Global Navigation Satellite Systems & their Applications

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Chapter 1

Satellite Navigation System

A **satellite navigation** or **sat nav** system is a system of satellites that provide autonomous geo-spatial positioning with global coverage. It allows small electronic receivers to determine their location (longitude, latitude, and altitude) to within a few metres using time signals transmitted along a line-of-sight by radio from satellites. Receivers calculate the precise time as well as position, which can be used as a reference for scientific experiments. A satellite navigation system with global coverage may be termed a **global navigation satellite system** or **GNSS**.

As of 2010, the United States NAVSTAR Global Positioning System (GPS) is the only fully operational GNSS. The Russian GLONASS is being developed towards full global coverage. The People's Republic of China is in the process of expanding its regional Beidou navigation system into the global Compass navigation system by 2020. The European Union's Galileo positioning system is a GNSS in initial deployment phase, scheduled to be fully operational by 2020 at the earliest.

Global coverage for each system is generally achieved by a satellite constellation of 20–30 Medium Earth Orbit (MEO) satellites spread between several orbital planes. The actual systems vary, but use orbit inclinations of >50° and orbital periods of roughly twelve hours (height 20,000 km / 12,500 miles).

Classification

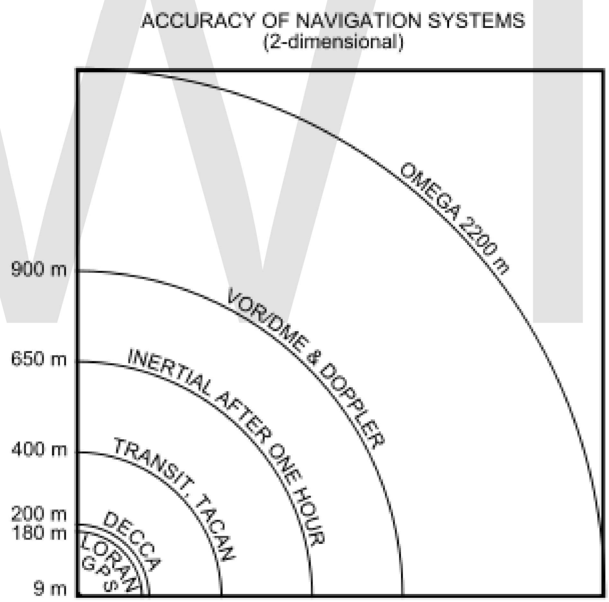
Satellite navigation systems that provide enhanced accuracy and integrity monitoring usable for civil navigation are classified as follows:

- **GNSS-1** is the first generation system and is the combination of existing satellite navigation systems (GPS and GLONASS), with Satellite Based Augmentation Systems (SBAS) or Ground Based Augmentation Systems (GBAS). In the United States, the satellite based component is the Wide Area Augmentation System (WAAS), in Europe it is the European Geostationary Navigation Overlay Service (EGNOS), and in Japan it is the Multi-Functional Satellite Augmentation System (MSAS). Ground based augmentation is provided by systems like the Local Area Augmentation System (LAAS).

- **GNSS-2** is the second generation of systems that independently provides a full civilian satellite navigation system, exemplified by the European Galileo positioning system. These systems will provide the accuracy and integrity monitoring necessary for civil navigation. This system consists of L1 and L2 frequencies for civil use and L5 for system integrity. Development is also in progress to provide GPS with civil use L2 and L5 frequencies, making it a GNSS-2 system.[1]

- Core Satellite navigation systems, currently GPS, Galileo and GLONASS.
- Global Satellite Based Augmentation Systems (SBAS) such as Omnistar and StarFire.
- Regional SBAS including WAAS(US), EGNOS (EU), MSAS (Japan) and GAGAN (India).
- Regional Satellite Navigation Systems such as China's Beidou, India's yet-to-be-operational IRNSS, and Japan's proposed QZSS.
- Continental scale Ground Based Augmentation Systems (GBAS) for example the Australian GRAS and the US Department of Transportation National Differential GPS (DGPS) service.
- Regional scale GBAS such as CORS networks.
- Local GBAS typified by a single GPS reference station operating Real Time Kinematic (RTK) corrections.

History and theory



Early predecessors were the ground based DECCA, LORAN and Omega radio navigation systems, which used terrestrial longwave radio transmitters instead of satellites. These positioning systems broadcast a radio pulse from a known "master" location, followed by repeated pulses from a number of "slave" stations. The delay between the reception and sending of the signal at the slaves was carefully controlled, allowing the receivers to compare the delay between reception and the delay between sending. From this the distance to each of the slaves could be determined, providing a fix.

The first satellite navigation system was Transit, a system deployed by the US military in the 1960s. Transit's operation was based on the Doppler effect: the satellites traveled on well-known paths and broadcast their signals on a well known frequency. The received frequency will differ slightly from the broadcast frequency because of the movement of the satellite with respect to the receiver. By monitoring this frequency shift over a short time interval, the receiver can determine its location to one side or the other of the satellite, and several such measurements combined with a precise knowledge of the satellite's orbit can fix a particular position.

Part of an orbiting satellite's broadcast included its precise orbital data. In order to ensure accuracy, the US Naval Observatory (USNO) continuously observed the precise orbits of these satellites. As a satellite's orbit deviated, the USNO would send the updated information to the satellite. Subsequent broadcasts from an updated satellite would contain the most recent accurate information about its orbit.

Modern systems are more direct. The satellite broadcasts a signal that contains orbital data (from which the position of the satellite can be calculated) and the precise time the signal was transmitted. The orbital data is transmitted in a data message that is superimposed on a code that serves as a timing reference. The satellite uses an atomic clock to maintain synchronization of all the satellites in the constellation. The receiver compares the time of broadcast encoded in the transmission with the time of reception measured by an internal clock, thereby measuring the time-of-flight to the satellite. Several such measurements can be made at the same time to different satellites, allowing a continual fix to be generated in real time using an adapted version of trilateration.

Each distance measurement, regardless of the system being used, places the receiver on a spherical shell at the measured distance from the broadcaster. By taking several such measurements and then looking for a point where they meet, a fix is generated. However, in the case of fast-moving receivers, the position of the signal moves as signals are received from several satellites. In addition, the radio signals slow slightly as they pass through the ionosphere, and this slowing varies with the receiver's angle to the satellite, because that changes the distance through the ionosphere. The basic computation thus attempts to find the shortest directed line tangent to four oblate spherical shells centered on four satellites. Satellite navigation receivers reduce errors by using combinations of signals from multiple satellites and multiple correlators, and then using techniques such as Kalman filtering to combine the noisy, partial, and constantly changing data into a single estimate for position, time, and velocity.

Civil and military uses

The original motivation for satellite navigation was for military applications. Satellite navigation allows for hitherto impossible precision in the delivery of weapons to targets, greatly increasing their lethality whilst reducing inadvertent casualties from mis-directed weapons. Satellite navigation also allows forces to be directed and to locate themselves more easily, reducing the fog of war.

Satellite navigation using a laptop and a GPS receiver

In these ways, satellite navigation can be regarded as a force multiplier. In particular, the ability to reduce unintended casualties has particular advantages for wars where public relations is an important aspect of warfare. For these reasons, a satellite navigation system is an essential asset for any aspiring military power.

The ability to supply satellite navigation signals is also the ability to deny their availability. The operator of a satellite navigation system potentially has the ability to degrade or eliminate satellite navigation services over any territory it desires.

Global navigation systems

Operational

GPS

The United States' Global Positioning System (GPS) consists of up to 32 medium Earth orbit satellites in six different orbital planes, with the exact number of satellites varying as older satellites are retired and replaced. Operational since 1978 and globally available since 1994, GPS is currently the world's most utilized satellite navigation system.

In development

GLONASS

The formerly Soviet, and now Russian, *GLObal'naya NAvigatsionnaya Sputnikovaya Sistema*(Global Navigation Satellite System), or GLONASS, was a fully functional navigation constellation but after the collapse of the Soviet Union it fell into disrepair, leading to gaps in coverage and only partial availability. Restoration was underway in 2010.

Compass

China has indicated they intend to expand their regional navigation system, called *Beidou* or *Big Dipper*, into a global navigation system by 2020 a program that has been called *Compass* in China's official news agency Xinhua. The Compass system is proposed to utilize 30 medium Earth orbit satellites and five geostationary satellites. A 12-satellite regional version is expected to be completed by 2012.

Galileo

The European Union and European Space Agency agreed in March 2002 to introduce their own alternative to GPS, called the Galileo positioning system. At an estimated cost of EUR 3.0 billion, the system of 30 MEO satellites was originally scheduled to be operational in 2010. The estimated year to become operational is 2014. The first experimental satellite was launched on 28 December 2005. Galileo is expected to be compatible with the modernized GPS system. The receivers will be able to combine the signals from both Galileo and GPS satellites to greatly increase the accuracy. Galileo is now not expected to be in full service until 2020 at the earliest and at a substantially higher cost.

Comparison of systems

System	Country	Coding	Orbital height & period	Number of satellites	Frequency	Status
GPS	United States	CDMA	20,200 km, 12.0h	≥ 24	1.57542 GHz (L1 signal) 1.2276 GHz (L2 signal)	operational
GLONASS	Russia	FDMA/CDMA	19,100 km, 11.3h	24 (30 when CDMA signal launches)	Around 1.602 GHz (SP) Around 1.246 GHz (SP)	operational with restrictions, CDMA in preparation
Galileo	European Union	CDMA	23,222 km, 14.1h	2 test bed satellites in orbit 22 operational satellites budgeted	1.164-1.215 GHz (E5a and E5b) 1.215-1.300 GHz (E6) 1.559-1.592 GHz (E2-L1-E11)	in preparation
COMPASS	China	CDMA	21,150 km, 12.6h	35	B1: 1,561098 GHz B1-2: 1.589742 GHz B2: 1.207.14 GHz B3: 1.26852 GHz	5 satellites operational, additional 30 satellites planned

Regional navigation systems

Beidou 1

Chinese regional network to be expanded into the global COMPASS Navigation System.

DORIS

Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) is a French precision navigation system.

IRNSS

The **Indian Regional Navigational Satellite System** (**IRNSS**) is an autonomous regional satellite navigation system being developed by Indian Space Research Organisation which would be under the total control of Indian government. The government approved the project in May 2006, with the intention of the system to be completed and implemented by 2014. It will consist of a constellation of 7 navigational satellites. All the 7 satellites will be placed in the Geostationary orbit (GEO) to have a larger signal footprint and lower number of satellites to map the region. It is intended to provide an all-weather absolute position accuracy of better than 7.6 meters throughout India and within a region extending approximately 1,500 km around it. A goal of complete Indian control has been stated, with the space segment, ground segment and user receivers all being built in India.

QZSS

The Quasi-Zenith Satellite System (QZSS), is a proposed three-satellite regional time transfer system and enhancement for GPS covering Japan. The first demonstration satellite was launched in September 2010.

Augmentation

Examples of augmentation systems include the Wide Area Augmentation System, the European Geostationary Navigation Overlay Service, the Multi-functional Satellite Augmentation System, Differential GPS, and Inertial Navigation Systems.

Low Earth orbit satellite phone networks

The two current operational low Earth orbit satellite phone networks are able to track transceiver units with accuracy of a few kilometers using doppler shift calculations from the satellite. The coordinates are sent back to the transceiver unit where they can be read using AT commands or a graphical user interface. This can also be used by the gateway to enforce restrictions on geographically bound calling plans.

Chapter 2

GNSS Applications

Global Navigation Satellite System (GNSS) receivers, using the GPS, GLONASS, or Beidou system, are used in many applications.

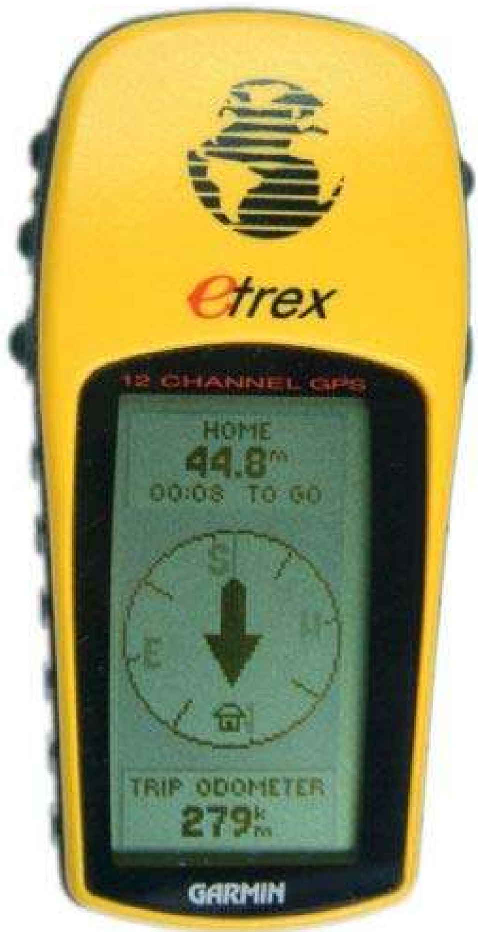
Navigation

- **Automobiles** can be equipped with GNSS receivers at the factory or as aftermarket equipment. Units often display moving maps and information about location, speed, direction, and nearby streets and points of interest.

A GPS receiver in civilian automobile use.

- **Aircraft** navigation systems usually display a "moving map" and are often connected to the autopilot for en-route navigation. Cockpit-mounted GNSS receivers and glass cockpits are appearing in general aviation aircraft of all sizes, using technologies such as WAAS or LAAS to increase accuracy. Many of these systems may be certified for instrument flight rules navigation, and some can also be used for final approach and landing operations. Glider pilots use GNSS Flight Recorders to log GNSS data verifying their arrival at turn points in gliding competitions. Flight computers installed in many gliders also use GNSS to compute wind speed aloft, and glide paths to waypoints such as alternate airports or mountain passes, to aid en route decision making for cross-country soaring.

- **Boats and ships** can use GNSS to navigate all of the world's lakes, seas and oceans. Maritime GNSS units include functions useful on water, such as "man overboard" (MOB) functions that allow instantly marking the location where a person has fallen overboard, which simplifies rescue efforts. GNSS may be connected to the ships self-steering gear and Chartplotters using the NMEA 0183 interface. GNSS can also improve the security of shipping traffic by enabling AIS.



A GPS unit showing basic way point and tracking information which is typically required for outdoor sport and recreational use

- **Heavy Equipment** can use GNSS in construction, mining and precision agriculture. The blades and buckets of construction equipment are controlled automatically in GNSS-based machine guidance systems. Agricultural equipment may use GNSS to steer automatically, or as a visual aid displayed on a screen for the driver. This is very useful for controlled traffic and row crop operations and when spraying. Harvesters with yield monitors can also use GNSS to create a yield map of the paddock being harvested.

- **Bicycles** often use GNSS in racing and touring. GNSS navigation allows cyclists to plot their course in advance and follow this course, which may include quieter, narrower streets, without having to stop frequently to refer to separate maps. Some GNSS receivers are specifically adapted for cycling with special mounts and housings.

- **Hikers**, climbers, and even ordinary pedestrians in urban or rural environments can use GNSS to determine their position, with or without reference to separate maps. In isolated areas, the ability of GNSS to provide a precise position can greatly enhance the chances of rescue when climbers or hikers are disabled or lost (if they have a means of communication with rescue workers).

- **GNSS equipment for the visually impaired** is available.

- **Spacecraft** are now beginning to use GNSS as a navigational tool. The addition of a GNSS receiver to a spacecraft allows precise orbit determination without ground tracking. This, in turn, enables autonomous spacecraft navigation, formation flying, and autonomous rendezvous. The use of GNSS in MEO, GEO, HEO, and highly elliptical orbits is feasible only if the receiver can acquire and track the much weaker (15 - 20 dB) GNSS side-lobe signals. This design constraint, and the radiation environment found in space, prevents the use of COTS receivers. Low earth orbit satellite constellations such as the one operated by Orbcomm uses GPS receivers on all satellites

Surveying and mapping

- **Surveying** — Survey-Grade GNSS receivers can be used to position survey markers, buildings, and road construction. These units use the signal from both the L1 and L2 GPS frequencies. Even though the L2 code data are encrypted, the signal's carrier wave enables correction of some ionospheric errors. These dual-frequency GPS receivers typically cost US$10,000 or more, but can have positioning errors on the order of one centimeter or less when used in carrier phase differential GPS mode.

- **Mapping and geographic information systems (GIS)** — Most mapping grade GNSS receivers use the carrier wave data from only the L1 frequency, but have a precise crystal oscillator which reduces errors related to receiver clock jitter. This allows positioning errors on the order of one meter or less in real-time, with a differential GNSS signal received using a separate radio receiver. By storing the carrier phase measurements and differentially post-processing the data, positioning errors on the order of 10 centimeters are possible with these receivers.

  - Several projects, including OpenStreetMap allow users to create maps collaboratively using consumer-grade GPS receivers.

- **Geophysics and geology** — High precision measurements of crustal strain can be made with differential GNSS by finding the relative displacement between GNSS sensors. Multiple stations situated around an actively deforming area (such as a volcano or fault zone) can be used to find strain and ground movement. These measurements can then be used to interpret the cause of the deformation, such as a dike or sill beneath the surface of an active volcano.

- **Archeology** — As archaeologists excavate a site, they generally make a three-dimensional map of the site, detailing where each artifact is found.

- Survey-grade GNSS receiver industry include a relatively small number of major players who specialize in the design of complex dual-frequency GNSS receivers capable of precise tracking of carrier phases for all or most of available signals in order to bring the accuracy of relative positioning down to cm-level values required by these applications. The most known companies are Javad, Leica, NovAtel, Septentrio, Topcon, Trimble.

Other uses

- **Precise time reference** — Many systems that must be accurately synchronized use GNSS as a source of accurate time. GNSS can be used as a reference clock for time code generators or Network Time Protocol (NTP) time servers. Sensors (for seismology or other monitoring application), can use GNSS as a precise time source, so events may be timed accurately. Time division multiple access (TDMA) communications networks often rely on this precise timing to synchronize RF generating equipment, network equipment, and multiplexers.

- **Mobile Satellite Communications** — Satellite communications systems use a directional antenna (usually a "dish") pointed at a satellite. The antenna on a moving ship or train, for example, must be pointed based on its current location. Modern antenna controllers usually incorporate a GNSS receiver to provide this information.

- **Emergency and Location-based services** — GNSS functionality can be used by emergency services to locate cell phones. The ability to locate a mobile phone is required in the United States by E911 emergency services legislation. However, as of September 2006 such a system is not in place in all parts of the country. GNSS is less dependent on the telecommunications network topology than radiolocation for compatible phones. Assisted GPS reduces the power requirements of the mobile phone and increases the accuracy of the location. A phone's geographic location may also be used to provide location-based services including advertising, or other location-specific information.

- **Location-based games** — The availability of hand-held GNSS receivers has led to games such as Geocaching, which involves using a hand-held GNSS unit to travel to a specific longitude and latitude to search for objects hidden by other geocachers. This popular activity often includes walking or hiking to natural locations. Geodashing is an outdoor sport using waypoints.

- **Aircraft passengers** — Most airlines allow passenger use of GNSS units on their flights, except during landing and take-off when other electronic devices are also restricted. Even though consumer GNSS receivers have a minimal risk of interference, a few airlines disallow use of hand-held receivers during flight. Other airlines integrate aircraft tracking into the seat-back television entertainment system, available to all passengers even during takeoff and landing.

- **Heading information** — The GNSS system can be used to determine heading information, even though it was not designed for this purpose. A "GNSS compass" uses a pair of antennas separated by about 50 cm to detect the phase difference in the carrier signal from a particular GNSS satellite. Given the positions of the satellite, the position of the antenna, and the phase difference, the orientation of the two antennas can be computed. More expensive GNSS compass systems use three antennas in a triangle to get three separate readings with respect to each satellite. A GNSS compass is not subject to magnetic declination as a magnetic compass is, and doesn't need to be reset periodically like a gyrocompass. It is, however, subject to multipath effects.

- **GPS tracking** systems use GNSS to determine the location of a vehicle, person, pet or freight, and to record the position at regular intervals in order to create a log of movements. The data can be stored inside the unit, or sent to a remote computer by radio or cellular modem. Some systems allow the location to be viewed in real-time on the Internet with a web-browser.

- Recent innovations in GPS tracking technology include its use for monitoring the whereabouts of convicted sex offenders, using GPS devices on their ankles as a condition of their parole. This passive monitoring system allows law enforcement officials to review the daily movements of offenders for a cost of only $5 or $10 per day. Real time, or instant tracking is considered too costly for GPS tracking of criminals.

- **GNSS Road Pricing** systems charge of road users using data from GNSS sensors inside vehicles. Advocates argue that road pricing using GNSS permits a number of policies such as tolling by distance on urban roads and can be used for many other applications in parking, insurance and vehicle emissions. Critics argue that GNSS could lead to an invasion of people’s privacy

- **Weather Prediction Improvements** — Measurement of atmospheric bending of GNSS satellite signals by specialized GNSS receivers in orbital satellites can be used to determine atmospheric conditions such as air density, temperature, moisture and electron density. Such information from a set of six micro-satellites, launched in April 2006, called the Constellation of Observing System for Meteorology, Ionosphere and Climate COSMIC has been proven to improve the accuracy of weather prediction models.

- **Photographic Geocoding** — Combining GNSS position data with photographs taken with a (typically digital) camera, allows one to view the photographs on a map or to lookup the locations where they were taken in a gazeteer. It's possible to automatically annotate the photographs with the location they depict by integrating a GNSS device into the camera so that co-ordinates are embedded into photographs as Exif metadata. Alternatively, the timestamps of pictures can be correlated with a GNSS track log.

- **Skydiving** — Most commercial drop zones use a GNSS to aid the pilot to "spot" the plane to the correct position relative to the dropzone that will allow all skydivers on the load to be able to fly their canopies back to the landing area. The "spot" takes into account the number of groups exiting the plane and the upper winds. In areas where skydiving through cloud is permitted the GNSS can be the sole visual indicator when spotting in overcast conditions, this is referred to as a "GPS Spot".

