Modernization of satellite Navigation Systems and theirs New Maritime Applications

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ABSTRACT: The last years gave a rise to many important changes in the operational status and practical exploitation of satellite navigation systems (SNS) GPS & GLONASS, differential mode of these systems (DGPS, DGLONASS) and Satellite Based Augmentation Systems (SBAS) as EGNOS or WAAS. Therefore the modernization of these systems as new satellites, new civil signals, new codes, new monitoring stations etc. and the details about new systems under construction as Galileo, Compass and IRNSS, the problem of interoperability and new maritime applications are presented in this paper.

1 SATELLITE NAVIGATION SYSTEMS TODAY AND IN THE FUTURE

The last years gave a rise to many important changes in the operational status and practical exploitation of satellite navigation systems GPS and GLONASS, in particular, differential mode of these systems and Satellite Based Augmentation Systems. These changes include improvements to the ground support segment, and augmentation to provide differential services and to support Search and Rescue (SAR) service.

1.1 *GPS system*

GPS system consists of three segments: the Space Segment, the Operational Control Segment (OCS) and the User Segment.

The current (March 2007) GPS constellation consists of 30 satellites under Full Operational Capability (FOC) – 15 Block IIA, 12 Block IIR and 3 Block IIR–M. Satellite PRN24/SVN24 is usable since August 30, 1991; nearly 16 years ago!

The first satellite, GPS Block IIR–M, PRN17/SVN53, incorporating civil code C at L2 and, a modernized military signal with enhanced security the M–code at L1 & L2, has been operating since December 16, 2005. For the first time the new M−code was successfully acquired and tracked by Raytheon Company of El Segundo, California; this news was announced November 6, 2006. The M–code provides enhanced accuracy, encryption, and anti–jamming capability for authorized users.

The next 5 satellites IIR–M will be launched in 2007 or later.

After Block IIR–M the "follow–on" satellites will be Block IIF. The IIF spacecrafts will broadcast the same 6 signals, which are transmitted by current Block IIR–M satellites and additionally a new third civil signal at 1,176.45 MHz (L5 carrier). The first GPS Block IIF satellite can be launched in 2008.

The Block IIF SV is designed for a life of 12 years with a mean mission duration (MMD) of 9.9 years, its autonomous operations are for up to 60 days, body dimensions: 248 x 202 x 178 cm, other parameters – increased disposal capability, uplink rate 1 or 2 kbps, downlink data rate: up to 1.9 Mbps.

In OCS the satellite signals are tracked from six U.S. Air Force monitor stations and from six monitor stations operated by the National Geospatial–Intelligence Agency (NGA) of the Department of Defence. Boeing has successfully completed live demonstration of a newly architected six Air Force monitor stations, which, when fully operational, will control the 32 GPS satellites now in orbit as well as that will join the fleet in the coming months.

The twelve–station network allows the system operators to watch each satellite from at least two monitor stations at all times. Five more NGA–operated monitor stations will be added to the actual network in the future (Misra, P & Enge, P. 2006).

Satellite IIF upgrade will be compatible with OCS architecture. After modernization this segment will be characterized by the following parameters: total constellation space vehicle contract available using crosslinks, time accuracy offset reduced, enhanced navigation planning capability, 50% reduction in operator workload, comprehensive maintenance and support infrastructure. Boeing is building 12 GPS Block IIF satellites under contract from the GPS Wing, U.S. Air Force Space and Missile Systems Center, and expects to deliver the first satellite in 2007 or later.

The GPS III program was conceived to reassess the entire GPS architecture as it has involved to its present state and determine the correct architecture to lead into the future. This program has two main goals: reduce the government's total ownership costs and provide sufficient architectural flexibility to satisfy evolving requirements through 2030. GPS III with the next generation satellites is expected to provide significant increase in position, velocity and time (PVT) accuracy, high level of continuity and signal availability, greater timing accuracy, a system integrity solution (GPS II is without integrity service), autonomous navigation, a high data capacity intersatellite crosslink capability, and higher signal power to meet military antijam requirements.

