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# Understanding GPS principles and applications

**Authors:** Elliott D. Kaplan and Scott Lewis
**Date:** Jan. 1997
**From:** Journal of Electronic Defense(Vol. 20, Issue 1)
**Publisher:** Horizon House Publications, Inc.
**Document Type:** Article
**Length:** 2,655 words

Full Text:
Each one of us conducts some form of navigation in our daily lives. Driving to work or walking to a store requires that we employ fundamental navigation skills. For most of us, these skills require utilizing our eyes, common sense and landmarks. However, in some cases where a more accurate knowledge of either our position, intended course and/or transit time to a desired destination is required, navigation aids other than landmarks are used. These may be in the form of a simple clock to determine the velocity over a known distance or the odometer in our car to keep track of the distance traveled. Some other navigation aids are more complex and transmit electronic signals. These are referred to as radionavigation aids.

Signals from one or more radionavigation aids enable a person (herein referred to as the user) to compute his or her position. It is important to note that it is the user's radionavigation receiver that processes these signals and computes the position fix. The receiver performs the necessary computations (e.g., range, bearing, estimated time of arrival) for the user to navigate to a desired location. In some applications, the receiver may only process the received signals with the navigation computations performed by a separate processor.

Various types of radionavigation aids exist, and they can be categorized as either ground based or space based. For the most part, the accuracy of ground-based radionavigation aids is proportional to their operating frequencies. Highly accurate systems generally transmit at relatively short wavelengths and the user must remain within line of sight, whereas systems broadcasting at lower frequencies (longer wavelengths) are not limited to line of sight but are less accurate.

Early developed spaced-based systems (namely the US Navy Navigation Satellite System, referred to as Transit, and the Russian Tsikada system) provide a two-dimensional high-accuracy positioning service. However, the frequency of obtaining a position fix varies with latitude. Theoretically, a Transit user at the equator could obtain a position fix on the average of once every 110 min, whereas, at 80 [degrees] latitude the fix rate would improve to an average of once every 30 min. Limitations applicable to both systems are that each position fix requires approximately 10 to 15 min of receiver processing and an estimate of the user's position. These attributes were suitable for shipboard navigation because of the low velocities, but not for aircraft and high-dynamic users. It was these shortcomings that led to the development of both the US Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS).

GPS OVERVIEW

Presently, GPS is fully operational and meets the criteria established in the 1960s for an optimum positioning system. The system provides accurate, continuous, worldwide, three-dimensional position and velocity information to users with the appropriate receiving equipment. GPS also disseminates a form of Coordinated Universal Time (UTC). The satellite constellation consists of 24 satellites arranged in 6 orbital planes with 4 satellites per plane. A worldwide ground control/monitoring network monitors the health and status of the satellites. This network also uploads navigation and other data to the satellites. GPS can provide service to an unlimited number of users since the user receivers operate passively (i.e., receive only). The system utilizes the concept of one-way time of arrival (TOA) ranging. Satellite transmissions are referenced to highly accurate atomic frequency standards on board the satellites, which are in synchronism with an internal GPS system time base. The satellites broadcast ranging codes and navigation data on two frequencies using a technique called code division multiple access (CDMA); that is, there are only two frequencies in use by the system, called L1 (1,575.42 MHz) and L2 (1,227.6 MHz). Each satellite transmits on these frequencies, but with different ranging codes than those employed by other satellites. These codes were selected because they have low cross-correlation properties with respect to one another. The navigation data provide the means for the receiver to determine the location of the satellite at the time of signal transmission, whereas the ranging code enables the user's receiver to determine the transit (i.e., propagation) time of the signal and thereby determine the satellite-to-user range. This technique requires that the user receiver also contain a clock. Utilizing this technique to measure the receiver's three-dimensional location requires that TOA ranging measurements be made to four satellites. If the receiver clock was synchronized with the satellite clocks, only three range measurements would be required. However, a crystal clock is usually employed in navigation receivers to minimize the costs, complexity and size of the receiver. Thus, four measure merits are required to determine user latitude, longitude, height and receiver clock offset from internal system time, if either system time or altitude is accurately known, fewer than four satellites are required.

GPS provides two services: the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). The SPS is designated for the civil community, whereas the PPS is slated for US authorized military and select government agency users. Access to the GPS PPS is controlled through cryptography.

PRECISE POSITIONING SERVICE

The PPS is specified to provide a predictable accuracy of at least 22 m in the horizontal plane and 27.7 m in the vertical plane. The PPS provides a UTC time transfer accuracy within 200 nsec referenced to the time kept at the US Naval Observatory and is denoted as UTC (USNO). Velocity measurement accuracy is specified as 0.2 m/sec.