- **Marketing** — Some market research companies have combined GIS systems and survey based research to help companies to decide where to open new branches, and to target their advertising according to the usage patterns of roads and the socio-demographic attributes of residential zones.

- **Wreck diving** — A popular variant of scuba diving is known as wreck diving. In order to locate the desired shipwreck on the bottom of the ocean floor GPS is used to navigate to the approximate location and then the shipwreck is found using an echosounder.

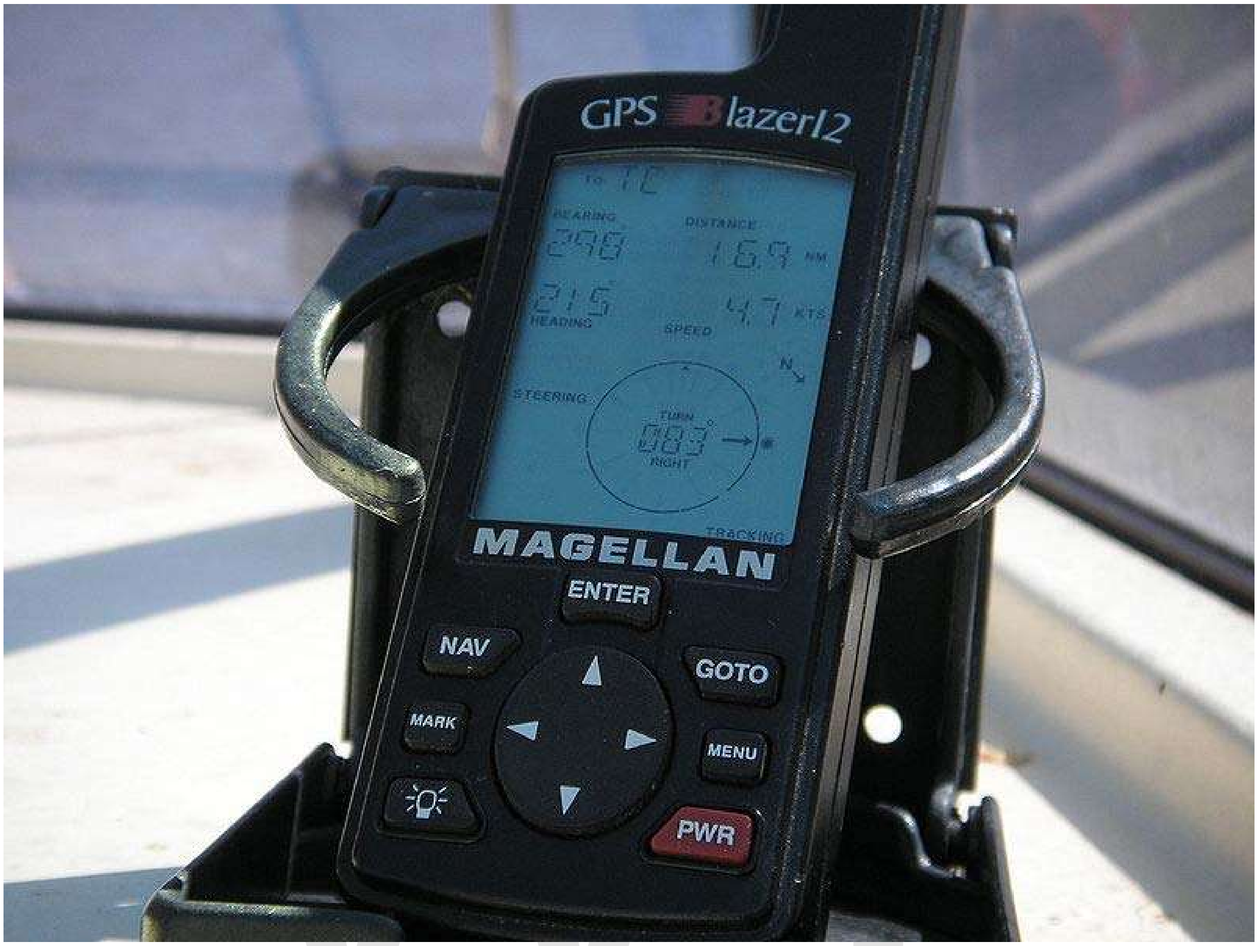
- **Social Networking** A growing number of companies are marketing cellular phones equipped with GPS technology, offering the ability to pinpoint friends on custom created maps, along with alerts that inform the user when the party is within a programmed range. Not only do many of these phones offer social networking functions, they offer standard GPS navigation features such as audible voice commands for in-vehicle GPS navigation.

Chapter 3

Global Navigation Systems

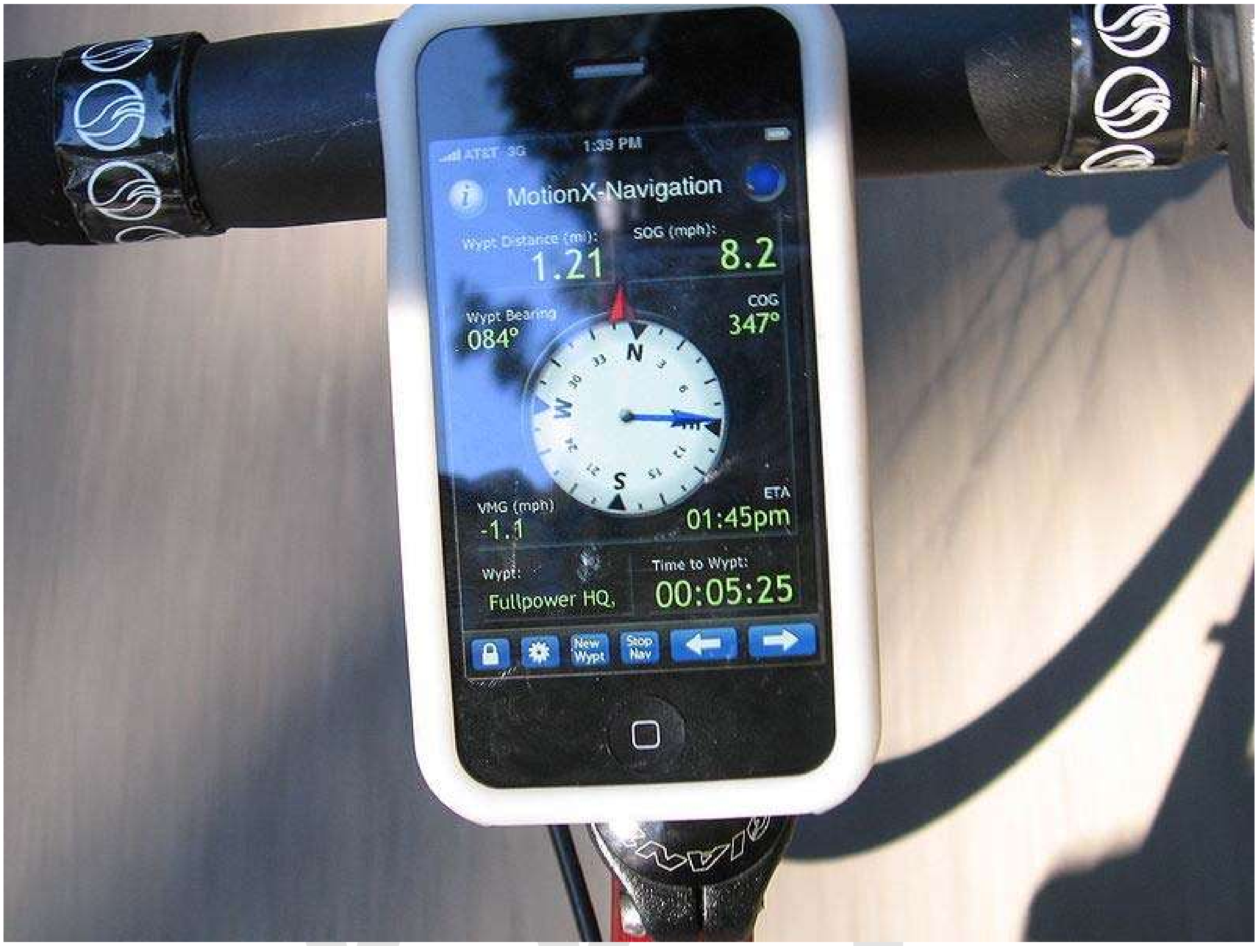
Global Positioning System

Artist's conception of GPS Block II-F satellite in orbit



Civilian GPS receiver ("GPS navigation device") in a marine application.

Automotive navigation system in a taxicab.



GPS receivers are now integrated in many mobile phones.

The **Global Positioning System** (**GPS**) is a space-based global navigation satellite system that provides reliable location and time information in all weather and at all times and anywhere on or near the Earth when and where there is an unobstructed line of sight to four or more GPS satellites. It is maintained by the United States government and is freely accessible by anyone with a GPS receiver. In addition to GPS other systems are in use or under development. The Russian GLObal NAvigation Satellite System (GLONASS) is for use by the Russian military. There are also the planned Chinese Compass navigation system and Galileo positioning system of the European Union (EU). GPS was created and realized by the U.S. Department of Defense (DOD) and was originally run with 24 satellites. It was established in 1973 to overcome the limitations of previous navigation systems.

History

The design of GPS is based partly on similar ground-based radio navigation systems, such as LORAN and the Decca Navigator developed in the early 1940s, and used during World War II. In 1956 Friedwardt Winterberg proposed a test of general relativity using accurate atomic clocks placed in orbit in artificial satellites. To achieve accuracy requirements, GPS uses principles of general relativity to correct the satellites' atomic clocks. Additional inspiration for GPS came when the Soviet Union launched the first man-made satellite, Sputnik in 1957. A team of U.S. scientists led by Dr. Richard B. Kershner were monitoring Sputnik's radio transmissions. They discovered that, because of the Doppler effect, the frequency of the signal being transmitted by Sputnik was higher as the satellite approached, and lower as it continued away from them. They realized that since they knew their exact location on the globe, they could pinpoint where the satellite was along its orbit by measuring the Doppler distortion.

The first satellite navigation system, Transit, used by the United States Navy, was first successfully tested in 1960. It used a constellation of five satellites and could provide a navigational fix approximately once per hour. In 1967, the U.S. Navy developed the Timation satellite that proved the ability to place accurate clocks in space, a technology that GPS relies upon. In the 1970s, the ground-based Omega Navigation System, based on phase comparison of signal transmission from pairs of stations, became the first worldwide radio navigation system. However, limitations of these systems drove the need for a more universal navigation solution with greater accuracy.

While there were wide needs for accurate navigation in military and civilian sectors, almost none of those were seen as justification for the billions of dollars it would cost in research, development, deployment, and operation for a complex constellation of navigation satellites. However during the Cold War arms race, the nuclear threat to the very existence of the United States was the one need that did justify this cost in the view of the US Congress. This deterrent effect is why GPS was funded. The nuclear triad consisted of the US Navy's submarine-launched ballistic missiles (SLBMs) along with the US Air Force's strategic bombers and intercontinental ballistic missiles (ICBMs). Considered vital to the nuclear deterrence posture, accurate determination of the SLBM launch position was a force multiplier.

Precise navigation would enable US submarines to get an accurate fix of their positions prior to launching their SLBMs. The US Air Force with two-thirds of the nuclear triad also had requirements for a more accurate and reliable navigation system. The Navy and Air Force were developing their own technologies in parallel to solve what was essentially the same problem. To increase the survivability of ICBMs, there was a proposal to use mobile launch platforms so the need to fix the launch position had similarity to the SLBM situation.

In 1960, the Air Force proposed a radio-navigation system called MOSAIC (Mobile System for Accurate ICBM Control) that was essentially a 3-D LORAN. A follow-on study called Project 57 was worked in 1963 and it was "in this study that the GPS concept was born." That same year the concept was pursued as Project 621B, which had "many of the attributes that you now see in GPS" and promised increased accuracy for Air Force bombers as well as ICBMs. Updates from the Navy Transit system were too slow for the high speeds that the Air Force operated at. The Navy Research Laboratory continued advancements with their Timation (Time Navigation) satellites, first launched in 1967, and with the third one in 1974 carrying the first atomic clock put into orbit.

With these parallel developments out of the 1960s, it was realized that a superior system could be developed by synthesizing the best technologies from 621B, Transit, Timation, and SECOR in a multi-service program.

Over the Labor Day weekend in 1973, a meeting of about 12 military officers at the Pentagon discussed the creation of a *Defense Navigation Satellite System*

(DNSS). It was at this meeting that "the real synthesis that became GPS was created." Later that year, the DNSS program was named *Navstar*. With the individual satellites being associated with the name Navstar (as with the predecessors Transit and Timation), a more fully encompassing name was used to identify the constellation of Navstar satellites, *Navstar-GPS*, which was later shortened simply to GPS.

After Korean Air Lines Flight 007, carrying 269 people, was shot down in 1983 after straying into the USSR's prohibited airspace, in the vicinity of Sakhalin and Moneron Islands, President Ronald Reagan issued a directive making GPS freely available for civilian use, once it was sufficiently developed, as a common good. The first satellite was launched in 1989, and the 24th satellite was launched in 1994.

Initially, the highest quality signal was reserved for military use, and the signal available for civilian use was intentionally degraded ("Selective Availability", SA). This changed with U.S. President Bill Clinton ordering Selective Availability turned off at midnight May 1, 2000, improving the precision of civilian GPS from 300 meters (about 1000 feet) to 20 meters (about 65 feet). The U.S. military by then had the ability to deny GPS service to potential adversaries on a regional basis.

GPS is owned and operated by the U.S. Government as a national resource. Department of Defense (DOD) is the steward of GPS. *Interagency GPS Executive Board (IGEB)* oversaw GPS policy matters from 1996 to 2004. After that the *National Space-Based Positioning, Navigation and Timing Executive Committee* was established by presidential directive in 2004 to advise and coordinate federal departments and agencies on matters concerning the GPS and related systems. The executive committee is chaired jointly by the deputy secretaries of defense and transportation. Its membership includes equivalent-level officials from the departments of state, commerce, and homeland security, the joint chiefs of staff, and NASA. Components of the executive office of the president participate as observers to the executive committee, and the FCC chairman participates as a liaison.

DOD is required by law to "maintain a Standard Positioning Service (as defined in the federal radio navigation plan and the standard positioning service signal specification) that will be available on a continuous, worldwide basis," and "develop measures to prevent hostile use of GPS and its augmentations without unduly disrupting or degrading civilian uses."

Timeline and modernization

Summary of satellites

Block	Launch Period	Satellite launches: Suc-cess	Fail-ure	In prep-aration	Plan-ned	Currently in orbit and healthy
I	1978–1985	10	1	0	0	0
II	1989–1990	9	0	0	0	0
IIA	1990–1997	19	0	0	0	10 of 19 launched
IIR	1997–2004	12	1	0	0	12 of 13 launched
IIR-M	2005–2009	8	0	0	0	7 of 8 launched
IIF	2010–2011	1	0	11	0	1 of 1 launched
IIIA	2014–?	0	0	0	12	0
IIIB		0	0	0	8	0
IIIC		0	0	0	16	0
	Total	59	2	11	36	30

(Last update: 24 May 2010)

PRN 01 from Block IIR-M is unhealthy
PRN 25 from Block IIA is unhealthy
PRN 32 from Block IIA is unhealthy

- In 1972, the U.S. Air Force Central Inertial Guidance Test Facility (Holloman AFB), conducted developmental flight tests of two prototype GPS receivers over White Sands Missile Range, using ground-based pseudo-satellites.
- In 1978, the first experimental Block-I GPS satellite was launched.
- In 1983, after Soviet interceptor aircraft shot down the civilian airliner KAL 007 that strayed into prohibited airspace due to navigational errors, killing all 269 people on board, U.S. President Ronald Reagan announced that GPS would be made available for civilian uses once it was completed.
- By 1985, ten more experimental Block-I satellites had been launched to validate the concept.
- On February 14, 1989, the first modern Block-II satellite was launched.
- The Gulf War from 1990 to 1992, was the first conflict where GPS was widely used.
- In 1992, the 2nd Space Wing, which originally managed the system, was de-activated and replaced by the 50th Space Wing.
- By December 1993, GPS achieved initial operational capability.
- By January 17, 1994 a complete constellation of 24 satellites was in orbit.
- Full Operational Capability was declared by NAVSTAR in April 1995.
- In 1996, recognizing the importance of GPS to civilian users as well as military users, U.S. President Bill Clinton issued a policy directive declaring GPS to be a dual-use system and establishing an Interagency GPS Executive Board to manage it as a national asset.
- In 1998, U.S. Vice President Al Gore announced plans to upgrade GPS with two new civilian signals for enhanced user accuracy and reliability, particularly with respect to aviation safety and in 2000 the U.S. Congress authorized the effort, referring to it as *GPS III*.
- In 1998, GPS technology was inducted into the Space Foundation Space Technology Hall of Fame.
- On May 2, 2000 "Selective Availability" was discontinued as a result of the 1996 executive order, allowing users to receive a non-degraded signal globally.
- In 2004, the United States Government signed an agreement with the European Community establishing cooperation related to GPS and Europe's planned Galileo system.
- In 2004, U.S. President George W. Bush updated the national policy and replaced the executive board with the National Executive Committee for Space-Based Positioning, Navigation, and Timing.

- November 2004, QUALCOMM announced successful tests of assisted GPS for mobile phones.
- In 2005, the first modernized GPS satellite was launched and began transmitting a second civilian signal (L2C) for enhanced user performance.
- On September 14, 2007, the aging mainframe-based Ground Segment Control System was transferred to the new Architecture Evolution Plan.
- The most recent launch was on May 28, 2010. The oldest GPS satellite still in operation was launched on November 26, 1990, and became operational on December 10, 1990.
- On May 19, 2009, the U. S. Government Accountability Office issued a report warning that some GPS satellites could fail as soon as 2010.
- On May 21, 2009, the Air Force Space Command allayed fears of GPS failure saying "There's only a small risk we will not continue to exceed our performance standard."
- On January 11, 2010, an update of ground control systems caused a software incompatibility with 8000 to 10000 military receivers manufactured by a division of Trimble Navigation Limited of Sunnyvale, Calif.

Structure

Ground monitor station used from 1984 to 2007, on display at the Air Force Space & Missile Museum

GPS consists of three parts: the space segment, the control segment, and the user segment. The U.S. Air Force develops, maintains, and operates the space and control segments. GPS satellites broadcast signals from space, which each GPS receiver uses to calculate its three-dimensional location (latitude, longitude, and altitude) plus the current time.

The space segment is composed of 24 to 32 satellites in medium Earth orbit and also includes the payload adapters to the boosters required to launch them into orbit. The control segment is composed of a master control station, an alternate master control station, and a host of dedicated and shared ground antennas and monitor stations. The user segment is composed of hundreds of thousands of U.S. and allied military users of the secure GPS Precise Positioning Service, and tens of millions of civil, commercial, and scientific users of the Standard Positioning Service.

Applications

While originally a military project, GPS is considered a *dual-use* technology, meaning it has significant military and civilian applications.

GPS has become a widely used and useful tool for commerce, scientific uses, tracking and surveillance. GPS's accurate timing facilitates everyday activities such as banking, mobile phone operations, and even the control of power grids. Farmers, surveyors, geologists and countless others perform their work more efficiently, safely, economically, and accurately.

Civilian

This antenna is mounted on the roof of a hut containing a scientific experiment needing precise timing.

Many civilian applications use one or more of GPS's three basic components: absolute location, relative movement, and time transfer.

- Surveying: Surveyors use absolute locations to make maps and determine property boundaries
- Map-making: Both civilian and military cartographers use GPS extensively.
- Navigation: Navigators value digitally precise velocity and orientation measurements.
- Cellular telephony: Clock synchronization enables time transfer, which is critical for synchronizing its spreading codes with other base stations to facilitate inter-cell handoff and support hybrid GPS/cellular position detection for mobile emergency calls and other applications. The first handsets with integrated GPS launched in the late 1990s. The U.S. Federal Communications Commission (FCC) mandated the feature in 2002 so emergency services could locate 911 callers. Third-party software developers later gained access to GPS APIs from Nextel upon launch, followed by Sprint in 2006, and Verizon soon thereafter.
- Tectonics: GPS enables direct fault motion measurement in earthquakes.
- Disaster relief/emergency services: Depend upon GPS for location and timing capabilities
- GPS tours: Location determines which content to display; for instance, information about an approaching point of interest is displayed.
- Geofencing: Vehicle tracking systems, person tracking systems, and pet tracking systems use GPS to locate a vehicle, person, or pet. These devices attach to the vehicle, person, or the pet collar. The application provides 24/7 tracking and mobile or Internet updates should the trackee leave a designated area.
- Recreation: For example, geocaching, geodashing, GPS drawing and waymarking
- GPS Aircraft Tracking
- Geotagging: Applying location coordinates to digital objects such as photographs and other documents for purposes such as creating map overlays.
- Phasor measurement units: GPS enables highly accurate timestamping of power system measurements, making it possible to compute phasors.

Restrictions on civilian use

The U.S. Government controls the export of some civilian receivers. All GPS receivers capable of functioning above 18 kilometers (11 mi) altitude and 515 metres per second (1,001 kn) are classified as munitions (weapons) for which U.S. State Department export licenses are required. These limits attempt to prevent use of a receiver in a ballistic missile. They would not prevent use in a cruise missile since their altitudes and speeds are similar to those of ordinary aircraft.

This rule applies even to otherwise purely civilian units that only receive the L1 frequency and the C/A (Clear/Acquisition) code and cannot correct for Selective Availability (SA), etc.

Disabling operation above these limits exempts the receiver from classification as a munition. Vendor interpretations differ. The rule targets operation given the combination of altitude and speed, while some receivers stop operating even when stationary. This has caused problems with some amateur radio balloon launches, which regularly reach 30 kilometers (19 mi).

