Bringing New Benefits to Users
GNSS Development

Precise positioning and timing services have evolved considerably over the past decades. They now represent a vital part of the modern information infrastructure and are entering everyday life. This fantastic growth has been made possible by GNSS (Global Navigation Satellite System). These systems are widely used, not only in professional applications but also, by enabling personal navigation (e.g. car navigation or hand-held GPS navigators), in the mass market. Furthermore, a number of key communication technologies like GSM (Global System for Mobile Communications) mobile networks rely on timing information provided by GNSS. At present there are two GNSS: the US Global Positioning System (GPS) and the Russian GLONASS (GLObal NAvigation Satellite System).

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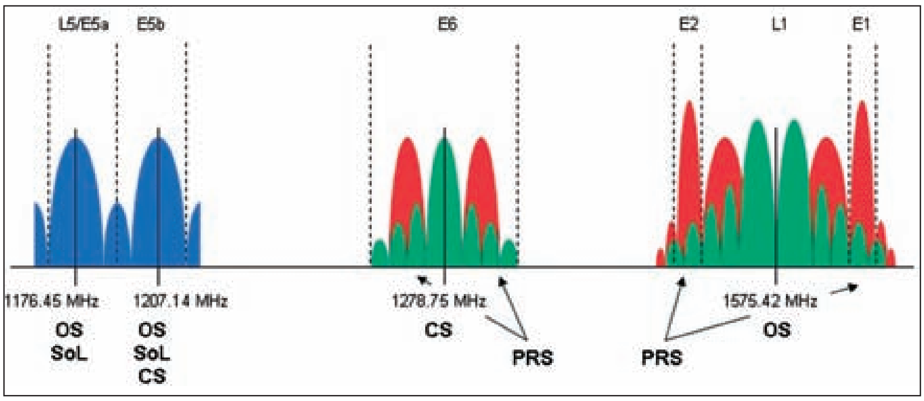


Overview of Galileo Signals

GPS

GPS was originally built by the US to support military applications; it is still operated and controlled by the US Department of Defense. However already in the early 1990's GPS has been declared as a dual purpose, civil and military, system. Presently, GPS dominates the satellite navigation market. The US national policy on GPS, approved by the US President in December 2004, is to "...provide on a continuous, worldwide basis, civil space-based positioning, navigation, and timing services free of direct user fees for civil, commercial, and scientific uses...through the Global Positioning System and its augmentations, and provide open, free access to information necessary to develop and build equipment to use these services."

Nevertheless, due to its original objective and its institutional status, GPS cannot provide firm service guarantees to civil users. The liability issues are also quite complex. Ultimately, modern civil applications give rise to new performance requirements, especially with respect to integrity and continuity.

To improve GPS sevices for both military and civil users, the US government commissioned a GPS modernization program.

Aside from the satellite design issues, the modernized GPS will: provide civil ranging code on the carrier frequency L2; provide civil ranging code on the carrier frequency L5 (L5 is a new frequency in the GPS frequency plan); and include a number of new features for military users (BOC military ranging signals [M-code]etc.). In addition, the accuracy of GPS satellite ephemeris and satellite clock parameters will be improved according to plan.

GLONASS

Like GPS, GLONASS (GLObal NAvigation Satellite System) was also originally built as a military system; it is operated by the Russian Ministry of Defense. However, the Presidential Decree of 1999 declared GLONASS is to be available for civil use, and transferred responsibility for GLONASS development and application to the Russian Space Agency while the Ministry of Defense remained in charge of its operation. GLONASS did not generate as many civil applications as GPS, mainly because of system maintenance problems following 1996. Another complication for receiver manufacturers was the signal access scheme implemented in GLONASS. It is based on Frequency Division Multiple Access (FDMA) principle (satellites transmit different carrier frequencies) whereas GPS utilized Code Division Multiple Access (CDMA) approach (satellites transmit the same carrier frequency, signals are distinguished due to the difference in the satellite spreading codes).

Galileo

Facing the GPS monopoly, the European Union launched the Galileo program to build a GNSS for civil purposes and under civil control. The European Union, in close cooperation with ESA (European Space Agency), initiated the program and funds and supervises it.

Galileo will respond to the technical demands of user applications in terms of performance and signal quality. It is also intended to stimulate the European market, foster technology development and secure the role of Europe as a global player in satellite navigation.

Galileo will not be controlled by any single state; responsibility is to be shared between the GNSS Supervisory Authority and the Concessionaire.

Galileo users will also benefit from increased positioning accuracy and signal robustness against multipath errors and interference. This will be achieved through the implementation of an increased number of civil signals, greater bandwidths and advanced spreading codes.

