

Global Navigation Satellite Systems – Perspectives on Development and Threats to System Operation

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ABSTRACT: The rapid development of satellite navigation and timing technologies and the broad availability of user equipment and applications has dramatically changed the world over the last 20 years. It took 38 years from the launch of the world's first artificial satellite, Sputnik 1, (October 4, 1957) to the day NAVSTAR GPS became fully operational (July 17, 1995). In the next 20 years user equipment became widely available at the consumer level, and 10 global and regional satellite systems were partially or fully deployed. These highly precise signals provided free to the user have been incorporated by clever engineers into virtually every technology. At the same time interference with these signals (spoofing and jamming) have become a significant day to day problem in many societies and pose a significant threat to critical infrastructure. This paper provides information on the current status and development of navigation satellite systems based on data provided by the systems' administrators. It also provides information on Loran/eLoran, a system which many nations have selected as a complement and backup for satellite navigation systems.

1 INTRODUCTION

While the industrial revolution brought an unprecedented revolution in material wealth to many nations in the 19th and 20th centuries, the turn of the 21st century saw technology enabling the creation of a virtual global village. The internet and increase in computational speed increased the pace of individuals' lives, accelerated change and brought nearly every point of the globe much closer together in virtual space. Satellite navigation systems augmented this by both providing an enabling precise, synchronized timing capability, and by making it much easier to overcome physical spaces that still separated individuals and societies.

The dawn of satellite navigation dates to 1958, and the TRANSIT system created by the Johns Hopkins University Applied Physics Laboratory, USA.

TRANSIT was used by naval vessels for navigation, and as a surveying aid and frequency reference. While there were some limited civilian uses, the inflection point for the technical revolution was not reached until NAVSTAR GPS became fully operational on July 17, 1995. Since then it has become a silent utility supporting everything from electronic banking to cellular telephone systems and electrical grids – not to mention transportation. Few can imagine life without these and other services. Many have become necessities as the systems and methods they replaced are no longer available.

Launch of the first NAVSTAR GPS satellite in 1978 began this new technological era. It was followed by the first launches of GLONASS (Russia) in 1982, GALILEO (Europe) in 2005, QZSS (Japan-regional) in 2010, IRNSS (India-regional) in 2013, and Bei Dou (China) in 2015.

The first retail consumer GPS receivers, the Magellan GPS NAV 1000, were shipped in 1989. With an increasing number of satellites and the proliferation of receivers, the idea of regarding all satellite navigation systems holistically was born. In 1994 the European Commission, European Space Agency and Eurocontrol proposed creating the Global Navigation Satellite System (GNSS). European talks with the U.S. government that took place from 1995–1999 resulted in an official agreement on cooperation and Europe’s continental EGNOS augmentation system was established. Originally, “GNSS” was intended to be an EGNOS complemented combination of GPS and GLONASS. With the emergence of the Galileo and Bei Dou systems, GNSS has come to mean all the systems generally. More and more frequently receivers are configured to access and use any and all navigation satellite systems available. As Professor David Last has pointed out, the national systems have become interchangeable and invisible to the user. GNSS has become a system of systems.

But a system of system still requires its component parts to function properly for users to access the services they need. The following paragraphs describe the operational and construction status of national satellite systems that are most frequently referred to in the context of the Global Navigation Satellite System. The information presented has been updated from information obtained by national authorities, at the 15th IAIN World Congress held in Prague in October 2015, and at the 10th Annual Meeting of the International Committee on Global Navigation Satellite Systems held in Boulder, CO, in November 2015.

Because these systems are so important to virtually every facet of daily life in technological societies, it is also important to understand their vulnerabilities, threats against them, and mitigation measures. Such a discussion is included after the system descriptions.

While readers of this paper may be primarily interested in the positioning and navigation properties of GNSS, it is essential to recognize that the most important and broadest use of GNSS signals is for highly precise and synchronized time. The timing function supports IT networks, telecommunications, broadcast, financial, transportation, and energy industries. Professor Brad Parkinson of Stanford University, widely acknowledged as the “father of GPS” as said that the system should more properly be renamed Global Positioning and timing Services (GPtS) [Parkinson 2012].

2 NAVIGATION SIGNAL TIMING AND RANGING GLOBAL POSITIONING SYSTEM (NAVSTAR GPS)

The system commonly known as GPS was created for the U.S. Armed Forces. Work aimed at developing a system began in 1960 when Dr. Ivan Getting, was elected the President of Aerospace Corporation. In 1973, Air Force Major Bradford Parkinson and his small group of engineers took over from earlier researchers and created the final system concept that was subsequently launched in 1978. The system

achieved full operational capability on July 17, 1995. Currently the GPS system is utilized by more than one trillion of users and transmits 4 civilian signals:

- L1 C/A - the legacy signal;
- L2C - the second civilian-use signal;
- L5 - aviation safety of life signal;
- L1C - international signal

Also, the GPS satellites transmit signals for the military use.

Presently, the system constellation consists of 31 satellites. Table 1 presents a detailed list of blocks of currently operational satellites.

Table 1. Current GPS constellation - status at 10 January, 2015 [Brennan 2015]

Satellite Block	Quantity	Average Age	Age of the Oldest Satellite
GPS IIA	2	23.4	24.8
GPS IIR	12	13.7	18.2
GPS IIR-M	7	8.2	10.0
GPS IIF	10	2.1	5.3
Total	31	9.3	24.8

It must be noted that the system constellation has been intensely rejuvenated throughout its life. For example, 5 Block IIF satellites were deployed in 2015. From the year 2016 the constellation will be supplemented by new generation satellites. The GPS Block III satellites will transmit 4 civilian-use signals: L1 C/A, L1C, L2C, L5 and 4 military-use signals: L1/L2 P(Y), L1/L2M. The first GPS III satellite is planned to be launched in August 2016 [Brennan 2015].

