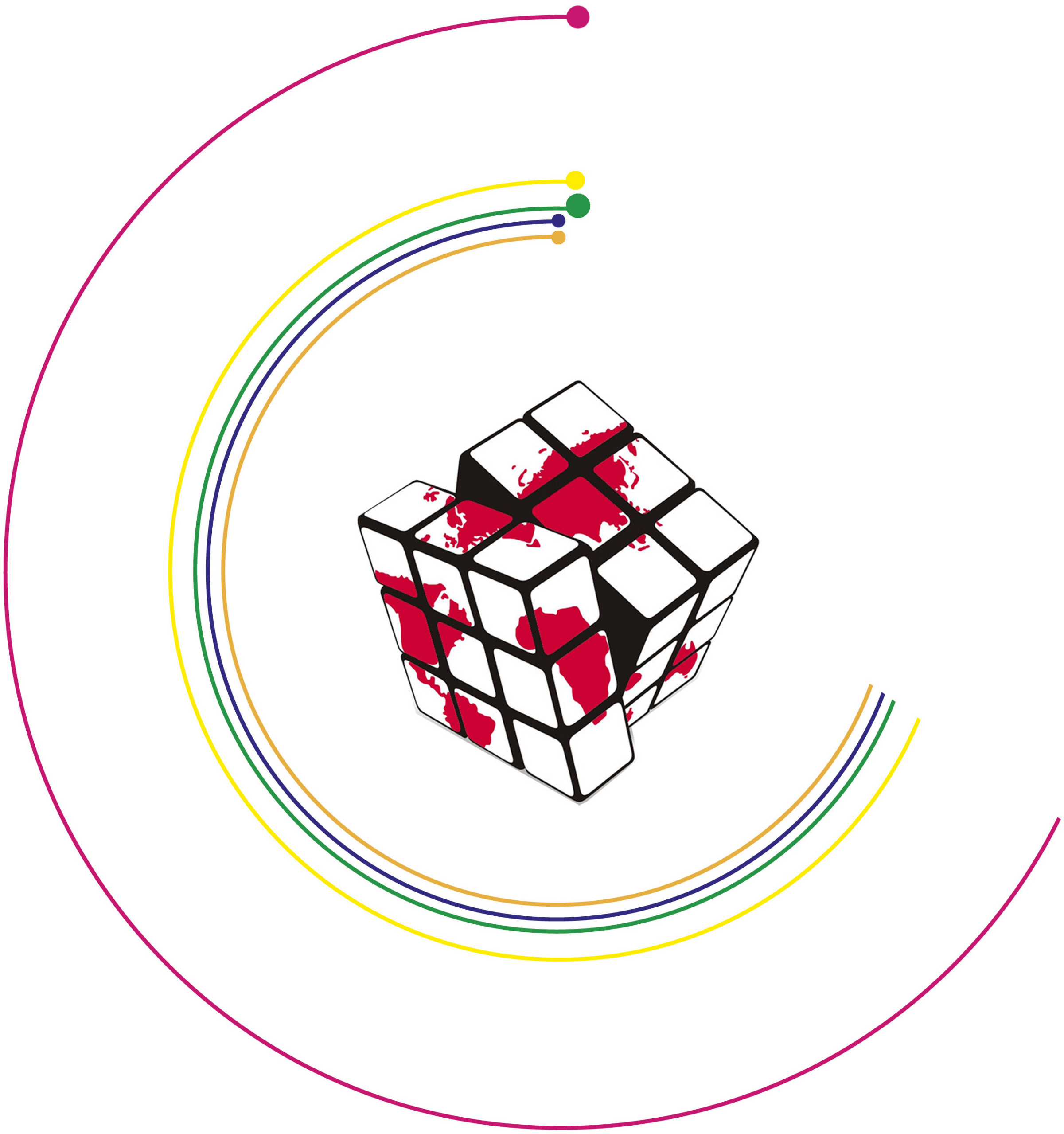
International Competition for Global Navigation Satellite Systems (GNSS)

CGS Global Focus | October 2019



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International Competiton for Global Navigation Satellite Systems (GNSS)

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The Center for Global Studies (CGS) at the University of Bonn is dedicated to the exploration of power and power shifts in international relations. The series CGS Global Focus investigates selected issues in contemporary global politics.

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CONTENT

EXECUTIVE SUMMARY
DEUTSCH

Spitzenreiter im Bereich räumliche Signalabdeckung

- Als das am weitesten verbreitete System mit voller globaler Funktionsfähigkeit und im Vergleich etwas besserer Abdeckung, führt GPS knapp im Bereich der räumlichen Abdeckung.

- BeiDou und Galileo sollen 2020 voll funktionsfähig werden sowie ihre Anzahl an Satelliten in der Umlaufbahn mit dann 35 bzw. 32 Satelliten substanziell erhöht haben, was ihre Konkurrenzfähigkeit im GNSS-Wettkampf wesentlich verbessert.

- Der Schlüssel zu einer erheblich vergrößerten Abdeckung, insbesondere durch Satelliten in großen Höhenlagen, liegt in der Kompatibilität der verschiedenen Systeme.

Spitzenreiter im Bereich Standortgenauigkeit

- Bei voller Einsatzfähigkeit versprechen BeiDou und insbesondere Galileo das höchste Niveau der Genauigkeit unter den vier untersuchten GNSS (bis zu 0,01 Meter bei Galileo).

- Mit dem Start seines neuen Vespucci-Satelliten im Dezember 2018 hat GPS kürzlich eine Steigerung bei der Präzision in Angriff genommen, um den heutigen Ansprüche in einem zunehmend kompetitiven Marktumfeld gerecht zu werden.

- Alle vier untersuchten GNSS bieten sowohl öffentliche als auch verschlüsselte Frequenzen, die jeweils im verschlüsselten Modus ein wesentlich höheres Genauigkeitsniveau aufweisen können.

Spitzenreiter bei der Nutzung von GNSS in Smartphones

- GPS führt, da es derzeit das einziges GNSS ist, das von allen 40 untersuchten Smartphone-Modellen unterstützt wird.

- Bezüglich Smartphone-Support ist Galileo das Schlusslicht der vier gebrauchsfertigen GNSS, obwohl es großes Potential, gerade im Bereich der Doppelfrequenz-Ortung, aufweist.
- Unter den zehn untersuchten Smartphone-Herstellern unterstützen lediglich Samsung und Xiaomi alle vier GNSS.

Spitzenreiter im Bereich gegenseitige Kompatibilität

- Drei technische Faktoren – Signal-in-Space, das geodätische Bezugssystem sowie die Referenzzeit – bestimmen maßgeblich die Kompatibilität und Interoperabilität zwischen den Systemen.
- Der technologische Vorsprung ermöglicht GPS die Führung im Bereich der Kompatibilität und Interoperabilität. Zudem wird GPS durch eine Zusammenarbeit mit anderen Ländern und internationalen Organisationen begünstigt.
- Bei Galileo wird die Weiterentwicklung seiner Kompatibilität durch finanzielle Schwierigkeiten eingeschränkt. Verlangsamt wird auch die Zusammenarbeit von GLONASS, GPS und Galileo im Zuge politischer Krisen, während China und Russland die Kompatibilität ihrer Systeme vorantreiben.
- Die aktuelle Interoperabilität der GNSS‘ weist verschiedene Entwicklungsstufen auf. Die in ihrer militärischen wie zivilen Nutzung dualen Systeme GPS und GLONASS sind seit langem etabliert, während BeiDou und Galileo noch in der Entwicklung begriffen sind.

Spitzenreiter im Bereich Zuverlässigkeit und Widerstandsfähigkeit

- Aufgrund enormer Distanzen zwischen Sende- und Empfangsvorrichtungen bleibt GNSS anfällig für Störungen sowie – in geringerem Umfang – für Manipulationen.
- Fortschritte im Bereich der Sende- und Verschlüsselungstechnologie müssen sich mit hochentwickelten Gegenmaßen, gerade seitens staatlicher Akteure, messen.
- Darüber hinaus entwickeln einige staatliche Akteure vielfältige Technologien der physischen Zerstörung von Satelliten, was die GNSS im Konfliktfall zusätzlich bedroht.

EXECUTIVE SUMMARY
ENGLISH

Leadership in Terms of Geospatial Coverage

- Due to being most widely used, having full global operationality and providing slightly better coverage than its competitors, GPS is just in the lead in geospatial coverage.
- BeiDou and Galileo are supposed to achieve their full operational ability in 2020 and with 35 and 32 will then have greatly increased their amounts of satellites in the orbit, thus making both fierce competitors for GNSS leadership.
- For significantly extended coverage, especially from satellites in higher altitudes, inter-compatibility is trump.

