Envisioning a Future GNSS System of Systems

Part 1

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Seven years ago, the U.S. Global Positioning System was the only real GNSS around. The GLONASS constellation had dwindled to seven satellites. Final approval and funding of Europe's Galileo program was yet to be achieved. Since then, Russia has gone a long way toward rebuilding and modernizing GLONASS. Galileo has put its first experimental GNSS satellite, GIOVE-A, into space. And China has announced plans to build a full-fledged GNSS of its own – Compass – building on three Beidou satellites that it has launched in recent years. With those activities under way, it's not too early to begin thinking about what a multisystem GNSS might look like and mean for users, receiver manufacturers, and service providers.

We have just made the transition into the new year of 2007. Most of us probably already have our eyes focused onto the next 12 months along with some wishes and perspectives that we would like to have fulfilled in the coming 365 days.

In the same spirit, over the next two issues of *Inside GNSS* this column will take a look into the near future and — what is even more exciting — into the further future of satellite navigation. But what that future will look like depends to an enormous extent on what the past was; so, we should have first a look back into the roots of GNSS.

Long ago the Americans entered the global navigation satellite system (GNSS) era with the Global Positioning System (GPS) as the result of efforts that began in the late 1960s. The Russians followed soon afterwards (or did they do it in parallel?) with GLONASS. Both of these systems are now undergoing extensive modernization. Moreover, the European Galileo system is joining the GNSS club, and China is now planning its own version called Compass.

In the meantime lots of augmentation and regional systems have been developed or are currently under consideration. From military to civil signals, from medium Earth orbit (MEO) to geostationary Earth orbit (GEO) and inclined geosynchronous orbits (IGSO), the palette of systems and offered services is as wide as imagination allows.

Is it not time, therefore, to pause and think for a moment about where we want GNSS to move? Is it not already time to really "think global" and to coordinate and harmonize all the existing and projected navigation satellite systems? If so, then the question naturally arises: what should the "Global Navigation Satellite System of Systems" look like?

This column will try to shed some light on the fascinating new world of GNSS in which we will live around the year 2020 if all the currently modernizing and planned new systems come into reality. It will be a complex world where the word "coordination" will be the key and from which, if we do it right, users will be the ones that will profit the most. After all, why should a GNSS user really care about whether one of his or her signals comes from GPS, the other from Galileo, the third from GLONASS and the fourth from Compass as long as the GNSS receiver works well?

Scenes from the Present

Today only GPS is fully operational. Nevertheless, Russia hopes to return GLONASS to full operation capability (FOC) with a completed constellation by 2009, and Galileo's FOC is now expected in 2012. Compass is already knocking on the door, and in spite of the fact that China has still a long way to go and lengthy negotiations will be needed, a scenario of four global coverage satellite systems seems to be very likely in a future not so far away from today.

From the experience with Galileo, we know how important the roles of interoperability and compatibility with GPS were from the very beginning. Unfortunately, major differences between those two systems and GLONASS still exist.

However, also on the GPS/GLONASS side, work on attaining real interoperability is continuing. Just recently during the GPS/GLONASS Working Group 1 meeting in December 2006, both sides emphasized the benefit to the user community that a common approach concerning FDMA/CDMA would bring in terms of interoperability. The Russian side announced that they will come to a decision on adding or converting to a CDMA format by the end of 2007. The formal U.S.-Russia statement can be view at < http://www.glonass-ianc.rsa.ru/i/glonass/joint_statement_eng.pdf>.

The direction in which COMPASS will go remains a large unknown. In fact, if the need of standardization was always there, it seems that the concept is gaining in interest the more systems come into play.

But before dreaming with our ideal GNSS, let us first look more closely into what the current reality is and what the plans for new GNSS systems are.

Global Positioning System

GPS is made up of a network of initially 24 active satellites placed into orbit by the U.S. Department of Defense. Although originally developed for military applications (we can also find some statements that GPS was intended to be a civil as well as military system from the very beginning), the U.S. government made GPS available to civilians, transforming it into the dual-use system it is today. Accordingly, certain signal capabilities are reserved for U.S. and allied military applications while the civilian signals are open and free for worldwide use.

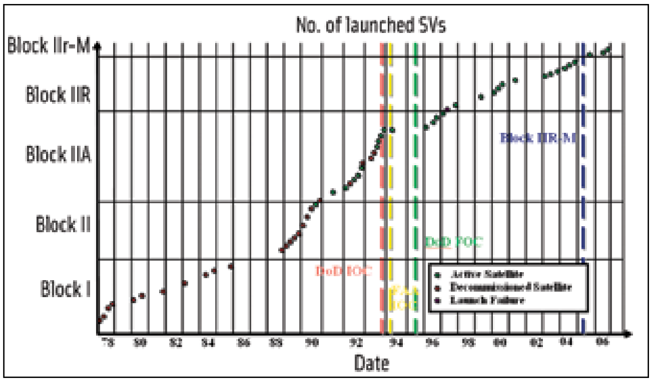


FIGURE 1 Launch history of GPS

The GPS baseline constellation consists of 24 satellites (21 + 3 active spares) in six circular MEO planes at a nominal average orbit semi-major axis of 26559.7 kilometers with an inclination of the orbital planes of 55 degrees with reference to the equatorial plane.