The PPS is primarily intended for military and select government agency users. Civilian use is permitted but only upon special US Department of Defense (DOD) approval. Access to the mentioned PPS position accuracies is controlled through two cryptographic features denoted as Antispoofing (AS) and Selective Availability (SA). AS is a mechanism intended to defeat deception jamming. Deception jamming is a technique in which an adversary would replicate one or more of the satellite ranging codes, navigation data signal(s) and carrier frequency Doppler effects with the intent of deceiving a victim receiver. Further, under current DOD policy, SA is implemented to deny full system accuracy to SPS users. SA "dithers" the satellite's clock, thereby corrupting TOA measurement accuracy. Further, SA induces errors into the broadcast navigation data parameters. PPS users remove SA effects through cryptography.

The PPS reached full operational capability in spring 1995, when the entire 24 production satellite constellation was in place and extensive testing of the ground control segment and its interactions with the constellation was completed.

STANDARD POSITIONING SERVICE

The SPS is available to all users worldwide. There are no restrictions on SPS usage. The service provides predictable accuracies of 100 m in the horizontal lane and 156 m in the vertical plane. UTC (USNO) time dissemination accuracy is within 340 nsec. SPS initial operating capability was attained in December 1993, when a combination of 24 prototype and production satellites were available and position determination/timing services complied with the associated specified predictable accuracies.

GLOBAL NAVIGATION SATELLITE

GLONASS is a Russian space-based radionavigation system that provides the capability for three-dimensional position and velocity determination as well as time dissemination on a worldwide basis. In many respects, GLONASS is quite similar to GPS. The system consists of a 24-satellite constellation, a ground monitoring network and various types of user equipment. When fully deployed, the constellation will consist of three orbital planes with eight satellites per plane. The ground network consists of a number of satellite-monitoring and data-up-loading facilities located throughout Russia. There are several manufacturers of user receiving equipment within Russia as well as throughout the world. Some manufacturers are developing combined GPS/GLONASS receivers.

GLONASS is operated by Russia's Ministry of Defense. Like GPS, the program was instituted in the mid-1970s with military design goals. However, in a similar manner to GPS, the number of civil applications quickly became apparent and the system is now truly dual use. Position, velocity and time determination is performed using pseudorandom noise ranging signals. However, the satellite transmissions differ from GPS. GLONASS employs frequency division multiple access (FDMA), in which each satellite transmits on a different frequency. This technique allows the same ranging codes to be broadcast from each satellite.

GLONASS provides separate civil and military services. The specified positioning accuracies of the civil service are 100 m in the horizontal plane and 150 m in the vertical. Civil velocity accuracy is specified at 0.15 m/sec. At the time of this writing, GLONASS has not employed an SA feature and actual measured civil accuracies are 26 m in the horizontal plane and 45 m in the vertical. Velocity measurements are on the order of 0.03 to 0.05 m/sec.

INMARSAT CIVIL NAVIGATION SATELLITE OVERLAY

The INMARSAT overlay is an implementation of a wide-area differential service. INMARSAT is an international consortium providing mobile services on a global basis and comprised 76 signatory countries in January 1995. In 1996, INMARSAT plans to launch four geostationary satellites that will provide complete coverage of the entire globe from [+ or -]70 [degrees] in latitude. However, it must be noted that the data broadcast by the satellite are applicable to users in regions that have a corresponding ground station network. The ground station network would be operated by the service provider (e.g., civil aviation administration), whereas INMARSAT is responsible for the space segment. The uplink Earth stations are operated by the respective INMARSAT signatory affiliate (e.g., COMSAT in the US).

The overlay message format has provisions for GPS and GLONASS differential corrections and integrity data. In addition to providing these data, the satellites will transmit a ranging code similar to those broadcast by the GPS satellites. Therefore, INMARSAT-3 satellites can also be used as ranging sources. Unlike GPS and GLONASS satellites, which have their own navigation payloads, INMARSAT-3 satellites contain navigation repeaters that rebroadcast the up-linked signals to users. Although the accuracy associated with the overlay is a function of numerous factors including the ground network architecture, expected accuracies for the US Federal Aviation Administration Wide Area Augmentation System are on the order of 7.6 m in the horizontal plane and 7.6 m in the vertical plane.

## APPLICATIONS

Satellite navigation technology is being utilized in numerous civil and military applications that range from leisure hiking to spacecraft guidance. Numerous disciplines including all sectors of transportation have been affected. Users are no longer restricted to specific routes because of accuracy and/or coverage limitations of ground-based navigation aids. As long as a user is in line of sight to the satellites, accurate navigation is obtainable. To illustrate the diverse uses of satellite navigation technology, several examples of current and projected applications are presented.

