GLOBAL POSITIONING SYSTEM

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Keywords: Global positioning system, Navigation system with timing and ranging, artificial satellite, navigation, survey, single point positioning, differential positioning, static survey, kinematic survey

Contents

Summary

The Global Positioning System is an all-weather, space-based navigation system operated by the Department of Defense to satisfy the requirements for the military forces and civilian users to accurately determine their position, velocity, and time in a common reference system, anywhere on or near the earth on a continuous basis.

GPS uses pseudoranges derived from the broadcast satellite signal. The pseudo-range is derived either from measuring the travel time of the coded signal and multiplying it by its velocity or by measuring the phase of the signal. The most accurate pseudo-ranges are computed from phase observation. This consists of the difference in phase of the incoming satellite signal and a receiver generated signal with the same frequency.

GPS survey uses this phase observation. There are two types of surveying; static surveying and kinematic surveying. The static surveying method is the most commonly used since the only basic requirement is a relatively unobstructed view of the sky for the occupied points. Conventional static surveys require observation periods depending on the baseline length, the number of visible satellites, the geometric configuration. The

accuracy is correlated with the baseline length and amounts to 1-0.1 ppm (or even better). Kinematic surveys enable observation while moving and are the most productive in that the greatest number of points can be determined in the least time.

1. Introduction

The Global Positioning System is the responsibility of the Joint Program Office (JPO) located at the U.S. Air Force Systems Command's Space Division, Los Angeles Air Force Base(AFB). In 1973, the JPO was directed by the U.S. Department of Defense (DoD) to establish, develop, test, acquire, and deploy a spaceborne positioning system. The present Navigation System with Timing and Ranging (NAVSTAR) Global Positioning System (GPS) is the result of this initial directive.

The Global Positioning System was conceived as a ranging system from known positions of satellites in space to unknown positions on land, sea, in air and space. Effectively, the satellite signal is continually marked with its own transmission time so that when received the signal transit period can be measured with a synchronized receiver. The original objectives of GPS were the instantaneous determination of position and velocity (i.e., navigation), and the precise coordination of time (i.e., time transfer).

Since the DoD is the initiator of GPS, the primary goals were military. But the U.S. Congress, with guidance from the President, directed DoD to promote its civil use.

GPS uses pseudoranges derived from the broadcast satellite signal. The pseudorange is derived either from measuring the travel time of the (coded) signal and multiplying it by its velocity or by measuring the phase of the signal. In both cases, the clocks of the receiver and the satellite are employed. Since these clocks are never perfectly synchronized, instead of true ranges "pseudoranges" are obtained where the synchronization error (denoted as clock error) is taken into account. Consequently, each equation of this type comprises four unknowns: the three point coordinates contained in the true range, and the clock error. Thus, four satellites are necessary to solve for the four unknowns. Indeed, the GPS concept assumes that four or more satellites are in view at any location on earth 24 hours a day. The solution becomes more complicated when using the measured phase. This observable is ambiguous by an integer number of signal wavelengths so that the model for phase pseudoranges is augmented by an initial bias, also called integer ambiguity.

The Global Positioning System managed by the JPO consists of three segments:

1) the space segment consisting of satellites which broadcast signals,
2) the control segment steering the whole system,
3) the user segment including the many types of receivers.

2. Overview of GPS

2.1 Space Segment

The GPS satellites have nearly circular orbits with an altitude of about 20,200km above the earth and a period of approximately 12 sidereal hours. The constellation and the number of satellites used have evolved from earlier plans for a 24-satellite and 3-orbit plane constellation, inclined at 63 degree to the equator. Later, for budgetary reasons, the space segment was reduced to 18 satellites, with three satellites in each of six orbital planes. This scheme was eventually rejected, since it did not provide the desired 24-hour worldwide coverage. In about 1986, the number of satellites planned was increased to 21, again three each in six orbital planes, and three additional active spares. The spare satellites were designated to replace malfunctioning active satellites. The present constellation consists of 24 operational satellites deployed in six evenly spaced planes (A to F) with an inclination of 55 degree and with four satellites per plane. Furthermore, four active spare satellites for replenishment will be operational.