Is it not already time to really "think global" and to coordinate and harmonize all the existing and projected navigation satellite systems?

The first developmental satellites were launched beginning in 1978, and the first operational satellites went into orbit in 1989. The system reached initial operational capability (IOC) in 1993 and achieved FOC in 1995. The present GPS constellation exceeds the baseline constellation with 30 orbiting satellites after the last successful launch on November 17, 2006. The history of all GPS launches can be seen in Figure 1.

GPS Modernization

Before December 2005 the basic GPS capability consisted of the Standard Positioning Service (SPS) provided by the C/A-code on the L1 frequency and the Precise Positioning Service (PPS) provided by the P(Y)-code on L1 and L2. Although those services are of relatively good quality, the United States envisaged modernizing the signals in order to improve the quality and protection of both civil and military users. To that objective the GPS Modernization plan can be timely divided in the following three blocks.

Block IIR-M (replenishment-modernized) satellites. This generation of spacecraft introduced a second civil signal with improved services (L2C) reaching the 24-satellite FOC around 2012. Additionally, for military purposes the modernized M-code — BOC(10,5) — will be placed on L1 and L2. Block IIR-M satellites also have antijam flex power capabilities for military needs. Figure 4 provides more details on the signal structure. The first operational IIR-M satellite was launched on December 16, 2005.

Block IIF (follow-on) satellites. The third civil signal (L5) – BPSK(10) — begins with the IIF satellites. The FOC with 24 satellites is expected to be reached around 2015

Block III. Still in the design phase, GPS Block III includes prospective improvements to both the ground and space segments. These will most likely include increased anti-jam power, increased security, increased accuracy, navigation surety, backward compatibility, assured availability, system survivability, and controlled integrity — among other improvements. The fourth civil signal (L1C) will probably be introduced with this block.

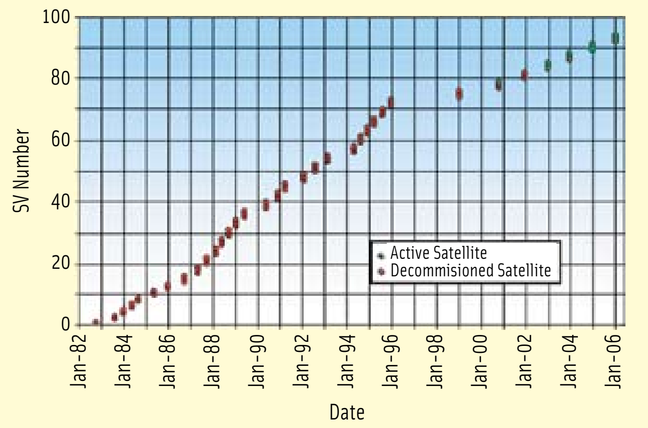


FIGURE 2 Launch history of GLONASS

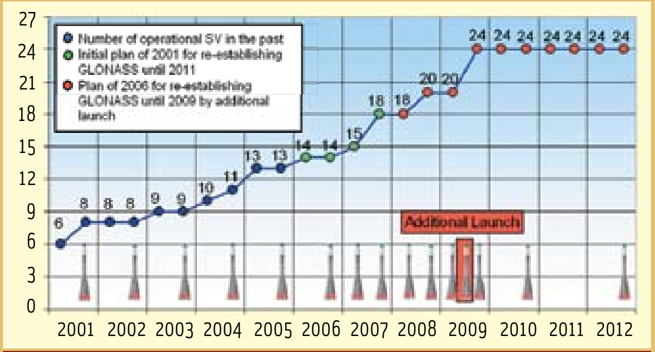


FIGURE 3 Plans to re-establish full operation capability of GLONASS

In the 2004 GNSS cooperation agreement between the United States and the European Union (EU), the two parties agreed to have BOC(1,1) as the baseline waveform on both the GPS L1C and Galileo E1 Open Service (OS) signals. Nevertheless, a group of experts from Working Group A set up under the 2004 agreement has proposed to optimize this signal using MBOC(6,1,1/11) instead, as previously discussed in this column in the May 2006 issue of *Inside GNSS*. Although an earlier schedule is under consideration, the first Block III satellite launch will probably occur somewhere around 2013 with FOC being reached by about 2020.

GLONASS

The GLObal NAvigation Satellite System (GLONASS) is the Russian navigation satellite system and, like GPS, it defines itself as a dual-use system. Its nominal constellation is composed of 24 satellites in three orbital planes with ascending nodes 120 degrees apart. Eight satellites are equally spaced in each plane with argument of latitude displacement of 45 degrees. The orbital planes have 15 degrees argument of latitude displacement relative to each other.