Military

As of 2009, military applications of GPS include:

- Navigation: GPS allows soldiers to find objectives, even in the dark or in unfamiliar territory, and to coordinate troop and supply movement. In the US armed forces, commanders use the *Commanders Digital Assistant* and lower ranks use the *Soldier Digital Assistant*.
- Target tracking: Various military weapons systems use GPS to track potential ground and air targets before flagging them as hostile. These weapon systems pass target coordinates to precision-guided munitions to allow them to engage targets accurately. Military aircraft, particularly in air-to-ground roles, use GPS to find targets (for example, gun camera video from AH-1 Cobras in Iraq show GPS co-ordinates that can be viewed with special software.
- Missile and projectile guidance: GPS allows accurate targeting of various military weapons including ICBMs, cruise missiles and precision-guided munitions. Artillery projectiles. Embedded GPS receivers able to withstand accelerations of 12,000 *g* or about 118 km/s^2 have been developed for use in 155 millimeters (6.1 in) howitzers.

- Search and Rescue: Downed pilots can be located faster if their position is known.
- Reconnaissance: Patrol movement can be managed more closely.
- GPS satellites carry a set of nuclear detonation detectors consisting of an optical sensor (Y-sensor), an X-ray sensor, a dosimeter, and an electromagnetic pulse (EMP) sensor (W-sensor), which form a major portion of the United States Nuclear Detonation Detection System.

Awards

Two GPS developers received the National Academy of Engineering Charles Stark Draper Prize for 2003:

- Ivan Getting, emeritus president of The Aerospace Corporation and engineer at the Massachusetts Institute of Technology, established the basis for GPS, improving on the World War II land-based radio system called LORAN (*Lo*ng-range *R*adio *A*id to *N*avigation).
- Bradford Parkinson, professor of aeronautics and astronautics at Stanford University, conceived the present satellite-based system in the early 1960s and developed it in conjunction with the U.S. Air Force. Parkinson served twenty-one years in the Air Force, from 1957 to 1978, and retired with the rank of colonel.

GPS developer Roger L. Easton received the National Medal of Technology on February 13, 2006.

On February 10, 1993, the National Aeronautic Association selected the GPS Team as winners of the 1992 Robert J. Collier Trophy, the nation's most prestigious aviation award. This team combines researchers from the Naval Research Laboratory, the U.S. Air Force, the Aerospace Corporation, Rockwell International Corporation, and IBM Federal Systems Company. The citation honors them "for the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago."

Basic concept of GPS

A GPS receiver calculates its position by precisely timing the signals sent by GPS satellites high above the Earth. Each satellite continually transmits messages that include

- the time the message was transmitted
- precise orbital information (the ephemeris)
- the general system health and rough orbits of all GPS satellites (the almanac).

The receiver utilizes the messages it receives to determine the transit time of each message and computes the distance to each satellite. These distances along with the satellites' locations are used with the possible aid of trilateration, depending on which algorithm is used, to compute the position of the receiver. This position is then displayed, perhaps with a moving map display or latitude and longitude; elevation information may be included. Many GPS units show derived information such as direction and speed, calculated from position changes.

Three satellites might seem enough to solve for position, since space has three dimensions and a position near the Earth's surface can be assumed. However, even a very small clock error multiplied by the very large speed of light — the speed at which satellite signals propagate — results in a large positional error. Therefore receivers use four or more satellites to solve for the receiver's location and time. The very accurately computed time is effectively hidden by most GPS applications, which use only the location. A few specialized GPS applications do however use the time; these include time transfer, traffic signal timing, and synchronization of cell phone base stations.

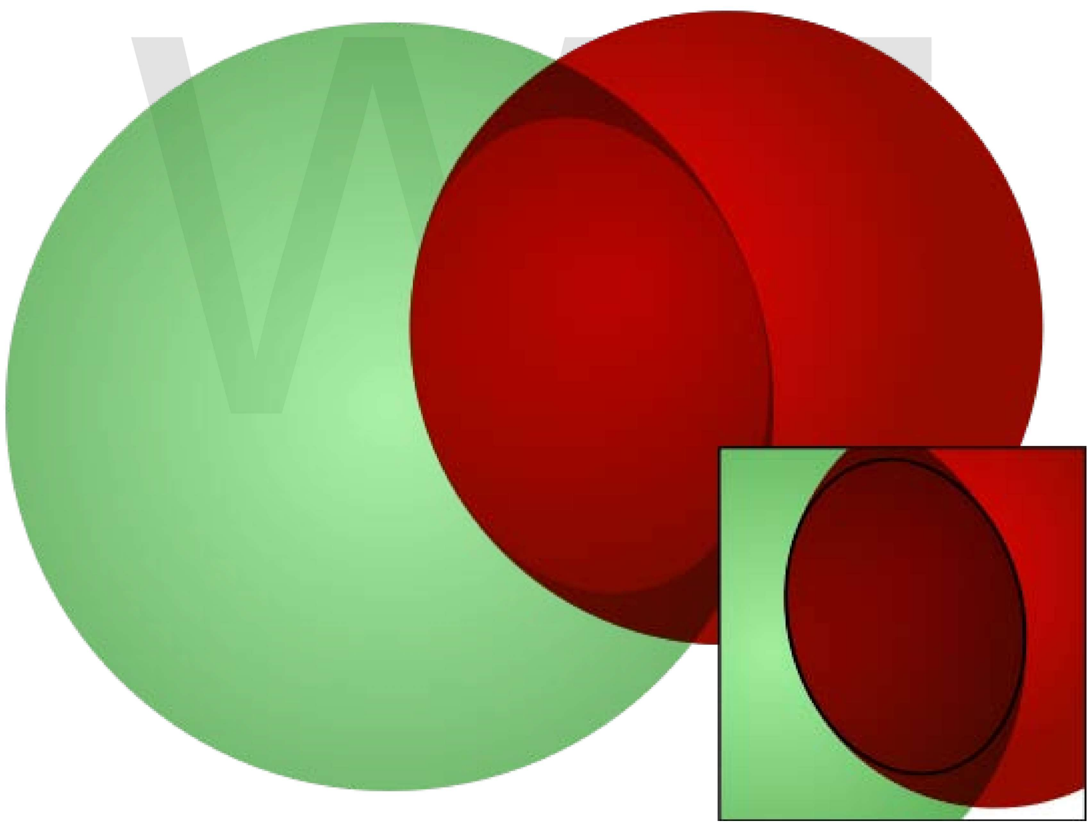
Although four satellites are required for normal operation, fewer apply in special cases. If one variable is already known, a receiver can determine its position using only three satellites. For example, a ship or aircraft may have known elevation. Some GPS receivers may use additional clues or assumptions (such as reusing the last known altitude, dead reckoning, inertial navigation, or including information from the vehicle computer) to give a less accurate (degraded) position when fewer than four satellites are visible.

Position calculation introduction

To provide an introductory description of how a GPS receiver works, error effects are deferred to a later section. Using messages received from a minimum of four visible satellites, a GPS receiver is able to determine the times sent and then the satellite positions corresponding to these times sent. The x, y, and z components of position, and the time sent, are designated as $[x_i, y_i, z_i, t_i]$ where the subscript *i* is the satellite number and has the value 1, 2, 3, or 4. Knowing the indicated time the message was received t_r, the GPS receiver can compute the transit time of the message as $(tr - t_i)$. Assuming the message traveled at the speed of light, *c*, the distance traveled or pseudorange, p_i can be computed as $(tr - t_i)c$.

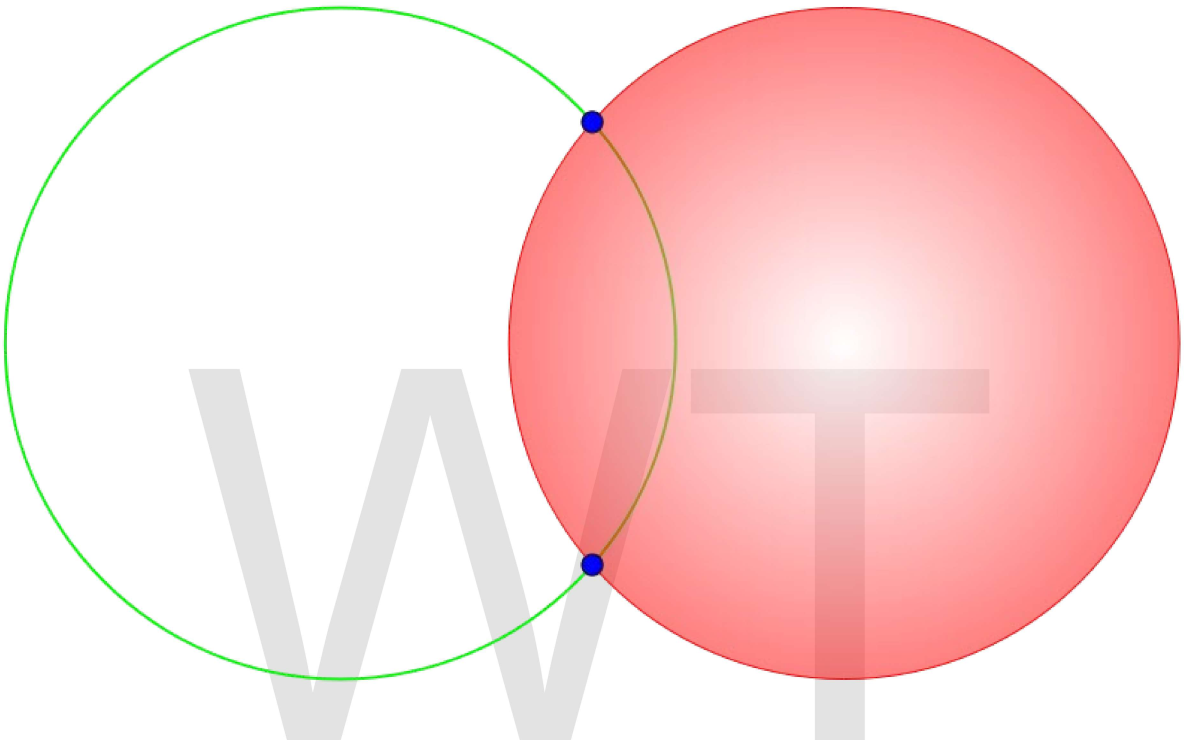
A satellite's position and pseudorange define a sphere, centered on the satellite with radius equal to the pseudorange. The position of the receiver is somewhere on the surface of this sphere. Thus with four satellites, the indicated position of the GPS receiver is at or near the intersection of the surfaces of four spheres. In the ideal case of no errors, the GPS receiver would be at a precise intersection of the four surfaces.

If the surfaces of two spheres intersect at more than one point, they intersect in a circle. Trilateration shows this mathematically. A figure, *Two Sphere Surfaces Intersecting in a Circle*, is shown below.



Two sphere surfaces intersecting in a circle

The intersection of a third spherical surface with the first two will be its intersection with that circle; in most cases of practical interest, this means they intersect at two points. Another figure, *Surface of Sphere Intersecting a Circle (not a solid disk) at Two Points*, illustrates the intersection. The two intersections are marked with dots. Again Trilateration clearly shows this mathematically.



Surface of sphere Intersecting a circle (not a solid disk) at two points

For automobiles and other near-earth vehicles, the correct position of the GPS receiver is the intersection closest to the Earth's surface. For space vehicles, the intersection farthest from Earth may be the correct one.

The correct position for the GPS receiver is also the intersection closest to the surface of the sphere corresponding to the fourth satellite.

Correcting a GPS receiver's clock

One of the most significant error sources is the GPS receiver's clock. Because of the very large value of the speed of light, *c*, the estimated distances from the GPS receiver to the satellites, the pseudoranges, are very sensitive to errors in the GPS receiver clock; for example an error of one microsecond (0.000 001 second) corresponds to an error of 300 metres (980 ft). This suggests that an extremely accurate and expensive clock is required for the GPS receiver to work. Since manufacturers prefer to build inexpensive GPS receivers for mass markets, the solution for this dilemma is based on the way sphere surfaces intersect in the GPS problem.

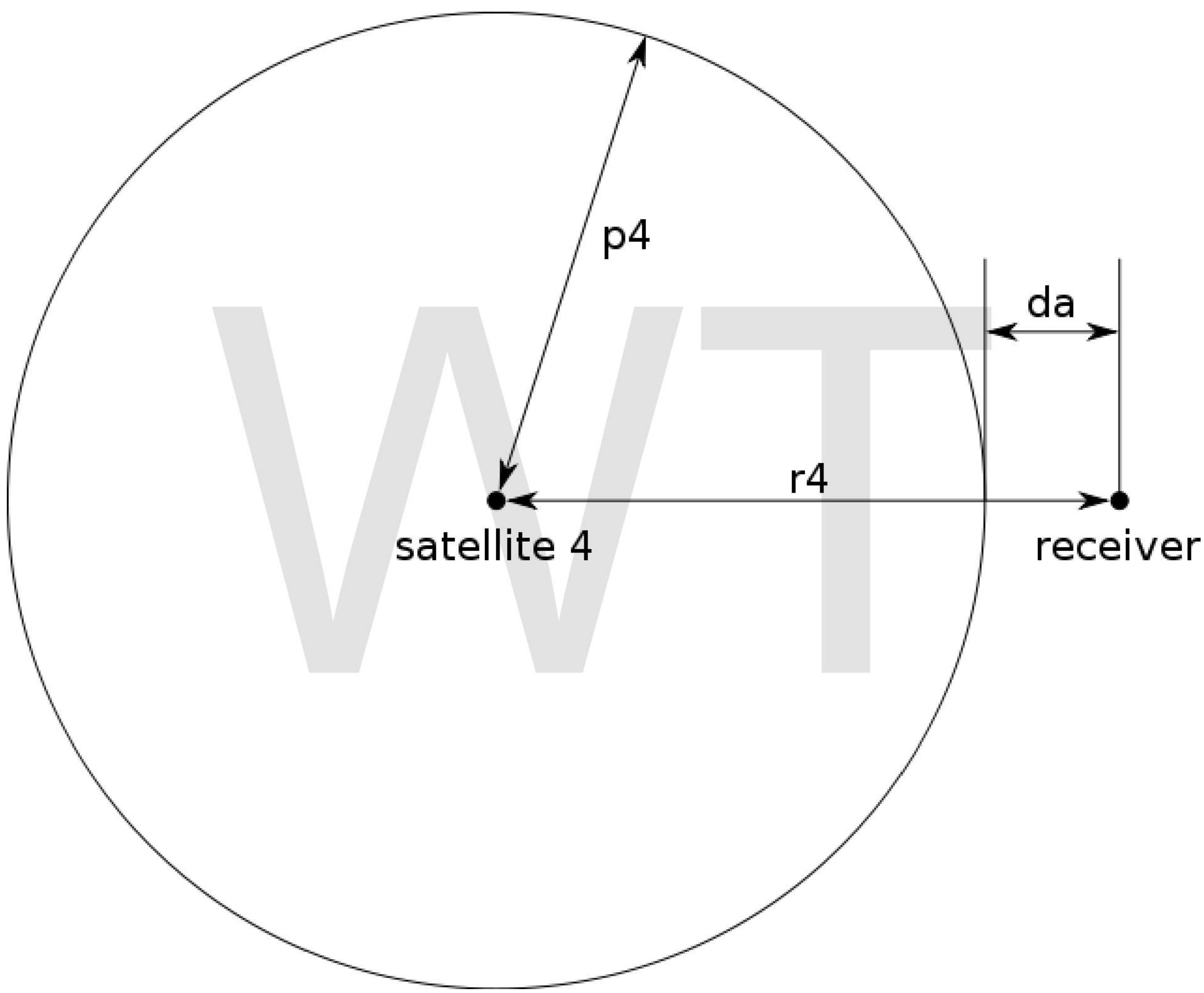


Diagram depicting satellite 4, sphere, p4, r4, and da

It is likely that the surfaces of the three spheres intersect, since the circle of intersection of the first two spheres is normally quite large, and thus the third sphere surface is likely to intersect this large circle. It is very unlikely that the surface of the sphere corresponding to the fourth satellite will intersect either of the two points of intersection of the first three, since any clock error could cause it to miss intersecting a point. However, the distance from the valid estimate of GPS receiver position to the surface of the sphere corresponding to the fourth satellite can be used to compute a clock correction. Let r_4 denote the distance from the valid estimate of GPS receiver position to the fourth satellite and let p_4 denote the pseudorange of the fourth satellite. Let $da = r_4 - p_4$. da is the distance from the computed GPS receiver position to the surface of the sphere corresponding to the fourth satellite. Thus the quotient, $b = da/c$, provides an estimate of

(correct time) – (time indicated by the receiver's on-board clock),

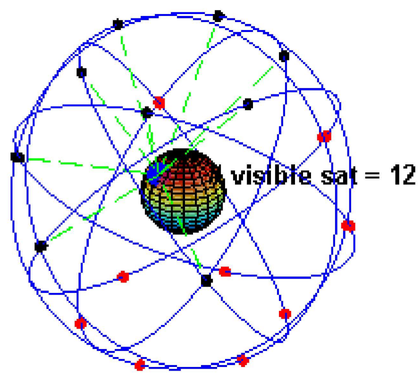
and the GPS receiver clock can be advanced if b is positive or delayed if b is negative. However, it should be kept in mind that a less simple function of da may be needed to estimate the time error in an iterative algorithm as discussed in the Navigation section.

System segmentation

Unlaunched GPS satellite on display at the San Diego Air & Space Museum

The current GPS consists of three major segments. These are the space segment (SS), a control segment (CS), and a user segment (US).

Space segment



A visual example of the GPS constellation in motion with the Earth rotating. Notice how the number of *satellites in view* from a given point on the Earth's surface, in this example at 45°N, changes with time.

The space segment (SS) is composed of the orbiting GPS satellites, or Space Vehicles (SV) in GPS parlance. The GPS design originally called for 24 SVs, eight each in three circular orbital planes, but this was modified to six planes with four satellites each. The orbital planes are centered on the Earth, not rotating with respect to the distant stars. The six planes have approximately 55° inclination (tilt relative to Earth's equator) and are separated by 60° right ascension of the ascending node (angle along the equator from a reference point to the orbit's intersection). The orbits are arranged so that at least six satellites are always within line of sight from almost everywhere on Earth's surface.

Orbiting at an altitude of approximately 20,200 kilometers (about 12,550 miles or 10,900 nautical miles; orbital radius of approximately 26,600 km (about 16,500 mi or 14,400 NM)), each SV makes two complete orbits each sidereal day, repeating the same ground track each day. This was very helpful during development, since even with just four satellites, correct alignment means all four are visible from one spot for a few hours each day. For military operations, the ground track repeat can be used to ensure good coverage in combat zones.

As of March 2008, there are 31 actively broadcasting satellites in the GPS constellation, and two older, retired from active service satellites kept in the constellation as orbital spares. The additional satellites improve the precision of

GPS receiver calculations by providing redundant measurements. With the increased number of satellites, the constellation was changed to a nonuniform arrangement. Such an arrangement was shown to improve reliability and availability of the system, relative to a uniform system, when multiple satellites fail. About eight satellites are visible from any point on the ground at any one time.

Control segment

The control segment is composed of

1. a master control station (MCS),
2. an alternate master control station,
3. four dedicated ground antennas and
4. six dedicated monitor stations.

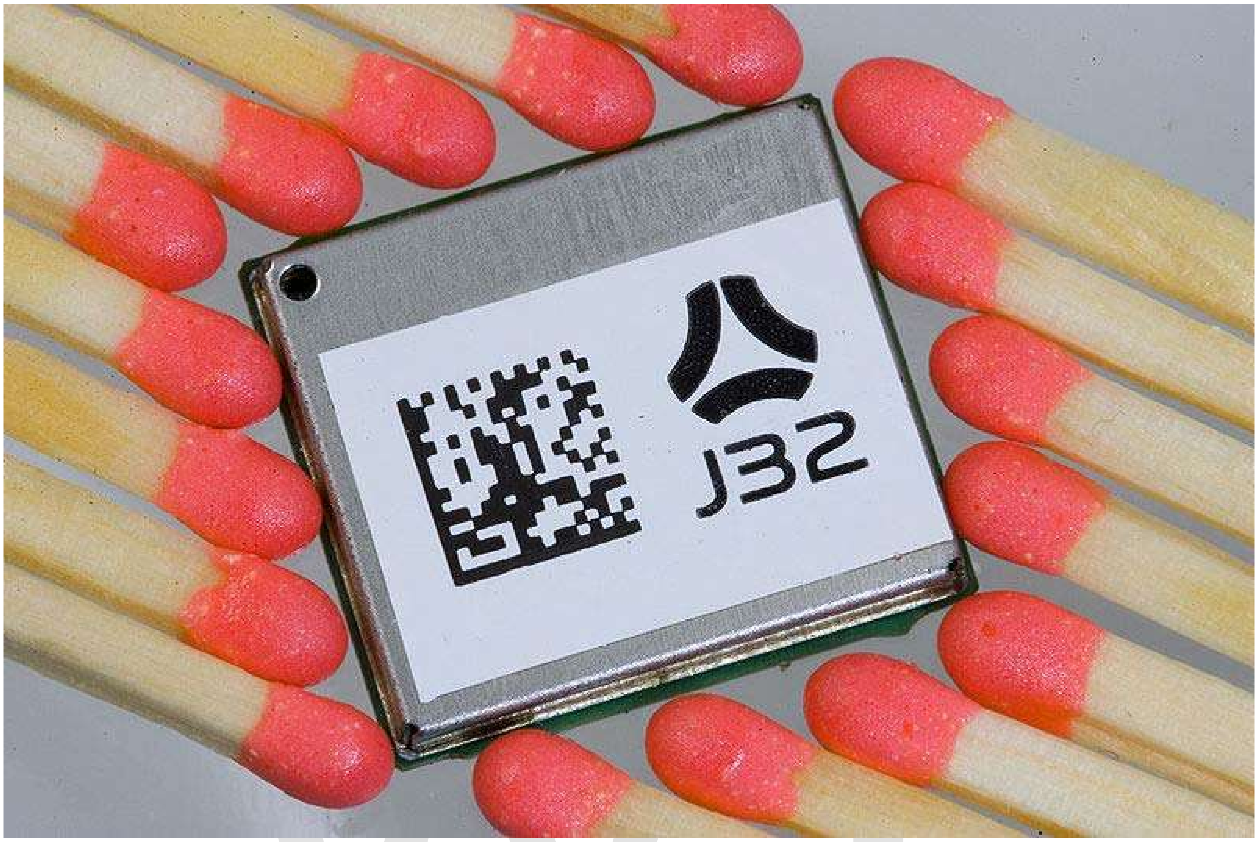
The MCS can also access U.S. Air Force Satellite Control Network (AFSCN) ground antennas (for additional command and control capability) and NGA (National Geospatial-Intelligence Agency) monitor stations. The flight paths of the satellites are tracked by dedicated U.S. Air Force monitoring stations in Hawaii, Kwajalein, Ascension Island, Diego Garcia, Colorado Springs, Colorado and Cape Canaveral, along with shared NGA monitor stations operated in England, Argentina, Ecuador, Bahrain, Australia and Washington DC. The tracking information is sent to the Air Force Space Command's MCS at Schriever Air Force Base 25 km (16 miles) ESE of Colorado Springs, which is operated by the 2nd Space Operations Squadron (2 SOPS) of the United States Air Force (USAF). Then 2 SOPS contacts each GPS satellite regularly with a navigational update using dedicated or shared (AFSCN) ground antennas (GPS dedicated ground antennas are located at Kwajalein, Ascension Island, Diego Garcia, and Cape Canaveral). These updates synchronize the atomic clocks on board the satellites to within a few nanoseconds of each other, and adjust the ephemeris of each satellite's internal orbital model. The updates are created by a Kalman filter, which uses inputs from the ground monitoring stations, space weather information, and various other inputs.