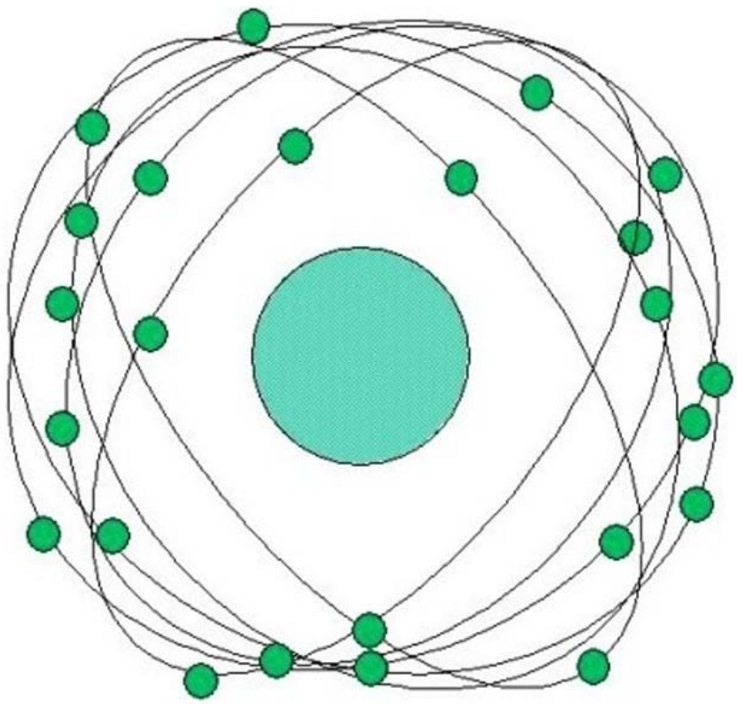

Figure 1: The Constellation of GPS Satellites

With the full constellation, the space segment provides global coverage with four to eight simultaneously observable satellites above 15 degree elevation at any time of day. If the elevation mask is reduced to 10 degree, occasionally up to 10 satellites will be visible; and if the elevation mask is further reduced to 5 degree, occasionally 12 satellites will be visible.

The GPS satellites, essentially, provide a platform for radio transceivers, atomic clocks, computers, and various units of ancillary equipment used to operate the system. The electronic equipment of each satellite allows the user to measure a pseudorange to the satellite, and each satellite broadcasts a message which allows the user to determine the spatial position of the satellite for arbitrary instants. Given these capabilities, users are able to determine their position on or above the earth by resection. The auxiliary equipment of each satellite, among others, consists of solar panels for power supply and a propulsion system for orbit adjustments and stability control.

The actual carrier broadcast by the satellite is a spread spectrum signal that makes it less subject to intentional or unintentional jamming.

The key to the system's accuracy is the fact that all signal components are precisely controlled by atomic clocks. The Block↳ satellites have four on-board time standards, two rubidium and two cesium clocks. The long-term frequency stability of these clocks reaches a few parts in 10^{-13} and 10^{-14} over one day. These highly accurate frequency standards being the heart of GPS satellites produce the fundamental L-band frequency of 10.23MHz. Coherently derived from this fundamental frequency are two signals, the L1 and L2 carrier waves generated by multiplying the fundamental frequency by 154 and 120 respectively yielding.

L1=1574.42MHz
L2=1227.60MHz

The pseudoranges that are derived from measured travel time of the signal from each satellite to the receiver use two pseudorandom noise (PRN) codes that are modulated (superimposed) onto the two base carriers.

The first code is the C/A-code (Coarse/Acquisition-code) which is available for civilian use. The C/A-code, designated as the Standard Positioning Service (SPS), has an effective wavelength of approximately 300m. The C/A-code is modulated upon L1 only and is purposely omitted from L2. This omission allows the JPO to control the information broadcast by the satellite and, thus, denies full system accuracy to nonmilitary users.

The second code is the P-code (Precision-code) which has been reserved for U.S. military and other authorized users. The P-code, designated as the Precise Positioning Service (PPS), has an effective wavelength of approximately 30m. The P-code is modulated on both carriers L1 and L2. In addition to the PRN codes, a data message is modulated onto the carriers consisting of status information, satellite clock bias, and satellite ephemeredes.

Component	Frequency(MHz)
Fundamental frequency	$f_{0=10.23}$ $f_0 = 10.23$
Carrier L1	$f_0 154 = 1575.42$
Carrier L2	$f_0 120=1227.60$
P code	$f_0 = 10.23$
C/A code	$f_0 / 10 = 1.023$
Navigation message	$f_0 / 204600 = 50 \times 10^{-6}$

Table 1: GPS Signal Structure

2.2 Control segment

The Operational Control System (OCS) consists of a master control station, monitor stations, and ground control stations. The main operational tasks of the OCS are: tracking of the satellites for the orbit and clock determination and prediction, time synchronization of the satellites, and upload of the data message to the satellites. The OCS is also responsible for imposing SA on the broadcast signals. However, SA was switched off in May 2000. The OCS performs many non-operational activities, such as procurement and launch activities, that will not be addressed here.