The satellites operate in circular 19,100-kilometer orbits at an inclination of 64.8 degrees, and each satellite completes the orbit in approximately 11 hours 15 minutes. The spacing of the satellites allows for continuous and global coverage of the terrestrial surface and the near-earth space.

As can be seen in **Figure 2**, the current GLONASS status is far away from its nominal numbers and as of January 18, 2007 only 9 active GLONASS satellites were transmitting from space. Seven additional space vehicles are on orbit but have been temporarily switched off and are currently not broadcasting any signals. On December 25, Russia launched three additional GLONASS-M (modernized) satellites from Baikonur Cosmodrome in Kazakhstan that are currently in the commissioning phase.

The initial GLONASS Program Budget of 2001 was designed for achieving FOC in 2011. However the GLONASS program appears to be speeding up on its course in accordance with a presidential directive issued January 18, 2006.

As announced in September 2006 at the 46th Civil GPS Service Interface Committee (CGSIC) Meeting in Fort Worth, Texas, current modernization plans of GLONASS envision the achievement of minimal operational capability (18 satellites) again by the end of 2007 and FOC by end of 2009 (See **Figure 3**).

For realizing this ambitious schedule for constellation deployment, an extra budget for the GLONASS program has been set up for the years 2007 to 2011. In addition to reaching FOC, by 2010 Russia wants to achieve a performance of GLONASS comparable to that of GPS and Galileo.

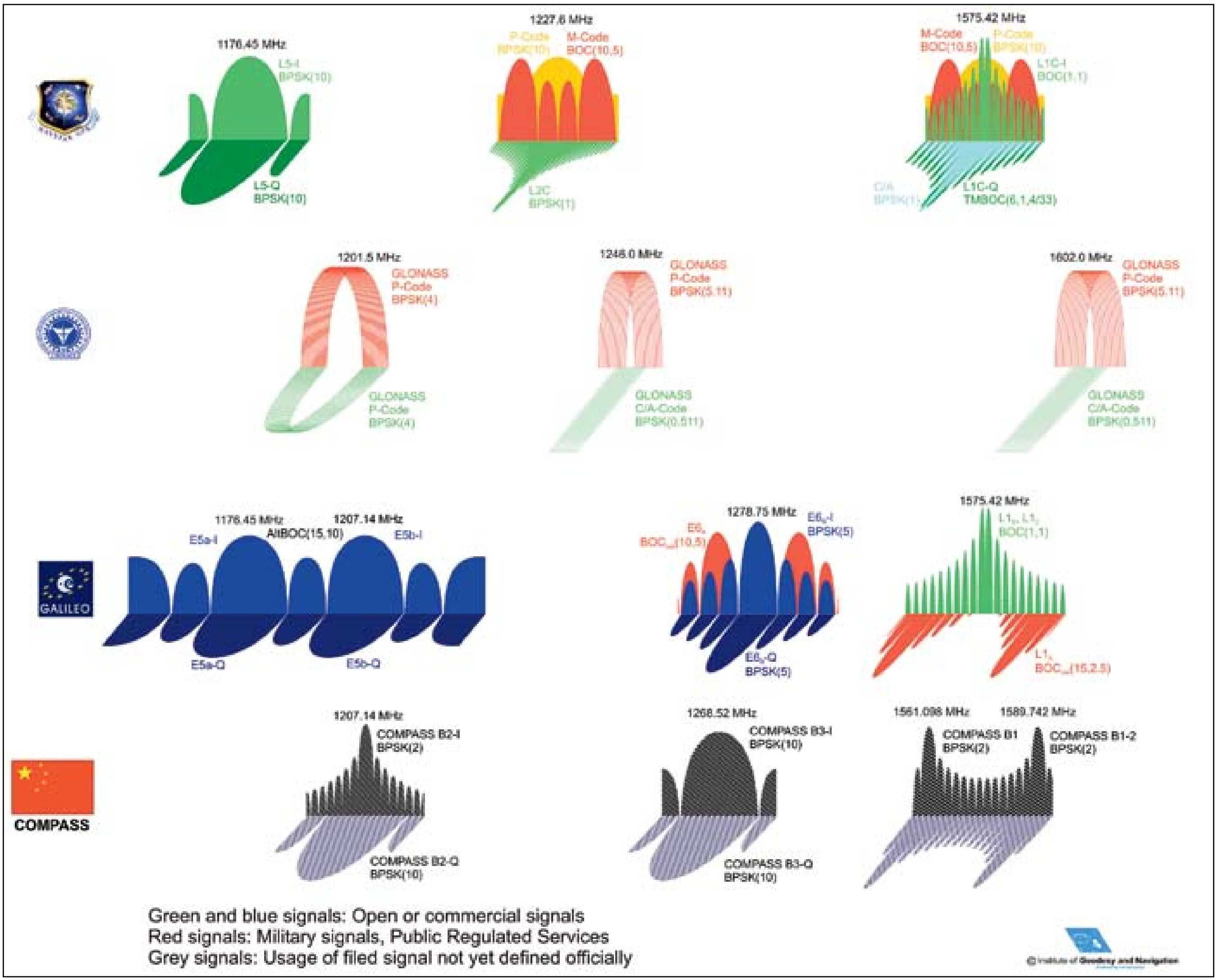
Nevertheless, with only nine satellites being in complete operation as of January 18, 2007, and in spite of the additional three recently launched satellites that should become operational, the fulfilment of the GLONASS program objectives is still difficult.