Satellite maneuvers are not precise by GPS standards. So to change the orbit of a satellite, the satellite must be marked *unhealthy*, so receivers will not use it in their calculation. Then the maneuver can be carried out, and the resulting orbit tracked from the ground. Then the new ephemeris is uploaded and the satellite marked healthy again.

User segment

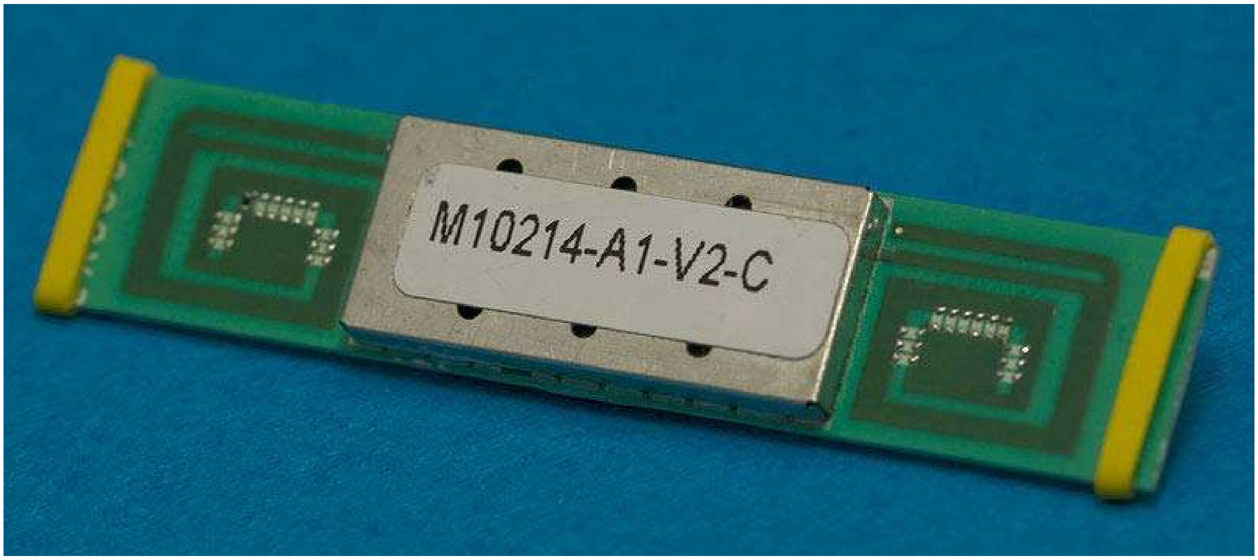
GPS receivers come in a variety of formats, from devices integrated into cars, phones, and watches, to dedicated devices such as those shown here from manufacturers Trimble, Garmin and Leica (left to right).

The user segment is composed of hundreds of thousands of U.S. and allied military users of the secure GPS Precise Positioning Service, and tens of millions of civil, commercial and scientific users of the Standard Positioning Service. In general, GPS receivers are composed of an antenna, tuned to the frequencies transmitted by the satellites, receiver-processors, and a highly stable clock (often a crystal oscillator). They may also include a display for providing location and speed information to the user. A receiver is often described by its number of channels: this signifies how many satellites it can monitor simultaneously. Originally limited to four or five, this has progressively increased over the years so that, as of 2007, receivers typically have between 12 and 20 channels.



A typical OEM GPS receiver module measuring 15×17 mm.

GPS receivers may include an input for differential corrections, using the RTCM SC-104 format. This is typically in the form of an RS-232 port at 4,800 bit/s speed. Data is actually sent at a much lower rate, which limits the accuracy of the signal sent using RTCM. Receivers with internal DGPS receivers can outperform those using external RTCM data. As of 2006, even low-cost units commonly include Wide Area Augmentation System (WAAS) receivers.



A typical GPS receiver with integrated antenna.

Many GPS receivers can relay position data to a PC or other device using the NMEA 0183 protocol, or the newer and less widely used NMEA 2000. Although these protocols are officially defined by the National Marine Electronics Association (NMEA), references to these protocols have been compiled from public records, allowing open source tools like gpsd to read the protocol without violating intellectual property laws. Other proprietary protocols exist as well, such as the SiRF and MTK protocols. Receivers can interface with other devices using methods including a serial connection, USB, or Bluetooth.

Communication

The navigational signals transmitted by GPS satellites encode a variety of information including satellite positions, the state of the internal clocks, and the health of the network. These signals are transmitted on two separate carrier frequencies that are common to all satellites in the network. Two different encodings are used, a public encoding that enables lower resolution navigation, and an encrypted encoding used by the U.S. military.

Message format

GPS message format	
Subframes	**Description**
1	Satellite clock, GPS time relationship
2–3	Ephemeris (precise satellite orbit)
4–5	Almanac component (satellite network synopsys, error correction)

Each GPS satellite continuously broadcasts a *navigation message* at a rate of 50 bits per second. Each complete message is composed of 30-second frames, distinct groupings of 1,500 bits of information. Each frame is further subdivided into 5 subframes of length 6 seconds and with 300 bits each. Each subframe contains 10 words of 30 bits with length 0.6 seconds each. Each 30 second frame begins precisely on the minute or half minute as indicated by the atomic clock on each satellite.

The first part of the message encodes the week number and the time within the week, as well as the data about the health of the satellite. The second part of the message, the *ephemeris*, provides the precise orbit for the satellite. The last part of the message, the *almanac*, contains coarse orbit and status information for all satellites in the network as well as data related to error correction.

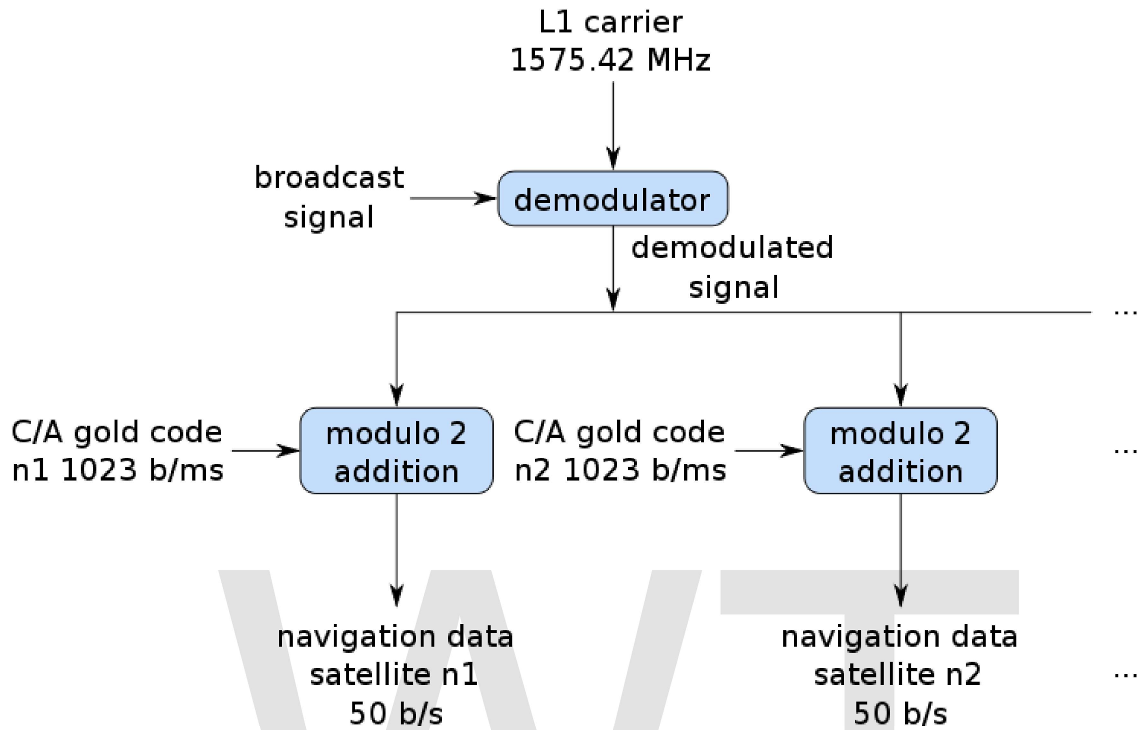
All satellites broadcast at the same frequencies. Signals are encoded using code division multiple access (CDMA) allowing messages from individual satellites to be distinguished from each other based on unique encodings for each satellite (which the receiver must be aware of). Two distinct types of CDMA encodings are used: the coarse/acquisition (C/A) code, which is accessible by the general public, and the precise (P) code, that is encrypted so that only the U.S. military can access it.

The ephemeris is updated every 2 hours and is generally valid for 4 hours, with provisions for updates every 6 hours or longer in non-nominal conditions. The almanac is updated typically every 24 hours. Additionally data for a few weeks following is uploaded in case of transmission updates that delay data upload.

Satellite frequencies

All satellites broadcast at the same two frequencies, 1.57542 GHz (L1 signal) and 1.2276 GHz (L2 signal). The satellite network uses a CDMA spread-spectrum technique where the low-bitrate message data is encoded with a high-rate pseudo-random (PRN) sequence that is different for each satellite. The receiver must be aware of the PRN codes for each satellite to reconstruct the actual message data. The C/A code, for civilian use, transmits data at 1.023 million chips per second, whereas the P code, for U.S. military use, transmits at 10.23 million chips per second. The L1 carrier is modulated by both the C/A and P codes, while the L2 carrier is only modulated by the P code. The P code can be encrypted as a so-called P(Y) code which is only available to military equipment with a proper decryption key. Both the C/A and P(Y) codes impart the precise time-of-day to the user. GPS Modernization added a third frequency, 1.17645 GHZ (L5 signal). The L5 consists of two carrier components that are in phase quadrature with each other. Each carrier component is bi-phase shift key (BPSK) modulated by a separate bit train.

Demodulation and decoding



Demodulating and Decoding GPS Satellite Signals using the Coarse/Acquisition Gold code.

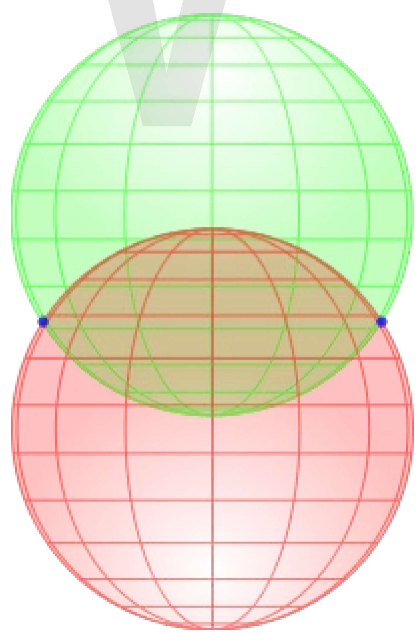
Since all of the satellite signals are modulated onto the same L1 carrier frequency, there is a need to separate the signals after demodulation. This is done by assigning each satellite a unique binary sequence known as a Gold code. The signals are decoded, after demodulation, using addition of the Gold codes corresponding to the satellites monitored by the receiver.

If the almanac information has previously been acquired, the receiver picks which satellites to listen for by their PRNs, unique numbers in the range 1 through 32. If the almanac information is not in memory, the receiver enters a search mode until a lock is obtained on one of the satellites. To obtain a lock, it is necessary that there be an unobstructed line of sight from the receiver to the satellite. The receiver can then acquire the almanac and determine the satellites it should listen for. As it detects each satellite's signal, it identifies it by its distinct C/A code pattern. There can be a delay of up to 30 seconds before the first estimate of position because of the need to read the ephemeris data.

Processing of the navigation message enables the determination of the time of transmission and the satellite position at this time.

Navigation equations

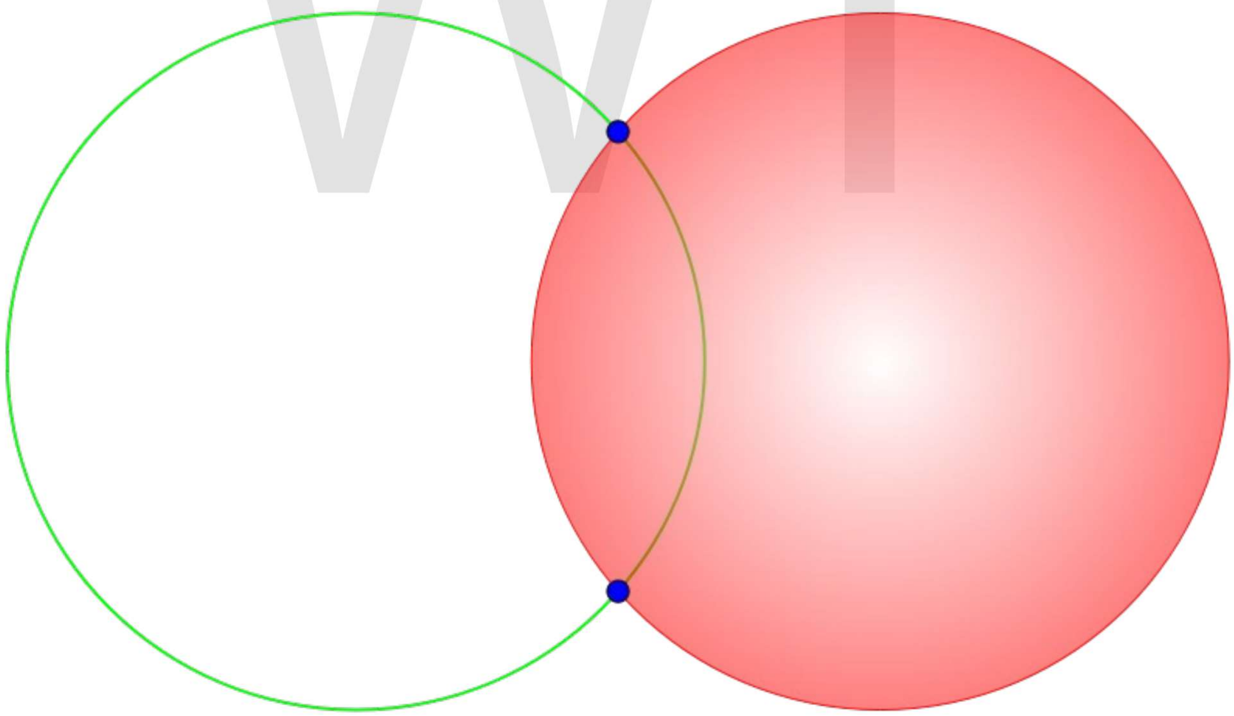
The receiver uses messages received from four satellites to determine the satellite positions and time sent. The *x, y,* and *z* components of position and the time sent are designated as $[x_i, y_i, z_i, t_i]$where the subscript *i* denotes the satellite and has the value 1, 2, 3, or 4. Knowing when the message was received tr_i, the receiver computes the message's transit time as $(tr_i - t_i)$. Assuming the message traveled at the speed of light (c) the distance traveled, $p_i$is $(tr_i - t_i)\,c$. Knowing the distance from receiver to satellite and the satellite's position implies that the receiver is on the surface of a sphere centered at the satellite's position. Thus the receiver is at or near the intersection of the surfaces of four spheres. In the ideal case of no errors, the receiver is at the intersection of the surfaces of four spheres. Excluding the unrealistic case (for GPS purposes) of two coincident spheres, the surfaces of two intersecting spheres is either a point (if they merely touch) or a circle as depicted in the illustration below. Two of the points at which the surfaces of the spheres intersect are clearly marked on the figure. The distance between these two points is the diameter of the circle of intersection.



Two sphere surfaces intersecting in a circle

This can be seen more clearly by considering a side view of the intersecting spheres. This view would match the figure because of the symmetry of the spheres. A view from any horizontal direction would look exactly the same. Therefore the diameter as seen from all directions is the same and thus the surfaces actually do intersect in a circle. Trilateration algebraically confirms this geometric argument that the two sphere surfaces intersect in a circle.

Having found that two sphere surfaces intersect in a circle, we now consider how the intersection of the first two sphere surfaces, the circle, intersect with the third sphere. A circle and sphere surface intersect at zero, one or two points. For the GPS problem we are concerned with the case of two points of intersection. Another figure, Surface of Sphere Intersecting a Circle (not a solid disk) at Two Points, is shown below to aid in visualizing this intersection. Trilateration algebraically confirms this geometric observation. The ambiguity of two points of intersection of three sphere surfaces can be resolved by noting which point is closest to the fourth sphere surface.



Surface of a sphere intersecting a circle (i.e., the edge of a disk) at two points

Having provided a discussion of how sphere surfaces intersect, we now formulate the equations for the case when errors are present.

Let b denote the clock error or bias, the amount by which the receiver's clock is off. The receiver has four unknowns, the three components of GPS receiver position and the clock bias $[x, y, z, b]$. The equation of the sphere surfaces are given by:

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = \left([tr_i + b - t_i]c\right)^2,$$

$$i = 1, 2, 3, 4$$

Another useful form of these equations is in terms of *pseudoranges*, which are the approximate ranges based on the receiver clock's uncorrected time so that $p_i = (tr_i - t_i)\, c$. Then the equations becomes:

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - bc,\ i = 1, 2, 3, 4.$$

Methods of solution of navigation equations

- Bancroft's method is perhaps the most important method of solving the navigation equations since it involves an algebraic as opposed to numerical method. The method requires at least four satellites but more can be used.

Two numerical methods of computing GPS receiver position and clock bias are (1) by using trilateration and one dimensional numerical root finding and (2) multidimensional Newton-Raphson calculations.

- The receiver can solve by trilateration and one dimensional numerical root finding. Trilateration determines the intersection of the surfaces of three spheres. In the usual case of two intersections, the point nearest the surface of the sphere corresponding to the fourth satellite is chosen. The Earth's surface can also sometimes be used instead, especially by civilian GPS receivers, since it is illegal in the United States to track vehicles more than 60,000 feet (18,000 m) in altitude. Let da denote the signed magnitude of the vector from the receiver position to the fourth satellite (i.e. da = r4 - p4) as defined in the section "Clock correction". da is a function of the correction since the correction changes the satellite transmission times and thus the pseudoranges. The notation, da(correction) denotes this function. The problem is to determine the correction such that

$$da\,(correction) = 0.$$

This is the familiar problem of finding the zeroes of a one dimensional non-linear function of a scalar variable. Iterative numerical methods, such as those found in the chapter on root finding in *Numerical Recipes* can solve this type of problem. One advantage of this method is that it involves one dimensional as opposed to multidimensional numerical root finding.

- Alternatively, multidimensional root finding method such as Newton-Raphson method can be used. The approach is to linearize around an approximate solution, say $\left[x^{(k)}, y^{(k)}, z^{(k)}, b^{(k)}\right]$ from iteration *k,* then solve four linear equations derived from the quadratic equations above to obtain $\left[x^{(k+1)}, y^{(k+1)}, z^{(k+1)}, b^{(k+1)}\right]$. The Newton-Raphson method is more rapidly convergent than other methods of numerical root finding. A disadvantage of this multidimensional root finding method as compared to single dimensional root findiing is that, "There are no good general methods for solving systems of more than one nonlinear equations."

- When more than four satellites are available, the calculation can use the four best or more than four, considering number of channels, processing capability, and geometric dilution of precision (GDOP). Using more than four is an over-determined system of equations with no unique solution, which must be solved by least-squares or a similar technique. If all visible satellites are used, the results are as good as or better than using the four best. Errors can be estimated through the residuals. With each combination of four or more satellites, a GDOP factor can be calculated, based on the relative sky directions of the satellites used. As more satellites are picked up, pseudoranges from various 4-way combinations can be processed to add more estimates to the location and clock offset. The receiver then takes the weighted average of these positions and clock offsets. After the final location and time are calculated, the location is expressed in a specific coordinate system such as latitude and longitude, using the WGS 84 geodetic datum or a country-specific system.

- Finally, results from other positioning systems such as GLONASS or the upcoming Galileo can be incorporated or used to check the result. (By design, these systems use the same frequency bands, so much of the receiver circuitry can be shared, though the decoding is different.)

Error sources and analysis

The positioning data provided directly by the satellites is extremely precise but there are many factors that can create make the errors in the data non-trivial. In situations where high accuracy is necessary, understanding and compensating for these sources of error is important. Sources of error include atmospheric distortion (predominantly in the ionosphere), satellite clock inaccuracies, and the travel delays of the satellite signals.

The analysis of errors in the information reported by the Global Positioning System, a space-based satellite system for navigation, is important to estimating the accuracy of position estimates and correcting for the errors. The Global Positioning System (GPS) was created by the United States Department of Defense (DOD) in the 1970s. It has come to be widely used for navigation both by the U.S. military and the general public.