Leadership in Terms of Accuracy of Location

- Once fully operational, Beidou and especially Galileo hold out the highest levels of accuracy among the four major GNSS examined (up to 0.01 m for Galileo).
- With the launch of its new Vespucci satellites in December 2018, GPS has recently sought to increase its accuracy and meet present-day needs in an increasingly competitive environment.
- All four GNSS examined provide public/un-authorized and encrypted/authorized channels of operation with considerably higher levels of accuracy attainable in encrypted/authorized modes.

Leadership in Smartphone Application of GNSS

- GPS leads as the only GNSS supported by all 40 reviewed smartphone models.

- Galileo ranks last within the four ready-to-use GNSS when it comes to smartphone support, but it offers great potential, particularly regarding dual-frequency positioning.
- Among the ten reviewed smartphone vendors only Samsung and Xiaomi support all four GNSS.

Leadership in Terms of Reciprocal Compatibility

- Three technical factors - the signal-in-space, the geodetic coordinate reference system, and the time reference system - mainly determine the compatibility and interoperability between systems.
- The technical advantage of the US-American GPS guarantees its leadership in terms of compatibility and interoperability, also promoted by its cooperation with other countries and international organizations.
- Galileo has some technical advantages, but financial problems limit its development in reciprocal compatibility. The cooperation of GLONASS with GPS and Galileo has decelerated due to political crises, while China and Russia are promoting the compatibility between their systems.
- The present compatibility and interoperability of different GNSS show different levels of development. The dual military/civil systems GPS and GLONASS have existed for a long time whereas BeiDou and Galileo are currently under development.

Leadership in Reliability and Resilience

- GNSS will stay vulnerable to jamming (and to a lesser degree to spoofing) due to the enormous distances between the transmitting and receiving devices.
- Advances in transmitting and encryption technology compete with sophisticated countermeasures, especially engaged by state actors.
- Furthermore, major players are developing multiple technologies for the physical destruction of satellites, posing an additional threat to GNNS in a case of conflict.

INTRODUCTION

Space as a source of industrial excellence and technological development brings several potential spill-over effects on other sectors. Because of the central role of a satellite navigation system in the national economic, social and security sectors including aerospace security, the construction and development of a satellite navigation system is triggering a new round of competition among world powers. Countries and organizations worldwide have set up their own navigation satellite systems one after another aiming to rid themselves of the dependence on the navigation satellite systems of great powers. As in other domains of international relations today, including trade disputes or the global row over 5G technologies, the matter of GNSS can be regarded a contemporary hallmark of great power competition, especially between the United States of America, the Federal Republic of Russia, the European Union and the People's Republic of China. This study focusses on these four powers simply because of the fact that they alone possess satellite constellations providing global coverage. These systems include US-American Global Positioning System (GPS), Russian Global Navigation Satellite System (GLONASS), Chinese BeiDou (BDS) and European Galileo, whereas Japanese Quasi-Zenith Satellite System (QZSS) and Indian Navigation with Indian Constellation (NavIC) supply solely on a regional level.[1] The latter two exemplify that more and more countries are seeking to decrease dependency on the predominant GPS and to a lesser degree on the other global GNSS.

However, the question of which power disposes of the predominance in GNSS and who is the real leader in international competition for Global Navigation Satellite System remains open. This study attempts to answer the raised questions by systematically investigating and comparing the five aspects that substantially contribute to the quality of GNSS: geo-spatial coverage, accuracy of locating, Smartphone Application of GNSS, reciprocal compatibility, as well as reliability and resilience.

1. LEADERSHIP IN TERMS OF GEO-SPATIAL COVERAGE

To make this topic more feasible, the illustration below will show the specific coverage of the Center for Global Studies' home: Bonn. The more than one hundred satellites along with 23 augmenting satellites which provide coverage for Bonn are depicted here. They include 32 GPS satellites, 22 from GLONASS, 20 from Galileo, 33 from BeiDou, and four of QZSS, as well as 23 from augmentation systems.

1 Parker et al. 2018: 3.

Initially, this might indicate that in terms of coverage there is a competition mainly between the US and China. But there is more to it as this study will prove. The discussion of utilizing higher altitudes for satellites, the encompassing overall importance of geospatial coverage and its comparison across the different GNSS leads to this chapter's research question: Who leads in terms of geospatial coverage? For this purpose, the chapter at hand takes a closer look at the coverage, signal availability, augmentation and how the United States, Russia, the European Union, and China compete for them.

Table 1.1: Satellites over Central Europe

Source: Navmatix, GNSS mission planning, http://gnssmissionplanning.com [Accessed on September 30, 2019].

UTILIZING HIGHER ALTITUDES

Recently, the focus for GNSS has shifted from low (below 3,000 km above the Earth's surface) to high altitudes (3,000 km to 36,000 km). As signal reception in low altitudes is like on earth, in the past low Earth orbit (LEO) was primarily targeted for satellites use. But satellite constellations "are now increasingly utilized for autonomous navigation in space as well".[2] There it is much more difficulty to get sufficient availability and performance of GNSS signals due to "reduced signal power levels and visibility, potentially reduced pseudorange accuracy, less optimal geometric diversity, and in the case of elliptical orbits, highly dynamic motion".[3]

For this reason, compatible GNSS are crucial for coverage in higher altitudes. The rationale behind this extension into space with its more aggravating environmental conditions for coverage is that it allows to operate more satellites simultaneously. This, in turn, leads to higher coverage and precision, if the respective requirements are met. Generally, coverage in space is achieved when four satellites provide a user with four signals as it greatly increases availability and reduces the maximum continuous outage duration (MOD).[4] Moreover, augmentation systems assist coverage and precision.

2 United Nations 2018: v.
3 United Nations 2018: v.
4 Parker et al. 2017: 3; Swamy 2017: 1155.

THE IMPORTANCE OF GEOSPATIAL COVERAGE

Since satellite-dependent applications encompass a great variety of fields such as security, transport, navigation and telecommunication, their importance has grown. Many more appliances could be elaborated here but we will stick to these few as they demonstrate the enormous range of GNSS examples. Simultaneous to this development more competing satellite constellations have been established, making this area increasingly contested.[5] By backing one of the four major GNSS the leading powers therefore find themselves once more in an enhanced geopolitical competition. This provides the four powers behind the big four satellite constellations not only with an opportunity to reduce dependency, especially on the first generation of GNSS (GPS and GLONASS), but also to coin standards and to compete for global influence. For example, this goes hand in hand with Beijing's Made in China 2025 strategy and the PRC's ambitions in other technological areas like telecommunication.

However, there is also a lot of cooperation taking place as well. All the aforementioned GNSS and smaller regional systems work together through the United Nations International Committee on GNSS (ICG) to establish an interoperable multi GNSS Space Service Volume (SSV). The SSV determines "a common set of baseline definitions and assumptions for high-altitude service in space, documents the service [..] by each constellation, and provides a framework for continued support for space users."[6] This would create international law for GNSS and is proof of the benefits of inter-compatible systems. Parker et al. consider that the "abundance of signals available in an interoperable multi-GNSS SSV greatly reduces the constraints for navigation at high altitudes".[7]

COMPARING GEOSPATIAL COVERAGE

Table 1.2: Coverage of the big four

System name	No. of Satellites	Coverage	Status	No. of civil frequencies/ signals	Semi-major axis (km)	In-clination (°)
GPS	31	Global	Operational	3/4	26,560	55
GLONASS	24	Global	Operational	2/6	25,519	64,8
Galileo	26*	Global	Operational	5/10	29,000	56
BDS	33**	Global	Operational (Regional) In build-up global***	3/5	27,906	55

Source: All information except for column "No. of Satellites" is taken from a comparable table by Parker et al. 2017: 3. Said column is based on data by the four providers.

* Overall, it is planned that until 2020 Galileo will consist of 32 satellites. See Nawrocki 2019: 259.

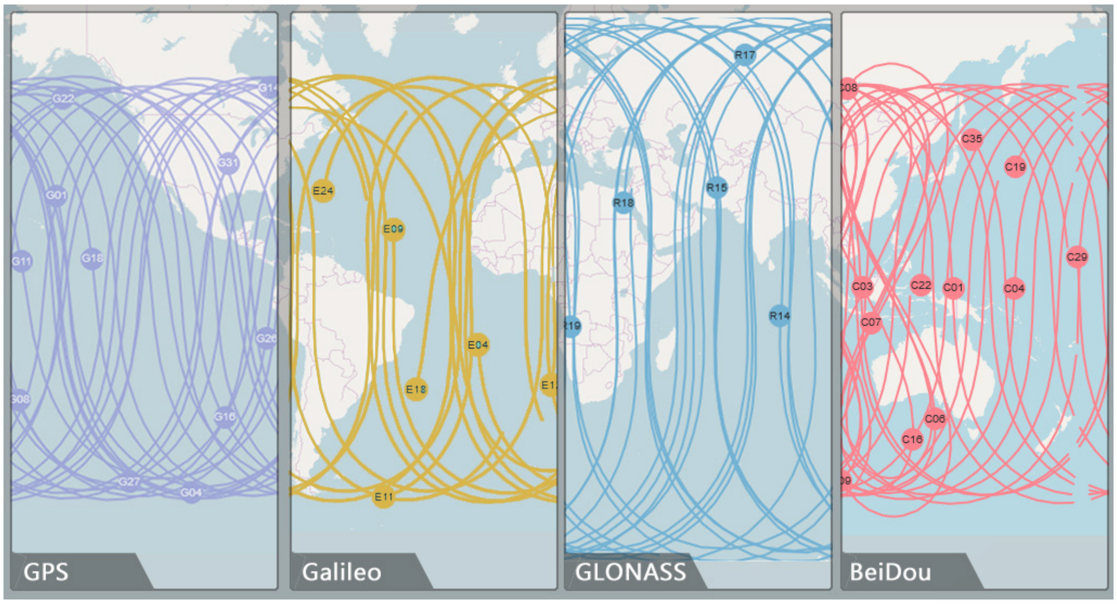
** According to the Test and Assessment Research Center of China Satellite Navigation Office. Yet Nawrocki describes the system as follows: "At present the BeiDou is a regional navigation system, operating in the Asia-Pacific region, with 15 operational satellites in orbit." (Nawrocki 2019: 264.)