The GPS III satellite constellation characteristics are not defined yet. Two ongoing studies are exploring two different solutions: an innovative three–plane constellation (as in GLONASS and Galileo systems) and the traditional six–plane constellation used in the current GPS. The first GPS III satellite launch is planned for year 2013 or later and Full Operational Capability for year 2030 (Kaplan, E.D. & Hegarty, C.J. 2006).

According to a different unofficial source, SVN23, an old Block IIA satellite decommissioned in 2004, might be recommissioned as PRN32. This may seek to test the ability of current GPS receivers to handle more than 31 PRN numbers. PRN code 32 is permitted but has not been used since 1993.

1.1.1 *Differential mode*

As existing GPS and GLONASS could not fulfil all institutional and technical demands, the maritime administrations of the countries all over world have implemented a radiobeacon DGNSS service to improve safety and efficiency of navigation in their coastal waters. It was necessary to expand the existing radiobeacon network at the coast with additional stations to cover all inland waterways.

That's why the number of beacons (stations) transmitting DGPS corrections has been increased in last years considerably (Table 1). In 2001 there were 138 beacons with status operational, 80 with status on trial, 15 planned, in 2006 these numbers were 234, 57 and 11 adequately. At present the beacons are localized in 41 countries, the greatest number of beacons operational are in USA (39), Japan (27), China (21), and India (19); Table 2. Additionally 6 stations are without status, e.g. Jaroslawiec in Poland (position, frequency of DGPS corrections, identification number of transmit station, and nominal range only). In Europe there are 73 operational and 25 on trial maritime differential beacons (ALRS. 2001–2006).

Table 1. The numbers of stations transmitting DGPS corrections in the period 2001÷2006 [1]

Year (volume)	Number of stations			
	Operational	On trial	Planned	Total
2001 (8)	138	80	15	233
2002 (8)	162	52	20	244
2003 (2)	189	84	15	288
2004 (2)	208	68	12	288
2006 (2)	234	57	11	302

Until recently, there was only one set of RTCM Special Committee 104 messages to support both code and carrier–based Local–Area DGPS services. This message set has evolved over time (1.0, 2.0, 2.1, 2.2); version 2.3 (published in 2001), is the most recent.

In February 2004 SC–104 has published the latest edition of its version, called 3.0 for differential Global Navigation Satellite System (GNSS) services. This standard supports very high accuracy navigation and positioning through a broadcast to mobile GNSS receivers, which allows the receivers to compensate for errors that exist in satellite positioning without augmentation. This latest edition includes an interoperable definition for Network Real–Time Kinematic (Network RTK).

1.2 *GLONASS system*

As with GPS, GLONASS is on the way to modernization of the system. Apart from the signals in the L1 band, GLONASS system has already established a second civil signal at L2 upon launch of the first GLONASS–M satellite in 2003. Three last satellites GLONASS–M, 715, 716 and 717, were launched December 25, 2006. These satellites are placed on orbit II. A third civil signal at L3 band (1,190–1,212 MHz range, near GPS L5), is expected to start in 2008 aboard GLONASS–K satellites. In addition to transmitting navigation–message data, the two new signals will also transmit GLONASS integrity and GLONASS wide–area differential correction information to enhance the accuracy and reliability of the navigation services (Kaplan, E.D. & Hegarty, C.J. 2006).

The current GLONASS status is far away from its nominal numbers (24) because the actual (March 2007) GLONASS constellation consists of 9 satellites under Full Operational Capability (FOC). 10 additional space vehicles are on orbit but have been temporarily switched off and are currently not broadcasting any signals (www.glonass-ianc.rsa.ru).

