1 and L2) with a Course Acquisition (C/A) and Precision (P) code on L1 and P code only on L2. The N1 signal has the frequency  $1602+0.5625n$ . The L2 signal has the frequency  $1246+0.4375n$ .  $n$  represents here the number of the satellite and it is similar to the NAVSTAR PRN number.

The Russians are moving the frequencies of operation of the satellites through the years. At the beginning of 1998, the satellites have ceased using the 1610.6..1613.8 MHz band for transmission of L1 navigation signals. The nominal frequency channels are  $n = 16..20$ . From now onwards, the channels 0..12, 22, 23, 24 will be used for normal operation. Channels 13, 14, 21 may be used under exceptional circumstances. A possibility to use channels -7...- 1 on upcoming GLONASS satellite launches at this stage will be specified. This situation will change again from 2005 onwards.

The Russians do not intentionally degrade the GLONASS signals. Therefore the signal is not encrypted. The claimed accuracy of the system establishes the horizontal error in 30 m 2 drms (95% probability).

Due to the orbital inclination of the satellites (64.8°) the constellation is approximately 10 degrees higher than the NAVSTAR satellites. This places the satellites in portion of the globe not covered by NAVSTAR.

GLONASS as well as NAVSTAR (and later GalileoSAT) are free of charge. Anyone can receive the NAVSTAR and GLONASS signals at no cost, provided the user has a compatible receiver.

NAVSTAR and GLONASS GPS constellations are being used for other purposes rather than navigation (see [10]).

NAVSTAR and GLONASS provides several observable quantities to the user's receivers: the code, the carrier [2], etc. From the phase of the code, the receiver can extract the pseudorange. From the frequency of the carrier the receiver can extract the Integrated Doppler Count. Apart from these observables, the receiver can get the GPS system time.

Since midnight of the 1 May 2000, the United States has ended the practice of intentionally degrading signals available to the public from NAVSTAR. This action improves civilian use which now can be compared to the GLONASS accuracy.

In Europe, considerable progress has been made on the European satellite navigation program. The European Commission, after having obtained approval for the so-called Action Plan on Satellite Navigation, started the consultations with the various bodies within Europe but also with potential partners outside Europe.

Dual receivers NAVSTAR-GLONASS have appeared in the market already. They have a wider bandwidth than a NAVSTAR-only type or a GLONASS-only type. These receivers can benefit from augmentation systems like the Wide Area Augmentation System (WAAS), Wide Area GPS Enhancement (WAGE) or the European Geostationary Navigation Overlay System (EGNOS).

Most recently, ESA Member States approved the full-scale development of EGNOS. A little earlier they granted already the funding for the initial work on the development of the European contribution to the GNSS-2 system [6]. Building on the earlier work, ESA is now in the process to initiate a number of major technology developments, investigations into specific GalileoSAT aspects such as the signal format and comprehensive system studies [5]. GalileoSAT will be a system providing higher performance than today's NAVSTAR or GLONASS (possibly an order of magnitude bigger).

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## 5 Time Elaboration

The international time scales are the International Atomic Time (TAI), the Universal Time (UT1), and the Coordinated Universal Time (UTC).

TAI scales are based on data from some 220 atomic clocks located in about 50 time laboratories around the world. The Time Section of the Bureau International des Poids et Mesures (BIPM) computes these time scales. BIPM is responsible for TAI steering. Although TAI is also called atomic time, it is a paper time scale not kept by a physical clock.

The International Earth Rotation Service (IERS) is responsible for UT1. UT1 is based on the Earth's rotation around the Sun and it is corrected for non-uniformities in the orbital speed, polar motion, and the inclination of the Earth. What is important about UT1 is that this time defined the actual orientation of the ECEF co-ordinate system with respect to the celestial sphere. However, UT1 drift respect to atomic time.

The Universal time coordinated (UTC) is an international, highly accurate and stable uniform TAI system kept very close, by offsets, to UT1 corrected for seasonal variations in the earth's rotation rate.

Presently, the stability of TAI and UTC is currently about 2 parts in  $10^{15}$  over a period of a few weeks.

A derivative of UTC called UTC(USNO) is maintained by The US Naval Office using an assemble of 20 Cesium atomic clocks and astronomical data derived from UTC. UTC(USNO) itself is kept very close to the international benchmark UTC.

## 6 Time On-Board a Satellite

All spacecraft must maintain a time reference on-board. In most cases, spacecraft could maintain several time references on-board (platform, different payloads, etc).

When an on-board time reference is maintained for time tagging telemetry events this is commonly called *Spacecraft Elapsed Time* or SET. SET is the most commonly way to manage on-board time.