*** BDS is supposed to achieve its full operational ability in 2020.

5 Swamy 2017: 1155.
6 Parker et al. 2017: 1.
7 Parker et al. 2017: 2.

In total, the number of satellites encompasses more than one hundred. GLONASS possesses the smallest numbers of them, whereas China is expected to get the highest number with 35 satellites in the orbit.[8] GPS and GLONASS have full operational ability, whereas Galileo and BeiDou (BDS) plan to achieve this in 2020. The already established Russian and US systems of the first generation are less error-prone than their European and Chinese counterparts. For instance, Galileo's ability to operate was briefly interrupted in July 2019 through a technical incident related to its ground infrastructure.[9]

Illustration 1.1: GNSS Satellites Orbits and Coverage



Source: Map based on four mappings by Navmatix, GNSS mission planning, http://gnssmissionplanning.com [Accessed on August 30, 2019].

2020 will therefore see new levels of competition once both BDS and Galileo achieve full operationality. As opposed to the other three, which were originally designed for military purposes and still are under the control of their respective country's ministry of defense, Galileo is a civilian-led satellite constellation. This might explain its leadership in the number of civil frequencies and signals. Besides, it could be deduced that the distance of the semi-major axis indicates technological development. As signal power gets stronger, the coverage reaches longer distances. Also, the inclination reveals coverage aims. GLONASS is more inclined to cover Northern areas, while BeiDou, GPS, and Galileo aim only for polar latitudes of up to 75°N, for which they have chosen an inclination of 56 ° for the orbits. Corresponding to Russian goals, GLONASS works with a higher inclination of 64,8 °, which enables coverage at high latitudes.[10] The Illustration 1.1 shows this in further detail.

According to Vasile et al., the GLONASS achieves better coverage around the extreme latitudes and GPS around the equator. In comparison, they rate Galileo's and BeiDou's coverage as worse and explain that those two systems are still under development.[11]

GPS is still most widely used, has full operationality and slightly better coverage than its competitors. In this context, the US system is thus still the leader in GNSS. Nonetheless, European Galileo and Chinese BeiDou have caught up and will continue to do so, especially since they will both complete their operation plans in 2020. This is

8 Nawrocki 2019: 264.

9 Galileo 2019; Frankfurter Allgemeine Zeitung 2019.

10 Swamy 2017: 1165-1166; Vasile et al. 2018: 5-6.

11 Vasile et al. 2018: 6.

likely to start a new wave of competition in space, rivalling GPS's once uncontested status. Accordingly, it does not appear unlikely that space will become just another arena of competition in which China will challenge the US-led pecking order. From a user's perspective, however, technological cooperation appears to be the favorable choice and obvious solution to achieve better coverage. Since environmental factors, topology, jamming and lacking inter-compatibility are common obstacles for better coverage, cooperation between the big four to overcome these challenges might, despite the ongoing technological competition between major powers, cleave a way for a cooperative future in navigation systems.

SATELLITE-BASED AUGMENTATION SYSTEMS

Augmentation is instrumental for the safety of aircraft landings and can be divided into three kinds of systems: (i) satellite-based augmentation systems (SBAS), (ii) ground-based augmentation systems (GBAS), (iii) and aircraft-based augmentation systems (ABAS).[12] For our purposes, the SBAS are most interesting as they are most helpful in providing coverage. As was shown above through the example of coverage in Bonn, 23 satellites augment the user coverage, so that the 111 satellites from GNSS are supplemented by augmentation. Standalone GPS is unable to fulfil the requirement of accuracy, availability, continuity, and integrity according to the Required Navigation Performance (RNP).[13] In this sense, SBAS are instruments to supplement coverage from GNSS.

2. LEADERSHIP IN TERMS OF PRECISION OF LOCATING

Finding ways to accurately determine one's position has been the philosopher's stone for explorers and seafarers through the ages as it affected the success or failure of their journeys and, at times, their very lives – and for centuries it required considerable skill in observation and reckoning. At it, various natural phenomena have been drawn upon to ascertain one's position or to calculate the distance travelled: the position of the stars and planets, wave or wind patterns, even the routes taken by migrating birds. With the development of such navigation instruments as the compass or, later, the octant and sextant, the delicate task steadily became easier. It was, however, the advent of satellite navigation which since the late 1970s not only simplified localization, but also rendered it much more accurate.[14]

As these systems, with GPS leading the way, became available for civilian use, they have been incorporated in a broad and ever-increasing spectrum of branches and services, including navigation, geodesy, or agriculture.[15] At it, both the quantity as well

12 Swamy 2017: 1169-1170.

13 Swamy 2017: 1169.

14 Royal Geographical Society 2011: 82-83.

15 Nawrocki 2019: 257.

as the quality of GNSS have increased considerably in recent years.[16] In fact, with the advent of the European Galileo and the Chinese BeiDou systems on the international stage, alongside renewed efforts to refurbish the older GPS and GLONASS, “the world of satellite navigation is undergoing dramatic changes”.[17] In a way, the strife for more precise and reliable satellite navigation has thus set in motion a footrace among several of the world’s great powers.

In fact, alongside availability, continuity, and integrity, accuracy accounts for one of the four major parameters to determine GNSS performance.[18] In this regard, accuracy has been succinctly defined by the 2008 US Federal Radionavigation Plan,

> “In navigation, the accuracy of an estimated or measured position of a craft (vehicle, aircraft, or vessel) at a given time is the degree of conformance of that position with the true position of the craft at that time. Since accuracy is a statistical measure of performance, a statement of navigation system accuracy is meaningless unless it includes a statement of the uncertainty in position that applies.”[19]

Starting from these premises, the following paragraph discusses and compares the accuracy of select leading GNSS today – especially, as is frequently the case, with respect to positioning.[20]

ACCURACY OF THE BIG FOUR: GPS, GLONASS, GALILEO, BEIDOU

Table 2.1 provides an overview of the four leading GNSS primarily considered by the study. Besides the respective operator, or owner, the table includes the number of (operational) satellites currently (and prospectively) in orbit, the orbital height of these satellites, as well as the best accuracy of positioning.

Table 2.1: Accuracy of the big four

System Category	GPS	GLONASS	Galileo	Beidou
Operator	United States of America	Russian Federation	European Union	People’s Republic of China
Number of Satellites	31 (operational)	24 (operational)	26 (32 by 2030)	15 (30 by 2020)
Orbital Height	20,180 km	19,130 km	23,222 km	21,150 km
Best Accuracy of Positioning	15 m (Vespucci Satellites: 0.5 m)	4.5 to 7.4 m	1 m (public) 0.01 m (encrypted)	10 m (public) 0.1 m (encrypted)

Source: CGS 2019, based on information taken from a comparable table in Nawrocki 2019: 258-259.

16 Galileo GNSS 2018.
17 Li et al. 2015: 608.
18 European Space Agency 2018d.
19 Department of Defense 2008: B-1.
20 European Space Agency 2018a.

Starting from the left column, the United States' GPS system can look back on the longest tradition of operation. The system was initially developed for the US Armed Forces but has been made available for commercial and public use in 1983.[21] Despite this long tradition, the year 2000 in particular marks a decisive turning point because only since that year did US authorities cease to deliberately deteriorate the GPS signal publicly available, resulting in what has been called "the GPS boom".[22] Respective channels of the 31 operational GPS satellites are presented in the table 2.2. As indicated by the grey shading, channels L1 und L2 are used primarily.

Table 2.2: GPS Chanels and their specifications

Channel Specification	L1	L2	L3	L4	L5
Carrier Frequency (in MHz)	1575.42	1227.60	1381.05	1379.913	1176.45
(Prospective) Usage	all users	authorized users	messages on nuclear detonation	tested for ionospheric correction services	prepared for sending safety-of-life (SoL) messages

Source: CGS 2019, table based on information and data from Nawrocki 2019: 259-260.