Galileo Constellation

The Galileo Space Segment will consist of a constellation of 27 satellites in MEO (Medium-Earth Orbit) with 3 additional spare satellites (one per orbit plane). Each satellite will broadcast navigation signals on several carrier frequencies (see figure). These signals will be comprised of the pseudorandom (spreading) codes which enable range measurements, navigation mes-

Parameter	GPS	GLONASS	Galileo
Operator	Department of Defense, USA	Russian Space Agency and Department of Defense, Russia	Commercial operator
Number of satellites	24 due, currently 31 (2 unhealthy)	24 due, currently 16 (6 unhealthy)	27 + 3 spares
Full Operational Capability	1995	1995 (presently constellation is degraded)	2011 (personal best guess)
Orbits	MEO	MEO	MEO
Number of orbital planes	6	3	3
Orbit altitude	20 350 km	19 140 km	23 616 km
Orbit eccentricity	~0	~0	~0
Orbit inclination	55°	64.8°	56°
Carrier frequencies, MHz	L1 1575.42 L2 1227.6 L5 1176.45	G1 1598.0625 - 1607.0625 G2 1242.9375 - 1249.9375 G3 1198.55 - 1205.30 (TBC)	L1 1575.42 E5 1191.795 E6 1278.75
Modulation	CDMA; BPSK	FDMA; BPSK	CDMA; BPSK and BOC
Open services	Standard Positioning Service	Open Access Service	Open Service

Satellite navigation systems at one glance.

sages containing satellite orbit and clock data, integrity, and other information.

To enable accurate synchronization of satellite clocks, and thus to enable precise user positioning, each satellite will carry two space-qualified rubidium frequency standards and two passive hydrogen masers based on European technology.

The Galileo Ground Segment will control the Galileo constellation, compute mission data (satellite ephemeris and clock, integrity and other service data) and upload them to the navigation satellites. It will consist of: two main control centers which will host control, processing, storage, and time synchronization facilities; a worldwide network of Galileo se sor stations which will perform the continuous range measurements towards the Galileo satellites (these measurements are necessary to compute satellite orbit and clock parameters and integrity); and telemetry and uplink stations.

In addition to the Satellite and Ground Segments, built-in augmentation systems and local elements are also foreseen in the Galileo architecture.

Galileo Services

Galileo will support the most demanding safety-critical applications such as civil aviation. It will do this not only by providing system integrity information (warning of any system malfunction within six seconds of its occurrence), but also by elaborating dedicated certification schemes. Furthermore, as the first among navigation systems, Galileo will offer service guarantees. Additionally, professional users of Galileo will benefit from the Galileo commercial service which will include extended navigation signals and information related to value-added services.

Galileo will provide four basic navigation services based on a certain combination of Galileo ranging signals, navigation and other broadcast information (e.g. integrity):

1. Open Service: provides global, free-of-charge positioning and timing capabilities by means of navigation signals separated in frequency by using the L1 and E5 frequency bands.
2. Safety-of-Life Service: provides integrity information by means of encrypted supplementary signals, and navigation capabilities based on the Open Service signals, and navigation capabilities based on the Open Service signals. The performance of this service will be guaranteed.
3. Commercial Service: provides additional data dissemination services and a third navigation signal with controlled access. Positioning capabilities (including precise positioning based on carrier phase measurements) are provided in combination with the signals of Open Service. This service is based on the L1, E5b and E6 frequency bands.
4. Public Regulated Service: provides global positioning and timing capabilities by means of two navigation signals separated in frequency (on the L1 and E6 frequency bands); access to these signals will be controlled.

Galileo Performance

The performance of Galileo services is defined for users whose location, dynamic, environment (in terms of ionospheric effects, tropospheric effect, multipath, interference), and receiver are compatible with specifications given in the Galileo system requirements document.

The specifications given in the table below are based on pseudorange (code) measurements. However, high-end GNSS receivers used in professional applications like geodesy and cadastre, produce high-accuracy measurements based on the carrier frequency of the satellite signals. Combined with a ground station, this positioning method can achieve cen-

Parameter	Open Service		Safety-of-Life (dual freq.)	Public Regulated (dual freq.)	
	Single freq.	Dual freq.		Single freq.	Dual freq.
Accuracy, 95%					
- horizontal	15 m	4 m	4 m	15 m (L1) 24 m (E6)	6.5 m
- vertical	35 m	8 m	8 m	35 m	12 m
- timing	30 ns	30 ns	30 ns	30 ns	30 ns
Service availability	99.5%	99.5%	99.5%	99.5%	99.5%
Integrity					
- Alert limit	n/a	n/a	12 m (H) 20 m (V)	n/a	20 (H) 35 m (V)
- Time to alert			6 s		10 s
- Integrity risk			3.5×10^{-7} per 150 s		3.5×10^{-7} per 150 s
Continuity risk	n/a	n/a	1×10^{-5}/15s	n/a	1×10^{-5}/15s

Performance of Galileo navigation service.

timeter-level accuracy and is often referred to as RTK (Real-Time Kinematic).