GLONASS Service Modernization. As with GPS, GLONASS is on the way to modernization of the system. Apart from the signals in the L1 band, the Russian system has already established a second civil signal at L2 upon launch of the first GLONASS-M satellite in 2003. A third civil signal at L3 band is expected to start in 2008 aboard GLONASS-K satellites. For more details on the GLONASS signal structure refer to Figure 4. We should note that the definition of the GLONASS L3 signals is still subject to changes.

Europe's Galileo System

Galileo is the European global navigation satellite system, designed to provide a highly accurate, guaranteed global positioning service under civilian control. According to the Galileo SIS ICD, the system will be interoperable with GPS and, at least to some extent — excluding the real-time high-precision services of the systems — with GLONASS, the two other global satellite navigation systems available today.

The fully deployed Galileo system will consist of 30 satellites (27 operational + 3 non-active spares), positioned in three circular MEO planes at a nominal average orbit semi-major axis of 29,601.297 kilometers, and at an inclination of the orbital planes of 56 degrees with reference to the equatorial plane.



Green and blue signals: Open or commercial signals
Red signals: Military signals, Public Regulated Services
Grey signals: Usage of filed signal not yet defined officially

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FIGURE 4 GPS, GLONASS, Galileo, and planned Compass signals.

Once FOC is achieved, the Galileo navigation signals will provide good coverage even at latitudes up to 75 degrees north and 75 degrees south. Galileo provides enhanced distress localization and call features for the provision of a search and rescue (SAR) service interoperable with the COSPAS-SARSAT system.

The European GNSS approach began with the European Geostationary Navigation Overlay Service (EGNOS), which provides civil complements to GPS and GLONASS since mid-2005 in its initial operation. From the very beginning, EGNOS was meant to be the bridge to Europe's own full-fledged GNSS. Galileo's first developmental satellite, GIOVE-A, was launched in December 2005, and GIOVE-B should be launched late in 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 modernization. Galileo is not yet in operation but already the so-called evolution program for the second generation is planned to start in the middle of 2007. 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. Intersatellite links could be introduced at that time and aeronautical certification could be of relevance. In fact, under current plans only the first phase of Galileo – EGNOS — will be certified for aeronautical users.

China's Compass

Compass is the GNSS system planned by China. As with GPS, GLONASS, and Galileo, the system will provide two navigation services: an open service for (commercial) customers and an "authorized" positioning, velocity, and timing communications service. Compass consists of a constellation of 30 non-geostationary satellites and five GEO satellites with positions at 58.75° E, 80° E, 110.5° E, 140° E, and 160° E.

Each satellite transmits the same four carrier frequencies for navigational signals. These navigational signals are modulated with a predetermined bit stream, containing coded ephemeris data and time, and having a sufficient bandwidth to produce the necessary navigation

FIGURE 5 Ground Tracks of QZSS and IRNSS.

precision without recourse to two-way transmission or Doppler integration.

China sent three Compass navigation test satellites into orbit between 2000 and 2003. The launch of the two "Beidou" (Compass first version) satellites, scheduled for early in 2007, is expected to cover China and parts of neighboring countries by 2008, before being expanded into a global system.

The will of China to develop its own global navigation system is clearly reflected in the policy document released by the State Council Information Office on October 12, 2006, which stated that China will "independently develop application technologies and products in applying satellite navigation, positioning and timing services" as reported in the November 13, 2006, issue of *China Daily*. Compass could begin operation in 2012 if the political statements are brought into reality.

As a summary, the overall constellation parameters of the four global GNSS — GPS, GLONASS, Galileo and Compass — are shown in **Table 1**.

Finally, **Figure 4** shows the signal structure of all the existing and planned GNSSes. Negotiations among various countries are still needed to ensure compatibility (and to fulfil ITU regulations) and interoperability of the signals.

Regional Satnav Systems

In addition to the global satellite-based navigation systems already under way, two regional satnav systems are also being developed by Japan and India.