With respect to the first channel, the all-user L1 band, accuracy levels between 10 and 100 meters can be reached, while the reception of a combined L1-L2-signal improves the accuracy tenfold.[23] Accordingly, GPS services can be divided between the Standard Positioning Service (SPS), using L1, and the Precise Positioning Service (PPS), using a combination of L1- and L2-signals.[24] With today's applications demanding ever-increasing accuracy and with global competition increasing, the United States recently began to update its satellites by launching the so-called Vespucci (or GPS III) satellites in December 2018, promising accuracy levels of about 50 centimeters.[25] Indicating the immense importance attributed to the issue by the US government, the launch, subcontracted to SpaceX, was designated a matter of national security.[26] Besides the increased accuracy (expected to be about threefold), as Colonel Steven Whitney, director of the Global Positioning Systems Directorate, emphasized, the new generation of satellites also promises stronger signals, thus reducing the dangers of signals being jammed.[27]

Like its American counterpart, the Russian (formerly Soviet) GLONASS has its origins within the military: initiated in 1976, its first test satellite was launched in 1982, while the system did not become fully operational until 1996 on a global scale with 24 operational satellites in orbit.[28] Subsequently, however, the system increasingly fell into disrepair, only to be revived by the Russian government in 2005.[29] Signals are transmitted in

21 Nawrocki 2019: 259.
22 Lüthje 2019.
23 Nawrocki 2019: 260.
24 Vasile et al. 2018: 1; European Space Agency 2015.
25 Nawrocki 2019: 263.
26 Wall 2018.
27 Wall 2018.
28 Nawrocki 2019: 263.
29 Lüthje 2019.

the L1 (1602 MHz) and L2 (1246 MHz) channels, with a third band, L3 (1202 MHz) opened in 2011.[30] Again, comparable to SPS and PPS with respect to GPS, different levels of accuracy can be reached among authorized and unauthorized GLONASS users, "referred to as Channel of Standard Accuracy (CSA) and Channel of High Accuracy (CHA), respectively"[31] and Search & Rescue (SAR) services, as the following table 2.3 depicts.

Table 2.3: Accuracy levels of GLONASS

Application Category	Unauthorized Users	Authorized Users	Search & Rescue Services (SAR)
Horizontal position	30 m	5 m	5-7 m
Vertical Position	60 m		
Velocity	5 km/h		

Source: CGS 2019, based on information and data from Nawrocki 2019: 264.

As figures show, and as is confirmed by the Russian System for Differential Correction and Monitoring (SDCM), accuracy levels are somewhat lower than the ones reached by GPS.[32] However, after years of lagging behind at larger margins, due to poorer atomic clocks and other factors, recent modernizations have allowed GLONASS to catch up.[33] While the two systems hitherto dealt with are national endeavors, the Galileo system has been created by the European Union and the European Space Agency. Currently still in the build-up, its first two pairs of satellites were launched in October 2011 and October 2012.[34] Having conducted its first independent positioning in 2013, the system is expected to include a total of 30 operational satellites orbiting Earth at 23,616 km by 2020.[35] By that time, Galileo will provide four different services, as depicted in Illustration 2.1.

For these services, Galileo uses the three frequency bands E1 (1575.42 MHz, the same frequency as GPS' L1), E5 (1191.795 MHz), and E6 (1278.75 MHz).[36] In timing, accuracy levels of 30 ns are reached, to "be used for synchronization in finance branch, telecommunications, IT and other sectors of industry or business".[37] Particularly in HAS, due to dual frequency techniques, positioning accuracy at a decimeter level can be attained, with the capability of encrypting signals.[38] Besides these advantages in accuracy, of up to 0.01 m (encrypted), the Galileo system has some unique features which sets it apart from other (national) GNSS: First, its SAR in some cases allows to send feedback to emergency beacons, once their signals have been picked up and transmitted to rescue centers by Galileo satellites.[39] Second, Galileo is not only a multi-national but, in stark contrast to GPS, GLONASS, and BeiDou, also a distinct non-military, civilian

30 Vasile et al. 2018: 1.
31 European Space Agency 2018c.
32 European Space Agency 2018c.
33 European Space Agency 2018c.
34 Li et al. 2015: 609.
35 Nawrocki 2019: 265.
36 Vasile et al. 2018: 1.
37 Nawrocki 2019: 265.
38 European Space Agency 2019; Siejka 2018: 1-2.
39 Nawrocki 2019: 277.

project.[40] This aspect, besides its technological prowess in accuracy and signal strength, in particular provides a considerable advantage for Galileo in terms of trust, offering what has been called a potential "leap of faith"[41] for the European system.

Finally, the launch of BeiDou as an independent Chinese system has created considerable waves within the GNSS world. Initially restricted to the Asia-Pacific, the system was officially put into operation on December 27, 2012.[42] BeiDou, like Galileo, is still under development but meanwhile has gone global, using "three frequency bands – B1 (1561.098 MHz), B2 (1207.14 MHz) and B3 (1268.52 MHz) – offering two-level positioning services: one available to the general public and one for the military and government agencies".[43]

Illustration 2.1: The four Galileo Services

Open Service (OS)	"Galileo open and free of charge service set up for positioning and timing services."
High Accuracy Service (HAS)	"A service complementing the OS by providing an additional navigation signal and added-value services in a different frequency band. The HAS signal can be encrypted in order to control the access to the Galileo HAS services."
Public Regulated Service (PRS)	"Service restricted to government-authorised users, for sensitive applications that require a high level of service continuity."
Search and Rescue Service (SAR)	"Europe´s contribution to COMPAS-SARSAT, an international satellite-based search and rescue distress alert detection system."

Source: CGS 2019; all definitions taken from European Space Agency 2019.

Concerning the BeiDou system's accuracy, it "has been designed to reach accuracy levels similar to those of GPS and Galileo Open Service: positioning accuracy within 10 meters, timing accuracy within 50 ns and velocity accuracy within 0.2 meters per second".[44] The authorized service, with a position accuracy of up to 0.1 m, even provides levels of accuracy improved a hundredfold as compared to the open service.[45] With these specifications, BeiDou is set to rival or even outperform the accuracy of GPS[46] – while additional improvements in accuracy are planned through the establishment of further ground stations.[47] Furthermore, in what has been described by Chinese state media as a "period of unprecedentedly intensive launches," the number of operational satellites has been increased sharply in recent years.[48] In the wake of these constant expansions and improvements in BeiDou services, its chief designer, Yang Changfeng, left no doubts about Chinese ambitions, "China's BeiDou is the world's BeiDou, and the global satellite navigation market is certainly BeiDou's market".[49] As some observers have cautioned, however, the matter of trust in the consistent and reliable functionality of BeiDou, especially in contrast to the long-established GPS, remains an unanswered

40 Lüthje 2019; Siejka 2018: 15.
41 Lüthje 2019.
42 Chen et al. 2019: 14; Li et al. 2015: 607.
43 Vasile et al. 2018: 1.
44 European Space Agency 2018b.
45 Nawrocki 2019: 265.
46 Lüthje 2019.
47 Jakhar 2018.
48 Jakhar 2018.
49 Quoted in Jakhar 2018.

question among users.[50]

In total, the four systems considered here not only share their basic functions as well as the challenges posed to them with respect to attainable accuracy, they also share the existence of open/un-authorized and closed/authorized channels of operation.

Illustration 2.2: BeiDou - Services and Performance

Source: CGS 2019; all definitions taken from European Space Agency 2018b.

This distinction is crucial in determining respective levels of accuracy, since the authorized (and encrypted) channels of operation regularly provide much higher levels of accuracy than attainable to every-day private or commercial users. (The same holds true for Japan's QZSS and India's NAVIC/IRNSS, both of which reach accuracy levels of 10 m for the public and 0.1 m for the authorized varieties.) Therefore, while GPS has long been considered the gold standard among GNSS in terms of coverage and accuracy, the recent push for independent and high-performance GNSS among other competitors has opened up new levels of accuracy, with BeiDou and especially Galileo – at least once the two system are fully operational – promising impressive performances, in the case of Galileo of up to 0.01 m.

3. LEADERSHIP IN SMARTPHONE APPLICATION OF GNSS

In this chapter, we take a closer look at the application of GNSS among the world's leading smartphone vendors. In the civilian life of most people around the world, the application of navigation or positioning software on their smartphones is the main point of contact with GNSS so that questions about the reliability and accuracy of positioning apps are at the center of attention of smartphone vendors. First, it needs to be asked to what degree current smartphone models support the four major GNSS. The combination of different positioning satellite systems accelerates the positioning process and increases the accuracy of position determination.[51] A wider range of GNSS support could also

50 Jakhar 2018.

51 Szot et al. 2019: 3.

possibly protect the user against possible failures (or even deliberate shutdowns), as the smartphones can use the satellites of another system. Although seemingly unlikely, an almost seven-day interruption of Galileo services in July 2019 exposed the real possibility of such an event. While the interruption of services was hardly felt by most navigation users as the other systems compensated for the failure, a loss of confidence in the system's reliability has been widely discussed.[52] The level of compatibility between the satellite systems can thus be differentiated by the degree of smartphone support per vendor. The technical data of four of the latest smartphones on sale is the basis of this comparison. That data may differ from the real-life combination of satellite positioning due to the technical parameters of the satellite systems, satellite geometry, chip performance, and other reasons.[53] The vendor degree of GNSS compatibility may also vary by selecting a different set of smartphone models, which may be useful for future and past comparisons of smartphone support.