The currently active ground segment of the system is presented in Fig. 1.

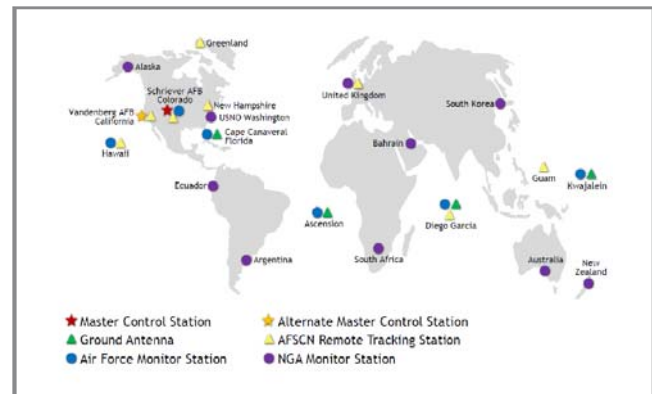


Figure 1. The ground segment of the GPS system [Brennan 2015]

Presently, the NavSTaR GPS system provides for better accuracy than the published system standard. The accuracy levels are different for the civilian users (Fig. 2) and military users (Fig. 3).

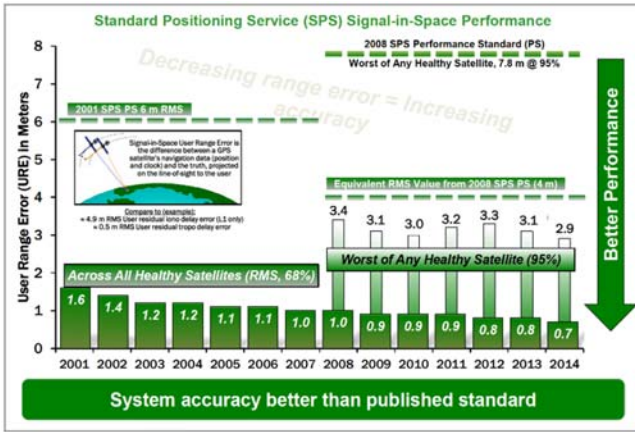


Figure 2. Standard Positioning Service (SPS) for civilian users [Whitney 2015]

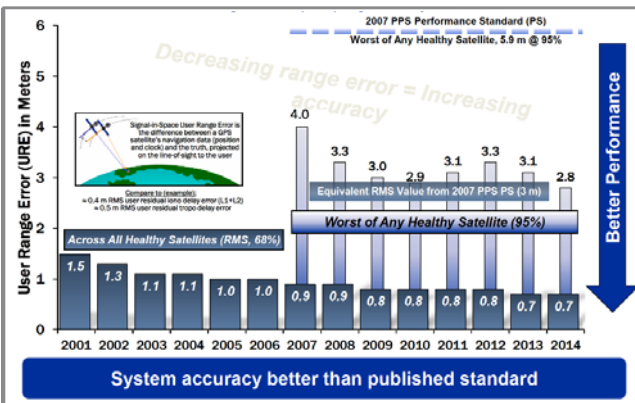


Figure 3. Standard Positioning Service (SPS) for military users [Whitney 2015]

3 WIDE AREA AUGMENTATION SYSTEM (WAAS)

The regional WAAS system was jointly developed by the US Department of Transportation and the Federal Aviation Administration as part of the Federal Radionavigation Plan augmenting the GPS system operation. First activated in 1994 in North America, the system was to ensure the use of high accuracy satellite navigation for aircrafts during taking-offs and landings (comparable with ILS category 1). Not until WAAS was introduced, could GPS be used in aviation. The ionospheric disturbances, clock drift, and satellite orbit errors made the GPS signal not accurate enough to meet the requirements for a precision approach.

The ground segment of the system consists of [Januszewski 2010]:

- a network of 38 ground-based reference WRS stations receiving signals from the GPS system satellites; after preliminary data processing the measurements are transmitted to master stations: 20 WRS stations are located in the continental U.S. (Albuquerque, Auburn, Aurora, Billings, Farmington, Fort Worth, Fremont, Hampton, Hilliard, Houston, Leesburg, Longmont, Memphis, Miami, Nashua, Oberlin, Olathe, Palmdate, Ronkonkoma, Salt Lake City), 7 in Alaska (Anchorage, Barrow, Bethel, Cold Bay, Fairbanks,

Juneau, Kotzebue) 1 in Hawaii (Honolulu), 1 in Puerto Rico (San Juan), 5 in Mexico (Merida, Mexico City, Puerto Vallarta, San Jose del Cabo, Tapachula), 4 in Canada (Gander, Goose Bay, Iqaluit, Winnipeg); another 9 will be built in the future;

- 3 WMS master stations processing data and determining the correction values in Hampton (Georgia), Leesburg (Virginia) and Palmdole (California);
- two pairs of GUS stations transmitting the correction messages to geostationary satellites at frequency of 6455.42 MHz located in Napa (California), Littleton (Colorado) and Brewster (Washington), Woodbine (Massachusetts), respectively.