Quasi-Zenith Satellite System (QZSS). QZSS is the Japanese regional system that will serve as enhancement for GPS in Japan. The constellation consists of three satellites inclined in elliptic orbits with different orbital planes in order to pass over the same ground track. QZSS was designed so as to guarantee that at any time at least one of its three satellites is close to the zenith over Japan.

Initially, QZSS was conceived as a government–private sector program aiming for new satellite business, in which the private sector would be responsible for mobile communications and mobile broadcasting while the government would be responsible for the navigation part. Due to the lack of Japanese communication industry participation, however, QZSS satellites will not carry any communication payloads but rather will concentrate on the navigation element funded by the government alone.

QZSS and GPS will be fully interoperable and the first satellite launch date is planned for the year 2008. **Figure 5** shows in detail the ground track of the three QZSS satellites.

Indian Radionavigation Satellite System (IRNSS). The IRNSS is an independent seven-satellite constellation that will be built and operated by India. IRNSS will seek to maintain compatibility with other GNSS and augmentation systems of the region and is planned to provide services for critical national applications (perhaps including military uses).

Of the seven satellites that comprise the constellation, three are geostationary (known as GAGAN, see the following section of this column) and the other four, geosynchronous. The geostationary satellites have designated positions at 34° E, 83° E and 132° E, while the geosynchronous have equatorial crossings at 55° E (two satellites) and 111° E (two satellites), with an inclination of 29° and relative phasing of 56°.

Parameter	Galileo	GPS	GLONASS	Compass
Constellation	Walker MEO (27/3/1) plus 3 non-active spares	MEO(24/6) incl 3 active spares	MEO(24/3)	GEO(5), MEO(27),IGSO(3)
GEO Longitudes	-	-	-	58.75°, 80°, 110.5°, 140° and 160° E
GSO Equatorial Crossing	-	-	-	118°
Eccentricity	0	0	0	0
GSO Inclination	-	-	-	55°
MEO Inclination	56°	55°	64.8°	55°
Semi-major axis	29601.297 km	26559.7 km	25440 km	27840 km

TABLE 1. Space Constellation Parameters

Parameter	QZSS	IRNSS
Constellation	GSO(3)	GEO(3)+GSO(4)
GEO Longitudes	-	34°, 83°, 132° E
GSO Equatorial Crossing	-	55°(2), 112°(2)
Eccentricity	0.099	0
Inclination	45°	29°
Semi-major axis	42164.0 km	42164.0 km

TABLE 2. Space Constellation Parameters of QZSS and IRNSS

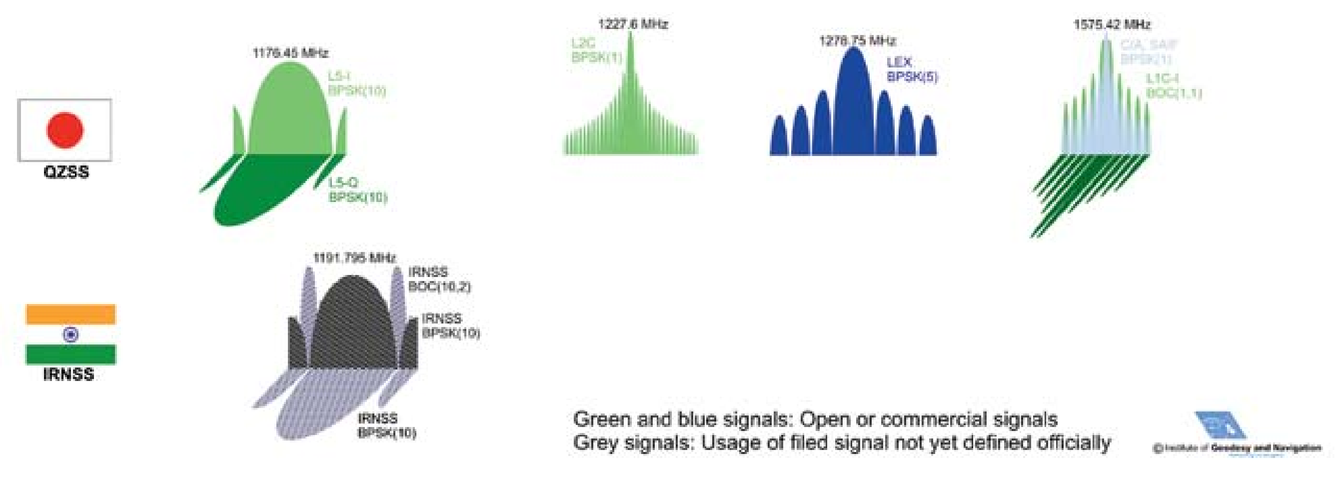

FIGURE 6 QZSS and IRNSS planned signals. Note that IRNSS is also expected to transmit augmentation signals on L1

Parameter	EGNOS	WAAS	MSAS	GAGAN
Constellation	GEO(3)	GEO(4)	GEO(2)	GEO(3)
GEO Longitudes	15.5° W 64.0° E 21.5° E	53° W 98° W 120° W 178° W	140° E 145° E	34° E 83° E 132° E
Semi-major axis	42164.0 km	42164.0 km	42164.0 km	42164.0 km

TABLE 3. GNSS Augmentation Systems Constellation Parameters

The first IRNSS payload is expected to be put into orbit in 2007 and the second, in 2008, reaching FOC in 2009. The overall constellation parameters of the two planned regional navigation satellite systems are shown in Table 2.