For reasons of feasibility, ten of the biggest vendors by global market share have been selected for comparison. Samsung, Huawei and Apple, the world's top three leading smartphone vendors, together hold a global market share of 46 percent in 2019, according to TrendForce.[54] While the market shares of Samsung and Apple faced an overall decline over the last years, market shares from its Chinese competitors Huawei, Xiaomi, Oppo and Vivo have made remarkable gains. With a worldwide market share of 16 percent in 2019, frontrunner Huawei has more than doubled its global market share since 2013 by expanding overseas.[55] Behind the leading pack, LG and Lenovo (including Motorola) each presented a market share of three percent at the end of 2018. They are not very closely followed by Nokia and Alcatel (around 1 percent).[56] Other smartphone producers such as Tecno or ZTE are also on the rise but are not included in the GNSS comparison of this paper. By checking the GNSS support of the four of the latest smartphone models, a high score of 16 can be reached marking full support of all systems in contrast to the zero point, with no support at all. The technical data about the GNSS support is largely based on vendor information, checked and complemented by Kimovil.com.
We find that out of our list, only Samsung and Xiaomi reach the high score of full GNSS support, followed by Huawei and Oppo, each with a score of 14. While Huawei's premium smartphones show a perfect GNSS support, its middle-class P Smart Z-model does neither support BeiDou nor Galileo on paper. Oppo, on the other hand, lacks the two points for Galileo application but fully supports BeiDou. GPS and GLONASS. Listed below are Vivo, LG, and Lenovo, each presenting a score of 13. All of them have the greatest deficiency in Galileo, while the Vivo Z1 Pro and the Lenovo K9 Note also do not support BeiDou according to their technical description. With a GNSS support score of 12, Apple and Nokia are seemingly lagging behind the technical standards of the others, whereas Alcatel only scored a poor six points for GNSS support. Neither Apple nor Alcatel support the BeiDou system at all, which is rather surprising for the latter due to its Chinese license holder TCL Corporation. Regarding Apple, the exclusion of BeiDou is consistent with the past, as older models also lacked the support. Still, the decision recurrently sparks discussions whether BeiDou is excluded due to technical immaturity or for political reasons in the era of US-Chinese power competition.[57]

52 Seidler 2019.
53 The complete list can be found in the appendix of this study.
54 TrendForce 2019.
55 TrendForce 2019.
56 Gadgets Now Bureau 2019.
57 Cong 2019.

Alcatel, however, only scored full points for GPS support, thus shows deficiencies for GLONASS and Galileo support as well. Nokia, by contrast, reached full points for GPS, GLONASS and BeiDou, hence only completely lacking Galileo support in the technical descriptions of its smartphones models Nokia 9 Pure View, X71, 3.2, and the 4.2. While Nokia has already listed eight smartphones on the webpage UseGalileo.eu, among them the entry-level smartphone Nokia 3.1 Plus of 2018, its future support remains to be seen.

Illustration 3.1: GNSS Support Score of the Ten Biggest Vendors

Source: CGS 2019

Taking together all results, the global GNSS leader GPS scores perfectly with a 100 percent support of all smartphones under review. GLONASS reaches a score of 92.5 percent mainly due to the lacking support of Alcatel. BeiDou ranks third with 72.5 percent, which is especially due to the lack of support from Apple and Alcatel, but also to some missing points among Chinese vendors. With a score of 57.5 percent, Galileo ranks last among the GNSS' smartphone support, presenting a mixed picture. Samsung, Apple, and Xiaomi are the only three companies among the ten selected that present all of the selected smartphones with Galileo compatibility. With the exception of Nokia, all other companies present mixed records of Galileo support. Concerning Nokia's Finnish origin, this result seems rather unexpected, but may also be the result of a selection error as eight older models are listed on the UseGalileo.eu website. However, comparing these results of Galileo support with its official website by the European Global Navigation Satellite Systems Agency (GSA), the website seems currently to underestimate the system's potential. It only counts 156 smartphone and tablet models of 28 different brands (last updated 27/08/2019). Among them, the leading vendors are also found in the pole positions: Samsung presents 24 models, Huawei 17 and Apple 14 in the ready for Galileo list.[58] Around 95 percent of all chipsets marketed today can theoretically process Galileo-signals, indicating a practical application gap of the European GNSS which may be closed in the near future.[59] In view of the fact that Galileo has only been available for trial operation since 2016, these results represent an optimistic development in contrast to the bad publicity related to the July 2019 service interruption.

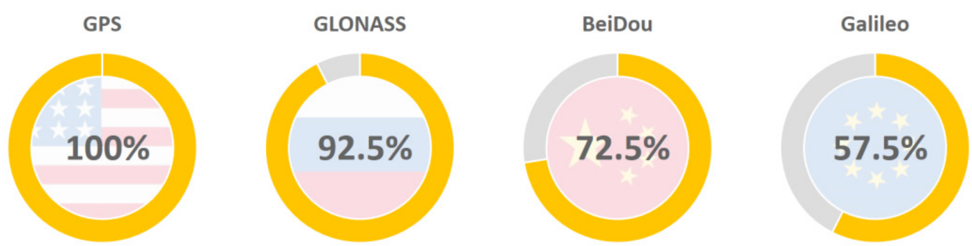
58 European Global Navigation Satellite Systems Agency 2019.

59 Inside digital, inside digital 2018.

The geopolitical competition in the domain of GNSS has quite advantageous effects for the civilian smartphone user that is mainly interested in sharing his or her position with friends, checking nearby locations or using navigation apps in everyday life. Greater accuracy, higher reliability as well as greater prevention of failures are also key to the advancement of the Internet of Things (IoT) economy of today and tomorrow, allowing, for instance, intelligent transportation. Despite the presented achievements in greater GNSS support, as we have shown, qualitative assessments of positioning accuracy by portable mobile devices still pose major challenges that need to be tackled.[60] Nevertheless, these devices already reach good positioning results even without fee-based high accuracy services and sufficient for most normal users.[61] Future studies in this field may thus concentrate on the extension of GNSS smartphone support with the evolving Japanese QZSS or the Indian NavIC systems, the field validation of technical and practical GNSS use, or comparative measures of smartphone positioning accuracy regarding combined GNSS application.

The market introduction of the first dual-frequency smartphone, the Xiaomi Mi 8, in 2018 revealed a new trend of GNSS receivers in consumer devices which is also an interesting area for future research. The Galileo website already lists 10 compatible dual-frequency

Illustration 3.2: GNSS Smartphone Compatibility in Comparison



Source: CGS 2019

models – all of them are produced by Chinese smartphone manufacturers (Xiaomi, Huawei, OnePlus, Oppo), underlining China's trendsetting position and innovative competitiveness. Broadcom launched the first dual-frequency chipset (BCM47755) only in September 2017, specifically aiming at the smartphone market. Other producers have followed this trend, promising great potential for higher accuracy and robustness particularly for consumers in cities facing positioning problems such as urban canyons. It is also noteworthy that Galileo plays a critical role in the implementation of dual-frequency positioning because it is said to provide a crucial amount of signals needed according to the GNSS User Technology Report.[62] Concerning these current trends in the smartphone and chip market, as well as the changing GNSS constellations due to the evolving systems, the field offers vast opportunities for research, which often seem to be neglected by the public.

60 Szot et al. 2019 : 1.
61 Dabove et al. 2019.
62 European Global Navigation Satellite Systems Agency 2019: 32-34.

4. LEADERSHIP IN RECIPROCAL COMPATIBILITY

Compatibility is defined by the ICG Forum as: "refer[ring] to the ability of global and regional navigation satellite systems and augmentations to be used separately or together without causing unacceptable interference and/or other harm to an individual system and/or service".[63] The issue of compatibility relates not only to the simultaneous operation of two systems aimed to provide the same service, but also impacts systems providing different services (navigation, communication, positioning, timing, etc.).[64]

Apart from the compatibility, interoperability is also important for GNSS. According to the ICG, interoperability refers to "the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system".[65] Achieving interoperability can promote better sharing of information and resources among multiple systems. The improvement of the interoperability of different systems helps to provide better services for global users. Moreover, they can use multiple satellite signals at the same time without significantly increasing any costs. Meanwhile, the accuracy and reliability of navigation will be further improved with more compatible satellite systems.

