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GNSS frequencies, signals, receiver capabilities and applications

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Abstract

Nowadays (August 2017) position data can be obtained generally from satellite navigation systems (SNS), such as GPS and GLONASS, and satellite based augmentation systems (SBAS) which can be either global, such as EGNOS, GAGAN, MSAS and WAAS, or regional, such as NAVIC (IRNSS) in India. Two new global SNSs, Galileo and BeiDou, three new global SBASs, SDCM, KASS and SNAS, and one new regional SBA, QZSS in Japan, are under construction. The generic name given to all these abovementioned systems is GNSS (Global Navigation Satellite Systems). This paper presents details of the following: changes that have occurred in the cumulative core revenue in different GNSS market segments (road, Location Based Service LBS, surveying, agriculture, timing & synchronization, aviation, maritime, drones and rail in 2017) in the last 8 years; an overview of the GNSS industry and location-based services in the world; details of current and future GNSS market evolution; GNSS unit shipments in 13 different categories of maritime application; the frequency and constellation capabilities of GNSS receivers; GNSS frequencies that will be common in the future; the adoption of multi-constellation, multi-frequency and dual-frequency as key enablers of improved accuracy and integrity; GNSS services available for civil and authorized users, and multiple signals in the case of all four global SNSs.

Introduction

Currently (August 2017), two global satellite navigation systems (SNS) are fully operational, the American GPS and Russian GLONASS. Two new global systems, Beidou in China and Galileo in Europe, are currently under construction. Four satellite based augmentation systems (SBAS) are currently operational: EGNOS in Europe, GAGAN in India, MSAS in Japan and WAAS in USA. Four new systems, SDCM (System for Differential Correction and Monitoring) in Russia, KASS (Korean Augmentation Satellite System) in Korea, SNAS (Satellite Navigation Augmentation System) in China and SACCSA (Solución de Aumentación para Caribe, Centro y Sudamérica) in South America, are also under construction. All these SBASs allow or will allow compatible GNSS receivers to compute position estimates with improved accuracy and associated integrity warnings. Additionally, one regional SNS, the Indian NAVIC (NAVigation Indian Constellation), previously called IRNSS, is operational. Another regional system, QZSS (Quasi−Zenith Satellite System), in Japan is currently under construction (Kaplan & Hegarty, 2017). The generic name given to all of the abovementioned systems, including GBAS (Ground Based Augmentation Systems), is GNSS (Global Navigation Satellite Systems). Aproximately 120 satellites within these systems orbit the Earth, transmitting about 25 different signals for users. Unfortunately, in some publications, the acronym GNSS is also widely used to refer to any individual global SNS.

Growing demand for precise location information, in combination with the ongoing evolution of GNSS technology, means that today's GNSS

market is bigger than even. At the time of writing, more than 5.8 bln different GNSS devices are used around the globe. The installed base is forecasted to increase to about 8 bln in 2020 and to over 9 bln in 2023 – more than one device per person (GNSS User Technology Report, 2016; GNSS Market Report, 2017).

GNSS Market Reports

The GNSS Market Report, edited by The European GNSS Agency (GSA), takes a comprehensive look at the global GNSS market, providing detailed analysis per market segment and application type. This market report is published on average every 20 months. In the first issue, October 2010, the number of GNSS market segments was equal to 4, in the latest (fifth) issue of the publication from May 2017, the number of segments increased to 9. The changes in the cumulative core revenue (as a percentage) in each segment during the last 8 years are presented in Table 1.

Since the report was first published, the segments with the biggest revenues have been LBS (Location Based Service) and Road. In each issue, these two segments' total share of the revenue has been more than 90%. The maritime segment accounts for only around 1%.