Figure 5 shows the ground tracks of the two regional navigation satellite systems discussed here. Figure 6 presents the signal plan of QZSS and IRNSS.

GNSS SBAS Augmentations

The European Geostationary Navigation Overlay Service (EGNOS) is a satellite-based augmentation system (SBAS) under development by the European Space Agency (ESA), the European Commission (EC), and EUROCONTROL. EGNOS would supplement GPS (and perhaps GLONASS in the future) by reporting on the reliability and accuracy of the signals. EGNOS consists of three geostationary satellites (AOR-E, IOR-W and ARTEMIS) and a network of ground stations. The system started its initial operations in July 2005, and is intended to be certified for use in safety of life applications in 2008.

WAAS. The Wide Area Augmentation System (WAAS) augments GPS over the North American territory to provide the additional accuracy, integrity, and availability needed to enable users to rely on GPS for safety-critical applications, particularly in the field of aviation. Before WAAS, the U.S. National Airspace System (NAS) did not have the capability of providing horizontal and vertical navigation for aviation precision approach operations for all users at all locations. WAAS is constituted by four geostationary satellites as shown in Table 3.

MSAS. The Japanese equivalent to WAAS and EGNOS incorporates the Multifunctional Transport Satellite (MTSAT) into MSAS (MTSAT Space-based Augmentation System). In addition to transmitting correction and integrity data for GPS, the MTSAT satellites are used for meteorological observations and communication services following a multi-mission concept. After failing with the initial launch of the first MTSAT satellite in 1999 the substitute satellite MTSAT-1R was set into orbit in February 2005. An additional satellite — MTSAT-2 — was put into mission in February 2006. (For further details, see news article on page 16 of the March 2006 issue of *Inside GNSS.*)

GAGAN. The GPS and GEO Augmented Navigation system (GAGAN) is India's SBAS for the south Asian region. Established by the Indian Space and Research Organization (ISRO) and the Airports Authority of India to aid civil aviation in the country, GAGAN will eventually expand into IRNSS.

The first geo-stationary navigation payload in C-band and L1 and L5 frequencies (L-band) will be carried on an Indian geostationary satellite, GSAT-4, to be placed at 82°E. GSAT-4 is scheduled for launch by mid-2007. Two more satellites, GSAT8 and GSAT9 will follow it to complete the augmentation system, with FOC expected by 2009.

NIGCOMSAT. With its Nigerian Communications Satellite (NIGCOMSAT-1), Nigeria is the first African country planning to enter the field of GNSS by transmitting two L-band signals in L1 and L5.

The manufacturing of the satellite was assigned to China's state-owned space hardware manufacturer and is thus China's first satellite export sale. The satellite is to be launched by a Long March 3B carrier rocket at the Xichang Satellite Launch Center in mid-2007.

Two ground stations are going to be built, one each in Nigeria and in China. NIGCOMSAT-1 will be placed in a geostationary orbit at 42°E, although it is a less than optimal location for covering Nigeria. The overall constellation parameters of all GNSS augmentation systems are shown in Table 3.

Figure 7 shows the coverage region of the satellite-based augmentation systems visible to users at elevations higher than 10 degrees.