The compatibility and interoperability of GNSSs are intertwined and inseparable. Compatibility serves as a prerequisite for interoperability. Interoperability necessarily implies compatibility. These two capabilities of GNSS are certainly key to the wide acceptance of the systems by the user.[66] In the following part, the compatibility and interoperability of different GNSSs are introduced.

On the technical level, the compatibility can be improved by the selection of radio frequency and spectral separation between each system's authorized service signals and other systems.[67] In reality, some signal overlap may be inevitable. Therefore, discussions and consultations among providers play an important role to ensure compatibility.

Generally, there are four main factors that affect the compatibility and interoperability between two or more systems: constellation layout, signal-in-space, geodetic coordinate reference system, and time reference system.[68] The assessment of the compatibility and interoperability of GNSSs was guided mainly by these considerations: signal-in-space, geodetic coordinate reference system, and time reference system. The overall parameters of compatibility and interoperability of GNSSs – GPS, GLONASS, Galileo and BeiDou - are shown in the table 4.1.

STATUS QUO OF DESIGN FOR THE COMPATIBILITY AND INTEROPERABILITY OF GPS

In the matter of signal-in-space, two frequencies were utilized in the original GPS

63 ESA 2011a.
64 Detoma, Lisi 2012: 663.
65 ESA 2011b.
66 Detoma, Lisi 2012: 663.
67 Bartolomé et al. 2015: 31.
68 Wang(王垚), Luo (罗显志) 2014.

design, namely L1 (1575.42 MHz) and L2 (1227.60 MHz). Two new civil signals, an L2 civil (L2C) signal and a signal at 1176.45 MHz referred to as L5, which belongs to GPS satellite modernization, were operated. Except of L5, a fourth civilian GPS signal, L1C, will be backward compatible with L1 and will provide greater civilian interoperability with Galileo.[69] A new military signal, M code, will also be added to L1 and L2.[70] The M code is designed exclusively for military use and its primary benefits to improve "security plus spectral isolation from the civil signals to permit noninterfering higher power M code modes that support antijam resistance".[71]

Table 4.1: Compatibility and Interoperability of GNSSs

GNSS	Center Frequency	Coordinate Reference System	Time Reference Frame
GPS	L1, L2, L5	WGS84	GPST
GLONASS	L1, L2, L3	PZ-90	UTC-SU
Galileo	E1, E5, E6	GTRF	GST
BeiDou	B1, B2, B3	CGS2000	BDT

Source: CGS 2019

Coordinate is an important parameter to express the ground position. In the aspect of coordinate reference, the GPS uses the World Geodetic System (WGS84) as its reference coordinate system.[72] Referring to the time system, GPS uses a time reference frame called GPS Time (GPST), which is referenced to "the Universal Coordinated Time (UTC) and is in synchronous with the UTC maintained by the US Naval Observatory (USNO) at 0:00 on January 6, 1980".[73]

STATUS QUO OF DESIGN FOR THE COMPATIBILITY AND INTEROPERABILITY OF GLONASS

Like GPS, GLONASS is a global system with dual use and free of charge. Each GLONASS satellite transmits on two different L1 (1598.0625 – 1609.3125 MHz) and L2 (1242.9375 – 1251.6875 MHz) frequencies. Additionally, in order to interoperate with other GNS systems, GLONASS owns introduced code division multiple access (CDMA) signals as well. Traditionally, GLONASS uses a frequency division multiple access (FDMA) which is distinct of the CDMA of GPS.[74] The first CDMA signal of GLONASS, designated L3 (centered at 1202.025 MHz), aims to ease interoperability with GPS and Galileo.[75]

Since 1993, GLONASS has used the parameters of the Earth 1990 System (PZ-90) as its reference coordinate system. PZ-90 is an Earth-Centered Earth-Fixed (ECEF) terrestrial

69 Hexagon.
70 Kaplan 2017: 145.
71 Kaplan 2017: 148-150.
72 GIS Geography 2018.
73 Ning et al. 2009: 361.
74 Chen 2013: 8.
75 Hexagon.

frame. Despite the difference between the two employed geodetic reference systems (WGS 84 for GPS and PZ-90 for GLONASS), their parameters can be transformed to adequately combine both systems which could lead to a significant improvement in accuracy and reliability of satellite measurements.[76]
GLONASS uses the Universal Coordinate Time, Soviet Union Standard (UTC-SU), as its reference time frame.[77] Unlike GPS, in which the parameters transforming GPS Time to UTC-USNO are broadcast in the signals, GLONASS directly broadcasts the difference of GLONASS and UTC-SU in its navigation message.[78] As a result, the system time difference between GPS and GLONASS increases the difficulty of compatibility between the two systems.

The Galileo timescale is called Galileo System Time (GST) and can be seen as the equivalent of the GPS Time (GPST) scale used in the Global Positioning System. For GPS/Galileo interoperability, the two systems are designed to "transmit within their navigation messages the so-called GPS to Galileo Time Offset (GGTO)".[79]

STATUS QUO OF DESIGN FOR THE COMPATIBILITY AND INTEROPERABILITY OF GALILEO

Unlike GPS and GLONASS, Galileo is currently being developed to provide a highly accurate and guaranteed global positioning service under civilian control. Galileo shall be an autonomous civil system, independent but compatible and interoperable with other existing GNSSs, especially GPS.[80] In order to increase the accuracy and reliability of future navigation services, Galileo makes efforts to be interoperable and fully compatible for integrating with other systems.[81]

The Galileo navigation signals are transmitted in three frequency bands, E1 (1575.42 MHz), E5a/b and E6 (1278.75 MHz). The Galileo E5a/b band is located in the lower L-band. The E5a frequency is centered at 1176.45 MHz, which has the same center frequency as GPS L5. The E5b frequency is centered at 1207.14 MHz. Both signals own a bandwidth of 20.46 MHz, which makes the Galileo E5 the most wide-ranging signal in the GNSS spectrum.[82]
All Galileo products and services base on the highly precise and stable Galileo Terrestrial Reference Frame (GTRF), which shall be compatible with the latest International Terrestrial Reference Frame (ITRF) within a precision level of 3 cm (2 sigma).[83] The error between WGS-84 and GTRF is expected to be a few centimeters, which means that both can realize the same accuracy. The coordinate reference standard between GPS and Galileo are compatible with each other.

76 Rossbach 1996.
77 Keong, Lachapelle 2000: 2.
78 Keong, Lachapelle 2000: 3.
79 Píriz et al. 2006.
80 Crescimbeni 2003: 103.
81 Chen 2013: 9.
82 Vuckovic, Stanic 2014: 51.
83 Gendt et al. 2011: 174.

STATUS QUO OF DESIGN FOR THE COMPATIBILITY AND INTEROPERABILITY OF BEIDOU

The Chinese government aims to complete the last step of the "three-step" strategy of the BDS , providing global coverage by the end of 2020. The successful launch of five new-generation experimental satellites of BeiDou, namely BeiDou I1-S, I2-S, M1-S, M2-S and M3-S, indicates a significant step for BeiDou in becoming a navigation system with global coverage.[84] The development of the BeiDou satellite navigation follows the 4 principles of openness, autonomy, compatibility and gradual progress.

The BeiDou signals, based on CDMA technology, include B1 (1561.098 MHz), B2 (1207.140 MHz) and B3 (1268.520 MHz). The new-generation BeiDou-3 signals are comparable to those of GPS L1/L2/L5 and Galileo E1/E5a/E5b signals. In order to achieve compatibility, BeiDou selects frequencies that do not overlap with other GNSSs. In practice, however, the corresponding frequency bands of BeiDou system overlap with those of Galileo. In addition, when the BeiDou receiver receives the desired signal, it will often be intervened by the other signals resulting in performance degradation.

BeiDou adopts the BeiDou Coordinate System (BSCS) which is in accordance with the specifications of the International Earth Rotation and Reference System Service (IERS). It is compatible with the definition of the China Geodetic Coordinate System 2000 (CGCS2000), as both are having the same ellipsoid parameters.[85] This design contributes to the compatibility of BeiDou with other GNSSs.

Concerning to the time reference, BeiDou adopts the BeiDou Navigation Satellite System Time (BDT). BDT takes "the international system of units (SI) second as the base unit, and accumulates continuously without leap seconds".[86] BDT started with 00:00:00 on January 1, 2006 of Coordinated Universal Time (UTC), which helps compatibly between BeiDou and GLONASS.