Accuracy enhancement and surveying

Augmentation

Integrating external information into the calculation process can materially improve accuracy. Such augmentation systems are generally named or described based on how the information arrives. Some systems transmit additional error information (such as clock drift, ephemera, or ionospheric delay), others characterize prior errors, while a third group provides additional navigational or vehicle information.

Examples of augmentation systems include the Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay Service (EGNOS), Differential GPS, Inertial Navigation Systems (INS) and Assisted GPS.

Precise monitoring

Accuracy can be improved through precise monitoring and measurement of existing GPS signals in additional or alternate ways.

The largest remaining error is usually the unpredictable delay through the ionosphere. The spacecraft broadcast ionospheric model parameters, but errors remain. This is one reason GPS spacecraft transmit on at least two frequencies, L1 and L2. Ionospheric delay is a well-defined function of frequency and the total electron content (TEC) along the path, so measuring the arrival time difference between the frequencies determines TEC and thus the precise ionospheric delay at each frequency.

Military receivers can decode the P(Y)-code transmitted on both L1 and L2. Without decryption keys, it is still possible to use a *codeless* technique to compare the P(Y) codes on L1 and L2 to gain much of the same error information. However, this technique is slow, so it is currently available only on specialized surveying equipment. In the future, additional civilian codes are expected to be transmitted on the L2 and L5 frequencies. Then all users will be able to perform dual-frequency measurements and directly compute ionospheric delay errors.

A second form of precise monitoring is called *Carrier-Phase Enhancement* (CPGPS). This corrects the error that arises because the pulse transition of the PRN is not instantaneous, and thus the correlation (satellite-receiver sequence matching) operation is imperfect. CPGPS utilizes the L1 carrier wave, which has a period of $\frac{1 \text{ sec}}{1575.42 * 10^6} = 0.63475 \text{ nanoseconds} \approx 1 \text{ nanosecond}$ which is about one-thousandth of the C/A Gold code bit period of $\frac{1 \text{ sec}}{1023 * 10^3} = 977.5 \text{ nanosecond } \approx 1000 \text{ nanosecond}$, to act as an additional clock signal and resolve the uncertainty. The phase difference error in the normal GPS amounts to 2–3 metres (6.6–9.8 ft) of ambiguity. CPGPS working to within 1% of perfect transition reduces this error to 3 centimeters (1.2 in) of ambiguity. By eliminating this error source, CPGPS coupled with DGPS normally realizes between 20–30 centimetres (7.9–12 in) of absolute accuracy.

Relative Kinematic Positioning (RKP) is a third alternative for a precise GPS-based positioning system. In this approach, determination of range signal can be resolved to a precision of less than 10 centimeters (3.9 in). This is done by resolving the number of cycles in which the signal is transmitted and received by the receiver. This can be accomplished by using a combination of differential GPS (DGPS) correction data, transmitting GPS signal phase information and ambiguity resolution techniques via statistical tests—possibly with processing in real-time (real-time kinematic positioning, RTK).

Timekeeping

While most clocks are synchronized to Coordinated Universal Time (UTC), the atomic clocks on the satellites are set to *GPS time*. The difference is that GPS time is not corrected to match the rotation of the Earth, so it does not contain leap seconds or other corrections that are periodically added to UTC. GPS time was set to match Coordinated Universal Time (UTC) in 1980, but has since diverged. The lack of corrections means that GPS time remains at a constant offset with International Atomic Time (TAI) (TAI - GPS = 19 seconds). Periodic corrections are performed on the on-board clocks to correct relativistic effects and keep them synchronized with ground clocks.

The GPS navigation message includes the difference between GPS time and UTC, which as of 2009 is 15 seconds due to the leap second added to UTC December 31, 2008. Receivers subtract this offset from GPS time to calculate UTC and specific timezone values. New GPS units may not show the correct UTC time until after receiving the UTC offset message. The GPS-UTC offset field can accommodate 255 leap seconds (eight bits) which, given the current rate of change of the Earth's rotation (with one leap second introduced approximately every 18 months), should be sufficient to last until approximately the year 2300.

As opposed to the year, month, and day format of the Gregorian calendar, the GPS date is expressed as a week number and a seconds-into-week number. The week number is transmitted as a ten-bit field in the C/A and P(Y) navigation messages, and so it becomes zero again every 1,024 weeks (19.6 years). GPS week zero started at 00:00:00 UTC (00:00:19 TAI) on January 6, 1980, and the week number became zero again for the first time at 23:59:47 UTC on August 21, 1999 (00:00:19 TAI on August 22, 1999). To determine the current Gregorian date, a GPS receiver must be provided with the approximate date (to within 3,584 days) to correctly translate the GPS date signal. To address this concern the modernized GPS navigation message uses a 13-bit field, which only repeats every 8,192 weeks (157 years), thus lasting until the year 2137 (157 years after GPS week zero).

Carrier phase tracking (surveying)

Another method that is used in surveying applications is carrier phase tracking. The period of the carrier frequency times the speed of light gives the wavelength, which is about 0.19 meters for the L1 carrier. Accuracy within 1% of wavelength in detecting the leading edge, reduces this component of pseudorange error to as little as 2 millimeters. This compares to 3 meters for the C/A code and 0.3 meters for the P code.

However, 2 millimeter accuracy requires measuring the total phase—the number of waves times the wavelength plus the fractional wavelength, which requires specially equipped receivers. This method has many surveying applications.

Triple differencing followed by numerical root finding, and a mathematical technique called least squares can estimate the position of one receiver given the position of another. First, compute the difference between satellites, then between receivers, and finally between epochs. Other orders of taking differences are equally valid.

The satellite carrier total phase can be measured with ambiguity as to the number of cycles. Let $\phi(r_i, s_j, t_k)$denote the phase of the carrier of satellite *j* measured by receiver *i* at time t_k. This notation shows the meaning of the subscripts *i, j,* and *k.* The receiver (*r*), satellite (*s*), and time (*t*) come in alphabetical order as arguments of $\phi$and to balance readability and conciseness, let $\phi_{i,j,k} = \phi(r_i, s_j, t_k)$be a concise abbreviation. Also we define three functions, :$\Delta^r, \Delta^s, \Delta^t$, which return differences between receivers, satellites, and time points, respectively. Each function has variables with three subscripts as its arguments. These three functions are defined below. If $\alpha_{i,j,k}$is a function of the three integer arguments, *i, j,* and *k* then it is a valid argument for the functions, :$\Delta^r, \Delta^s, \Delta^t$, with the values defined as

$$\Delta^r(\alpha_{i,j,k}) = \alpha_{i+1,j,k} - \alpha_{i,j,k},$$

$$\Delta^s(\alpha_{i,j,k}) = \alpha_{i,j+1,k} - \alpha_{i,j,k}, \text{ and}$$

$$\Delta^t(\alpha_{i,j,k}) = \alpha_{i,j,k+1} - \alpha_{i,j,k}.$$

Also if $\alpha_{i,j,k}\ and\ \beta_{l,m,n}$are valid arguments for the three functions and *a* and *b* are constants then $(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n})$is a valid argument with values defined as

$$\Delta^r(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n}) = a\ \Delta^r(\alpha_{i,j,k}) + b\ \Delta^r(\beta_{l,m,n}),$$

$$\Delta^s(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n}) = a\ \Delta^s(\alpha_{i,j,k}) + b\ \Delta^s(\beta_{l,m,n}), \text{ and}$$

$$\Delta^t(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n}) = a\ \Delta^t(\alpha_{i,j,k}) + b\ \Delta^t(\beta_{l,m,n}).$$

Receiver clock errors can be approximately eliminated by differencing the phases measured from satellite 1 with that from satellite 2 at the same epoch. This difference is designated as $\Delta^s(\phi_{1,1,1}) = \phi_{1,2,1} - \phi_{1,1,1}$

Double differencing computes the difference of receiver 1's satellite difference from that of receiver 2. This approximately eliminates satellite clock errors. This double difference is:

$$\Delta^r(\Delta^s(\phi_{1,1,1})) = \Delta^r(\phi_{1,2,1} - \phi_{1,1,1}) = \Delta^r(\phi_{1,2,1}) - \Delta^r(\phi_{1,1,1}) = (\phi_{2,2,1} - \phi_{1,2,1}) - (\phi_{2,1,1} - \phi_{1,1,1})$$

Triple differencing subtracts the receiver difference from time 1 from that of time 2. This eliminates the ambiguity associated with the integral number of wave lengths in carrier phase provided this ambiguity does not change with time. Thus the triple difference result eliminates practically all clock bias errors and the integer ambiguity. Atmospheric delay and satellite ephemeris errors have been significantly reduced. This triple difference is:

$$\Delta^t(\Delta^r(\Delta^s(\phi_{1,1,1})))$$

Triple difference results can be used to estimate unknown variables. For example if the position of receiver 1 is known but the position of receiver 2 unknown, it may be possible to estimate the position of receiver 2 using numerical root finding and least squares. Triple difference results for three independent time pairs quite possibly will be sufficient to solve for receiver 2's three position components. This may require the use of a numerical procedure. An approximation of receiver 2's position is required to use such a numerical method. This initial value can probably be provided from the navigation message and the intersection of sphere surfaces. Such a reasonable estimate can be key to successful multidimensional root finding. Iterating from three time pairs and a fairly good initial value produces one observed triple difference result for receiver 2's position. Processing additional time pairs can improve accuracy, overdetermining the answer with multiple solutions. Least squares can estimate an overdetermined system. Least squares determines the position of receiver 2 which best fits the observed triple difference results for receiver 2 positions under the criterion of minimizing the sum of the squares.

Other systems

Other satellite navigation systems in use or various states of development include:

- Galileo – a global system being developed by the European Union and other partner countries, planned to be operational by 2014
- Beidou – People's Republic of China's regional system, covering Asia and the West Pacific
- COMPASS – People's Republic of China's global system, planned to be operational by 2020
- GLONASS – Russia's global navigation system
- IRNSS – India's regional navigation system, planned to be operational by 2012, covering India and Northern Indian Ocean
- QZSS – Japanese regional system covering Asia and Oceania

Galileo (satellite navigation)

Galileo logo

Galileo is a global navigation satellite system (GNSS) currently being built by the European Union (EU) and European Space Agency (ESA). The €3.4 billion project is an alternative and a complement to the U.S. NAVSTAR Global Positioning

System (GPS) and the Russian GLONASS. On 30 November 2007 the 27 EU transportation ministers involved reached an agreement that it should be operational by 2013, but later press releases suggest it was delayed to 2014.

When in operation, it will have two ground operations centers, one near Munich, Germany, and another in Fucino, 130 km east of Rome, Italy. Since 18 May 2007, at the recommendation of Transport Commissioner Jacques Barrot, the EU took direct control of the Galileo project from the private sector group of eight companies called European Satellite Navigation Industries, which had abandoned this Galileo project in early 2007.

Galileo was intended to provide more precise measurements than available through GPS or GLONASS (Galileo will be accurate down to the metre range) including the height (altitude) above sea level, and better positioning services at high latitudes. The political aim is to provide an independent positioning system upon which European nations can rely even in times of war or political disagreement, since Russia or the USA could disable use of their national systems by others (through encryption). Unfortunately due to continued delays in the planning and development of Galileo, the incremental capability of the system relative to both GPS and GLONASS has decayed significantly since the inception of the project. Arguably the real contribution of the Galileo program thus far has been in motivating a faster upgrade schedule for both GPS and GLONASS. While the Galileo specifications are still superior to those of GLONASS, since 2008 the signal in space errors of the GPS constellation have been below the 1-metre level promised by Galileo while during the same timeframe the GLONASS constellation has been completely repopulated with modernized satellites. Both systems have also made improvements to reliability, and while not eliminating the impetus for Galileo safety of life signals, the relative advantage of this promised feature has also been greatly reduced over the last decade.

Like the US GPS, use of basic (low-accuracy) Galileo services will be free and open to everyone. However, the high-accuracy capabilities will be restricted to military use and paying commercial users.

Named for the Italian astronomer Galileo Galilei, the positioning system is officially referred to as just *Galileo*. It is also sometimes colloquially described as the *Galileo positioning system*; however, since this abbreviates to GPS, the shorter astronomer's name is preferred to avoid confusion with Navstar GPS.

History

In 1999, the different concepts (from Germany, France, Italy and the United Kingdom) for Galileo were compared and reduced to one by a joint team of engineers from all four countries. The first stage of the Galileo programme was agreed upon officially on 26 May 2003 by the European Union and the European Space Agency. The system is intended primarily for civilian use, unlike the United States system, which the U.S. military runs and uses on a primary basis. The U.S. reserves the right to limit the signal strength or accuracy of the GPS systems, or to shut down public GPS access completely (although it has never done the latter), so that only the U.S. military and its allies would be able to use it in time of conflict. Until 2000, the precision of the signal available to non-U.S.-military users was limited (due to a timing pulse distortion process known as *selective availability*). The European system will only be subject to shutdown for military purposes in extreme circumstances. It will be available at its full precision to both civil and military users.

The European Commission had some difficulty getting money for the project's next stage, after several allegedly "per annum" sales projection graphs for the project were exposed in November 2001 as "cumulative" projections (which for each year projected, necessarily included all previous years of sales). The attention that was brought to this multi-billion euro exponentially growing error in sales forecasts resulted in a general awareness in the Commission and elsewhere that the program did not have near the return on investment that had been presented to the investors and decision-makers up until that point. Additionally, following the September 11, 2001 attacks, the United States Government wrote to the European Union opposing the project, arguing that it would end the ability of the United States to shut down GPS in times of military operations. On 17 January 2002 a spokesman for the project stated that, as a result of U.S. pressure and economic difficulties, "Galileo is almost dead." A few months later, however, the situation changed dramatically. Partially in reaction to the pressure exerted by the U.S. Government, European Union member states decided it was important to have a satellite-based positioning and timing infrastructure that the US could not easily turn off in times of political conflict.

The European Union and the European Space Agency agreed in March 2002 to fund the project, pending a review in 2003 (which was finalised on 26 May 2003). The starting cost for the period ending in 2005 is estimated at €1.1 billion. The required satellites (the planned number is 30) will be launched throughout the period 2006–2010 and the system will be up and running and under civilian control from 2010. The final cost is estimated at €3 billion, including the infrastructure on Earth, which is to be constructed in the years 2006 and 2007. The plan was for private companies and investors to invest at least two-thirds of the cost of implementation, with the EU and ESA dividing the remaining cost. An encrypted higher-bandwidth *Commercial Service* with improved accuracy would be available at an extra cost, with the base *Open Service* freely available to anyone with a Galileo-compatible receiver.

In June 2004, in a signed agreement with the United States, the European Union agreed to switch to a modulation known as BOC(1,1) (Binary Offset Carrier 1.1) allowing the coexistence of both GPS and Galileo, and the future combined use of both systems. The European Union also agreed to address the "mutual concerns related to the protection of allied and U.S. national security capabilities."

Early 2007, the EU had yet to decide how to pay for the system and the project was said to be "in deep crisis" due to lack of more public funds. German Transport Minister Wolfgang Tiefensee, was particularly doubtful about the consortium's ability to end the infighting at a time when only one testbed satellite had been successfully launched.

Although a decision was yet to be reached, EU countries on Friday the 13th of July 2007 discussed cutting €548m ($755m, £370m) from the union's competitiveness budget for next year and shift some of that cash to other parts of the financing pot, a move that could meet part of the cost of the union's Galileo satellite navigation system. European Union research and development projects could be scrapped to overcome a funding shortfall.

In November 2007, it was agreed to reallocate funds from the EU's agriculture and administration budgets and to soften the tendering process in order to invite more EU companies.

In April 2008, the EU transport ministers approved the Galileo Implementation Regulation. This allowed the €3.4bn to be released from the EU's agriculture and administration budgets. This will allow the issuing of contracts to start construction of the ground station and the satellites.

In June 2009 European Court of Auditors published a report, pointing out governance issues, substantial delays and budget overruns that led to project stalling in 2007, leading to further delays and failures.

In October 2009 European Commission cut number of satellites to from 28 to 22 with plans to order remaining 6 at later time. It also announced that first OS, PRS and SoL signal will be available in 2013 and the CS and SOL sometime later. Current budget for 2006-2013 period planned for €3.4 billion was also considered as insufficient.

In November 2009, a ground station for Galileo was inaugurated near Kourou (French Guiana).

The launch of the first two of four in-orbit validation (IOV) satellites is currently planned for the end of April 2011, while the launch of full operational capability (FOC) satellites is planned to start in late 2012.

As of March 2010 it was verified that the budget for Galileo would only be available to provide the 4 IOV and 14 FOC satellites by 2014, with no funds currently committed to bring the constellation above this 60% capacity. Paul Verhoef, the then current satellite navigation program manager at the European Commission indicated that this limited funding would have serious consequences commenting at one point "To give you an idea, that would mean that for three weeks in the year you will not have satellite navigation" in reference to the currently proposed 18 vehicle constellation.

International involvement

In September 2003, China joined the Galileo project. China was to invest €230 million (USD 302 million, GBP 155 million, CNY 2.34 billion) in the project over the following years.

In July 2004, Israel signed an agreement with the EU to become a partner in the Galileo project.

On 3 June 2005 the EU and Ukraine signed an agreement for Ukraine to join the project, as noted in a press release.

As of November 2005, Morocco have also joined the programme.

On 12 January 2006, South Korea joined the programme.

In November 2006, China abandoned the programme and decided to develop an independent global navigation system: Beidou navigation system.

On 30 November 2007, the 27 member states of the European Union unanimously agreed to move forward with the project, with plans for bases in Germany and Italy. Spain did not approve during the initial vote, but approved it later that day. This greatly improves the viability of the Galileo project: "The EU's executive had previously said that if agreement was not reached by January 2008, the long-troubled project would essentially be dead."

On 3 April 2009, Norway too joined the programme pledging €68.9 million toward development costs and allowing its companies to bid for the construction contracts. Norway while not a member of the EU is a member of the ESA.

Political implications of Galileo project

Tension with the United States

Galileo is intended to be an EU GNSS civilian system that allows all users access to it. GPS is a US GNSS military system that provides location signals that have high accuracy to US military users, while also providing somewhat accurate location signals to others. The GPS had the capability to block the "civilian" signals while still being able to use the "military" signal (M-band). A primary motivation for the Galileo project was international concern that the US could deny others access to GPS during political disagreements.

Since Galileo was designed to provide the highest possible accuracy (possibly even greater than GPS) to anyone, the US was concerned that an enemy could use Galileo signals in military strikes against the US (some weapons like missiles use GNSS systems for guidance). The frequency initially chosen for Galileo would have made it impossible for the US to block the Galileo signals without also interfering with their own GPS signals. The US did not want to lose their GNSS capability with GPS while denying enemies the use of GNSS. Some US officials became especially concerned when Chinese interest in Galileo was reported.

Some US officials have threatened to potentially shoot down Galileo satellites in the event of a major conflict in which Galileo was used in attacks against American forces. The EU's stance is that Galileo is a neutral technology, available to all countries and everyone. Originally, EU officials did not want to change their original plans for Galileo, but have since reached a compromise, that Galileo was to use a different frequency. This allowed the blocking/jamming of one GNSS system without affecting the other, giving the US a greater advantage in conflicts in which it has the electronic warfare upper hand.

GPS and Galileo

One of the reasons given for developing Galileo as an independent system was that GPS is widely used worldwide for civilian applications, which until 2000 had Selective Availability (SA) enabled (and could be re-enabled). This could intentionally render the locations given via GPS inaccurate. Galileo's proponents argued that civil infrastructure, including aeroplane navigation and landing, should not rely solely upon GPS.

On May 1, 2000, SA was disabled by the then President of the United States Bill Clinton, and in late 2001, the entity managing the GPS confirmed that they never intend to enable selective availability again. Though Selective Availability still exists, on 19 September 2007, the US Department of Defense announced that the new GPS satellites will not be capable of implementing Selective Availability. This means the next wave of Block IIF satellites launching in 2009 will not support SA. As old satellites are replaced in the GPS modernization program, SA will cease to exist. The modernization programme also contains standardized features that allow GPS III and Galileo systems to inter-operate, allowing a new receiver to utilise both systems to improve accuracy. By combining GPS and Galileo, it can create an even more accurate GNSS system.

Final system description

Galileo satellites

- 30 in-orbit spacecraft (including 3 spares)
- orbital altitude: 23,222 km (MEO)
- 3 orbital planes, 56° inclination, ascending nodes separated by 120° longitude (9 operational satellites and one active spare per orbital plane)
- satellite lifetime: >12 years
- satellite mass: 675 kg
- satellite body dimensions: 2.7 m x 1.2 m x 1.1 m
- span of solar arrays: 18.7 m
- power of solar arrays: 1,500 W (end of life)

Services

The Galileo system will have five main services:

- **Open Access Navigation**: This will be 'free to air' and for use by the mass market; Simple timing and positioning down to 1 meter.
- **Commercial Navigation** (Encrypted): High accuracy to the centimeter; Guaranteed service for which service providers will charge fees.
- **Safety Of Life Navigation**: Open service; For applications where guaranteed accuracy is essential; Integrity messages will warn of errors.
- **Public Regulated Navigation** (Encrypted): Continuous availability even in time of crisis; Government agencies will be main users.
- **Search And Rescue**: System will pick up distress beacon locations; Feasible to send feedback, confirming help is on its way.

Other secondary services will also be available.

The concept

Each satellite will have two types of atomic clocks 4 in total (2 rubidium frequency standards and 2 passive hydrogen masers) - critical to any sat-nav system and a number of other components. These clocks will provide an accurate timing signal for a receiver to calculate the time that it takes the signal to reach the target. This information is used to calculate the position of the receiver by triangulating the difference in received signals from multiple satellites.

Satellite system

Galileo satellite test beds: GIOVE

GIOVE-A was successfully launched 28 December 2005.