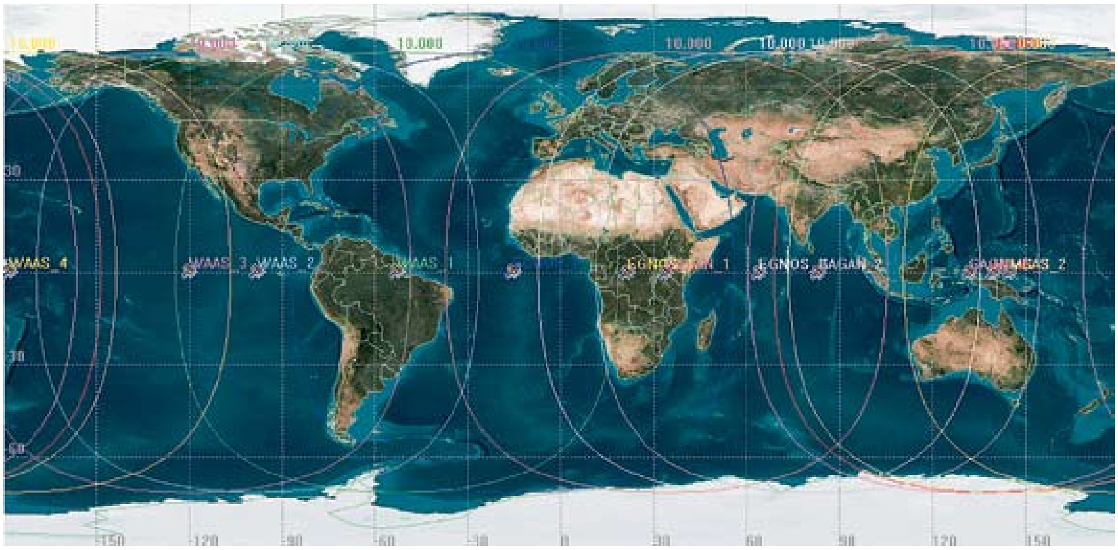

FIGURE 7 Ground tracks of EGNOS, WAAS, MSAS and GAGAN.

The Future of GNSS

This wide range of activities on existing and new GNSSes, regional satellite systems, and augmentations raise a number of questions about what the future directions of a GNSS system of systems should be.

Should a future GNSS serve civil, military, or dual-use purposes? GPS and GLONASS were originally intended for military applications. In contrast, Galileo stated from the very beginning its intention of being (primarily) a civil system. The intentions for Compass are unclear in this regard.

This is the way things are today. Going forward, what should be the approach? And more difficult yet, who should pay for it or in other words how should it be financed? Government sponsorship, as with GPS and GLONASS? Private-public partnership as sought for Galileo?

Civil and military applications work with different standards. Therefore, splitting the civil and military payloads could have interesting benefits. Civil and military signals now come from one and the same signal generator; so, inevitably the greater constraints of the military requirements have to be applied also to civil signal components for which they might not be needed or optimal.

Separating military signals from the civil signals in the frequency and signal plan would seem to offer benefits to everyone. But wouldn't a logical consequence of this approach also suggest separating military and civil elements in the satellite itself. Further, might not this principle also extend to control of those elements by separating the corresponding control centers? This would facilitate the development of different concepts for civil and military sectors without having to depend on what the other does. In the end, splitting the system into civil and military from the top would make life much easier.

Having independent military and civil services would open the additional possibility of creating true interoperability in GNSS system control. Indeed, the open (civil) services of the various GNSSes could be jointly optimized and mission control independently coordinated to minimize failures and ensure back-up.

The current scheme of existing dual-use GNSS systems makes interoperability and compatibility much more difficult to accomplish.

The current scheme of existing dual-use GNSS systems makes interoperability and compatibility much more difficult to accomplish. Although until now solutions have been found as we have recently seen with the agreement on GPS and Galileo regarding L1 signals, if more systems begin operating in this band, as Compass proposes to do, the complexity of the picture might grow to levels where an optimal solution can no longer be found.

National Security Compatibility Compliance (NSCC) is part of the 2004 US/EU agreement and deals with the problems associated with having military and civil signals together.

In fact, Galileo had to change its baseline for the public regulated service (PRS) from the original planned BOC(14,2) design to the $\text{BOC}_{cos}(15,2.5)$ design now in place to meet the NSCC requirements. Equally, the Galileo OS signal had to change from BOC(2,2) to the current BOC(1,1) baseline

What could or should the "satellite navigation system of systems" look like in the year 2020? Let us dare to imagine how the different segments of a hypothetical GNSS could appear in the future. To that objective we will analyze the three fundamental parts of any satellite navigation system: space, control, and user segments.

Space Segment. An optimal GNSS constellation would be one in which each individual system is optimized in light of the design and operations of all the other systems. This is indeed not the case today where the GPS, GLONASS and Galileo constellations do not take into account the others. Nevertheless, a real global constellation of all the systems together should be the objective because only then could an optimal coverage through a system of systems be more efficiently assured. This means that the number of orbital planes, inclination, and altitude should be ideally harmonized, although unique features of a sub-constellation (of each GNSS alone) could be retained to serve special purposes.

If a global position dilution of precision (PDOP, a factor of positioning accuracy derived from satellite geometry) could be assured by any combination of GNSS spacecraft (considering the probability of satellite failures), we would achieve an ideal global GNSS constellation from the user point of view no matter to which GNSS system a specific satellite belongs. This situation would also simplify many system operations, because the need for moving satellites to optimize a particular constellation would be eliminated (or much reduced) and replacement of satellites could be globally coordinated.

Overall, however, the demand for backward compatibility will ultimately depend mostly on the cost of GNSS receivers in a couple of years and the extent to which the software (defined) radio concept is realized.

Backward compatibility – do we really need it? As we know, until now backward compatibility has been one of the major drivers in the development of GNSS. But technology advances in ever-faster steps. For example, today customers' replacement ("churn") of mobile phones is increasingly common after only a few months or two years at the maximum.