SET is primarily used to give orders to a spacecraft or to receive its status in a ground station. SET is generated and maintained by a central clock on board a



spacecraft. If the format used by the clock is CCSDS compliant, the time code format chosen is the Unsegmented Time Code or CUC format. This format is represented as a combination of a preamble field (P) and a time specification field (T).

Reference [14] gives a detailed specification of the SET format, its construction and its use. This specification is compliant with the telemetry and telecommand CCSDS specifications.

SET can be transported to ground using a standard CCSDS telemetry Source Packet. This allows time correlation with UTC.

SET can also be used to know the position and attitude of a spacecraft, that is, for navigation purposes. In most cases, SET can be generated on-ground and uploaded to the spacecraft.

When SET is defined as the time elapsed since the mission started and it is generated on-board (on-board signal oscillator) it can also be called the on-board flight time (OBFT).

## 7 Global Positioning System Time

In this section, the time description of a global positioning system has been restricted to the NAVSTAR case. The GLONASS system is quite similar. The GalileoSAT system has not been defined as this technical note is being raised.

In the GPS NAVSTAR constellation, each Block II/IIA satellite contains two cesium (Cs) and two rubidium (Rb) atomic clocks. Each Block IIR satellite contains three Rb atomic clocks.

The navigation message from the NAVSTAR constellation carries the so-called GPS time, or NAVSTAR time. NAVSTAR time is given by its Composite Clock (CC). The CC or "paper" clock consists of all Monitor Station and satellite operational frequency standards.

The NAVSTAR epoch is 0000 UT (midnight) on January 6, 1980. NAVSTAR time is not adjusted and therefore is offset from UTC by an integer number of seconds, due to the insertion of leap seconds. The number remains constant until the next leap second occurs. This offset is also given in the navigation message. Any receiver should apply the correction automatically. As of January 1, 1999, GPS time is ahead of UTC by thirteen (13) seconds.

The NAVSTAR system time is referenced to the Master Clock (MC) at the USNO. This time is steered at the UTC(USNO). The system time will not deviate by more than one microsecond (according to the precise positioning system requirement).

Apart from the time itself, the exact difference between UTC and NAVSTAR system time is contained in the navigation message in the form of two constants, A0 and A1, giving the time difference and rate of system time against UTC(USNO,MC).

The GPS NAVSTAR system time is automatically steered on a daily basis to keep system time within one microsecond of UTC(USNO), but during the last several years have been within a few hundred nanoseconds. The rate of steer being applied is  $\pm 1.0^{-19}$  seconds per second squared.

## 8 Obtaining GPS Time On-Board a Spacecraft

GPS systems (NAVSTAR, GLONASS, GalileoSAT) can also be used to distribute time and synchronize clocks across large distances with a high degree of precision and accuracy [4]. In fact, this feature was one of the original uses of the system. For example, for military purposes, worldwide time dissemination allows users to switch communication frequencies simultaneously.

GPS time civil usage activities has recently exploded because of the development and availability of multichannel receivers, the falling receiver prices, and the enormous requests from the timing community.

In principle, a receiver on-board could benefit from this time broadcasting capability to provide accurate time for a spacecraft [1]. The figure 1 represents schematically the elaboration of the NAVSTAR system time and its broadcasting to mobile user receivers across the globe.

In general, any receiver can reconstruct UTC(USNO) from the navigation message. These receivers can be commanded to take the two constants, A0 and A1, from the NAVSTAR navigation message for a linear extrapolation to the USNO MC.

By means of the information given in the NAVSTAR navigation message, the SPS user can obtain a time transfer accuracy to UTC(USNO) within 340 nanoseconds (95 percent) [13].

For military privileged receivers (PPS users) the time transfer accuracy to UTC(USNO) can be determined within 200 ns (95 percent).