In 2004 the Galileo System Test Bed Version 1 (GSTB-V1) project validated the on-ground algorithms for Orbit Determination and Time Synchronisation (OD&TS). This project, led by ESA and European Satellite Navigation Industries, has provided industry with fundamental knowledge to develop the mission segment of the Galileo positioning system.

- GIOVE-A is the first GIOVE (Galileo In-Orbit Validation Element) test satellite. It was built by Surrey Satellite Technology Ltd (SSTL), and successfully launched on 28 December 2005 by the European Space Agency and the Galileo Joint. Operation of GIOVE-A ensured that Galileo meets the frequency-filing allocation and reservation requirements for the International Telecommunication Union (ITU), a process that was required to be complete by June 2006.

- GIOVE-B, built by Astrium and Thales Alenia Space, has a more advanced payload than GIOVE-A. It was successfully launched on 27 April 2008 at 22:16 UTC (4.16 a.m. (Baikonur time) aboard a Soyuz-FG/Fregat rocket provided by Starsem.

A third satellite, GIOVE-A2, was originally planned to be built by SSTL for launch in the second half of 2008. Construction of GIOVE-A2 was terminated due to the successful launch and in-orbit operation of GIOVE-B.

The GIOVE Mission segment operated by European Satellite Navigation Industries is exploiting the GIOVE-A/B satellites to provide experimental results based on real data to be used for risk mitigation for the IOV satellites that will follow on from the testbeds. ESA organised the global network of ground stations to collect the measurements of GIOVE-A/B with the use of the GETR receivers for further systematic study. GETR receivers are supplied by Septentrio as well as the first Galileo navigation receivers to be used to test the functioning of the system at further stages of its deployment. Signal analysis of GIOVE-A/B data has confirmed successful operation of all the Galileo signals with the tracking performance as expected.

In-Orbit Validation (IOV) satellites

These testbed satellites will be followed by four IOV Galileo satellites that will be much closer to the final Galileo satellite design. The launch of the first pair of satellites is scheduled in April 2011. Once this In-Orbit Validation (IOV) phase has been completed, the remaining satellites will be installed to reach the Full Operational Capability.

Full Operational Capability (FOC) satellites

On 7 January 2010, it was announced that the contract to build the first 14 FOC satellites was awarded to OHB System and Surrey Satellite Technology Limited (SSTL). Fourteen satellites will be built at a cost of 566M euros ($811M; £510M). The first two are expected to be ready in October 2012. Arianespace will launch the satellites for a cost of 397M euros ($569M; £358M).

The European Commission announced also that the contract of 85 million euros for the System support covering industrial services required by ESA for integration and validation of Galileo System was awarded to Thales Alenia Space. Thales Alenia Space subcontract performances to Astrium Gmbh and security to Thales Communications.

Science projects using Galileo

In July 2006, an international consortium of universities and research institutions embarked on a study of potential scientific applications of the Galileo constellation. This project, dubbed GEO6, is a 360-degree study oriented to the scientific community in its broader sense, aiming to define and implement new applications of Galileo.

Among the various GNSS users identified by the Galileo Joint Undertaking, the GEO6 project addresses the Scientific User Community (UC).

The GEO6 project aims at fostering possible novel applications within the scientific UC of GNSS signals, and particularly of Galileo.

The AGILE project is an EU-funded project devoted to the study of the technical and commercial aspects of Location-based Services (LBS). It includes technical analysis of the benefits brought by Galileo (and EGNOS); also studying the hybridisation of Galileo with other positioning technologies (network-based, WLAN, etc.). Within these project, some pilot prototypes were implemented and demonstrated.

On the basis of the potential number of users, potential revenues for Galileo Operating Company or Concessionaire (GOC), international relevance, and level of innovation, a set of Priority Applications (PA) will be selected by the consortium and they will be developed within the time frame of the same Project.

These applications will help to increase and optimise the use of the EGNOS services as well as the opportunities offered by the Galileo Signal Test-Bed (GSTB-V2) and the Galileo (IOV) phase.

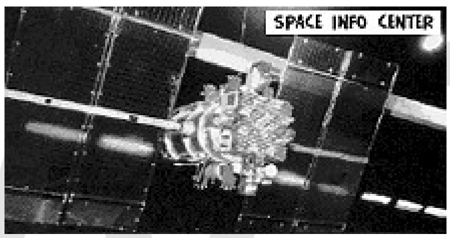
Coins

European Satellite Navigation commemorative coin

The European Satellite Navigation project was selected as the main motif of a very high value collectors' coin: the Austrian European Satellite Navigation commemorative coin, minted on 1 March 2006. The coin has a silver ring and niobium “pill”, colour gold-brown. In the reverse, the niobium portion depicts navigation satellites orbiting the Earth. The ring shows different modes of transport (an aeroplane, a car, a container ship, a train and a lorry) for which satellite navigation was developed.

GLONASS

GLONASS logo



GLONASS

GLONASS is a radio-based satellite navigation system operated for the Russian government by the Russian Space Forces. It is an alternative and complementary to the United States' Global Positioning System (GPS), the Chinese Compass navigation system, and the planned Galileo positioning system of the European Union (EU).

Development on the GLONASS began in the Soviet Union in 1976, with a goal of global coverage by 1991. Beginning on 12 October 1982, numerous rocket launches added satellites to the system until the constellation was completed in 1995. Following completion, the system fell into disrepair with the collapse of the Russian economy.

Beginning in 2001, Russia committed to restoring the system and by September 2010 it is now fully restored (24 of 24 satellites are operational). The GLONASS satellites designs have undergone several upgrades, with the latest version being GLONASS-K.

System description

Purpose

GLONASS was developed to provide real-time position and velocity determination, initially for use by the Soviet military for navigation and ballistic missile targeting. It was the Soviet Union's second generation satellite navigation system, improving on the Tsiklon system which required one to two hours of signal processing to calculate a location with high accuracy. By contrast, once a GLONASS receiver is tracking the satellite signals, a position fix is available instantly. It is stated that at peak efficiency the system's standard positioning and timing service provide horizontal positioning accuracy within 57–70 meters, vertical positioning within 70 meters, velocity vector measuring within 15 cm/s, and time transfer within 1 μs (all within 99.7% probability).

Orbital characteristics

A fully operational GLONASS constellation consists of 24 satellites. The three orbital planes' ascending nodes are separated by 120° with each plane containing eight equally spaced satellites. The orbits are roughly circular, with an inclination of about 64.8°, and orbit the Earth at an altitude of 19,100 km (11,868 mi), which yields an orbital period of approximately 11 hours, 15 minutes. The planes themselves have a latitude displacement of 15°, which results in the satellites crossing the equator one at a time, instead of three at once. The overall arrangement is such that, if the constellation is fully populated, a minimum of five satellites are in view from any given point at any given time.

Each satellite is identified by a "slot" number, which defines the corresponding orbital plane and the location within the plane; numbers 1–8 are in plane one, 9–16 are in plane two, and 17–24 are in plane three.

A characteristic of the GLONASS constellation is that any given satellite only passes over the exact same spot on the Earth every eighth sidereal day. However, as each orbit plane contains eight satellites, a satellite will pass the same place every sidereal day. For comparison, each GPS satellite passes over the same spot once every sidereal day.

Signals

A Russian military rugged, combined GLONASS/GPS receiver

GLONASS satellites transmit two types of signal: a standard precision (SP) signal and an obfuscated high precision (HP) signal.

All satellites transmit the same code as their SP signal, however each transmits on a different frequency using a 15-channel frequency division multiple access (FDMA) technique spanning either side from 1602.0 MHz, known as the L1 band. The center frequency is 1602 MHz + $n \times 0.5625$ MHz, where n is a satellite's frequency channel number ($n=-7,-6,-5,...,7$). Signals are transmitted in a 38° cone, using right-hand circular polarization, at an EIRP between 25 to 27 dBW (316 to 500 watts). Note that the 24 satellite constellation is accommodated with only 15 channels by using identical frequency channels to support antipodal (opposite side of planet in orbit) satellite pairs, as these satellites will never be in view of an earth based user at the same time.

The HP signal is broadcast in phase quadrature with the SP signal, effectively sharing the same carrier wave as the SP signal, but with a ten times higher bandwidth than the SP signal.

The L2 signals use the same FDMA as the L1 band signals, but transmit straddling 1246 MHz with the center frequency determined by the equation 1246 MHz + n×0.4375 MHz, where n spans the same range as for L1. Other details of the HP signal have not been disclosed.

A combined GLONASS/GPS Personal Radio Beacon

At peak efficiency, the SP signal offers horizontal positioning accuracy within 5–10 meters, vertical positioning within 15 meters, a velocity vector measuring within 10 cm/s, and timing within 200 ns, all based on measurements from four satellite signals simultaneously (this reference is outdated, as it's based on URAGAN satellites while the current constellation is 18/19 URAGAN-M satellites. The more accurate HP signal is available for authorized users, such as the Russian Military, yet unlike the US P(Y) code which is modulated by an encrypting W code, the GLONASS P codes are broadcast in the clear using only 'security through obscurity'. Use of this signal bears risk however as the modulation (and therefore the tracking strategy) of the data bits on the L2P code has recently changed from unmodulated to 250bps burst at random intervals. The GLONASS L1P code is modulated at 50bps without a manchester meander code, and while it carries the same orbital elements as the CA code, it allocates more bits to critical Luni-Solar acceleration parameters and clock correction terms.

Currently, an additional civil reference signal is broadcast in the L2 band with an identical SP code to the L1 band signal. This is available from all satellites in the current constellation, except satellite number 795 which is the last of the inferior original GLONASS design, and one partially inoperable GLONASS-M satellite which is broadcasting only in the L1 band.

GLONASS uses a coordinate datum named "PZ-90" (Earth Parameters 1990 – Parametry Zemli 1990), in which the precise location of the North Pole is given as an average of its position from 1900 to 1905. This is in contrast to the GPS's coordinate datum, WGS 84, which uses the location of the North Pole in 1984. As of September 17, 2007 the PZ-90 datum has been updated to differ from WGS 84 by less than 40 cm (16 in) in any given direction.

CDMA signals

In 2008, three new signals were added to the GLONASS standard. Two of them are CDMA signals, one with a binary offset carrier (2,2) centered at 1575.42 MHz, and another with a binary offset carrier (4,4) centered at 1176.45 MHz. These two signals are placed at the center points of correspoding GPS signals in the L1 and L5 bands, and nearby Galileo and Compass signals. This arrangements makes GLONASS compatible with GPS/GALILEO/Compass signals and allows easier and cheaper implementation of multi-standard GNSS receivers. An additional FDMA signal is located in L3 band (1197.648–1212.255 MHz) below the GPS M-code in L2 band.

Satellites

As with GLONASS's predecessor program, Tsiklon, GLONASS satellites are developed under the leadership of the JSC Information Satellite Systems (formerly called NPO PM), with the assistance of the Institute for Space Device Engineering (ru:РНИИ КП) and the Russian Institute of Radio navigation and Time. Serial production of the satellites is primarily accomplished by the company PC Polyot.

Over the three decades of development, the satellites themselves have gone through numerous revisions, separated here as generations. The name of each satellite was **Uragan** (English: *hurricane*), followed either by a number for operational satellites or by an acronym GVM (Russian: габаритно-весовой макет; English: *size weight dummy*) for test satellites. All Uragan satellites had a GRAU designation 11F654, and each of them also had the usual ordinal "Cosmos-NNNN" designation.

Prototypes (Generation zero)

The first GLONASS vehicles to be launched, referred to as Block I vehicles, were prototypes and GVM dummy vehicles. Three dummies and 18 prototypes were launched between 1982 and 1985. Designed to last only one year, they averaged an actual lifetime of 14 months.

First generation

The true first generation of Uragan (also called Glonass) satellites were all 3-axis stabilized vehicles, generally weighing 1,250 kg and were equipped with a modest propulsion system to permit relocation within the constellation. Over time they were upgraded to Block IIa, IIb, and IIv vehicles, with each block containing evolutionary improvements.

Six Block IIa satellites were launched in 1985–1986 with improved time and frequency standards over the prototypes, and increased frequency stability. These spacecraft also demonstrated a 16-month average operational lifetime. Block IIb spacecraft, with a 2-year design lifetimes, appeared in 1987, of which a total of 12 were launched, but half were lost in launch vehicle accidents. The six spacecraft that made it to orbit worked well, operating for an average of nearly 22 months.

Block IIv was the most prolific of the first generation. Used exclusively from 1988 to 2000, and continued to be included in launches through 2005, a total of 25 satellites were launched. The design life was three years, however numerous spacecraft exceeded this, with one late model lasting 68 months.

Block II satellites were typically launched three at a time from the Baikonur Cosmodrome using Proton-K Blok-DM-2 or Proton-K Briz-M boosters. The only exception was when, on two launches, an Etalon geodetic reflector satellite was substituted for a GLONASS satellite.

Second generation

The second generation of satellites, known as *Uragan-M* (also called *Glonass-M*), were developed beginning in 1990 and first launched in 2001.

These satellites possess a substantially increased lifetime of seven years and weigh slightly more at 1,480 kg. They are approximately 2.4 m (7 ft 10 in) in diameter and 3.7 m (12 ft) high, with a solar array span of 7.2 m (24 ft) for an electrical power generation capability of 1600 watts at launch. The aft payload structure houses 12 primary antennas for L-band transmissions. Laser corner-cube reflectors are also carried to aid in precise orbit determination and geodetic research. On-board cesium clocks provide the local clock source.

A total of fourteen second generation satellites were launched through the end of 2007. As with the previous generation, the second generation spacecraft were launched in triplets using Proton-K Blok-DM-2 or Proton-K Briz-M boosters.

Third generation

The third generation satellites are known as Uragan-K (also called Glonass-K) spacecraft. These satellites are designed with a lifetime of 10 to 12 years and a reduced weight of only 750 kg. As with the previous satellites, these are 3-axis stabilized, nadir pointing with dual solar arrays. They will enter service in 2010.

The third generation satellites will broadcast three additional signals, two of them GPS/Galileo compatible CDMA navigational signals, and one additional L-Band FDMA navigational signal.

Due to their weight reduction, Uragan-K spacecraft can be launched in pairs from the Plesetsk Cosmodrome launch site using the substantially lower cost Soyuz-2 boosters or in six-at-once from the Baikonur Cosmodrome using Proton-K Briz-M launch vehicles.

Ground control

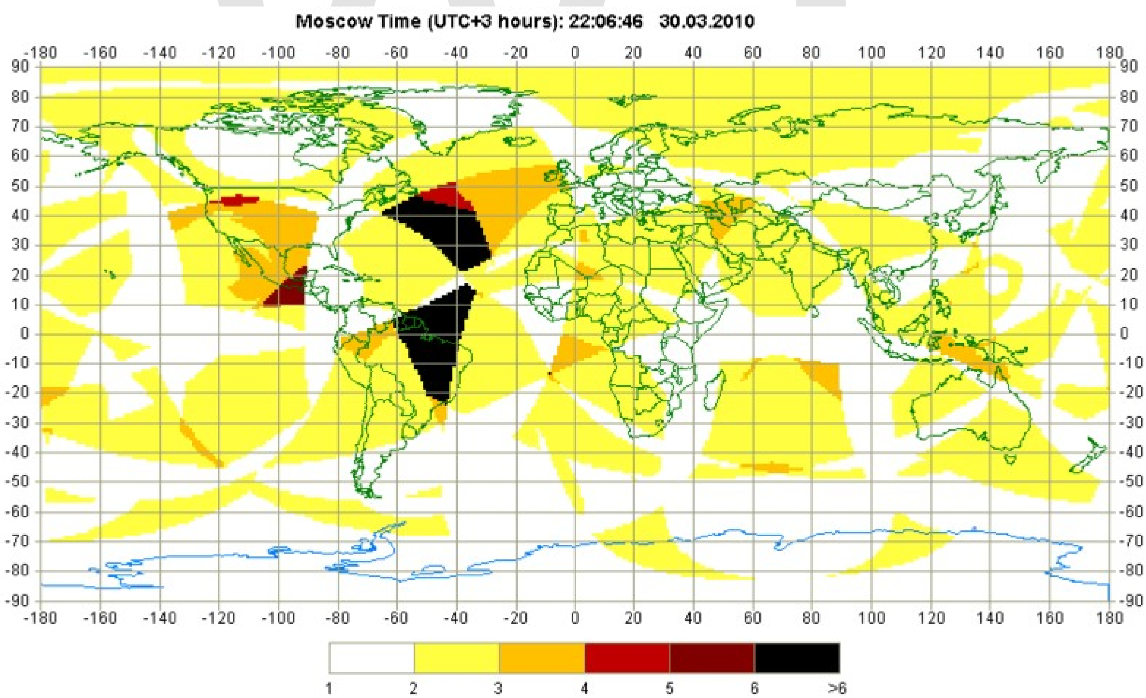
The ground control segment of GLONASS is entirely located within former Soviet Union territory. The Ground Control Center and Time Standards is located in Moscow and the telemetry and tracking stations are in Saint Petersburg, Ternopol, Eniseisk, Komsomolsk-na-Amure.

Receivers

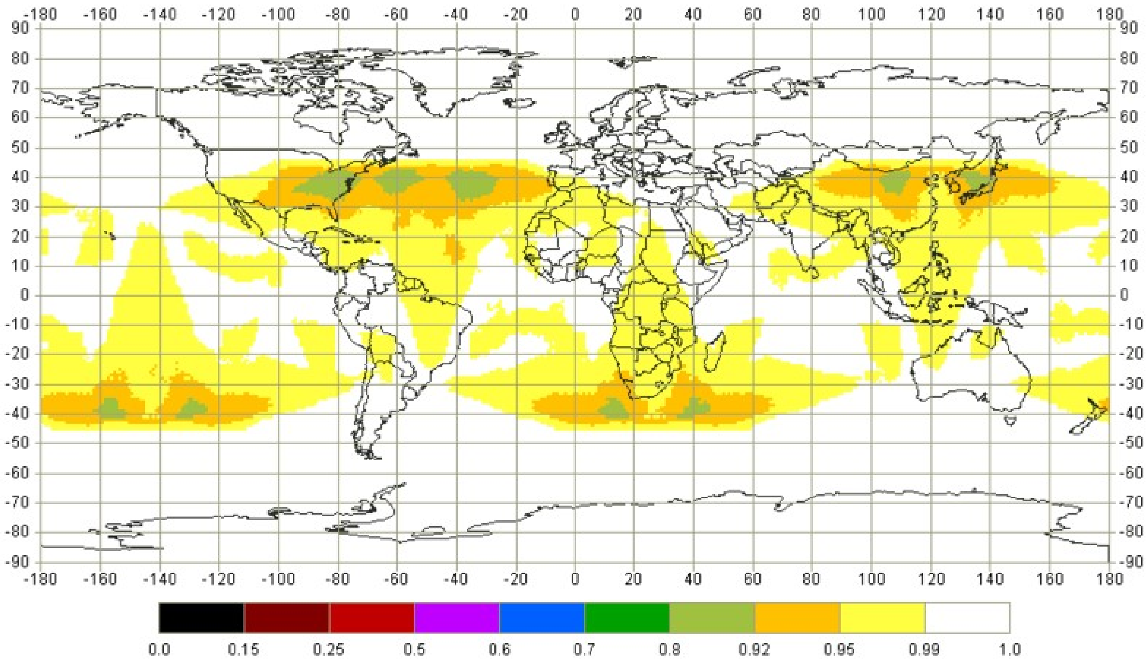
Septentrio, Topcon, JAVAD, Magellan Navigation, Novatel, Leica Geosystems and Trimble Inc produce GNSS receivers making use of GLONASS. NPO Progress describes a receiver called "GALS-A1" which combines GPS and GLONASS reception. SkyWave Mobile Communications manufactures an Inmarsat-based satellite communications terminal that uses both GLONASS and GPS.

Current status

Availability



Map showing current values of position geometry factor PDOP on the Earth surface (the mask angle: 5°) on 30 March 2010 19:06:46 UTC.



Integral navigation availability for GLONASS customer (PDOP≤6) on the diurnal range for elevation not less than 5 degrees on 30 March 2010

As of 6 September 2010, the GLONASS constellation status is:

Total satellites in constellation	26 SC
Operational	21 SC
In commissioning phase	3 SC
In maintenance	–
Spares	2 SC
In decommissioning phase	–

The system requires 18 satellites for continuous navigation services covering the entire territory of the Russian Federation, and 24 satellites to provide services worldwide.

The GLONASS system currently covers 100% of Russian territory.

Accuracy

Currently GLONASS is slightly less accurate than GPS.

According Russian system of differentional correction and monitoring's data as of 2010 precisions of GLONASS navigation definitions (for p=0.95) for latitude and longitude were 4.46—8.38 m with mean number of NSV equals 7—8 (depends on station). In the same time precisions of GPS navigation definitions were 2.00—8.76 m with mean number of NSV equals 6—11 (depends on station).

For using both navigation systems simultaneously precisions of GLONASS/GPS navigation definitions were 2.37—4.65 m with mean number of NSV equals 14—19 (depends on station).

Russian Federal Space Agency's director Anatoly Perminov claimed that some actions are in progress to increase GLONASS's accuracy. By 2011 accuracy should achieve 2.8 m by means of expanding GLONASS's constellation, improving ground segment, increasing ephemerides accuracy etc.

History

Development by the Soviet Union

In the late 1960s and early 1970s, the Soviet Union identified the need and benefits of developing a new satellite-based radio navigation system. Their existing Tsiklon satellite navigation system, while highly accurate for stationary or slow-moving ships, required several hours of observation by the receiving station to fix a position, making it unusable for many navigation purposes and for the guidance of the new generation of ballistic missiles.

From 1968 to 1969, the research institutes of the Ministry of Defence, Academy of Sciences, and Soviet Navy cooperated to develop a single system for navigation of their air, land, sea, and space forces. This collaboration resulted in a 1970 document that established the requirements for such a system. Six years later, in December 1976, a plan for developing GLONASS was accepted in a *Decision of the Central Committee of the CPSU and of the Council of Ministers of the USSR* entitled "On Deployment of the Unified Space Navigation System GLONASS."