And the same is true for civil GPS receivers, which for the tax authorities nowadays have a usable life expectancy of only three years.

Having in mind that a GNSS receiver might be implemented in every mobile phone, backward compatibility in the mass market would no longer be such a great issue as these gadgets will be replaced anyway after a very short period in use. Moreover, going to digital signal generators and receivers enable flexibility and easy changes from one to the other minute. However, communication standards like CDMA or GSM as well as the GPS ICD remained constant during the last decades.

Of course, some applications exist in which backward compatibility remains vitally important — aviation, for example. In such sectors, substantial amounts of money have to be invested every time a receiver is qualified for aeronautical use and certification. Such sectors, therefore, have a great interest in assuring that, no matter what the future signals or what new technologies are developed, the old receivers will still be able to function in the future.

Overall, however, the demand for backward compatibility will ultimately depend mostly on the cost of GNSS receivers in a couple of years and the extent to which the software (defined) radio concept is realized.

Control Segment. As discussed earlier, a great advantage of separating civil and military GNSS operations would be that civil users would gain (more) access to the control segment, which was until now reserved to the military sector — at least with respect to GPS and GLONASS. Another very important consideration is that in a real GNSS system of systems, the monitoring stations should be spread all over the world.

GPS and Galileo (will) have a global uniform distribution, but as we know this is not the case for GLONASS, which only has stations in the Russian territory. The case of Compass is still unclear as no statement has been seen as to whether Compass will include a global monitoring network.

User Segment. What will the GNSS receiver look like in 20 years? Will it be a piece of software running on a generic computer implant under our skins powered by bio-energy, broadcasting people's positions permanently to the government or somebody else? Or will it be (only) the result of a consequent improvement of already known technologies? Whereas cultural/technological revolutions of the first kind can definitely not be predicted, we can summarize key technology trends and discuss their likely effects on future receiver development.

We focus here on the civil market that, in contrast to military or aviation applications, has rather short receiver life-cycles of roughly three years.

- Size: Current GNSS receiver chips are already quite small; so, further substantial reductions in size are difficult to envision. However, GNSS functionality might by integrated as intellectual property rights (IPRs) into systems on a chip. Most likely, within 20 years most standard GNSS applications will be based on software (defined) receiver technology, taking up no physical space at all.
- Power: Signal processing and positioning is generally a well defined task requiring a fixed number of computations. The required electrical power to perform these operations has been markedly decreasing in recent years and will continue to decrease.
- Functionality: Current GPS receivers are considered to be quite optimized, but the development of true GNSS receivers making use of the upcoming multitude of signals and systems is just starting.
- External data: Assistance data is essential for GNSS positioning, and we expect that the use of this data will definitely increase. Internet-based services such as ESA's SISNET or the NASA Jet Propulsion Laboratory (JPL) real-time precise ephemeris along with commercial counterparts may also enable mass market applications to achieve sub-meter accuracy. Furthermore, mobile phone network providers may equip their base stations with GNSS time and positioning sensors, supporting centimeter to millimeter positioning accuracy for mobile units by ranging to the base stations.
- Other sensors: Today GPS is already frequently combined with other sensors such as inertial or dead reckoning systems, where required to improve positioning robustness

and continuity. Since this is often the only way to obtain position fixes in poor GNSS signal environments, we expect that this trend will gain even more in importance. Future receiver platforms (e.g., software receivers) will definitely alleviate the often cumbersome integration process currently encountered. Integrating "INS on a chip" and into the tracking loops of a GNSS receivers will result in a more robust tracking capability of future receivers.

Conclusion

Our discussion to this point has focused on the current and relatively near-future prospects for moving toward a GNSS system of systems in light of current program plans and evolutionary technology trends. In Part 2, we will examine some of the possibilities further "outside the box," including the potential for revolutionary leaps in technology and new approaches to operational advances and cooperation.

Manufacturers

Figures 5 and 7 were generated using the Satellite Tool Kit (STK) from **Analytical Graphics, Inc.** (AGI), Exton, Pennsylvania, USA.

Additional Resources

[1] Avila-Rodriguez, J.A. et al. (2005), "Revised Combined GALILEO/GPS Frequency and Signal Performance Analysis", *Proceedings of ION GNSS 2005* – 13-16 September 2005, Long Beach, California, USA.

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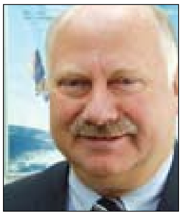

"Working Papers" explore the technical and scientific themes that underpin GNSS programs and applications. This regular column is coordinated by **PROF. DR.-ING. GÜNTER HEIN.**

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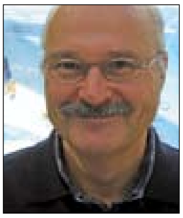

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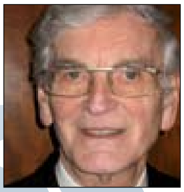

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