The location of the master control station was formerly at Vandenberg AFB, California, but has been moved to the Consolidated Space Operations Center (CSOC) at Falcon AFB, Colorado Springs, Colorado. CSOC collects the tracking data from the monitor stations and calculates the satellite orbit and clock parameters using a Kalman estimator. These results are then passed to one of the three ground control stations for eventual upload to the satellites. The satellite control and system operation is also the responsibility of the master control station.

There are five monitor stations located at: Hawaii, Colorado Springs, Ascension Island in the South Atlantic Ocean, Diego Garcia in the Indian Ocean, and Kwajalein in the North Pacific Ocean. Each of these stations is equipped with a precise cesium time standard and receivers which continuously measure pseudoranges to all satellites in view. Pseudoranges are measured every 1.5 seconds and, using the ionospheric and meteorological data, they are smoothed to produce 15-minute interval data which are transmitted to the master control station.

The tracking network described above is the official network for determining the broadcast ephemeredes as well as modeling the satellite clocks. The data of five additional sites are used to compute the precise ephemeredes. Other tracking networks exist. These networks generally have no part in managing the system. A private tracking network was operated by the manufacturer of Macrometer during the early 1980s. Today, more globally oriented tracking networks are operated.

These stations collocated with the monitor stations at Ascension, Diego Garcia, and Kwajalein are the communication links to the satellites and mainly consist of ground antennas. The satellite ephemeredes and clock information, calculated at the master control station and received via communication links.

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Bibliography

Axelrad P. and Brown R. G. (1994), *GPS Navigation Algorithms*, 409-434, Global Positioning System: Theory and Applications Vol. 1. Axelrad and Enge, Assoc. Eds. [This paper provides an algorithm of point positioning]

Goad C. (1995), *Surveying with the Global Positioning System*, 501-518, Global Positioning System: Theory and Applications Vol. 2. Axelrad and Enge, Assoc. Eds. [This paper provides an overview of surveying with GPS]

Hofman B., Lichtenegger H., and Collins J. (1997). *Global Positioning System: Theory and Practice*, 133-140, Springer-Verlag, Vienna and New York. [This paper gives detailed information about carrier phase processing in GPS surveying]

Parkinson W. (1994), *GPS Error Analysis*, 469-484, Global Positioning System: Theory and Applications Vol. 1. Axelrad and Enge, Assoc. Eds. [This article gives detailed information about errors in GPS observables]

Parkinson W. and Enge K.(1995), *Differential GPS*, 3-50, Global Positioning System: Theory and Applications Vol. 2. Axelrad and Enge, Assoc. Eds. [This paper provides an algorithm of differential GPS positioning]

Spilker Jr. J. J. (1994), *Satellite Constellation and Geometric Dilution of Precision*, 177-208, Global Positioning System: Theory and Applications Vol. 1. Axelrad and Enge, Assoc. Eds. [This article gives a detail information about DOP]

Spilker Jr. J. J. and Parkinson W. (1994), *Overview of GPS Operation and Design*, 29-55, Global Positioning System: Theory and Applications Vol. 1. Axelrad and Enge, Assoc. Eds. [This paper provides an overview of GPS]

Strang G., Borre K. (1997), *Linear Algebra, Geodesy, and GPS*, 458-460, Wellesley-Cambridge Press. [This article gives detailed information about GPS data processing]

Biographical Sketch

Tatunori Sada, Dr. Eng., is an engineer with the Technical Research Institute, Mitsui Construction Co., Ltd. He graduated from the department of civil engineering of Tokyo University in 1984 and received his Dr. Eng., from Tokyo University in 1992.

He has been engaged in research and development of GPS applications for construction projects since 1990. His team developed “GPS Navigation-type Surveying system” using RTK receivers in 1993 and has used the system in more than 80 construction projects such as dams, roads, and building constructions. His team also developed machine control system using Differential GPS and RTK positioning for the roller compaction machine and bulldozer. His current research focuses on Differential GPS and RTK by VRS (Virtual Reference Station).