Currently, the WAAS system uses two geostationary satellites to send correction messages to GPS receivers, augmenting the horizontal position accuracy provided by GPS to 2-3 m. The system's coverage is planned to encompass both Americas. The planned development will involve the operation of 4 geostationary satellites (Fig. 4)

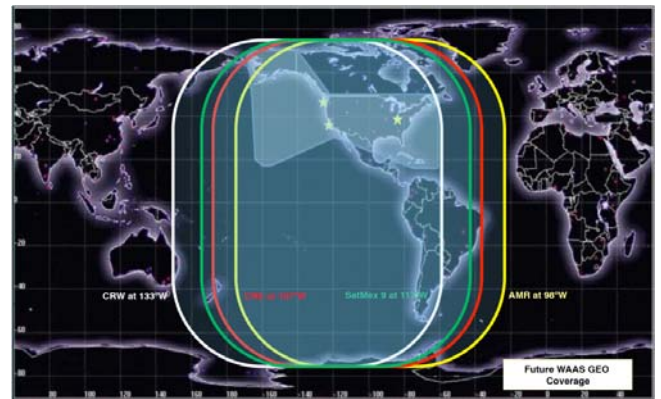


Figure 4. The planned coverage of WAAS geostationary satellites [Lawrence 2015]

4 GLOBAL NAVIGATION SATELLITE SYSTEM (GLONASS)

The development of Russian GLONASS (GLObalnaya NAVigatsionnaya Sputnikovaya Sistema) satellite system began in 1976 when the Soviet Union's governmental program was initiated. Since the first GLONASS satellite was launched on October 12, 1982, the system has competed with its American counterpart.

The system configuration was complete for the first time in 1995. However, due to a short lifespan of satellites, structural changes in the Soviet Union and insufficient funding in the period from 1995 to 2001, the system constellation was reduced to 7 satellites. In 2001, the revitalization and modernization program was started, which resulted in fast development of constellation. Currently, it is composed of 28 satellites (Table No. 2).

Table No. 2. GLONASS constellation - status at October 2, 2015 [Karutin 2015]

Satellite Block	Quantity
Glonass - M	26
Glonass - K	2
Total	28

The signals transmitted by individual satellite blocks [Januszewski 2010] are as follows:

- for Block II M - L1/L2 (C/A);
- for Block II K - L1/L2 (P), L3 with CDMA.

The ground segment [Januszewski 2010] consists of:

- 1 System Control Center (SCC)
- 6 Monitoring Stations (MS);
- 4 UpLink Stations (ULC);
- 4 Telemetry, Tracking & Command Stations (TT&C);
- 2 Central Clock Stations (CC);
- 1 Satellite Laser Ranging Stations (SLR).

Currently, the GLONASS system provides service with accuracy of 2.8 m.

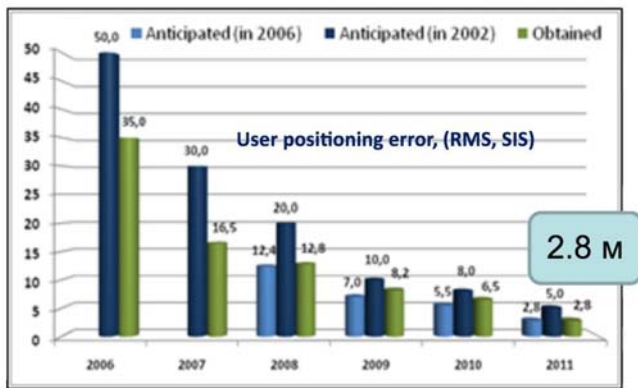


Figure 5. The overview of GLONASS positioning errors in years 2006-2011 [Mirgorodskaya 2012]

9 rockets carrying Glonass-M satellites will be launched in the years 2015-2016. The objectives of the upgrade scheduled for 2012-2020 include:

- satellite lifespan extension;
- extension of service provided by the system;
- increase of satellite clock stability;
- introduction of SAR service;
- addition of new signals to the modernized Glonass-K satellites: L10C/L1SC, L20C/L2SC.

The upgrade is expected to ensure 4 times better accuracy owing to [Karutin 2015]:

- the introduction of a new CDMA signal;
- the upgrade of the ground-based control segment;
- the introduction of new atomic frequency standards (2 CAFs + 2 RAFs);
- the introduction of advanced satellite, orbit and clock control system;
- the change of the geodetic reference system from the presently used PZ-90 system to PZ-90.11 aligned to the International Terrestrial Reference Frame (ITRF) at the millimeter level.
- the synchronization of GLONASS time with UTC (SU) at less than 2ns while keeping long-term stability.

S/V Type	Glonass-M		Glonass-K1			Glonass-K2	
S/V #	≤ 54	55-61	11/1	12/1 15/1 16/1	17/1-23/1	13/1, 14/1	≥ 24/1
S/V General View							
Phased Array Antenna 1 Phase Center centered at the longitudinal -X axis, passing through the CoM	-	-	L10F L1SF L20F L2SF	L10F L1SF L20F L2SF L30C	L10F L1SF L20F L2SF L30C	L10C L18C L20C L28C L30C	L10C L18C L20C L28C L30C L10F L1SF L20F L2SF
Phased Array Antenna 2 Phase Center displaced of longitudinal -X axis	L10F L1SF L20F L2SF	L10F L1SF L20F L2SF	-	-	-	L10F L1SF L20F L2SF	-
Helical Antenna 3 Phase Center displaced of longitudinal -X axis	-	L30C	L30C	-	L28C	-	-

Legend: "SF" – Secured FDMA Signal, "OF" – Open FDMA Signal, "SC" – Secured CDMA Signal, "OC" – Open CDMA Signal

Figure 5. New CDMA Signals Implementation Plan [Revnivykh 2015]

5 BEIDOU NAVIGATION SATELLITE SYSTEM (BEIDOU)

The first satellite of the Chinese satellite system was placed in geostationary orbit on October 30, 2000. Once the full operational capability is achieved, the constellation will be composed of 5 geostationary satellites (GEO), 3 satellites in geosynchronous orbits (IGSO) and 27 satellites in medium Earth orbits (MEO). The system is designed as a regional system covering the area of the People's Republic of China and a part of South-East Asia.