From 1982 through April 1991, the Soviet Union successfully launched a total of 43 GLONASS-related satellites plus five test satellites. In 1991, twelve functional GLONASS satellites in two planes were available; enough to allow limited usage of the system.

Completion delays

Following the disintegration of the Soviet Union in 1991, continued development of GLONASS was undertaken by the Russian Federation. It was promised to be operational on September 24, 1993 by then-president Boris Yeltsin, however the constellation was not completed until December 1995.

In the six years following completion, Russia was unable to maintain the system. By April 2002, this resulted in only eight satellites remaining in operation, which rendered the system almost useless as a global navigation aid.

Restoration and modernization

With GLONASS falling rapidly into disrepair, a special-purpose federal program named "Global Navigation System" was undertaken by the Russian government on August 20, 2001. According to it, the GLONASS system was to be restored to fully deployed status (i.e. 24 satellites in orbit and continuous global coverage) by 2011.

The New York Times reported in April 2007 that Russia had committed to accelerated launches, with eight satellites scheduled to be orbited in 2007 and a goal of reaching global coverage in 2009. Microcom Systems reported on its website that two launches, in September and December 2007, would lift the final six second-generation satellites, and that April 2008 will see the first launch of two third-generation satellites.

The 2007 launches occurred on 26 October and 25 December. Both launches were successful, orbiting six satellites altogether. Following the launches, Russia's First Deputy Prime Minister Sergei Ivanov predicted that the launches would bring the GLONASS satellite fleet to up 18 satellites, the number necessary to provide navigation services over the entire Russian territory, and repeated that the system would have the required 24 satellites for worldwide coverage by 2010. Once all of these satellites are fully commissioned and set to healthy, GLONASS signals will be available across 90 percent of Russia and 80 percent of the globe, according to RISDE.

Six new GLONASS satellites were added to the network in 2008. Three spacecrafts were launched in 2009. Two more triplets of GLONASS-M satellites were placed into orbit in March and September 2010.

Anatoly Perminov, the head of Russian Space Agency, disclosed in September 2008 that the number of satellites in the GLONASS constellation would be increased up to 30 by 2011 with the launch of third-generation GLONASS-K satellites. These satellites implement additional navigational signals which enhance performance of GLONASS and make it compatible with GPS/GALILEO/Compass. Launch of the first GLONASS-K satellite was postponed from February to December 2010.

Cooperation with the Indian government

In January 2004 the Russian Space Agency (RSA) announced a joint venture deal with India's space agency, the Indian Space Research Organization, wherein the two government agencies would collaborate to restore the system to constant coverage of Russian and Indian territory by 2008 with 18 satellites, and be fully operational with all 24 satellites by 2010.

Details announced in mid-2005 reported that Russia would build the satellites and that between 2006 and 2008 two satellites would be launched from India's Satish Dhawan Space Centre in Andhra Pradesh state, using the Indian Geosynchronous Satellite Launch Vehicle (GSLV) rockets. As of December 2009, India has yet to launch any satellites as part of this project.

During a December 2005 summit between Indian Prime Minister Manmohan Singh and Russian President Vladimir Putin, it was agreed that India would share some of the development costs of the GLONASS-K series and launch two of the new satellites from India, in return for access to the HP signal.

Discussions with United States government

Following the December 2006 meeting in Moscow of the GPS-GLONASS Interoperability and Compatibility Working Group (WG-1), an announcement appeared on both US and Russian government websites stating both sides had made significant progress in understanding the benefit to the user community of changing GLONASS to a signal pattern that is in common with GPS and Galileo. A change in the GLONASS system from its current FDMA technique to the GPS and Galileo's DSSS format would enable a simply-designed receiver to use multiple satellite systems simultaneously. GPSWorld reported that the group had met twice prior to then and that the working group would likely make an announcement when they meet again in April 2007, during the International Satellite Forum 2007 in Moscow.

The use of CDMA signals was approved in 2008. The new Glonass-K satellites to be lanched from 2010 will include two additional CDMA signals which make GLONASS compatible with GPS/GALILEO/Compass receivers, as well as additional FDMA signal.

Discussions with Cuba and Venezuela

Russia could include Cuba and Venezuela in a satellite navigation system originally designed for missile targeting by the Soviet military, the head of Russia's space agency said."We discussed the theme of joint use of the GLONASS satellite navigation system," Roskosmos chief Anatoly Perminov was quoted by RIA Novosti news agency as saying, referring to talks with officials in Venezuela.

Civilian signals made officially available

On May 18, 2007, Russian president Vladimir Putin signed a decree officially providing open access to the civilian navigation signals of the GLONASS system, to Russian and foreign consumers, free of charge and without limitations. The Russian president also directed the Federal Space Agency to coordinating work to maintain, develop and enable the system for civilian and commercial needs.

GLONASS has the capability to monitor cattle and animals in the wild through the use of satellite collars.

Suggested requirement for imported GPS-capable products

On July 16, 2010, during a meeting with Russian Prime Minister Vladimir Putin, Vladimir Evtushenkov called for an import ban on all the GPS-capable devices unless these devices support Glonass as well. Vladimir Evtushenkov is currently a main shareholder of JFSC Sistema, which has major financial interests in GLONASS. Evtushenkov claimed that Russian authorities had already started negotiations with major vendors like Nokia, Siemens and Motorola. Vladimir Putin agreed that "It is good that our partners understand our need to protect our national interests and promote our product". According to Russian experts, it was possible that mobile devices like smartphones would be effectively banned as well. Some producers claimed that if additional expenses to add GLONASS were too high, they may consider turning off satnav feature in devices for Russian market to avoid import ban.

On August 11, 2010, Deputy Prime Minister Sergei Ivanov, who is in charge of GLONASS development, called for a 25% import duty on all GPS-capable devices unless they are compatible with GLONASS. The duty is proposed to be implemented from January 2011. Russian government believes this move would "stimulate international interest" in the system.

On October 27, 2010, Sergei Ivanov confirmed a plan to introduce a 25% import duty on all GPS-capable devices, including mobile phones, unless they are compatible with GLONASS. As well, the government is planning to force all car manufactures in Russia to make cars with GLONASS starting from 2011. This will affect all car makers, including foreign brands like Ford and Toyota, which have car assembling facilities in Russia.

ERA Glonass

The head of the Russian Federal Space Agency Anatoly Perminov said that there is a new GLONASS project called "ERA" (Russian: ЭРА ГЛОНАСС), an acronym for "Emergency Response to Accidents" (Russian: Система экстренного реагирования при авариях).

The first phase of the project will include equipping automobiles with GLONASS receivers and creation of a technology that allows operators of emergency service 112 to use geographic data. The second phase will also involve GPS/GLONASS enabled phones and smartphones.

There is also a planned project called "Social GLONASS". It will help people who require supervision, such as old people, children, and people with reduced vision.

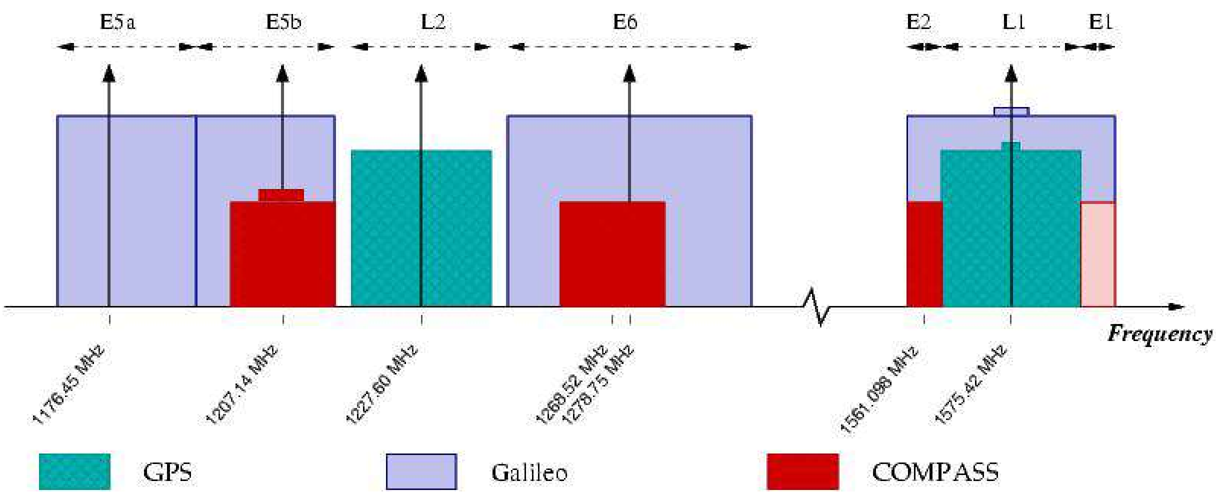
Compass navigation system

The **COMPASS** system (also known as **Beidou-2**, BD2) is a project by China to develop an independent global satellite navigation system.

COMPASS is not an extension to the previously deployed Beidou-1, but a new GNSS system similar in principle to GPS and Galileo.

General

The new system will be a constellation of 35 satellites, which include 5 geostationary orbit (GEO) satellites and 30 medium Earth orbit (MEO) satellites, that will offer complete coverage of the globe. The ranging signals are based on the CDMA principle and have complex structure typical to Galileo or modernized GPS. Similarly to the other GNSS, there will be two levels of positioning service: open and restricted (military). The public service shall be available globally to general users. When all the currently planned GNSS systems are deployed, the users will benefit from the use of a total constellation of 75+ satellites, which will significantly improve all the aspects of positioning, especially availability of the signals in so-called “urban canyons” . The general designer of Compass navigation system is Sun Jiadong, who is also the general designer of its predecessor, Beidou navigation system.



Frequency allocation of GPS, Galileo, and Compass; the light red color of E1 band indicates that the transmission in this band has not yet been detected

Frequencies for Compass are allocated in four bands: E1, E2, E5B, and E6 and overlap with Galileo. The fact of overlapping could be convenient from the point of view of the receiver design, but on the other hand raises the issues of inter-system interference, especially within E1 and E2 bands, which are allocated for Galileo’s publicly-regulated service . However, under International Telecommunications Union (ITU) policies, the first nation to start broadcasting in a specific frequency will have priority to that frequency, and any subsequent users will be required to obtain permission prior to using that frequency, and otherwise ensure that their broadcasts do not interfere with the original nation's broadcasts. It now appears that Chinese Compass satellites will start transmitting in the E1, E2, E5B, and E6 bands before Europe's Galileo satellites and thus have primary rights to these frequency ranges.

Although almost nothing has yet been officially announced by Chinese authorities about the signals of the new system, the launch of the first Compass satellite permitted independent researchers not only to study general characteristics of the signals but even to build a Compass receiver.

Compass-M1

Compass-M1 is an experimental satellite launched for signal testing and validation and for the frequency filing on April 14, 2007. The role of Compass-M1 for Compass is similar to the role of GIOVE satellites for Galileo. The signals of Compass-M1 are to a great extent unraveled by independent research. The orbit of Compass-M1 is nearly circular, has an altitude of 21,150 km and an inclination of 55.5 degrees.

Compass-M1 is transmitting in 3 bands: E2, E5B, and E6. In each frequency band two coherent sub-signals have been detected with a phase shift of 90 degrees (in quadrature). These signal components are further referred to as “I” and “Q”. The “I” components have shorter codes and are likely to be intended for the open service. The “Q” components have much longer codes, are more interference resistive, and are probably intended for the restricted service.

The investigation of the transmitted signals started immediately after the launch of COMPASS-M1 on April 14 2007. Already in June engineers at CNES reported the spectrum and structure of the signals. Next month researchers from the Stanford University reported complete decoding of the “I” signal scomponents. The knowledge of the codes allowed a group of engineers at Septentrio to build the COMPASS receiver and report tracking and multipath characteristics of the “I” signals on E2 and E5B.

Characteristics of COMPASS signals reported as of May 2008 compared to GPS-L1CA

Parameters	E2-I	E2-Q	E5B-I	E5B-Q	E6-I	E6-Q	GPS L1-CA
Native notation	B1	B1	B2	B2	B3	B3	---
Code modulation	BPSK(2)	BPSK(2)	BPSK(2)	BPSK(10)	BPSK(10)	BPSK (10)	BPSK (1)
Carrier frequency, MHz	1561.098	1561.098	1207.14	1207.14	1268.52	1268.52	1575.42
Chip rate, Mchips/sec	2.046	2.046	2.046	10.230	10.230	10.230	1.023
Code period, chips	2046	??	2046	??	10230	??	1023
Code period, msec	1.0	>400	1.0	>160	1.0	>160	1.0
Symbols/sec	50		50		50		50
Navigation frames, sec	6		6				6
Navigation sub-frames, sec	30		30				30
Navigation period, min	12.0		12.0				12.5

Characteristics of the "I" signals on E2 and E5B are generally similar to the civilian codes of GPS (L1-CA and L2C), but Compass signals have somewhat greater power. The notation of Compass signals used in this page follows the naming of the frequency bands and agrees with the notation used in the American literature on the subject, but the notation used by the Chinese seems to be different and is quoted in the first row of the table.

Compass launches

Mission	*Date*	*Name*	*Launch center*	*Launch vehicle*	*Bus*	*Orbit*
07-32	2007.04.13	Compass-M1	Xichang	CZ-3C	DFH-3	MEO ~21,500km
07-37	2009.04.14	Compass-G2	Xichang	CZ-3C	DFH-3	GEO drifting
07-38	2010.01.16	Compass-G1	Xichang	CZ-3C	DFH-3	GEO 144.5°E
07-39	2010.06.02	Compass-G3	Xichang	CZ-3C	DFH-3	GEO 84.7°E
07-40	2010.08.01	Compass-IGSO1	Xichang	CZ-3A	DFH-3	HEO ~36,000 km

Chapter 4

Regional Navigation Systems

Beidou navigation system

Coverage polygon of BeiDou

The BeiDou Navigation System is a project by China to develop an independent satellite navigation system. It may refer to either one or both generations of the Chinese navigation system.

The first BeiDou system, officially called *BeiDou Satellite Navigation Experimental System*, or known as *BeiDou-1*, consists of 3 satellites and has limited coverage and applications. It has been offering navigation services mainly for customers in China and from neighboring regions since 2000.

The second generation of the system, known as *Compass* or *BeiDou-2*, which shall be a global satellite navigation system consisting of 35 satellites, is still under construction. It is planned to offer services to customers in Asia-Pacific region by 2012 and the global system should be finished by 2020.

The chief designer of BeiDou navigation system is Sun Jiadong.

Nomenclature

The BeiDou Navigation System is named after the Big Dipper constellation, which is known in Chinese as *Běidǒu*. The name literally means "Northern Dipper", the name given by Chinese astronomers to the seven brightest stars of Ursa Major or 'the Great Bear' constellation. Historically, this set of stars was used in navigation to locate the North Star Polaris. As such, BeiDou also serves as a metaphor for the purpose of the satellite navigation system.

History

BeiDou system

According to the China National Space Administration, the development of the Chinese global navigation system should be carried out in three steps:

1. 2000 - 2003: experimental BeiDou navigation system consisting of 3 satellites
2. by 2012: regional BeiDou navigation system covering China and neighboring regions
3. by 2020: global BeiDou navigation system

The first two satellites, *BeiDou-1A* was launched on 30 October 2000, *BeiDou-1B* followed on 20 December 2000. The third satellite *BeiDou-1C* (as backup satellite), was put into orbit on 25 May 2003. The successful launch of *BeiDou-1C* also meant the establishment of the BeiDou-1 navigation system.

On November 2, 2006, China announced that from 2008 BeiDou would offer an open service with an accuracy of 10 meters, timing of 0.2 nanoseconds, speed of 0.2 meter/second.

It followed that in February 2007, the fourth and also the last satellite of BeiDou-1 system, the *BeiDou-1D* (sometimes called *BeiDou-2A*, serving as a backup satellite), was sent up into space. It was reported that the satellite had suffered from a control system malfunction but was then fully restored.

In April 2007, the first satellite of BeiDou-2, namely *Compass-M1* (to validate frequencies for the BeiDou-2 constellation) was successfully put into its working orbit. The second BeiDou-2 constellation satellite *Compass-G2* was launched on 15 April 2009. The third satellite (*Compass-G1*) was carried into its orbit by LM-3C on January 17, 2010. On the 2nd of June 2010, the fourth satellite was launched successfully into orbit. The fifth orbiter was launched into space by LM-3I carrier rocket from Xichang Satellite Launch Center on August 1, 2010.

On January 15, 2010 the official website of BeiDou Navigation Satellite System went online.

Involvement in Galileo

In September 2003, China intended to join the European Galileo positioning system project and was to invest €230 million (USD296 million, GBP160 million) in Galileo over the next few years. It's believed that China's "BeiDou" navigation system would then only be used by its armed forces. In October 2004, China officially joined the Galileo project by signing the *Agreement on the Cooperation in the Galileo Program between the "Galileo Joint Undertaking" (GJU) and the "National Remote Sensing Centre of China" (NRSCC)*. Based on the Sino-European Cooperation Agreement on Galileo program, China Galileo Industries (CGI), the prime contractor of the China's involvement in Galileo programs was founded in December 2004. By April 2006, eleven cooperation projects within the Galileo framework had been signed between China and EU.

The Hongkong based South China Morning Post reported in January 2008 that China was unsatisfied with her role in the Galileo project and was to compete with Galileo in Asian market.

System Description

Experimental System (BeiDou-1)

Description

BeiDou-1 is an experimental regional navigation system, which consists of four satellites (three working satellites and one backup satellite). The satellites themselves were based on the Chinese DFH-3 geostationary communications satellite and had a launch weight of 1,000 kilograms (2,200 pounds) each.

Unlike the American GPS, Russian GLONASS, and European Galileo systems, which use medium Earth orbit(MEO) satellites, BeiDou-1 uses satellites in geostationary orbit(GEO). This means that the system does not require a large constellation of satellites, but it also limits the coverage to areas on Earth where the satellites are visible. The area that can be serviced is from Logitude 70°E to 140°E, and from Latitude 5°N to 55°N.

Completion

The first satellite, *BeiDou-1A* was sent into its orbit on October 31, 2000. The second satellite, *BeiDou-1B* was successfully launched on December 21, 2000. The last satellite of the constellation, *BeiDou-1C* was carried into its orbit position on May 25, 2003, this launch also completed the construction of the experimental system.

Position calculation

To calculate a position, the following procedure is used:

1. A signal is transmitted skyward by a remote terminal.
2. Each of the geostationary satellites receive the signal.
3. Each satellite sends the accurate time of when each received the signal to a ground station.
4. The ground station calculates the longitude and latitude of the remote terminal, and determines the altitude from a relief map.
5. The ground station sends the remote terminal's 3D position to the satellites.
6. The satellites broadcast the calculated position to the remote terminal.

In 2007, the official Xinhua News Agency reported that the resolution of the BeiDou system was as high as 0.5 metres, considerably better than unaided GPS. With the existing user terminals appears that the calibrated accuracy is 20m (100m, uncalibrated).

Terminal

The terminal can communicate with the ground station by sending and receiving short messages.

As of 2008, one BeiDou-1 terminal costs about 20,000RMB (US$2,929), almost 10 times the price of GPS counterpart. It's said that the reason why is the terminal so expensive is due to "using expensive imported Chips", but China seemed to have found replacement and the price could lower to less than 1,000RMB. By the **China High-Tech Fair ELEXCON 2009**(November 16 - 21, 2009) in Shenzhen, China, a terminal solution costing no more than 3,000RMB was presented.

Applications

- Over 1000 BeiDou-1 terminals were used in the 2008 Sichuan earthquake, providing informations from the earthquake area.
- As of October 2009, all Chinese border guards in Yunnan are equipped with BeiDou-1 devices.

According to Sun Jiadong, chief designer of the navigation system, "Many organizations have been using our system for a while, and they like it very much."

Advantages and drawbacks

Global System (BeiDou-2 or Compass)

Description

BeiDou-2 is not an extension to the existing BeiDou-1. The new system will be a constellation of 35 satellites, which include 5 geostationary orbit (GEO) satellites, for backward compatibility with BeiDou-1, and 30 non-GSO satellites (27 in Medium Earth Orbit (MEO) and 3 in Inclined GSO (IGSO)), that will offer complete coverage of the globe. There will be two levels of service provided; free service to civilians and licensed service to Chinese government and military users:

- The free service will have a 10 meter location-tracking accuracy, will synchronize clocks with an accuracy of 10 ns, and measure speeds within 0.2 m/s.
- The licensed service will be more accurate than the free service, can be used for communication, and will supply information about the system status to the users.

Completion

By August 2010, five satellites for BeiDou-2 have been launched. It is planned that BeiDou-2 system will have more than 10 satellites by 2012 and may offer services for the Asia-Pacific region; The global navigation system should be finished by 2020.

List of Satellites (as of August 2010)

Date	Launcher	Satellite	Orbit	Usable	System
10/31/2000	LM-3A	BeiDou-1A	GEO 140°E	Yes	BeiDou-1
12/21/2000	LM-3A	BeiDou-1B	GEO 80°E	Yes	
5/25/2003	LM-3A	BeiDou-1C	GEO 110.5°E	Yes	
2/3/2007	LM-3A	BeiDou-1D	supersync orbit	No	
4/14/2007	LM-3A	Compass-M1	MEO ~21,500 km	Yes	BeiDou-2
4/15/2009	LM-3C	Compass-G2		Yes	

1/17/2010	LM-3C	Compass-G1	GEO 144.5°E	Yes	
6/2/2010	LM-3C	Compass-G3	GEO 84.7°E	Yes	
8/1/2010	LM-3A	Compass-IGSO1	HEO ~36,000 km	Yes	

- Note: all dates are based on China Standard Time

DORIS (geodesy)

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) is a French satellite system used for the determination of satellite orbits (e.g. TOPEX/Poseidon) and for positioning.

Principle

A so called beacon is installed on the ground and emits a radio signal, which is received by the satellite. A frequency shift of the signal occurs that is caused by the movement of the satellite (Doppler effect). From this observation satellite orbits, ground positions, as well as other parameters can be derived.