ENSURING COMPATIBILITY AND ACHIEVING INTEROPERABILITY THROUGH COOPERATION

International cooperation

In order to ensure greater compatibility, interoperability, and transparency among providers of global navigation satellite systems (GNSS), the International Committee on Global Navigation Satellite Systems (ICG) was established in 2005 as an informal body of the United Nations.[87] Three categories of participants can be found in the ICG: Members, Associate Members and Observers. Among the participants, China, the EU, the Russian Federation and the United States of America are current and future core system providers.[88] ICG provides the GNSS providers, international organizations and international entities a platform to discuss and coordinate the promotion of GNSS services and applications under governmental authority. The GNSS Providers focus on the issues

84 Zhang et al. 2017: 1225.
85 China Satellite Navigation Office 2018: 2.
86 China Satellite Navigation Office 2018: 3.
87 United Nations.
88 United Nations.

of compatibility and interoperability, encourage development of complimentary systems and exchange detailed information on systems and service provision plans. They have already agreed on the fact that all GNSS signals/services shall be compatible and that open signals/services shall be interoperable to the maximum possible extent.

Bilateral cooperation

GPS and Galileo

The European Galileo system was designed to be interoperable with the existing GPS and GLONASS systems with its Open Service (OS) constructed for mass-market applications.[89] The USA and EU have been cooperating since 2004 to ensure that GPS and Galileo are compatible and interoperable at the user level for the benefit of global civil users. With respect to the application of the interoperability principle, the frequency bands and central frequencies of L1/E1 and L5/E5a are common for both Galileo and GPS. The military GPS-M code and the Galileo Public Regulated Service (PRS) show signal interoperability on the L1 band.[90] Therefore, GNSS receivers can seamlessly combine GPS and Galileo signals in their positioning and timing applications.[91] Although Galileo and GPS have different coordinate reference frames, GTRF and WGS84 differ less than a very few centimeters with respect to the ITRF. This means that the interoperability between GPS and Galileo is guaranteed for most applications.[92]

GPS and GLONASS

The US and Russia initiated their cooperation in December 2004, with the primary goal of enabling civil interoperability at the user level between their systems - GPS and GLONASS.[93] One of the working groups focuses on the radio frequency compatibility and interoperability for enhanced positioning, navigation and timing. Another one strives for the technical interoperability between the search-and-rescue capabilities planned for GPS and GLONASS. In spite of the difference in the coordinate and time reference system between GPS and GLONASS, it is clear the technical advantage of coordination between the two systems. Nevertheless, the cooperation between the US and Russia in this sector has been, due to the Ukraine crisis since 2014, freezed.

GPS and BeiDou

The US and China concluded technical coordination discussions in 2010 on radio frequency compatibility between BeiDou and GPS.[94] In May 2014, the USA and China jointly established the US-China Civil GNSS Cooperation Dialogue to promote cooperation between the GPS and the Chinese BDS.[95] By means of this bilateral government-to-government collaboration, the two countries reached two main consensuses regarding to compatibility and interoperability between GPS and BDS at the end of 2017. Firstly, the two systems are radio frequency compatible under the framework of the International Telecommunication Union. Secondly, through using two different types of multiplexed binary offset carrier (MBOC) waveforms, the GPS L1C and BDS B1C are interoperable. The Joint Statement, however, shows that the consultations and cooperation between the

89 Vuckovic, Stanic 2014: 49.
90 Bartolomé et al. 2015: 32.
91 Vuckovic, Stanic 2014: 49.
92 Bartolomé et al. 2015: 32.
93 GPS.GOV.
94 GPS.GOV.
95 GPS.GOV.

two systems is limited to the civil signal. Their military applications still maintain their independence.

GLONASS and BeiDou

To both systems, GLONASS and BDS, GPS appears as a competitor, whose monopoly shall be broken up. Considering the close diplomatic relations and adjacency of China and Russia, the two governments promote the compatibility between their systems. From a technical point of view, the two navigation systems complement each other. In May 2015, China and Russia signed a joint statement of the compatibility and interoperability cooperation for BeiDou and GLONASS, strengthening bilateral cooperation of satellite navigation.[96] At the end of 2016, they then achieved a considerable progress in the field of cooperation on the harmonization and synchronization of the GLONASS and BeiDou systems. Lately, in July 2019, Russia passed law that sets forth cooperation between Russia and China on using GLONASS and BeiDou for peaceful purposes.[97]

Galileo and BeiDou

The Galileo satellites transmit an E5b signal at 1207.14 MHz that is identical to the BeiDou B2 signal. The frequency belongs to non-renewable resources and not all the frequencies can be used. The navigation satellite frequencies allocated by the ITU are limited. When the Galileo system suffered from an unexpected signal outage on July 11, some analysts concluded that the breakdown of Galileo could bring opportunities to China's navigation satellites, which could then serve European clients.[98] With the development of Galileo and BeiDou, the two systems must strengthen their coordination with each other.

GLONASS and Galileo

In order to achieve compatibility between GLONASS and Galileo, the designs of the receivers are simplified. The Galileo E5b signals overlap with GLONASS L3 signals. Other than the full compatibility between GPS and Galileo, Galileo is only partly compatible with GLONASS. Both systems show big differences in Signals-in-space, coordinate reference frame and time reference, which make reciprocal compatibility difficult.

LEADERSHIP IN COMPATIBILITY AND INTEROPERABILITY AND ITS DEVELOPMENT TREND

This analysis contributes to finding the leadership in terms of compatibility and interoperability of GNSS. The GPS is far ahead in the development of navigation satellite systems. Not only its technical advantage but also its system deployment make GPS attractive for the global market. The development of GPS in terms of compatibility and interoperability is central for the whole industry of GNSS. The National Space Policy of 2010 encourages international cooperation related to GPS and the other GNSSs. GPS takes full advantage of the cooperation with other countries and international organizations to promote its compatibility and interoperability. GLONASS itself owns

96 Inside GNSS 2017.

97 Cozzens 2019.

98 Yan 2019.

strong anti-interference capability which certainly guarantees its compatibility. In the respect of compatibility, GLONASS is under construction. Depending on the close cooperation with GPS, the civil navigation satellite system Galileo owns technical advantages but faces financial difficulties. The relatively new BeiDou strives to promote its compatibility and interoperability with the other systems. However, its development is confronted with an amount of challenges such as the undeveloped coverage of the civil market and the system deployment, especially regarding limited signal bands.

From the development tendency of GNSSs, interference between civil L-Band signals is inevitable. In the future, the interference of the inter- and intra-systems will further intensify with the increased number of navigation systems and service types. Satellite navigation system as an important space infrastructure can bring huge social and economic benefits. In the case that the satellite positioning system of one country is attacked by another country, the topic becomes a national security issue. The present compatibility and interoperability of different GNSSs have different levels of development. The dual military/civil systems GPS and GLONASS have already been in existence for a long time compared to the BeiDou and Galileo, which are currently being explored and developed. The design and development level of navigation satellites determines the performance of the system, including its compatibility and interoperability.

Even if technical solutions can mitigate the interference and the problem that different systems interfere with each other, coordination and cooperation are the main ways to promote compatibility between different systems. Nevertheless, there is still competition between the states, although a win-win situation for all systems has been proposed. The high compatibility and interoperability mean that users will enjoy better service from navigation apps supported by more than 100 satellites.

Satellite navigation systems with better compatibility and interoperability will also be more popular in the global civil market and have stronger competitiveness. The reason for that is, that the interoperability can significantly improve the function on navigation, positioning and timing. During this process, both, receiver manufacturers and users, are beneficial owners. Therefore, all of the providers of GNSSs take compatibility and interoperability as a basic principle of the development strategies for their Navigation Satellite Systems. In the case of a political or military crisis, given the fact that the two systems are autonomous before being made interoperable, a necessary satellite technology can transmit the two systems from an interoperable condition to a stand-alone operation.[99]

5. LEADERSHIP IN RELIABILITY AND RESILIENCE

As a quality of any infrastructure, especially of one as crucial as GNSS, reliability stands out if it is about the decision for one or another provider. And when it comes to reliability, the resilience to external disruptions of the system in terms of functionality and availability is a major point. This applies to both the military and civil dimension:

99 Detoma, Lisi 2012: 665.

cutting off an enemy's armed forces from satellite navigation during military operations could level the power balance between highly advanced battlefield forces that heavily rely on modern communication and navigation and guerilla or less modernized armies. As for the civil dimension, airplanes and cargo ships could struggle to find safe passages or even their destinations. Since 80 percent of global trade is carried out by sea, the financial fallout would be enormous.[100] For example, a single day without functioning GNSS services would cost the United Kingdom circa £1 billion.[101] And as a wide range of different examples of actual or potential breakdowns of GNSS services over the last decade made very clear; the question of resilience of the satellite navigation is not a hypothetical one for both, the military and the civil dimensions.

At first glance, jamming seems to pose a major threat to the use of satellite navigation of the user, since it is an effective and simple way to disrupt GNSS signals. In a nutshell, jammers produce "noise" – junk signals that overload the receiving devices, preventing the latter from detecting the real signal that is drowned by the noise. Due to the extreme distance of the satellite (20.000 km above the sea level and further) from the receiver on the ground the GNSS signal is relative weak[102] and easy to overlay. For example in 2017 the airport of Nantes experienced repeated failures of its tracking systems, assisting arriving and taking off planes. The reason was a small and simple GPS jammer connected to a cigarette lighter socket in a nearby parked car.[103] Such devices are illegal, but easy to obtain at relative low cost.