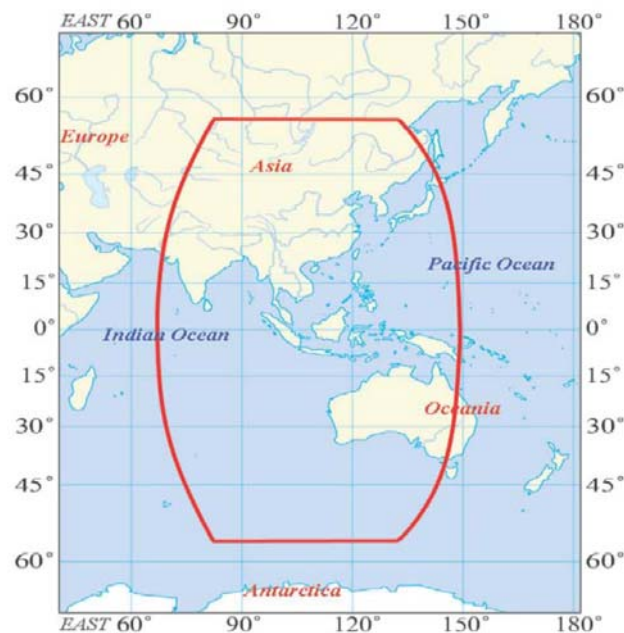


Figure 6. BeiDou coverage area [CSNO 2013]

Currently, BeiDou is composed of:

- 5 geostationary satellites (positioned at 58.75°E, 80°E, 110.5°E, 140°E and 160°E);
- 20 IGSO and MEO satellites.

From March to September 2015 4 satellites were deployed. If the pace at which new satellites are activated is maintained, the system will become fully operational in 2017 as planned.

The system accuracy is better than 10 m.

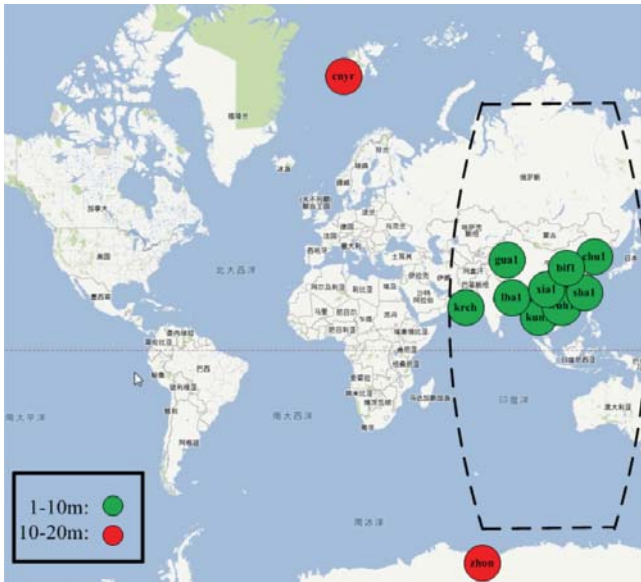


Figure 7. BeiDou system's accuracy [Ran 2015]

BeiDou ground segment consists of:

- Master Control Stations (MCS)
- Uplink Stations (US)
- Monitoring Stations (MS)

	GSAT0101	GSAT0102	GSAT0103	GSAT0104
Launch Date	21 Oct. 2011	21 Oct. 2011	12 Oct. 2012	12 Oct. 2012
SV ID	11	12	19	20
Orbital Slot	B05	B06	C04	C05
Clock	PHM	RAFS	PHM	RAFS
Technical Status	Healthy	Healthy	Healthy	Unavailable from 2014-05-27 (NAGU 2014014)
EIRP	All bands aligned to Public OS SIS ICD	All bands aligned to Public OS SIS ICD	All bands in temporary back-off	E1 only E5+E6 permanently not available
SAR	N/A	N/A	Transponder ON	Transponder ON

	GSAT0201	GSAT0202	GSAT0203	GSAT0204	GSAT0205	GSAT0206
Launch Date	22 Aug. 2014	22 Aug. 2014	27 Mar. 2015	27 Mar. 2015	11 Sep. 2015	11 Sep. 2015
SV ID	18	14	26	22	24	30
Orbital Slot	N/A (eccentric orbit)	N/A (eccentric orbit)	B08	B03	A08	A05
Clock	PHM	PHM	PHM	PHM	OFF	OFF
Technical Status	Under in-orbit testing	Under in-orbit testing	Under in-orbit testing	Under in-orbit testing	Under in-orbit testing	Under in-orbit testing
EIRP	All bands aligned to Public OS SIS ICD	All bands aligned to Public OS SIS ICD	All bands aligned to Public OS SIS ICD	All bands aligned to Public OS SIS ICD	Under in-orbit testing	Under in-orbit testing
SAR	Transponder OFF	Transponder OFF	Transponder OFF	Transponder OFF	Transponder OFF	Transponder OFF

Figure 8. The current constellation of GALILEO [Hein 2015]

6 THE EUROPEAN NAVIGATION SYSTEM (GALILEO)

In the 80's of the 20th century a need for developing a European satellite system emerged. In the years 1999–2000 technical and economic requirements of the project were specified. In December 2004, the testing of GALILEO ground segment was complete and on December 28, 2005 the first GIOVE-A satellite was placed in orbit. The constellation status as at October 15, 2015 is presented in Figure 8.

The initial problems with the system activation were overcome. The production, testing and activation of the following satellites are proceeding as planned. Currently, the system has 12 in-orbit satellites. The fact that their number doubled in 2015 is impressive. Soyuz rocket launched in French Guiana inserted the 11th and 12th GALILEO satellites into orbit on February 2, 2016.

The system's ground segment is complete. The visualization of deployment of the ground segment is presented below.