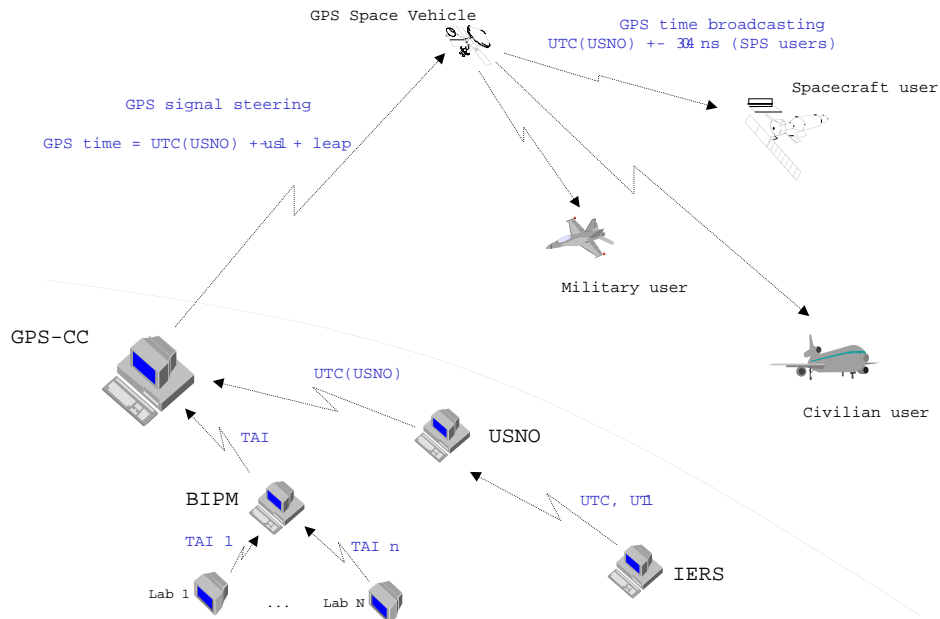


Figure 1: Schematic representation of the elaboration of UTC(USNO) time

## 9 GPS time on the Navigation Function

Spacecraft navigation is the process to find the present and imminent future position and orbit of a spacecraft using a series of measurements. The navigation function on-board can be defined as the process of calculating the position and orientation of a spacecraft at a given time.

The navigation function may need to computer ephemeris as a function of the spacecraft flight time. Other inputs may be planetary ephemeris and general information. If a very precise orbit determination is required, planetary ephemeris can be used to calculate the Earth polar motion and the nutation of the Earth in the ecliptic longitude.

In most occasions, flight software time has to be related to UTC in some way. Some on-board spacecraft navigation units contain complicated correlation tables to implement this function.

In other situations UTC times have to be converted into Ephemeris Time (ET) to

take into account situations like the ones mentioned before. The value of ET at a given instant is obtained by very accurate observation of abrupt variation of the movement of the Sun and the planets due to Earth rotation. ET is obtained by correcting UTC using a long series of astronomical observations.

*Can any on-board GPS receiver deliver system time? And UTC?* In principle, any space qualified receiver delivers system time. It is included in the navigation message and the user receiver can extract it. UTC can be computed in the firmware of the receiver using the navigation message parameters.

*Can GPS system time be standard for all GPS systems?* Each GPS system has and will have a different Interface Control Document (ICD) with the user receiver. In those documents it is explained which time is broadcasted, etc. Perhaps the most interesting feature is not the standardization of the time format of the navigation message but the way UTC can be recovered from the navigation message.

*Can SET be the only time available on-board?* The navigation function may need more time specifications as SET (e.g. ET). The efforts in standardization should be directed towards the consecution of conversion routines to quickly reproduce UTC on-board.

*What are the advantages and disadvantages of GPS system time used on-board?* The advantages of GPS system time on-board can be as follows:

- **AVAILABILITY:** For orbits under the umbrella of the constellation, GPS system time is available around the globe for an indefinite period. This feature is much desired by the GNC engineer who can design the navigation function without taking into account ground tracks constraints, etc.
- **AUTONOMY:** GPS system time can be acquired on-board directly from the constellation without ground intervention.
- **INTEGRITY:** GPS time is supplied in a continuous form in the navigation message of the constellations. GPS allows for a routine update of orbit and attitude determination algorithms.
- **ACCURACY:** GPS time errors are presently in the order of 350-400 nano seconds (this figure may be improved in the case of the new GalileoSAT system or the new series of NAVSTAR and GLOANSS space vehicles). This accuracy seems to be sufficient for a big number of presents missions. This point is perhaps one of the most important factors during the decision process of the navigation function build up.

The disadvantages can be enumerated as follows:

- **FAILURE TOLERANCE:** GPS time depends on an on-board GPS receiver assembly, which can become a single failure point. The duplication of receiver is an expensive measure which not many mission can afford.
- **DEPENDABILITY:** GPS system time is a free product any receiver can obtain. However, no claim can be made when the product is or is not delivered. The European dependability on the USA and Russian system has moved the EU to launch GalileoSAT. More over, no agreement with any civilian user has been made to guaranty the continuation of a GPS system in future.
- **FLEXIBILITY:** GPS system time is one of the outputs of a receiver which can be obtained under certain conditions and scenarios. If the conditions of the mission changes, the GPS receiver may not be able to provide the same output or the same quality of output.
- **ACCURACY:** Although the accuracy of the GPS time errors seems to be reasonable for a good number of missions, more and more demanding scenarios are appearing. There are more missions in which very accurate orbit determination has to be done in autonomous way.

## 10 Conclusions

The use of the GPS system time has clear advantages for autonomy and cost reduction in mission operations and control. To this point, it is clear that more and more missions will carry a GPS receiver on-board as part of the standard classic spacecraft sensors.