In a rural environment where multipath and interference are usually low, Galileo RTK is expected to have a precision similar to current GPS RTK solutions. Users, however, may still benefit from the reduced sensitivity of Galileo signals to multipath effects and interference. In addition, the processing of Galileo RTK could be simplified due to the availability of additional frequencies, a higher number of frequency combinations and higher measurement accuracy in Galileo.

Galileo may bring important benefits to professional users in urban environments where multipath and interference constitute the major error sources. Users of the Galileo Commercial Service will access three navigation signals in the L1, E5 and E6 bands. The third frequency would allow dramatic improvement of multipath detection and mitigation. It will also enable a more precise correction of the ionospheric errors.

Galileo Program Status

Galileo has successfully entered the implementation phase and is currently on the way to full system deployment. Along with the development of the core system infrastructure, ESA has commissioned the GSTB (Galileo System Test Bed) with two satellites, GIOVE-A and GIOVE-B.

The GSTB phase will be followed by the IOV (In-Orbit Validation) phase where four Galileo satellites will be brought into orbit, the Ground Segment will be fully deployed and the whole system will be validated against the key mission requirements.

Finally, the Galileo constellation will be extended to its nominal configuration with 27+3 satellites, the final validation will be performed and the system will achieve FOC (Full Operational Capability).

GIOVE-A and B

GIOVE-A was successfully launched on December 28, 2005. Since January 12, 2006 Galileo signals have been broadcast from space. GIOVE-A weighs 649 kg and is capable of transmitting navigation signals in all three frequency bands allocated to Galileo. However, only two signals can be transmitted simultaneously: either L1+E5 or L1+E6. The GIOVE-A navigation message and spreading codes differ from those of the final Galileo satellites.

The GIOVE-A satellite is equipped with two rubidium frequency standards. The GIOVE-B satellite will have extended functionality and will also carry a passive hydrogen maser, the most precise clock ever flown on board a navigation satellite.

30 meter dish antenna at the DLR in Weilheim

Galileo Test Environment

In 2002 the German Federal Ministry of Education and Research approached the German Aerospace Center (DLR) to develop a Galileo test environment for signals, user equipment and applications. This Galileo Test Environment, known as GATE, is to become fully operational in mid 2007. (See also the report on Navitec 2006 elsewhere in this issue.)

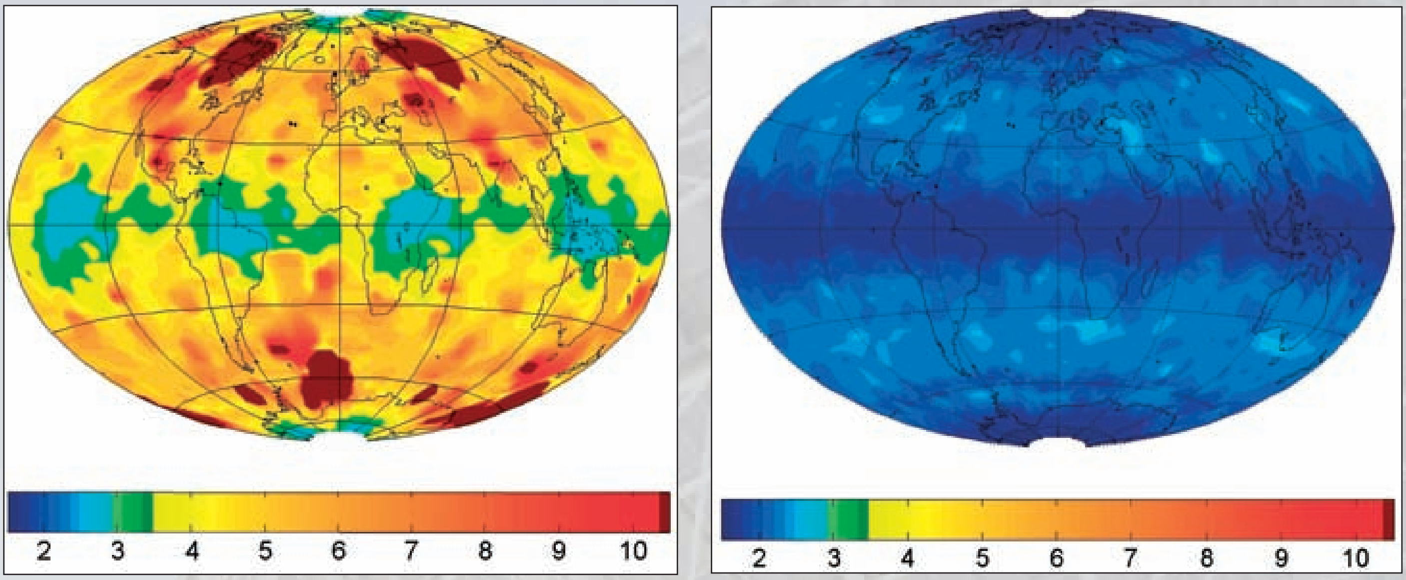
GLONASS System Overview and Program Status