Organization

DORIS is a French system which was initiated and is maintained by the French Space Agency (CNES). It is operated from Toulouse, where a master beacon ensures the communication with the satellites.

Ground network

There are about 50-60 stations equally distributed over the earth and ensure a good coverage for orbit determination. For the installation of a beacon only electricity is required because the station only emits a signal but does not receive any information. Therefore it is possible to install beacons in remote areas such as the Mount Everest base camp.

Satellites

The best known satellites equipped with DORIS are the two altimetry satellites TOPEX/Poseidon and Jason. They are used to observe the ocean surface as well as currents or wave heights. DORIS contributes to their orbit accuracy of about 2 cm.

Other DORIS satellites are the ERS, Envisat and SPOT satellites.

Positioning

Apart from orbit determination the DORIS oberservations are used for positioning of ground stations. The accuracy is a bit lower than with GPS, but it still contributes to the International Terrestrial Reference Frame (ITRF).

Indian Regional Navigational Satellite System

The **Indian Regional Navigational Satellite System** (**IRNSS**) is an autonomous regional satellite navigation system being developed by Indian Space Research Organisation which would be under total control of Indian government. The requirement of such a navigation system is driven by the fact that access to Global Navigation Satellite Systems, GPS, is not guaranteed in hostile situations.

Development

The government approved the project in May 2006, with the intention of the system to be completed and implemented by 2014. The first satellite of the proposed constellation, developed at a cost of Rs.1,600 crore (16 billion rupees), is expected to be launched in last quarter of 2011.

A goal of complete Indian control has been stated, with the space segment, ground segment and user receivers all being built in India.

It is unclear if recent agreements with the Russian government to restore their GLONASS system will supersede the IRNSS project or feed additional technical support to enable its completion. However reports came in Apr 2010 that India plans to start launching satellites by end of 2011 and six months periodic launches take place. It means the IRNSS optimally functional by 2014.

Description

The proposed system would consist of a constellation of seven satellites and a support ground segment. Three of the satellites in the constellation will be placed in geostationary orbit. These GEOs will be located at 34 East 83 East and 132 East longitude. The GSOs will be in orbits with a 24,000 km apogee and 250 km perigee inclined at 29 degrees. Two of the GSOs will cross the equator at 55 East and two at 111 East. Such an arrangement would mean all seven satellites would have continuous radio visibility with Indian control stations. The satellite payloads would consist of atomic clocks and electronic equipment to generate the navigation signals.

According to a presentation by A Bhaskaranarayana to a meeting of COSPAR in Montreal on 15 July 2008, IRNSS signals will consist of a Special Positioning Service and a Precision Service. Both will be carried on L5 (1176.45 MHz) and S band (2492.08 MHz). The SPS signal will be modulated by a 1 MHz BPSK signal. The Precision Service will use BOC(5,2).

The navigation signals themselves would be transmitted in the S-band frequency (2–4 GHz) and broadcast through a phased array antenna to maintain required coverage and signal strength. The satellites would weigh approximately 1,330 kg and their solar panels generate 1,400 watts.

The System is intended to provide an absolute position accuracy of better than 20 meters throughout India and within a region extending approximately 2,000 km around it.

The ground segment of IRNSS constellation would consist of a Master Control Center (MCC), ground stations to track and estimate the satellites' orbits and ensure the integrity of the network (IRIM), and additional ground stations to monitor the health of the satellites with the capability of issuing radio commands to the satellites (TT&C stations). The MCC would estimate and predict the position of all IRNSS satellites, calculate integrity, makes necessary ionospheric and clock corrections and run the navigation software. In pursuit of a highly independent system, an Indian standard time infrastructure would also be established.

Quasi-Zenith Satellite System

QZSS orbit

The **Quasi-Zenith Satellite System** (QZSS), is a proposed three-satellite regional time transfer system and enhancement for the Global Positioning System, that would be receivable within Japan. The first satellite 'Michibiki' was launched on 11 September 2010. Full operational status is expected by 2013.

Authorized by the Japanese government in 2002, work on a concept for a Quasi-Zenith Satellite System (QZSS), or *Juntencho* (準天頂) in Japanese, began development by the Advanced Space Business Corporation (ASBC) team, including Mitsubishi Electric Corp., Hitachi Ltd., and GNSS Technologies Inc. However, ASBC collapsed in 2007. The work was taken over by the Satellite Positioning Research and Application Center. SPAC is owned by four departments of the Japanese government, the Ministry of Education, Culture, Sports, Science and Technology; of Internal Affairs and Communications,; of Economy, Trade and Industry; and the Ministry of Land, Infrastructure and Transport.

QZSS is targeted at mobile applications, to provide communications-based services (video, audio, and data) and positioning information. With regards to its positioning service, QZSS can only provide limited accuracy on its own and is not currently required in its specifications to work in a stand-alone mode. As such, it is viewed as a GNSS Augmentation service. Its positioning service could also collaborate with the geostationary satellites in Japan's Multi-Functional Transport Satellite (MTSAT), currently under development, which itself is a Satellite Based Augmentation System similar to the U.S. Federal Aviation Administration's Wide Area Augmentation System (WAAS).

The satellites would be placed in a periodic Highly Elliptical Orbit (HEO). These orbits allow the satellite to dwell for more than 12 hours a day with an elevation above 70° (meaning they appear almost overhead most of the time) and give rise to the term "quasi-zenith" for which the system is named. Similar orbits are used by the Sirius Satellite Radio system (Tundra orbit). As of June 2003, the proposed orbits ranged from 45° inclination with little eccentricity, to 53° with significant eccentricity.

QZSS and positioning augmentation

QZSS can enhance GPS services in two ways: first, availability enhancement, whereby the availability of GPS signals is improved, second, performance enhancement whereby the accuracy and reliability of GPS derived navigation solutions is increased.

Because the GPS availability enhancement signals transmitted from Quasi-Zenith Satellites are compatible with modernized GPS signals, and hence interoperability is ensured, the QZSs will transmit the L1C/A signal, L1C signal, L2C signal and L5 signal. This minimizes changes to specifications and receiver designs.

Compared to standalone GPS, the combined system GPS plus QZSS delivers improved positioning performance via ranging correction data provided through the transmission of submeter-class performance enhancement signals L1-SAIF and LEX from QZS. It also improves reliability by means of failure monitoring and system health data notifications. QZSS also provides other support data to users to improve GPS satellite acquisition.

According to its original plan, QZSs was to carry two types of space-borne atomic clocks; a hydrogen maser and a Rb atomic clock. The development of a passive hydrogen maser for QZSs was abandoned in 2006. The positioning signal will be generated by a Rb clock and an architecture similar to the GPS timekeeping system will be employed. QZSS will also be able to use a Two-Way Satellite Time and Frequency Transfer (TWSTFT) scheme, which will be employed to gain some fundamental knowledge of satellite atomic standard behavior in space as well as for other research purposes.

QZSS timekeeping and remote synchronization

Although the first generation QZSS timekeeping system (TKS) will be based on the Rb clock, the first QZS, will carry a basic prototype of an experimental crystal clock synchronization system. During the first half of the two year in-orbit test phase, preliminary tests will investigate the feasibility of the atomic clock-less technology which might be employed in the second generation QZSS.

The mentioned QZSS TKS technology is a novel satellite timekeeping system which does not require on-board atomic clocks as used by existing navigation satellite systems such as GPS, GLONASS or the planned GALILEO system. This concept is differentiated by the employment of a synchronization framework combined with lightweight steerable on-board clocks which act as transponders re-broadcasting the precise time remotely provided by the time synchronization network located on the ground. This allows the system to operate optimally when satellites are in direct contact with the ground station, making it suitable for a system like the Japanese QZSS. Low satellite mass and low satellite manufacturing and launch cost are significant advantages of this novel system. An outline of this concept as well as two possible implementations of the time synchronization network for QZSS were studied and published in Tappero's PhD work.

Chapter 5

Differential GPS & GPS-Aided Geo Augmented Navigation

Differential GPS

Differential Global Positioning System (DGPS) is an enhancement to Global Positioning System that uses a network of fixed, ground-based reference stations to broadcast the difference between the positions indicated by the satellite systems and the known fixed positions. These stations broadcast the difference between the measured satellite pseudoranges and actual (internally computed) pseudoranges, and receiver stations may correct their pseudoranges by the same amount. The correction signal is typically broadcast over UHF radio modem.

The term can refer both to the generalized technique as well as specific implementations using it. It is often used to refer specifically to systems that re-broadcast the corrections from ground-based transmitters of shorter range. For instance, the United States Coast Guard and Canadian Coast Guard run one such system in the US and Canada on the longwave radio frequencies between 285 kHz and 325 kHz. These frequencies are commonly used for marine radio, and are broadcast near major waterways and harbors.

Australia runs two DGPS systems: one is mainly for marine navigation, broadcasting its signal on the longwave band; the other is used for land surveys and land navigation, and has corrections broadcast on the Commercial FM radio band.

Two systems for air navigation and precision landing of aircraft, in Australia, will eventually replace the Instrument Landing System. Both utilise DGPS techniques and are called the Ground Based Augmentation System and Ground based Regional Augmentation Systems. Both of these systems broadcast corrections via the aviation VHF band.

Transportable DGPS reference station *Baseline HD* by CLAAS for use in satellite-assisted steering systems in modern agriculture

A similar system that transmits range corrections from orbiting satellites instead of ground-based transmitters is called a Satellite Based Augmentation System. Different versions of this system include the Wide Area Augmentation System, European Geostationary Navigation Overlay Service, Japan's Multi-Functional Satellite Augmentation System, Canada's CDGPS and the commercial VERIPOS, StarFire and OmniSTAR.

History

When GPS was first being put into service, the US military was concerned about the possibility of enemy forces using the globally-available GPS signals to guide their own weapon systems. To avoid this, the main "coarse acquisition" signal (C/A) transmitted on the L1 frequency (1575.42 MHz) was deliberately degraded by offsetting its clock signal by a random amount, equivalent to about 100 meters of distance. This technique, known as "Selective Availability", or **SA** for short, seriously degraded the usefulness of the GPS signal for non-military users. More accurate guidance was possible for users of dual frequency GPS receivers that also received the L2 frequency (1227.6 MHz), but the L2 transmission, intended for military use, was encrypted and was only available to authorised users with the encryption keys.

This presented a problem for civilian users who relied upon ground-based radio navigation systems such as LORAN, VOR and NDB systems costing millions of dollars each year to maintain. The advent of a global navigation satellite system (GNSS) could provide greatly improved accuracy and performance at a fraction of the cost. The accuracy inherent in the S/A signal was however too poor to make this realistic. The military received multiple requests from the Federal Aviation Administration (FAA), United States Coast Guard (USCG) and United States Department of Transportation (DOT) to set S/A aside to enable civilian use of GNSS, but remained steadfast in its objection on grounds of security.

Through the early to mid 1980s, a number of agencies developed a solution to the SA "problem". Since the SA signal was changed slowly, the effect of its offset on positioning was relatively fixed – that is, if the offset was "100 meters to the east", that offset would be true over a relatively wide area. This suggested that broadcasting this offset to local GPS receivers could eliminate the effects of SA, resulting in measurements closer to GPS's theoretical performance, around 15 meters. Additionally, another major source of errors in a GPS fix is due to transmission delays in the ionosphere, which could also be measured and corrected for in the broadcast. This offered an improvement to about 5 meters accuracy, more than enough for most civilian needs.

The US Coast Guard was one of the more aggressive proponents of the DGPS system, experimenting with the system on an ever-wider basis through the late 1980s and early 1990s. These signals are broadcast on marine longwave frequencies, which could be received on existing radiotelephones and fed into suitably equipped GPS receivers. Almost all major GPS vendors offered units with

DGPS inputs, not only for the USCG signals, but also aviation units on either VHF or commercial AM radio bands.

They started sending out "production quality" DGPS signals on a limited basis in 1996, and rapidly expanded the network to cover most US ports of call, as well as the Saint Lawrence Seaway in partnership with the Canadian Coast Guard. Plans were put into place to expand the system across the US, but this would not be easy. The quality of the DGPS corrections generally fell with distance, and most large transmitters capable of covering large areas tend to cluster near cities. This meant that lower-population areas, notably in the midwest and Alaska, would have little coverage by ground-based GPS.

Instead, the FAA (and others) started studies for broadcasting the signals across the entire hemisphere from communications satellites in geostationary orbit. This has led to the Wide Area Augmentation System (WAAS) and similar systems, although these are generally not referred to as DGPS, or alternately, "wide-area DGPS". WAAS offers accuracy similar to the USCG's ground-based DGPS networks, and there has been some argument that the latter will be turned off as WAAS becomes fully operational.

By the mid-1990s it was clear that the SA system was no longer useful in its intended role. DGPS would render it ineffective over the US, precisely where it was considered most needed. Additionally, experience during the Gulf War demonstrated that the widespread use of civilian receivers by U.S. forces meant that SA was thought to harm the U.S. more than if it were turned off. After many years of pressure, it took an executive order by President Bill Clinton to get SA turned off permanently in 2000.

Nevertheless, by this point DGPS had evolved into a system for providing more accuracy than even a non-SA GPS signal could provide on its own. There are several other sources of error that share the same characteristics as SA in that they are the same over large areas and for "reasonable" amounts of time. These include the ionospheric effects mentioned earlier, as well as errors in the satellite position ephemeris data and clock drift on the satellites. Depending on the amount of data being sent in the DGPS correction signal, correcting for these effects can reduce the error significantly, the best implementations offering accuracies of under 10 cm.

In addition to continued deployments of the USCG and FAA sponsored systems, a number of vendors have created commercial DGPS services, selling their signal (or receivers for it) to users who require better accuracy than the nominal 15 meters GPS offers. Almost all commercial GPS units, even hand-held units, now offer DGPS data inputs, and many also support WAAS directly. To some degree, a form of DGPS is now a natural part of most GPS operations.

Operation

A reference station calculates differential corrections for its own location and time. Users may be up to 200 nautical miles (370 km) from the station, however, and some of the compensated errors vary with space: specifically, satellite ephemeris errors and those introduced by ionospheric and tropospheric distortions. For this reason, the accuracy of DGPS decreases with distance from the reference station. The problem can be aggravated if the user and the station lack "inter visibility"—when they are unable to see the same satellites.

Accuracy

The United States *Federal Radionavigation Plan* and the IALA *Recommendation on the Performance and Monitoring of DGNSS Services in the Band 283.5–325 kHz* cite the United States Department of Transportation's 1993 estimated error growth of 0.67 m per 100 km from the broadcast site but measurements of accuracy across the Atlantic, in Portugal suggest a degradation of just 0.22 m per 100 km.

Variations

DGPS can refer to any type of Ground Based Augmentation System (GBAS). There are many operational systems in use throughout the world, according to the US Coast Guard, 47 countries operate systems similar to the US NDGPS (Nationwide Differential Global Positioning System).

European DGPS Network

The European DGPS network has been mainly developed by the Finnish and Swedish maritime administrations in order to improve safety in the archipelago between the two countries.

In the UK and Ireland, the system was implemented as a maritime navigational to fill the gap left by the demise of the Decca Navigator System in 2000. With a network of 12 transmitters sited around the coastline and three control stations, it was set up in 1998 by the countries' respective General Lighthouse Authorities

(GLA) - Trinity House covering England, Wales and the Channel Islands, the Northern Lighthouse Board covering Scotland and the Isle of Man and the Commissioners of Irish Lights covering the whole of Ireland. Transmitting on the 300 kHz band, the system underwent testing and two additional transmitters were added before the system was declared operational in 2002.

Trinity House - DGNSS Stations: UK and Ireland

Effective Solutions (Data Products) - European Differential Beacon Transmitters - Details and map

United States NDGPS

The United States Department of Transportation, in conjunction with the Federal Highway Administration, the Federal Railroad Administration and the National Geodetic Survey appointed the Coast Guard as the maintaining agency for the U.S. Nationwide DGPS network. The system is an expansion of the previous Maritime Differential GPS (MDGPS) which the Coast Guard began in the late 1980s and completed in March 1999. MDGPS only covered coastal waters, the Great Lakes, and the Mississippi River inland waterways, while NDGPS expands this to include complete coverage of the continental United States. The centralized Command and Control unit is USCG Navigation Center, based in Alexandria, VA. The USCG has carried over its NDGPS duties after the transition from the Department of Transportation to the Department of Homeland Security. There are 82 currently broadcasting NDGPS sites in the US network, with plans for up to 128 total sites to be online within the next 15 years.

Canadian DGPS

The Canadian system is similar to the US system and is primarily for maritime usage covering the Atlantic and Pacific coast as well as the Great Lakes and Saint Lawrence Seaway.

Post processing

Post-processing is used in Differential GPS to obtain precise positions of unknown points by relating them to known points such as survey markers.

The GPS measurements are usually stored in computer memory in the GPS receivers, and are subsequently transferred to a computer running the GPS post-processing software. The software computes baselines using simultaneous measurement data from two or more GPS receivers.

The baselines represent a three-dimensional line drawn between the two points occupied by each pair of GPS antennas. The post-processed measurements allow more precise positioning, because most GPS errors affect each receiver nearly equally, and therefore can be cancelled out in the calculations.

Differential GPS measurements can also be computed in real-time by some GPS receivers if they receive a correction signal using a separate radio receiver, for example in Real Time Kinematic (RTK) surveying or navigation.

The improvement of GPS positioning doesn't require simultaneous measurements of two or more receivers in any case, but can also be done by special use of a *single* device. In the 1990s when even handheld receivers were quite expensive, some methods of ***quasi-differential*** GPS were developed, using the receiver by quick turns of positions or loops of 3-10 survey points. At the TU Vienna the method was named *qGPS* and adequate post processing software was developed.

GPS Aided Geo Augmented Navigation

The **GPS Aided Geo Augmented Navigation** or **GPS and Geo Augmented Navigation** system (**GAGAN**) is a planned implementation of a regional Satellite Based Augmentation System (SBAS) by the Indian government. It is a system to improve the accuracy of a GNSS receiver by providing reference signals.

The Rs. 7.74 billion (774 crore) project is being implemented in three phases through 2008 by the Airport Authority of India with the help of the Indian Space Research Organization's (ISRO) technology and space support. The goal is to provide navigation system for all phases of flight over the Indian airspace and in the adjoining area. It is applicable to safety-to-life operations, and meets the performance requirements of international civil aviation regulatory bodies. The final, operational phase of GAGAN is likely to be completed by May 2011. *Gagan* is a Hindi word of Sanskrit origin for the sky.

Technology

To begin implementing an SBAS over the Indian airspace, Wide Area Augmentation System (WAAS) codes for L1 frequency and L5 frequency were obtained from the United States Air Force and U.S Department of Defense on November 2001 and March 2005.. The system will use eight reference stations located in Delhi, Guwahati, Kolkata, Ahmedabad, Thiruvananthapuram, Bangalore, Jammu and Port Blair, and a master control center at Bangalore. U.S. defense contractor Raytheon has stated they will bid to build the system.

Technology Demonstration

As a part of the programme, a network of 18 total electron content (TEC) monitoring stations were installed at various locations in India to study and analyse the behaviour of the ionosphere over the Indian region. **GAGAN's Technology Demonstration System (TDS)** signal in space provides a three-metre accuracy as against the requirement of 7.6 metres. Flight inspection of GAGAN signal is being carried out at Kozhikode, Hyderabad and Bangalore airports and the results have been satisfactory so far. To study the ionospheric behavior more effectively over entire Indian Airspace, Indian universities and R&D labs, which are involved in the development of regional based IONO-TROP model for GAGAN, have suggested nine more TEC stations. The AAI's efforts towards implementation of operational SBAS can be viewed as the first step towards introduction of modern CNS/ATM system over Indian airspace .

Technology Integration

GAGAN, after its final operational phase completion, will be compatible with other SBAS systems such as the Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS) and the Multi-functional Satellite Augmentation System (MSAS) and will provide seamless air navigation service across regional boundaries. While the ground segment consists of eight reference stations and a master control centre, which will have sub systems such as data communication network, SBAS correction and verification system, operations and maintenance system, performance monitoring display and payload simulator, Indian land uplinking stations will have dish antenna assembly. The space segment will consist of one geo-navigation transponder.

Indian Regional Navigational Satellite System

The Indian government has stated that it intends to use the experience of creating the GAGAN system to enable the creation of an autonomous regional navigation system called the Indian Regional Navigational Satellite System (IRNSS) and that it might use the GSAT-4 satellite as a technology demonstration system phase of the proposed navigational system.

Effective Flight Management System

Flight Management System based on GAGAN will then be poised to save operators time and money by managing climb, descent and engine performance profiles. The FMS will improve the efficiency and flexibility by increasing the use of operator-preferred trajectories. It will improve airport and airspace access in all weather conditions, and the ability to meet the environmental and obstacle clearance constraints. It will also enhance reliability and reduce delays by defining more precise terminal area procedures that feature parallel routes and environmentally optimised airspace corridors.

- GAGAN will increase safety by using a three-diemensional approach operation with course guidance to the runway, which will reduce the risk of controlled flight into terrain i.e, an accident whereby an airworthy aircraft, under pilot control, inadvertently flies into terrain, an obstacle, or water.

- GAGAN will also offer high position accuracies over a wide geographical area like the Indian airspace. These positions accuracies will be simultaneously available to 80 civilian and more than 200 non-civilian airports and airfields and will facilitate an increase in the number of airports to 500 as planned. These position accuracies can be further enhanced with ground based augmentation system.

Developments

The first GAGAN transmitter was integrated into the GSAT-4 geostationary satellite, and had a goal of being operational in 2008. Following a series of delays, GSAT-4 was launched on 15 April 2010, however it failed to reach orbit after the third stage of the Geosynchronous Satellite Launch Vehicle Mk.II that was carrying it malfunctioned. The project involves establishment of 15 Indian Reference Stations, three Indian Navigation Land Uplink Stations, three Indian Mission Control Centers and installation of all associated softwares and communication links. GAGAN is planned to get into operation by the year 2014. It will be able to help pilots to navigate in the indian airspace by an accuracy of 3 Mts. This will be helpful for landing aircrafts in tough weather and terrain like Managalore airport and Leh.