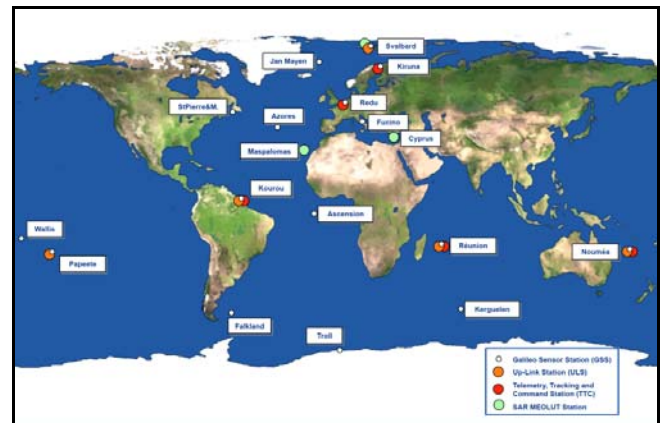


Figure 9. The Galileo ground segment [Jean 2015]

According to the estimations of the European Union, the system will have achieved its full operational capability by 2020. Three Ariane 5 rockets are due to be launched in the second half of the year 2016, each carrying 4 satellites. Satellites are produced in OHB's plant in Bremen, Germany. The system's activation is co-financed by the European Space Agency and the European Commission.

7 EUROPEAN GEOSTATIONARY NAVIGATION OVERLAY SERVICE (EGNOS)

The development of the European Geostationary Navigation Overlay Service was finished in 2006. It is a European system augmenting GPS and GLONASS systems. After GALILEO is initiated, EGNOS will also supplement this European system. The space segment is composed of 3 geostationary satellites providing coverage to all European countries. The ground segment comprises 40 reference and retransmission stations as well as 6 control and control-verification stations:

- 34 Ranging and Integrity Monitoring Stations (RIMS): receiving navigation signals from GPS satellites,

- 6 Navigation Land Earth Station (NLES): sending correction messages to satellites to allow end-user devices to receive them,
- 4 Mission Control Center (MCC): processing data and counting differential corrections,
- 2 control and verification stations: DVP (Development Verification Platform) and ASQF (Application Specific Qualification Facility).

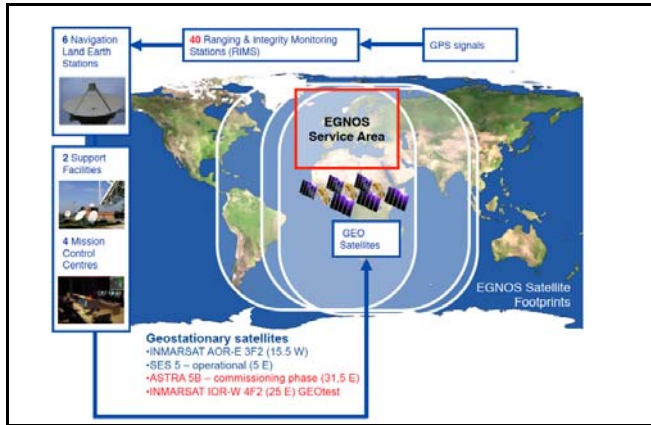


Figure 10. EGNOS architecture [Jean 2015]

EGNOS provides three services shown in Table 3.

Table 3. Service provided by EGNOS [Jean 2015]

Service	Accuracy	Service Status
Open Service	about 1m, free access	Available since October 2009
Safety of Life Service	About 1m, compliant to aviation standards	Available since March 2011
EGNOS Data Access Service	Less than 1m, corrections are provided by terrestrial networks	Available Since 2012

The European Commission has adopted projects to further develop the system in the following years. The projects are partially being performed. EGNOS is to provide service to the territory of 28 EU member states. Also, the works on the third version of EGNOS system capable of sending messages in dual frequency (L1 / L5) will have been finished by the end of 2016. The following version will provide augmentation to GALILEO and other systems to be initiated as part of GNSS in the future. The third version is scheduled to be launched in 2017. In the years to follow, EGNOS's coverage may be extended on other European countries (other than EU countries) and African countries provided all the required international agreements are concluded.

8 QUASI-ZENITH SATELLITE SYSTEM (QZSS)

The government of Japan approved the project to build its own satellite system in 2002. The concept of the system is different from the systems described above. It was proposed that three QZSS satellites are to be placed in the so called quasi-zenith orbit. The planned service area of the system is presented in Fig. 11.

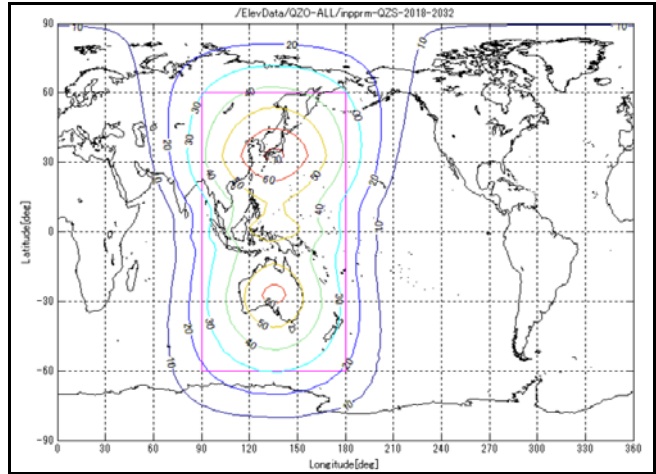


Figure 11. QZSS's service area [Moriyama 2015]

The parameters of the orbit have been chosen so that at least one of the satellites is always almost directly overhead above the Japanese islands. This will provide better correction signal availability even in Japanese cities crowded with skyscrapers. The accuracy of the system is expected to be better than 1-2 m in Japan.