Similar to GPS, GLONASS Open Services, a free-of-charge service for civil users, is provided through the civil signal in the L1 frequency band. GLONASS military signals are not decrypted unlike GPS. The GLONASS constellation was fully deployed by 1995. At that time Selective Availability (intentional performance degradation by the manipulation of broadcast signals) was still active in GPS, and GLONASS, whose signals were not intentionally degraded, was an attractive.

However, the GLONASS maintenance problems of the late 1990s, from which the system has not yet fully recovered, have considerably reduced user interest.

Furthermore, current accuracy is four to five times less than that of GPS.

To improve the situation and encourage civil applications, Russia adopted a Federal Program in 2001 aimed at completion of the GLONASS satellite constellation, modernization of its Ground Segment, improved accuracy and facilitation of civil applications. The program was amended in July 2006 with extra funding and increased requirements. On December 25, 2006 three Glonass-M satellites were launched from Baykonur. Presently the satellites are undergoing flight tests, after their completion the satellites will be put into nominal operations.



95% horizontal positioning error (with pseudorange measurements) corresponding to the worst-case satellite geometry: left - GPS only, right - GPS+Galileo

GLONASS Modernisation

GLONASS has already planned modernization of its satellites to increase their lifetime and provide new signals and services. The first generation of modernized satellites, GLONASS-M, will have the following capabilities in addition to those of standard GLONASS satellites: extended lifetime (seven years); civil signal in the L2 band; improved onboard clock (higher performance, longer lifetime); and improved platform (better solar panel pointing etc.).

The first GLONASS-M satellite became operational in 2003. The next generation of GLONASS satellites is called GLONASS-K. These satellites will have a lifetime of 10 years, a third civil signal, and improved performance. There are also plans to install a SAR payload on these satellites. The first GLONASS-K satellite is due to be launched in 2008. Russia is currently negotiating with the EU and the US regarding cooperation with Galileo and GPS to enable GLONASS interoperability with these systems and thus improve access to the navigation market.

Galileo Interoperability: on the Way to GNSS

Galileo and GPS

Interoperability with GPS has been one of the key Galileo design drivers. Most Galileo users (at least as far as mass-market applications are concerned) are expected to use combined GPS/Galileo equipment. Interoperability is ensured, first of all, by the selection of overlapping frequency bands (L1 and L5) for GPS and Galileo, and implementation of GPS-compatible spreading codes in Galileo. Thus, GPS and Galileo signals can be processed with the same hardware; just the signal processing part will differ. Another important decision to facilitate GPS/Galileo interoperability is the close alignment of GPS and Galileo geodetic reference frames (through alignment of both with the international reference system ITRF), and determination of the GPS/Galileo time offset which will be broadcast by both systems.

Users will benefit not only from the increased accuracy of positioning when using a combination of GPS and Galileo, but also from the dramatic increase in service availability provided by access to 57 navigation satellites (assuming 30 GPS satellites are active today). The combination of GPS and Galileo is capable of providing continuous, precise and reliable positioning service in urban environments as well.

The combination of GPS and Galileo signals should also be attractive to GPS users since Galileo signals will be more robust to multipath and interference. In addition, the use of two independent satellite systems could improve the integrity of user positioning through cross-checking. Professional users, who use carrier-phase-capable receivers, will also benefit from a GPS/Galileo combination. The improvement in accuracy in this case would not be dramatic but they will enjoy increased availability and reliability of service.

GLONASS, Galileo and GPS

The combination of GLONASS with Galileo and GPS is made somewhat more complicated due to a difference in frequency bands, signal modulation techniques and reference frames. Nevertheless, there are already dual-system GPS/GLONASS receivers that prove this combination is possible. At a technical level, the joint estimation of GLONASS, Galileo and GPS orbits and clock parameters in a unified spatial and time reference frame, and the provision of these products to users, would facilitate system interoperability. Such a service would pave the way to a global GNSS comprising all available navigation systems where users would not need to be concerned with what system they are using and how many of its satellites are available at their location. They could determine their position precisely, even in urban canyons, as easily as they receive phone calls on their mobiles.

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For more information on Galileo, visit www.esa.int.
For more information on GLONASS, visit www.glonass-ianc.rsa.ru.

A combination of GPS, GLONASS and Galileo will pave the way to a global GNSS comprising all available navigation systems. Users would not need to be concerned with what system they are using and how many of its satellites are available at their location. They could determine their position precisely, even in urban canyons, as easily as they receive phone calls on their mobiles.