Russian officials predict that GLONASS system performance will equal that of GPS system by 2008 with 18 satellite constellation and the frequency of launches would increase over the next years to provide a 24 satellite constellation and Full Operational Capability (FOC) by 2010−2011. Russia's president Putin decreed on 18 January 2006 to speed up the GLONASS program and made additional budgets available.

Table 2. The numbers of stations transmitting DGPS corrections in different countries in 2006 (ALRS. 2001–2006)

Country	Station status			Total
	Operational	On trial	Planned	
Australia	16	–	–	**16**
Canada	17	–	–	**17**
China	21	–	–	**21**
India	19	3	–	**21**
Japan	27	–	–	**27**
Norway	12	–	2	**14**
Spain	2	13	4	**19**
USA	39	3	2	**44**

1.3 *Galileo system*

The European Commission, together with the European Space Agency (ESA) and European industry, is building up a European Satellite Navigation System under name Galileo. This system will be controlled by civil authorities and be inter–operable with GPS and GLONASS. It will provide real–time position-ing and timing services at different levels of accuracy, integrity, and availability. Other than existing satellite navigation systems, Galileo is suitable system for safety critical applications, such as landing aircraft, guiding cars, tracking hazardous materials, and controlling rail traffic (Seeber, G. 2003).

Construction of the first of the two Galileo ground control centers at Oberpfaffenhofen, near Munich, in Germany, began on November 7, 2006. The 16 milion euro complex will employ 100 engineers and controllers. The second center will situated at Toulouse in France.

Galileo plans to provide four types of navigation services and a search and rescue service (p.4.2):

– Open Service (OS): Accessible to all without user fees; like GPS Standard Positioning Service (SPS), but claimed to be better. The OS will provide positioning, velocity, and timing information, this service is suitable for mass–market applications, such as in car navigation, is also suitable with integration in mobile tele-phones;
– Commercial Service (CS): Fee based service offering assured level of performance, including service availability;
– Public Regulated Service (PRS): Fee based service intended for government agencies and military applications requiring a higher level of protection. Controlled access (the PRS signals will be encrypted, authorized users only) with high integrity and availability, and interference–resistant signals;
– Safety of Life (SoL): Fee based service aimed at transport applications with high integrity. Authentication of signal, certification and guarantee of service, to comply with the requirements of the IMO and International Civil Aviation Organization (ICAO).

At present the first Galileo test satellite, GIOVE–A, is in orbit, with control administrated through its manufacturer's – Surrey Satellite Technology Ltd. – headquarters in Guildorf, United Kingdom. Launch of the second test satellite, GIOVE–B, is now set for 2007. The Galileo In–Orbit Validation (IOV) phase is planned to start at the end of 2008 with four satellites and achieve FOC in 2012.

Galileo is not yet in operation but already the so–called evolution program for the second generation is planned to start in 2007 or later. Galileo II could arrive somewhere around 2020 and is expected to introduce new modernization elements analogous to the steps made by its counterparts GPS and GLONASS (Hein, G. et al. 2007).

1.4 *Compass system*

Compass is the SNS planned in China. The will of this country is to develop own global navigation system. This system will provide two navigation services: an open service for commercial customers and an "authorized" positioning, velocity, and timing communications service. Spatial segment will consist of 27 MEO, 3 Geosynchronous (GSO) and 5 GEO satellites.

Each satellite transmits the same four carrier frequencies for navigational signals. These signals are modulated with a predetermined bit stream, containing coded ephemeris data and time, and having a sufficient bandwidth to produce the necessary navigation precision without recourse to two–way tran-smission or Doppler integration**.**

The three GEO satellites (080°E, 110°E, 140°E) were placed into orbit between 2000 and 2003. The launch of two last GEO (058.75°E, 160°E) scheduled for early in 2007, is expected to cover China and parts of neighboring countries by 2008, before being expanded into global system.

The first version of Compass was called Beidou. Compass can be operational in 2012 if the political statements are brought into reality (Hein, G et al. 2007), (Kaplan, E.D. & Hegarty, C.J. 2006).