For the first time in issue 5, May 2017, the segment Drones was considered. The European Maritime Safety Agency (EMSA) is preparing for the use of drones in its activities to complement the use of navigation system satellites. By deploying a large number of drones, the EMSA would be able to

Table 1. GNSS Market Report, cumulative core revenue (in %) of different market segments in different periods (GNSS Market Report, 2010, 2012, 2013, 2015, 2017)

Number of issue, month and year, number of pages	1, October 2010, 34	2, May 2012, 48	3, October 2013, 72	4, March 2015, 81	5, May 2017, 100
Segment	Period				
	2010−2020	2010−2020	2013−2022	2013−2022	2015−2025
Road	56.4	54.0	46.2	38.0	50.0
Location Based Service	42.8	43.7	47.0	53.2	43.2
Surveying	–	0.7	4.1	4.5	2.6
Agriculture	0.6	1.0	1.3	1.8	1.5
Timing Synchronization	–	–	–	0.1	0.7
Aviation	0.2	0.5	1.0	1.1	0.7
Maritime	–	0.1	0.3	1.1	0.7
Drones	–	–	–	–	0.5
Rail	–	–	0.1	0.2	0.1
Total [%]	100	100	100	100	100

Table 2. Maritime GNSS unit shipments (in thousands) by application in different years (GNSS Market Report, 2017)

Application	2006		2016		2025	
	number	percentage	number	percentage	number	percentage
Search and Rescue (PLB)	6	0.9	55	3.2	95	3.7
Search and Rescue (EPIRB)	16	2.3	6	0.4	67	2.6
Search and Rescue (AIS – MOB)	–	–	–	–	58	2.2
Search and Rescue (AIS – SART)	–	–	37	2.2	23	0.9
Traffic Management	17	2.4	17	1.0	25	1.0
Homeland Security	11	1.6	16	0.9	21	0.8
IWW Traffic info	8	1.1	19	1.1	29	1.1
Ports	–	–	5	0.3	31	1.2
Marine Engineering	6	0.9	6	0.4	9	0.3
Fishing Vessels	–	–	23	0.4	28	1.1
IWW Navigation	12	1.7	33	1.9	32	1.2
Merchant Navigation	49	7.0	45	2.6	69	2.6
Recreational Navigation	575	82.1	1438	84.6	2113	81.3
Total	700	100	1700	100	2600	100

increase its operational scope and monitor all of the so-called hotspots around Europe's maritime borders. The drones will make a valuable contribution to different maritime surveillance operations.

The distribution of maritime GNSS unit shipments, separated by application, in different years is presented in Table 2. The total number of GNSS shipments is expected to reach 2.1 mln units in 2020 and 2.6 mln units in 2025. In 2006 and 2016 this number was 0.7 mln and 1.7 mln respectively. In each year, more than 80% of the total shipments are shipments of recreational navigation devices. Due to the significant untapped addressable market of recreational vessels, the recreational navigation segment is expected to continue dominating annual shipments of GNSS devices with expected shipments of 1.7 mln units in 2020 and 2.1 mln units in 2025 (GNSS User Technology Report, 2016; GNSS Market Report, 2017).

GNSS signals

In the early stages of satellite navigation, in the 1990s, GPS (the only global SNS at that time fully operational) receivers were available to civil users. Additionally, as C/A code is transmitted on frequency L1 only, almost all receivers were adapted for "one frequency, one code" (L1, C/A). In the following years the number of GPS frequencies available to civil users increased, L2C – satellite block IIR−M (since 2005) and L5 – block IIF (since 2012) and code P became available to all users. Since December 2011 the GLONASS system has been fully operational and all 24 satellites (nominal constellation)

Table 3. Global satellite navigation systems and their frequencies, signals, satellite blocks, year of first operational satellite in orbit, number of operational satellites as of August 2017, year of full operational or service capability, number of satellites in the final constellation (Federal Radionavigation Plan, 2014; Betz, 2016; Kaplan & Hegarty, 2017)