Aviation: The aviation community has propelled the use of a global navigation satellite system (GNSS) and various augmentations to provide guidance for the en route through precision-approach phases of flight. (The International Civil Aviation Organization, ICAO, defines a system that contains at least one or more satellite navigation systems as a GNSS.) The continuous global coverage capability of GNSS permits aircraft to fly directly from one location to another provided factors such as obstacle clearance and required procedures are adhered to. Incorporation of a datalink with a GNSS receiver enables the transmission of aircraft location to other aircraft and/or to air traffic control (ATC). This function, called automatic dependent surveillance (ADS), is in use in some Pacific Ocean regions as an outgrowth of ICAO Future Air Navigation Systems Working Group activities. Key benefits are ATC monitoring for collision avoidance and optimized routing to reduce travel time and, consequently, fuel consumption. ADS techniques are also being applied to airport surface surveillance of both aircraft and ground support vehicles.

Spacecraft Guidance: Since 1992, a GPS receiver has been employed on the TOPEX/POSEIDON satellite which is being used to study ocean circulation. This is a joint NASA and CNES (French Space Agency) project. GPS has been used on several NASA Space Shuttle flights. In 1998, the Space Shuttle is expected to utilize GPS for guidance in all phases of operation (e.g., ground launch, on-orbit and reentry and landing.) The International Space Station (ISS) will employ GNSS to support control functions, data collection activities and navigation. Furthermore, GPS is planned to be used on NASA "small" satellite programs.

Maritime: GNSS has been embraced by both the commercial and recreational maritime communities. Navigation is enhanced on all bodies of waters, from oceanic travel to riverways, especially in inclement weather. Several nations are developing local area differential GPS networks to increase system accuracy for harbor, harbor approach and river usage. The Commonwealth of Independent States is considering the implementation of a local area differential GLONASS network. Wide-area differential GPS has been utilized by the offshore oil exploration community for several years.

One area in which differential GNSS will play a larger role is in vessel traffic services (VTSs). The combination of a datalink and differential GNSS receiver permits broadcast of the vessel's position to a control center. VTSs are used for collision avoidance and to expedite the flow of traffic during periods of restricted visibility and ice cover. VTSs can be used in conjunction with the electronic chart display information system (ECDIS). The ECDIS displays a vessel's position in relation to charted objects, navigation aids and land, as well as unseen hazards.

Land: The surveying community has relied on differential GPS to achieve measurement accuracies in the millimeter range. Similar techniques are in use within the railroad community to obtain train location with respect to an adjacent set of tracks. GPS is a key component in intelligent transportation systems. In terms of vehicle applications, GNSS will be used for route guidance, tracking and emergency messaging. Integrating a GNSS receiver with a street database, digital moving map display and processor will allow the driver to obtain directions and/or the shortest, most efficient route. Combining a cellular phone or datalink function with this system will enable vehicle tracking (i.e., form of ADS) and/or emergency messaging. A vehicle's position can be automatically reported to a control center for fleet management. The activation of a "panic" button by the driver broadcasts an emergency message, vehicle characteristics and vehicle location to law enforcement authorities for assistance.

## MILITARY AND SPACE APPLICATIONS

In the planning of GPS, the military held several nondevelopmental item competitions. These competitions solicited major electronics suppliers, detailing minimum performance standards for handheld, vehicle-mounted, airborne and embedded GPS receivers. The results were the precision lightweight GPS receiver (PLGR), the miniature airborne GPS receiver (MAGR) and the embedded GPS/inertial (EGI) receiver, which are standard items for use by troops on tactical vehicles, aircraft and missiles. The conflict in the Persian Gulf occurred before much of this technology could be implemented, however, and the military called on industry to provide currently available products for its use. It is interesting to note that during the conflict, SA was turned off, giving the highest possible accuracy without the use of the P(Y)-code. Such use highly popularized the technology, having a strong effect on the public perception of the utility of GPS.

The military market has been estimated on the basis of projecting out the current level of contracting activity through the decade. Military and political priorities may well change, however, and could slow the rate of equipage from that projected. Military market benchmarks by the year 2000 are:

1. A total of 93,999 of the handheld PLGRs should be delivered at a projected cost of $112.8 million.

2. A total of 10,000 US DOD airborne units will be delivered at a cost of $12 million.

3. There will be 6,000 receivers required for precision-guided munitions at a total cost of at least $89 million.

The use of GPS in spacecraft has been widespread. The DOD and NASA have applications for navigation, relative positioning and attitude determination. GPS has flown on several shuttle missions and has been useful in providing better orbital positioning in much shorter time than had been previously possible. Incorporation of GPS attitude determination in the space station design is currently mandated. Applications for use of GPS at orbits higher than 11,000 miles are being studied as well.

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**Source Citation** (MLA 9th Edition)
Kaplan, Elliott D., and Scott Lewis. "Understanding GPS principles and applications." *Journal of Electronic Defense*, vol. 20, no. 1, Jan. 1997, pp. S81+. *Gale Academic OneFile*, link.gale.com/apps/doc/A19161412/AONE?u=napier&sid=bookmark-AONE&xid=ea24d894. Accessed 5 Nov. 2025.
**Gale Document Number:** GALE|A19161412