2 REGIONAL AND SATELLITE–BASED AUGMENTATION SYSTEMS

In addition to the mentioned above global satellite navigation systems two regional systems are also being developed by Japan and India, QZSS and IRNSS respectively:

- Quasi–Zenith Satellite System (QZSS) will serve as enhancement for GPS. The constellation consists of three satellites inclined in elliptic orbits with different orbital planes in order to pass over the same ground track. QZSS and GPS will be fully interoperable, the first QZSS satellite will be launched in 2008;
- Indian Radionavigation Satellite System (IRNSS) is an independent seven satellites constellation that will be built and operated by India. This system will seek to maintain compatibility with other GNSS and augmentation systems of the region and is planned to provide services for critical national applications.

Nowadays Satellite Based Augmentation Systems (SBAS) are the following:

- the European Geostationary Navigation Overlay Service (EGNOS) would supplement GPS (and perhaps GLONASS in the future) by reporting on the reliability and accuracy of the signals. The system started its initial operations in July 2005, and is intended to be certified for use in safety of life applications in 2008;
- the Wide Area Augmentation System (WAAS) augments GPS over North American territory to provide the additional accuracy, integrity, and availability needed to enable users to rely on GPS for safety–critical applications;
- the Multifunctional Transport Satellite Augmentation System (MTSAT) in Japan is used for meteorological observations and communication services following a multi–mission concept. Two satellites were launched in 2005 and 2006;
- GAGAN. The GPS and GEO Augmented Navigation system is India's SBAS for the south Asian region. This system is under construction. GAGAN will eventually expand into IRNSS;
- NIGCOMSAT. With its Nigerian Communications Satellite, Nigeria is the first African country planning to enter the field of GNSS by transmitting two L–band signals in L1 and L5; (Kaplan, E.D. & Hegarty, C.J. 2006).

3 SATELLITE NAVIGATION SYSTEMS INTEROPERABILITY

In the agreement on the promotion, provision and use of Galileo and GPS satellite–based navigation systems and related applications signed by United States of America and European Community summit on June 26, 2004 in Ireland among other things we can read that both parties recognize that:

- the US operates a satellite–based navigation system known as GPS, a dual use system that provides precision timing, navigation, and position location signals civil and military purposes,
- the European Community is developing and plans to operate a civil global satellite navigation, timing and positioning system, Galileo, which would be radio frequency compatible with GPS and interoperable with civil GPS services at user level,
- civil GPS and Galileo, if radio frequency compatible and interoperable at the user level, could increase the number of satellites visible from any location on the Earth,
- the International Maritime Organization (IMO) established international standards and other guidance applicable to the use of global SBAS for maritime navigation.

The Russian government has stated that, like GPS system, GLONASS is a dual–use system and there will be no direct user fees for civil users. Russia are working with the European Union and the United States to achieve compatibility between GLONASS & Galileo and GLONASS & GPS, respectively. As in the case with GPS/Galileo interoperability, key elements to achieving interoperability are compatible signal structure, geodetic coordinate reference frame, and time reference frame (Table 3).

Nowadays GPS and GLONASS are not interoperable, even if there are GPS and GLONASS integrated receivers on the market, e.g. Javad Navigation System Gyro–4T, NovAtel OEMV–2–RT2. The first has 20 channels and its signal tracked are L1/L2 GPS, L1/L2 GLONASS and WAAS, while the second can have 72 channels, signal tracked are L1 C/A, L2C, carrier phase (CP), L1 and L2 GLONASS, SBAS (GPS Receiver Survey. 2007).