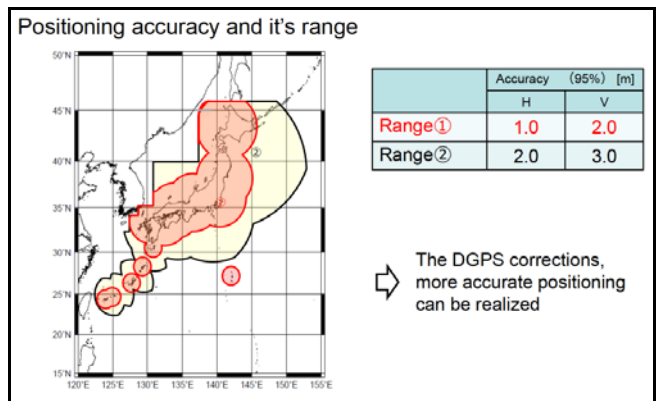


Figure 12. The planned accuracy of QZSS [Kogure 2015]

The first MICHIBIKI satellite was placed in orbit in 2010. The system constellation is to comprise 4 satellites: 3 QZSS satellites 1 geostationary satellite (127°E). The system will be further developed to include 7 satellites around the year 2023. The scheduled commissioning of subsequent satellites is presented in Fig. 13.

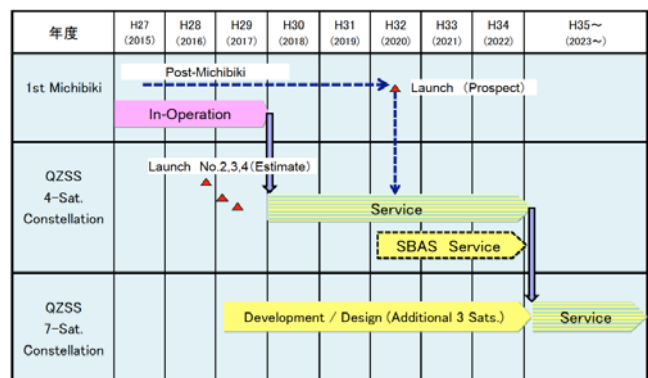


Figure 13. QZSS commissioning schedule [Moriyama 2015]

- The ground segment of the system is composed of:
 - 2 Master Control Stations

- 7 Satellite Control Stations
- Over 30 Monitor Stations around the world (including exclusive GPS monitoring use stations)

A complete ground station will begin to operate in 2018.

The Japanese space agency assumes that the Satellite Based Augmentation System will be available to QZSS in 2020. The frequencies available in the system are shown in Table 4.

Table 4. List of frequencies in QZSS [Moriyama 2015]

Signal	1 st Satellite		2 ^{nd-4th Satellite}		Services		Frequency (MHz)
	QZO	QZO	QZO	GEO			
L1C/A	○	○	○	○	Positioning	Complement GPS	1575.42
L1C	○	○	○	○	Positioning	Complement GPS	
L1S	○	○	○	○	Augmentation (Sub-meter) Message Service*		
L1Sb	—	—	○	○	SBAS**	ICAO Standard	
L2C	○	○	○	○	Positioning	Complement GPS	1227.6
L5	○	○	○	○	Positioning	Complement GPS	1176.45
L5S	—	○	○	○	Augmentation Experimental Use		
L6	○	○	○	○	Augmentation (Centimeter)		1278.75
S-band	—	—	○	○	Message Service (Safety Confirmation)		2GHz band

* Message service (Satellite Report for Disaster and Crisis Management) is also provided in L1S signal
 ** SBAS service will operated by MLIT (Ministry of Land, Infrastructure, Transport and Tourism)

9 MULTI-FUNCTIONAL SATELLITE AUGMENTATION SYSTEM MSAS

The Japanese MSAS augmentation system started operating in 2007. It provides service to the territory of Japan. It is not a typical system, when compared with WAAS and EGNOS, as the space segment is composed of two geostationary meteorological satellites (140°E and 145°E), whilst other systems of this kind use commercial telecommunication satellites. The first satellite was placed in orbit on August 1, 1999, and the system was commissioned on September 27, 2007. The system configuration is shown in Fig. 14.

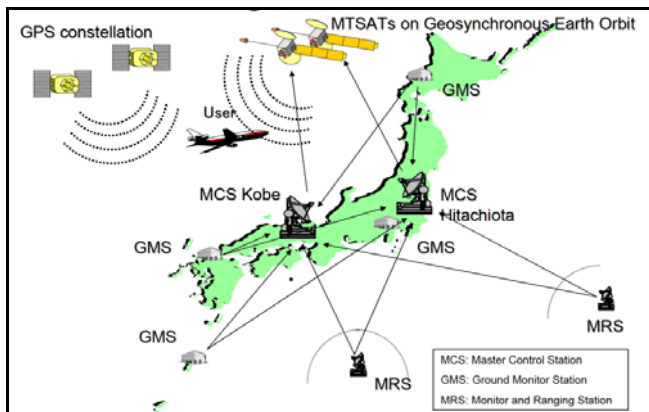


Figure 14. MSAS configuration [Terada 2008]

The Japanese government does not plan to develop the system. Once QZSS is declared operational, it is expected to take over the functions of MSAS.

10 INDIAN REGIONAL NAVIGATIONAL SATELLITE SYSTEM (IRNSS)

By the decision of the government of the Republic of India, a project to build a regional system called IRNSS was launched in May 2006. The decision was motivated by the concern about the safety of India and the intention to give India independence from GPS. The service area of the system will include the Indian Ocean, South and East Asia, East Africa and most of Australia.