This technical note concludes with several proposals:

- The extension of the present document to include other timing signals and needs on-board a spacecraft. For example, the timing broadcasting and consumption by payloads.
- The analysis of the need of the production of a CCSDS Blue-Book which could standardize the generation of UTC time on-board from GPS system time and the synchronization of this time. This may be discussed during the CCSDS Spring 2000 collocation. Other related routines could be also part of the task.

If this task is achieved, not only the spacecraft community would benefit but also civil aviation. It is therefore proposed the involvement of institutions like EUROCONTROL in this matter.

## 11 Definitions of terms

**Standard Positioning Service (SPS).** Three-dimensional position and time determination capability provided to a user equipped with a minimum capability GPS SPS receiver in accordance with GPS national policy and the performance specifications established in this Signal Specification.

**Selective Availability.** Protection technique employed by the DOD to deny full system accuracy to unauthorized users.

**Block I and Block II Satellites.** The Block I is a GPS concept validation satellite; it does not have all of the design features and capabilities of the production model GPS satellite, the Block II. The FOC 24 satellite constellation is defined to consist entirely of Block II/IIA satellites. For the purposes of this Signal Specification, the Block II satellite and a slightly modified version of the Block II known as the Block IIA provide an identical service.

**Operational Satellite.** A GPS satellite which is capable of, but may or may not be, transmitting a usable ranging signal. For the purposes of this Signal Specification, any satellite contained within the transmitted navigation message almanac is considered to be an operational satellite.

**Geometric Range.** The difference between the estimated locations of a GPS satellite and an SPS receiver.

**Navigation Message.** Message structure designed to carry navigation data. This structure is defined in Section 2.4.

**Navigation Data.** Data provided to the SPS receiver via each satellite's ranging signal, containing the ranging signal time of transmission, the transmitting satellite's orbital elements, an almanac containing abbreviated orbital element information to support satellite selection, ranging measurement correction information, and status flags.

**Position Solution.** The use of ranging signal measurements and navigation data from at least four satellites to solve for three position coordinates and a time offset.

**Dilution of Precision (DOP).** The magnifying effect on GPS position error induced by mapping GPS ranging errors into position through the position solution. The DOP may be represented in any user local coordinate desired. Examples are

HDOP for local horizontal, VDOP for local vertical, PDOP for all three coordinates, and TDOP for time.

**SPS Performance Standard.** A quantifiable minimum level for a specified aspect of GPS SPS performance. SPS performance standards are defined in Annex A to this Signal Specification.

**SPS Performance Envelope.** The range of variation in specified aspects of SPS performance. Expected SPS performance characteristics are defined in Annex B to this Signal Specification.

**Dilution of Precision (DOP).** A Root Mean Square (RMS) measure of the effects that any given position solution geometry has on position errors. Geometry effects may be assessed in the local horizontal (HDOP), local vertical (VDOP), three-dimensional position (PDOP), or time (TDOP) for example.

## 12 List of Acronyms

A-S	Anti-Spoofing
ASIC	Application Specific Integrated Circuit
BIPM	International Bureau of Weights and Measures
BIT	Built-In-Test
BPSK	Bi Phase Shift Keying
C/A-code	Coarse/Acquisition-Code
CDMA	Code Division Multiplex Access
CEP	Circular Error Probable
dB	Decibel ( $X = 10 \log X$ dB)
DGPS	Differential GPS
DoD	Department of Defense
DOP	Dilution of Precision
dRMS	Distance Root Mean Square
ECEF	Earth-Centered-Earth-Fixed
FOM	Figure Of Merit
GDOP	Geometric Dilution of Precision
GMT	Greenwich Mean Time
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
ILS	Instrument Landing System
INS	Inertial Navigation System
ION	Institute of Navigation

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L1	NAVSTAR GPS primary frequency, 1575.42 MHz
L2	NAVSTAR GPS secondary frequency, 1227.6 MHz
MHz	Megahertz (10 Hz)
N1	GLONASS GPS primary frequency, 1575.42 MHz
N2	GLONASS GPS secondary frequency, 1575.42 MHz
NAV-msg	Navigation Message
PC	Personal Computer
P-Code	Precise Code
PDOP	Position Dilution of Precision
PPS	Precise Positioning Service
PRN	Pseudo Random Noise
PVT	Position Velocity and Time
RMS	Root Mean Square
S/A	Selective Availability
SEP	Spherical Error Probable
SPS	Standard Positioning Service
TACAN	Tactical Air Navigation
UE	User Equipment
USA	United States of America
USNO	US Naval Observatory
UT	Universal Time
UTC	Universal Time Coordinated
VDOP	Vertical Dilution of Precision
WGS-84	World Geodetic System - 1984

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