These receivers look like a unique "box" to the user, but the truth is that there are two parallel receivers, which process separated signals and combine them in a manner that potentially still improves user performance. As GLONASS signal uses FDMA technology while GPS and Galileo use CDMA signals a very intriguing memo regarding GPS–GLONASS interoperability has appeared recently. At the September 2006 meeting of the ION GNSS Russian Federal Space Agency (RFSA) spoke of CDMA as an "option" for GLONASS and added the system "probably will be able to implement CDMA signals" on the new third frequency, to be added on GLONASS–K satellites during Phase 3 of GLONASS modernization, and at L1. Receiver operation in the GPS and Galileo mode is simpler with CDMA. A GLONASS switch to CDMA would make manufacture of combined receivers far easier.

The EU–U.S. agreement will allow precise estimation of the Galileo/GPS time offset and inclusion of it in each system's navigation message. The accuracy of this time offset modulo 1 second is specified to be less than 5 ns with 2–sigma confidence interval over any 24–hour period (Kaplan, E.D. & Hegarty, C.J. 2006).

Table 3. Comparison of satellite navigation systems

Parameter	GPS	GLONASS	Galileo
time base	GPS system time	GLONASS system time	Galileo system time
related system time	UTC_{USNO}	UTC_{SU}	TAI
geodetic datum	WGS–84	PZ–90	GTRF
satellite signal division	CDMA	FDMA	CDMA

4 MARITIME APPLICATIONS

Marine navigation was the first to embrace satellite navigation. Nowadays its market is maturing, additionally it is not the largest market segment.

4.1 *GPS system*

Along with radios and radar, a GPS receiver is a piece of standard equipment on any ship operating far from shore. The number of GPS receivers installed on the board depends on the different ship's parameters (type, deadweight, region of navigation etc.) and can be equal 1, 2, 3 or even 4.

In Federal Radionavigational Plan published in December 2005 we can read that the United States Coast Guard is exploring accuracy enhancement and the integration of Nationwide Differential Global Positioning Service (NDGPS) with other navigation sensors. Particular emphasis is being placed upon the integration of NDGPS with Inertial Navigation Systems (INS). Efforts are being conducted to determine the ability of INS to enhance GPS/DGPS navigation service, and to provide heading information for ECDIS use. Increasing numbers of WAAS receivers have emerged in the public market place and are being used in the maritime regions. Additionally the Coast Guard is developing a set of analysis tools to allow performance evaluations of navigation systems as GPS system, in particular, in specific ports and waterways (FRP Plan 2005).

Automatic Identification System (AIS) is a shipboard transponder system in which ships continually transmit data to all other nearby ships and shoreside authorities. AIS utilizes a unique self–organizing ti-me–division multiple access (STDMA) data communications scheme, which uses the precise timing data in the GPS signals to synchronize multiple data transmissions from many users on a single narrowband channel. The time reference is supplied by the precise timing in the GPS satellite message. Thus GPS plays a critical role in AIS, providing the time reference as well as positioning data for each ship.

GAPS is a unique Global Acoustic Positioning System based on Ixsea Oceano's mastery of Inertial Navigation System and acoustic Chirp modulation techniques. For the first time, Acoustic, Inertial and GPS measurements are merged in single process in a common housing and provide an all–in one solution (without external computer) for among other things precise positioning of several underwater vehicles and robust treatment of GPS drop–out and insensitivity to GPS jumps. As GAPS is able to position a subsea target fitted with any industry standard transponder beacon, it can accept input from any alternative GPS receiver (DGPS or RTK). Accuracy is about 0.2 % of slant range.

The long period gravity wave measurement system with arrayed buoys equipped with the kinematic GPS is proposed, which provides the precise propagational direction of the long period gravity wave. New method for measurement wave height and direction by installing point positioning GPS receiver on a buoy placed in the open sea was proposed in Japan. The scientists have showed that the propagation direction of the wave could be estimated accurately by applying the Multiple Signal Classification method to the wave signal on the basis of simulation and observation results when the observation buoys installed with the GPS system were arrayed in the double–triangle with this system arrayed in the double–triangle formation and the wave height could be measured in millimetre level. The measurements were realized in Osaka Bay (Fujii, H. et al. 2003).