System	Frequency [MHz]	Signals	Satellites blocks	On orbit since year	Number of satellites in August 2017, year of FOC (number of satellites)
BeiDou	1,561.098 1,207.140 1,268.520	B1I, B1Q B2I, B2Q B3	all	2007	20, 2020 (35)
Galileo	1,176.45	1 (E5a) 2 (E5a)	all	2011	13, 2019 (ES−26), 2021 (FOC− 30)
	1,207.14	3 (E5b) 4 (E5b)			
	1,278.45	5 (E6) 6 (E6) 7 (E6)			
	1,575.42	8 (L1) 9 (L1) 10 (L1)			
GLONASS	1,602 + n · 0.5625	L1OF L1SF	all	2003	24, since 2011
	1,246 + n · 0.4375	L2OF L2SF	all	2003	24, since 2011
	1,202.025	L3OC	K1, K2, KM	2014, 2018, 2025	1, 0, 0, 2030 or later (24)
	1,575.42	L1OCM	KM	2025	0, 2030 or later (24)
	1,207.14	L3OCM	KM	2025	0, 2030 or later (24)
	1,176.45	L5OCM	KM	2025	0, 2030 or later (24)
GPS	L1 1,575.42	C/A P M C	all all since IIR−M III	1997 1997 2005 2018	31, since 1997 31, since 1997 19, 2020 or later (24) 0, 2020s (24)
	L2 1,227.60	P C M	all since IIR−M since IIR−M	1997 2005 2005	31, since 1997 19, 2020 or later (24) 19, 2020 or later (24)
	L5 1,176.45	C	since IIF	2011	12, 2022 or later (24)

ES – Enhanced Services, n = − 7, − 6,…, + 6, O – Open Signal, F – FDMA, S – Obfuscated Signal, C − CDMA, M – satellite block

of this system transmit two frequencies available to civil users (Betz, 2016).

From their inception, the new global SNSs, currently under construction, Galileo and BeiDou, support open multi-frequency signals which helps drive the introduction of dual and triple-frequency commercial receivers. All satellites within the Galileo system and BeiDou system on MEO orbits will transmit the same signals: 10 in the case of Galileo and 5 in the case of BeiDou (Betz, 2016). The frequencies, signals, satellite blocks and some parameters of the constellation of all global SNSs are presented in Table 3. These signals are designed to enable several functions (Kaplan & Hegarty, 2017), namely:

- precise ranging by the user's equipment;
- conveyance of digital information about the location of the GNSS satellites, clock errors, satellite health, and other navigation data;
- for some systems, global ones in particular, utilization of a common carrier frequency among multiple satellites broadcasting simultaneously (e.g. 1,575.42 MHz in the case of GPS and Galileo).

Most GNSS signals today use carrier frequencies in the L−band, which is defined by the Institute of Electrical and Electronics Engineers (IEEE) to be the range of 1 to 2 GHz. The L−band offers several advantages for GNSS signals as compared to other bands. Two L−band frequency subsets, 1,164–1,300 MHz and 1,559–1,610 MHz, have been allocated globally by the International Telecommunication Union (ITU) for radionavigation satellite service (RNSS), which is the name given by the global spectrum management community to the services provided by GNSS constellations. Some GNSS constellations, e.g. the regional systems NAVIC and QZSS, utilize S−band (2−4 GHz) navigation signals also (Kaplan & Hegarty, 2017).

In October 2016 the European GNSS Agency edited the first issue of the GNSS User Technology Report. According to this report, analysis of 400 receivers, chipsets and modules, provided by several dozen manufacturers currently on the market, shows that more than 60% of them support, apart from the GPS constellation, two or three other constellations of global SNSs (Table 4). In terms of supported frequencies, the GSA analysis shows that only 32% of all receivers implement more than one of them (1,575.42 MHz) mostly in high precision (Table 5). This percentage is lower than that of multi-constellation receivers due to many factors, such as the cost of the receiver, its complexity, power draw and the relative novelty of open signals on multiple frequencies (GNSS User Technology Report, 2016).