Figure 15. IRNSS service area (source: <http://irnss.isro.gov.in/>)

The target system constellation will comprise 7 satellites:

- 4 satellites in geosynchronous orbits at 55°E and 111.75°E, with inclination 29°
- 3 satellites in geostationary orbits at 32.5° E, 83° E and 129.5° E

The first satellite of the system was placed in orbit in July 2013 and the following ones - in April and October 2014, and March 2015. The fifth satellite (IRNSS-1E) was located in a suitable orbital slot on January 20, 2016. The current system configuration comprises 5 satellites. The IRNSS system transmits signals at L5 (1176.45 MHz) and S (2492.048 MHz). The remaining two satellites will have been deployed by the end of 2016 when the system is expected to enter full operational status.

The positioning accuracy is expected to be 10-20 meters. The measurement sessions conducted in 2015 confirmed the feasibility of reaching the assumed values.

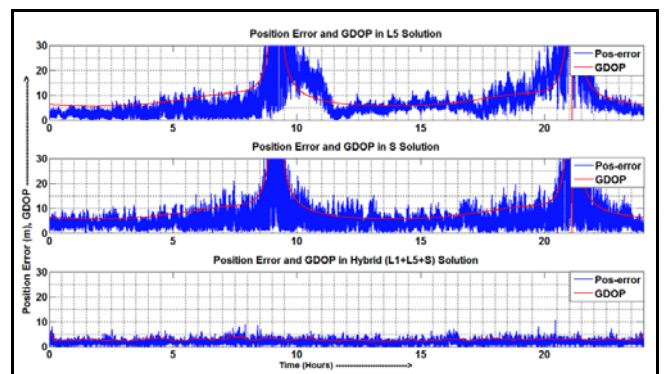


Figure 16. Position error and GDOP coefficient in IRNSS [Parikh 2015]

11 GPS AIDED GEO AUGMENTED NAVIGATION (GAGAN)

Indian Space Research Organization (ISRO) and Airports Authority of India (AAI) agreed to build their own augmentation satellite system (SBAS) in August 2001. After WASS, GALILEO and MSAS GAGAN has been the forth augmentation system in the world. Similarly to other systems of this kind, SBAS is intended to enable aircrafts to rely on GPS for all phases of flight.

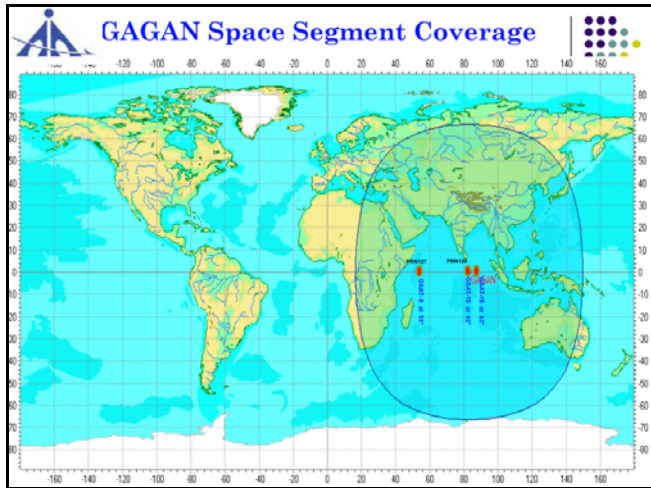


Figure 17. GAGAN service area [Indi, Sunda 2012]

The space segment of the system consists of 3 geostationary satellites located at 55°E, 82°E and 83°E. The first satellite, GSAT-8, was launched in March 2011, the second, GSAT-10, was inserted in orbit in April 2012. The last one, GSAT-15 was launched on November 11, 2015 from Kourou, French Guiana. The ground segment is composed of 15 reference stations (INRES) situated in the following cities: Ahmedabad, Bangalore, Bhubaneswar, Kolkata, Delhi, Dibrugarh, Gaya, Goa, Guwahati, Jaisalmer, Jammu, Nagpur, Porbandar, Port Blair, Trivandrum. The ground segment also includes the Indian Master Control Center (INMCC) in Bangalore which processes data received from reference stations to compute differential corrections, and estimates integrity levels. The SBAS messages are broadcast to geostationary satellites from three Indian Land Uplink Stations (INLUS) located in Bangalore (2 stations) and Delhi (1 station).

The Directorate-General for Civil Aviation (DGCA) confirmed GAGAN for enroute operations (RNP 0.1) on December 30, 2013 and subsequently on May 19, 2015 certified it for precision approach services (APV 1). GAGAN is the first SBAS system in the world to serve the equatorial region. GAGAN though primarily designed for aviation, will provide benefits to many other user segments such as intelligent maritime, road, railway transportation, surveying, security agencies, telecom industry, mobile networks.

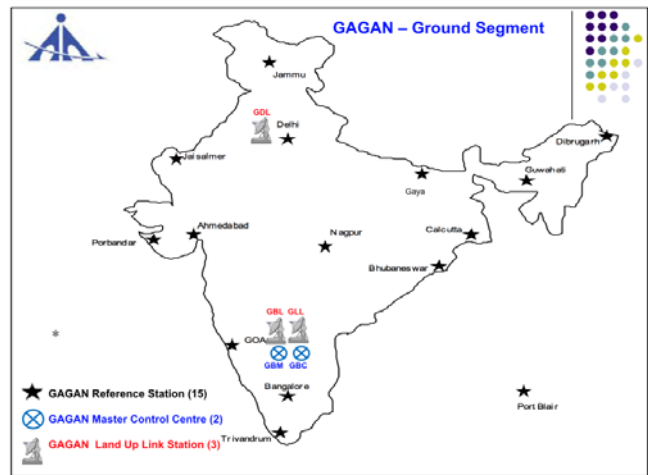


Figure 18. The ground segment of GAGAN [Indi, Sunda 2012]