Many Ports and Harbors around the world are experiencing tremendous growth and the number and size of ships is increasing dramatically. Modern ships have sophisticated bridge electronic systems including radar, satellite and terrestrial navigation systems and other navigation tools. Older ships may have limited navigation equipment or the equipment may not be working properly. Consequently harbor pilots around the world often carry on their own portable units with electronic chart displays. That's why a highly accurate positioning and heading system suitable for both portable and permanent installations, called PilotMate, was developed in USA, for the Port of Long Beach (CA), in particular. Determination of a ship's position is based on DGPS or KDGPS technologies. PilotMate system achevies a position accuracy of better than 3 m. This allows for accurate presentation of the position and orientation of a ship, regardless of whether it is moving forward, astern, sideways, or is dead in the water (Gilow, G. et al. 2003).

4.2 *Galileo system*

The efficiency, safety and optimisation of marine transportation are key issues. Satellite navigation is becoming a fundamental tool for bringing innovation and progress this sector and many other marine activities such as fishing, oceanography and oil and gas exploitation will also benefit from the availability of Galileo services.

The Galileo system also contributes to the international search and rescue service, enhancing the worldwide performance of the current COSPAS–SARSAT system. The actual positioning accuracy is rather poor (typically about few kilometres) and alerts are not always issued in real time. The Galileo search and rescue service (SAR) will drastically reduce the Time To Alert (from hour to minutes), and the position of the distress beacon from anywhere cross the globe will be determined to within a few metres. So far restricted to a professional type user community, there are some 200,000 COSPAS–SARSAT beacons in existence today. It has been shown that the market will rapidly grow to a few million beacons after the advent of Galileo.

Therefore the Galileo SAR services will provide enhanced service offerings, among other things, with significant improvements (Kaplan, E.D. & Hegarty, C.J. 2006):

– reduced detection, localization, and confirmation delay,
– multiple satellite coverage to avoid terrain blockage in severe conditions,
– new return–link service from Rescue Coordination Center to the distress–emitting beacon, thereby facilitating the rescue operations and helping to identify and reject the false alarms,
– forward link via stand–alone payload,
– return link integrated into navigation messages on L1, uplinked by the Galileo Ground Segment.

Finally this service will fulfill the requirements and regulations of IMO, via the detection of emergency position indicating radio beacons (EPIRB) of GMDSS of ICAO via the detection of emergency location terminals (ELT).

New project on maritime navigation, called MARUSE, developed by Kongsberg, was presented in 2006. The aim of this project is to introduce Galileo and EGNOS in the maritime domain. Demonstrations are held and planned for harbour approach including docking, inland waterways and intermodal transport. The key technical development activities within MARUSE will be among other things Maritime Galileo pseudolites, Galileo/GNSS receiver prototype capable of tracking GSTB–V2 signal and Galileo Pseudolites (Spaans, J. 2007).

4.3 *GLONASS system*

The Russian government plans to add a new SAR payload to the new GLONASS–K satellites. The payload will relay the 406 MHz SAR beacon transmissions that are designed to work with the currently deployed COSPAS–SARSAT system. This payload is similar in design and concept to the payload planned for Galileo system (Kaplan, E.D. & Hegarty, C.J. 2006).

5 CONCLUSIONS

– the GPS new civil signals, L2C and L5, will provide many advantages, such as higher signal strength, lower cross correlation, and improved support for high sensitivity indoor applications;
– the Russian government are working with European Union and United States to achieve compatibility between GLONASS and Galileo, and GLONASS and GPS, respectively;
– interoperability and effective synergy between the GPS and Galileo systems is the key to a bright future for satellite navigation;
– modernized system GPS, new systems Galileo and Compass, and the increasing of the number of GLONASS satellites will provide the new possibility for the users, positioning in restricted area and maritime applications, in particular.

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