Table 4. Percentage of global satellite navigation systems receivers capable of tracking 1, 2, 3 or all 4 constellations (GNSS User Technology Report, 2016)

Number of constellations	Systems	Percentage	Total percentage
1	GPS	37	37
2	GPS + BeiDou	2	28
	GPS + Galileo	5	
	GPS + GLONASS	21	
3	GPS + BeiDou + GLONASS	4	13
	GPS + Galileo + BeiDou	2	
	GPS + GLONASS + Galileo	7	
4	GPS + GLONASS + + Galileo + BeiDou	22	22

Table 5. The percentage of global satellite navigation systems receivers capable of tracking 1, 2, 3 or all 4 frequencies (GNSS User Technology Report, 2016)

Number of frequencies	Symbol	Percentage	Total percentage
1	L1 / E1	68	68
2	L1 / E1 + L2	18	19
	L1 / E1 + L5 / E5	1	
3	L1 / E1 + L2 + L5 /E5	12	12
4	L1 / E1 + L2 + L5 / E5 + L6	1	1
	Total	100	100

For 25 years, the annual GPS World Receiver Survey has been providing the longest running, most comprehensive database of GPS and GNSS equipment available in one place. In January 2017 information was provided by 45 manufacturers on 468 receivers. These numbers are very similar to the numbers presented in the GSA analysis. This indicates that a comparison of the percentage of GNSS receivers capable of tracking each of the four global SNS constellations, SBAS, and two regional systems, QZSS and NAVIC, according to GPS World

Table 6. Percentage of GNSS receivers capable of tracking each constellation according to GNSS User Technology Report and GPS World Receiver Survey (GNSS User Technology Report, 2016, GPS World Receiver Survey, 2017)

System	Percentage	
	GNSS Report	GPS World
GPS	100	100
BeiDou	28	47
Galileo	38	49
GLONASS	57	63
SBAS	67	64
QZSS	37	40
NAVIC	1	1

(author's calculations) and the European GSA Agency is both possible and reliable (Table 6). The greatest percentages are seen in the cases of SBAS, 67% in the GNSS Report and 64% in GPS World, and GLONASS, 57% and 63% respectively; the lowest (1%) in both cases is NAVIC.

In addition to the L1/E1 frequency band supported by all devices, the percentage of GNSS (GPS/Galileo) devices found to support additional bands were 30% for L2, 10% for L5/E5, and 1% for E6 (GNSS User Technology Report, 2016; GPS World Receiver Survey, 2017).

GNSS services

GNSS services are delivered by granting users access to one or several signals, allowing them to determine their position and/or time with a given level of performance. Some services are freely available for all users equipped with a suitable receiver, e.g. Standard Positioning Service (SPS) in the case of the GPS system and OPEN Service (OS) in the case of the Galileo system. Other services have controlled or restricted access, e.g. Precise Positioning Service (PPS) in the case of the GPS system and Public Regulated Service (PRS) in the case of the Galileo system, which are reserved for governmental use, and Commercial Service (CS) which is intended to provide enhanced performance to paying users only .

Some GNSS satellites, Galileo and GLONASS, may carry a Search and Rescue (SAR) payload to contribute to the COSPAS−SARSAT service. There are three ways in which GNSS can add and contribute to SAR missions (GNSS User Technology Report, 2016):

- by providing more satellites carrying a SAR payload relaying the Forward Link Service (FLS), thus enabling the build-up of the MEOSAR system that is expected to replace the aging LEOSAR system;
- by providing position information to the "Location Protocol" (LP) enabled distress beacons;
- in the case of Galileo satellites, by providing a Return Link Service (RLS) in addition to the abovementioned FLS.