12 THREATS TO GNSS OPERATION

Continuously transmitting from orbits over 20,000 km above the earth and powered by solar panels, GNSS signals received on earth are fainter than the cosmic background noise. This makes them very easy to disrupt either accidentally or purposefully. Extensive studies and analyses of these threats are available elsewhere. The following outline provides a summary:

1 Global Scale Threats

- Solar Activity – Coronal Mass Ejections have briefly disrupted GNSS reception twice since 2007. Larger and longer lasting instances such as Carrington Event in 1859 have the potential to either destroy satellites and/or ground-based electronics and/or disrupt the ionosphere for an extended period so as to prevent reception of signals.
- Hostile Military Action – Few nations have the ability to access space independently, let alone make war. Yet the United States military is very concerned about those that are able. Between 2016 and 2020 it plans to spend \$5B on defensive and offensive space capability in order to counter this threat.
- Space Debris /Collisions – As space becomes more crowded with satellites and debris, the threat grows. While a very low probability threat to satellites, and even lower to whole constellations, hostile and other actions that create space debris increase the risk and threat of cascading collisions.

2 Regional and Wide Area Scale Threats

- Hostile Military Action – Most national militaries have the ability to jam GNSS signals over wide areas, and some have done so. North Korea has repeatedly jammed signals on the Korean peninsula, and wide area jamming has been detected in the Ukraine and Middle-East in conjunction with military actions.
- Terrorist Action – GNSS jamming devices effective over short distances have been found in the possession of terrorist groups. Terrorist websites have extolled the virtues of GNSS jamming and spoofing. Since jamming over

larger distances is mostly a matter of a more powerful transmitter, it is reasonable to assume wide area GNSS jamming by terrorists is a threat.

3 Local Scale Threats

- Industrial Accidents/Unintentional Transmissions – US Navy technicians have twice disrupted GNSS reception in parts of cities through accidental transmissions. Sparking elevators and other electrical equipment have also been found to be sources of disruption.
- Easily Obtained Illegal Tactical Jamming Devices – Jamming devices that are effective from a hundred meters to tens of kilometers are easily obtained from any number of vendors via the internet. Users and possible users include:
 - Criminal Enterprises – The US Federal Bureau of Investigation has published a notice about use of jamming devices for theft of high value cargo. Similar problems have been documented in the UK and Europe
 - Privacy Seeking Citizens – Numerous cases have been documented of telephone and airport landing systems being disrupted by “personal privacy device” jammers used by citizens seeking to avoid surveillance by employers and others. One small scale sampling in the United States showed 25% to 30% of trucks in a port area carrying such devices. Last year cranes in a US container port were idled for hours because of jamming by such a device.
 - Terrorist Forces – Lower power devices can also serve the tactical needs of terrorist organizations. Terrorists have been apprehended with jamming devices in their possession.
 - Legal Tactical Jamming Devices – Special law enforcement units that protect political leaders and police Special Weapons and Tactics Teams are reported to have the ability to jam GNSS reception over limited distances as part of their operations. The US military is also investigating equipping foot soldiers with devices that would also jam GNSS for use to prevent improvised explosive devices from being triggered.
 - Spoofing Devices – Perhaps of even greater concern are spoofing devices that introduce hazardously misleading information into GNSS timing and navigation receivers. Beginning with a signal strength less than that of satellite signals, these devices gradually increase in signal strength until it is slightly greater and has “captured” the targeted device. Previously difficult and expensive to construct, an exhibitor at a hackers convention in Las Vegas, Nevada, USA in 2015 demonstrated and published steps for building a spoofing device from easily obtained materials. In fact, she sold kits for spoofers for around \$300.

13 ELORAN AS A JAMMING AND INTERFERENCE MITIGATION TOOL

The United Kingdom, Saudi Arabia, Russia, China and South Korea all operate some version of Loran as a terrestrial complement and backup for GNSS. Even though the United States shut down its Loran system in 2010, it has committed to establishing an eLoran timing system while it develops requirements for a larger system which will also provide positioning and navigation [RNT Foundation 2015].

Loran/eLoran is a tower-based hyperbolic navigation system that is generally effective within 800km of the transmitter, though the range is much greater over salt water. The system was developed by the United States during World War II and portable versions were developed by the US military in the 1960s and 1970s. The signal also incorporates a data channel which was used by the US Navy to communicate with submarines in the 1970s.

Loran/eLoran is considered by many as an ideal complement to and backup for GNSS. It provides similar services but has much different phenomenology than GNSS. Where GNSS is very high frequency, Loran is low frequency (100kHz). GNSS is very low power from space while Loran is very high power from terrestrial towers. Its high power (350kW to 1 MW) and low frequency also make Loran/eLoran very difficult to disrupt. A receiver with chips enabled for GNSS and eLoran would be exceptionally difficult to jam and nearly impossible to spoof.

Many policy professionals believe that establishment of eLoran systems and wide use of eLoran chips in navigation and timing receivers would help eliminate most GNSS jamming and spoofing by making it ineffective.

14 CONCLUSIONS

- 1 Satellite systems have affected many areas of human activity in the world. The increasing number of systems offering similar services results in the growing number of different receivers. What is urgently needed, therefore, is the unification of devices so that they could automatically and simultaneously use many different systems, improving the accuracy of estimates.
- 2 As these systems are commonly used in the world, further integration of all satellite systems as part of GNSS is required and further efforts must be made to make GNSS more immune to increasingly frequent incidents of jamming and spoofing.
- 3 The eLoran system is currently the best the technical and scientific solution to allowing for effective protection of the Global Navigation Satellite Systems.
- 4 Every day human activity around the world depends upon satellite systems for timing and navigation. EU Member States should strive to protect the GNSS by the construction of cooperating national eLoran station.

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