Multiple constellations, multiple frequencies, and multiple signals

It is commonly assumed that by definition, the expressions "more signals" and "more systems" must be referenced against some baseline configuration,

Table 7. One global SNS, one additional operational satellite in the same system transmitting the same frequencies and the same signals; benefits and challenges (GNSS User Technology Report, 2016; Petovello, 2017)

Benefits	Challenges	Remarks
– lower DOP coefficients, improved user position accuracy	– the number of receiver channels must be sufficient	– e.g., another GPS satellite block IIF

Table 8. One global SNS, one additional operational satellite in the same system transmitting the same frequencies and additional signal(s); benefits and challenges (GNSS User Technology Report, 2016; Petovello, 2017)

Benefits	Challenges	Remarks
– encoded or no additional signals designed for selected users	– capability of the user's receiver	– e.g., the first GPS satellite block IIR−M, additional signals L1M &, L2M (military user), L2C (civil user)

Table 9. One global SNS, one additional operational satellite in the same system transmitting additional frequencies and additional signals; benefits and challenges (GNSS User Technology Report, 2016; Petovello, 2017)

Benefits	Challenges	Remarks
– dual frequency capable devices can estimate and compensate for ionospheric delays up to first order, up to second order with three frequencies – averages out multiple errors – improves resilience to interference – access to RTK (Real Time Kinematic) and Precise Point Positioning (PPP); although theoretically possible for single frequency receivers, RTK and or real time PPP techniques practically require dual-frequency receivers – improved robustness; although rarely advertised, frequency diversity is a basic protection against jamming – improved accuracy; new modulations and higher chip rates enable more precise range measurements – improved multipath mitigation; new modulation and higher chip rates provide additional mitigation for multipath issues – improved sensitivity; pilot signals receivers through longer integration times	– removing ionosphere increases noise – user's receiver requires multiple front-ends – inter-frequency biases need to be properly handled	– the first GPS satellite block IIF (frequency and signal L5) – in the future the first satellite GLONASS block KM (frequency and signal L1OCM, L3OCM, L5OCM)

Table 10. One global SNS and one or more additional SNS transmitting own frequencies and own signals; benefits and challenges

Benefits	Challenges	Remarks
– improved solution availability in signal-obstructed areas in particular – lower DOP coefficients; greater improvements are realized in signal-obstructed (restricted) as urban canyon areas – better statistical reliability	– requirment of an integrated multi-system receiver – need to account for reference system (ellipsoids) and time scale differences between all used individual SNSs	– 63% of global SNS integrated receivers are capable of tracking two constellations or more

most frequently the GPS L1 C/A solution. "More signals" is most commonly interpreted as meaning more frequencies for a given GNSS, and "more satellites" is typically interpreted as using additional GNSSs relative to the baseline case (Petovello, 2017). A GNSS user must know all the consequences of any change in spatial segment, in particular changing the operational satellite (Januszewski, 2016; 2017). These consequences depend on the block of the satellite and its signals and frequencies. If it is an additional satellite of the same system we can distinguish three cases (GNSS User Technology Report, 2016):

- same block, same signals, and same frequencies;
- new block, additional signal(s), and same frequencies;
- new block, additional signal(s), and additional frequency(ies).

The benefits and the challenges of all these cases are presented in Tables 7–9.

In the case in which an additional SNS, with own satellites, frequencies and signals is added to a given global SNS, the user must have an integrated receiver for all these systems. The benefits and challenges of this solution are presented in Table 10. The percentage of integrated multi-system receivers capable of tracking the signals of two global SNSs, SBAS and regional systems is continuouly increasing.

Conclusions

- Today, all global satellite navigation systems use carrier frequencies in the L−band (1−2 GHz), regional systems use the S−band (2−4 GHz). Several GNSS service providers are considering the future addition of navigation signals in C−band (4−8 GHz).
- A multiple GNSS systems solution (integrated receivers) is beneficial in signal-obstructed areas such as urban canyons where the visibility of satellites is limited or when the user's receiver is not ideally located on the object being positioned, e.g., inside a car or bag. A multiple frequencies solution will be most useful for improving position accuracy when signal visibility is less of a concern.
- In 2017, for the first time, the segment Drones was considered in the GNSS Market Report, edited by The European GNSS Agency (GSA).
- Analysis of more than 400 GNSS receivers, chipsets and modules currently on the market shows that more than 20% are already capable of using all four available global (GPS, GLONASS, Galileo, BeiDou) constellations.
- The number of services available for civil and authorized users depends on the system.

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