Other than private persons, states are able to jam GNSS signals on a much bigger scale, since they operate much more powerful devices (the louder the junk signals and the more frequencies covered, the better the scope), which can include dangerous side effects for commercial users, too. For example, North Korean military repeatedly disturbed air traffic over the Korean peninsula with loss of GPS signals by operating jammers along the Demilitarized Zone.[104]

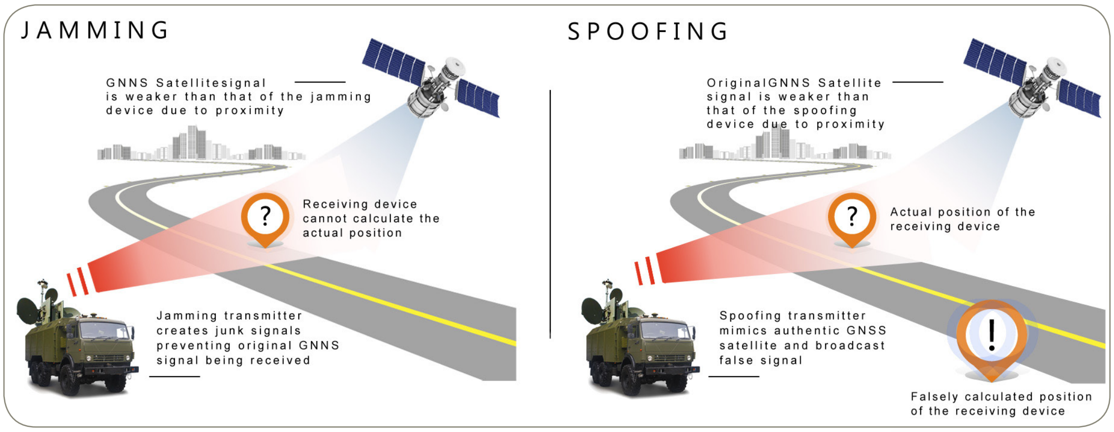
Especially the Russian Federation demonstrated recently on several occasions its electronic warfare abilities in suppressing satellite communication and radar. Not only during Russian military drill "Zapad" in 2017 but also during NATO-led "Trident Juncture" maneuvers in 2018 the GPS signals were scrambled, supposedly by the Russian side, leading the heads of defense and civil aviation in Finland and Norway to speak out a warning about a "…serious risk to both military and commercial aircraft using the affected airspace in the High North".[105] In eastern Ukraine and Syria the US troops were even forced to admit Moscow's superiority in terms of electronic warfare equipment – e.g. Krasukha-4, which jams radar and aircraft – leaving US troops "scrambling to catch up".[106] Of course the US military also trains on a regular basis to deny or degrade GNSS signals.[107]

Along with jamming, spoofing is another option to disrupt navigation. Spoofing devices deceive the receiving site by simulating and drown out true GNSS signals and providing wrong positions and are hence more treacherous, with the potential to manipulate actors' decisions by implying false positioning and timing.[108] Although spoofing equipment

100 Braw 2018.
101 Dunning 2018.
102 Braw 2018.
103 Resilient Navigation and Timing Foundation 2017.
104 Ricks 2016.
105 O'Dwyer 2018.
106 McLeary 2015.
107 Cenciotti 2019.
108 Bowman 2018.

prices also went down (from about $10,000 a few years ago to $350 today)[109] and even drug traffickers on the US-Mexican border were using it recently,[110] the use of this technique is easy only on unencrypted GNSS signals. The picture is different if it is deployed against encrypted military GNS systems such as the GPS' P(Y) and M-code, Galileo's Public Regulated Service (PRS) and P-code of GLONASS[111], which usually cannot be spoofed without the encryption key.[112] It is Moscow again, which proved its advances in this area, using spoofing for military operations and as a strategy for protection of VIPs and important facilities.[113] Because spoofing also affects a wider area, its use bears side effects, like "placing" a ship's navigation systems about 125 miles away from its actual place during a nearby visit of Putin and Medvedev at the new build "Crimea Bridge". According to researchers at C4ADS, between 2016 and 2018 the Russian side was accountable for at least 9,883 spoofing instances while affecting 1,311 ships.[114]

Illustration 5.1: Jamming and Spoofing of GNSS' Signals



Source: CGS 2019

To avoid these problems and increase the reliability of GNSS, countermeasures can be taken on both sites of the signal, the receiver and the transmitter. As for the latter, jamming can be addressed by a stronger signal, which would make it harder to silence the original input. The gradual upgrade of already long operating GNS Systems brings stronger broadcasting devices into use alongside with newer satellites of Galileo and BeiDou. However, it is barely possible to rise the transmitting power in significant ways without an increase in the mass of the satellites and hence the cost. On the other hand, combined with frequency-hopping and frequency-spreading additional security can be achieved, due to extreme requirements in terms of power for a wide frequency band jamming.[115]

As for today, the measurement of transmitter strength for the four global systems reveals that the modern units of the GPS-system provide (in 2017) the strongest signals (up to 240W) alongside with Galileo (up to 265W). While BeiDou, which is still under construction and only limitedly viable outside of China, reached the signal power of

109 Groll 2019.

110 Tucker 2015.

111 Inside GNSS 2009.

112 However, these communication channels can be "…vulnerable to another form of spoofing known as meaconing (masked beaconing). This technique uses a signal repeater to capture and rebroadcast genuine signals with a time offset. In practice, this effect is challenging to produce against advanced receivers with inbuilt signal integrity checks." (Bowman 2018.)

113 Groll 2019.

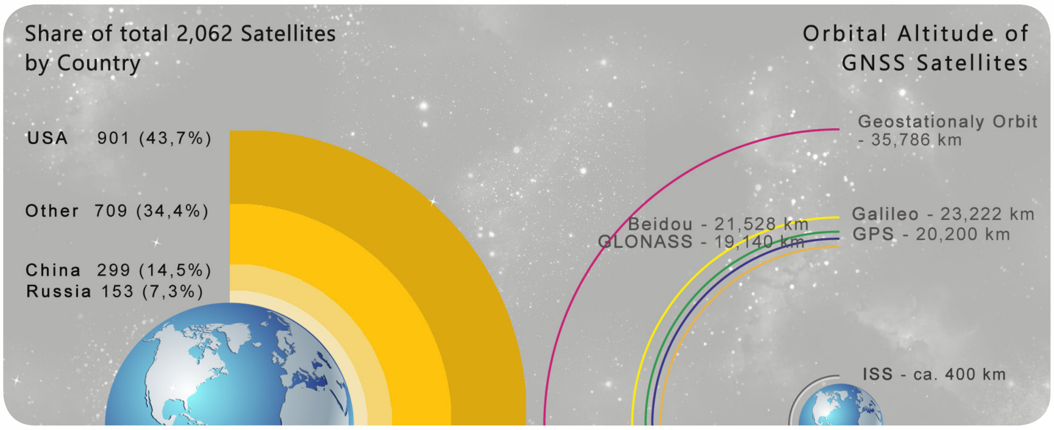
114 C4ADS 2019: 15.

115 Bowman 2018.

185W, the Russian GLONASS, mostly operating with older satellites, was the weakest of the four (135W).[116] While Moscow had to delay the rollout of the newest generation of GLONASS-K units due to the embargo of crucial high tech parts[117], Washington is about to upgrade its system further with GPS III satellites. The latter "will have a stronger military signal that's harder to jam".[118] Accordingly, the gap between the signals' strength will rise for the next years at least.

As a countermeasure for spoofing, all of the four GNS systems possess encrypted signal channels, mostly limited to military (except Galileo) use. Hence these channels are not available for the regular commercial use. The resilience could be improved further by implementing encryption to all transmitted channels and/or by "altering the GNSS signals themselves to include authentication checks with each message, thus validating the sender".[119] But this would also require significant software updates for the satellites and for the receiving devices.

Illustration 5.2: Share of Satellites and Orbital Altitude of GNSS



Source: CGS 2019, based on Union of Concerned Scientists Satellite Database

Additional to jamming and spoofing, electronic warfare can pose a danger to GNSS by compromising it via hacking. As the security research by Symantec made public in 2018, a group of hackers located in China were conducting espionage against "satellite operators, telecommunication companies and defense contractors in the US and Southeast Asia" and infecting computers controlling satellites.[120] The scope of the operation allows the assumption that those groups' "motives go beyond spying and may also include disruption."[121]

Besides the electronic warfare, physical destruction of the GNSS infrastructure is also a growing threat. When Prime Minister Narendra Modi announced a successful shoot down of a satellite in 2019, India became the fourth nation after the USA, Russia and China with proved capabilities to destroy orbital infrastructure.[122] However, while the targeted Indian satellite was orbiting only at 300km[123], the GNSS satellites operate usually between circa 20,000km (MEO) and ca 35,000km (geostationary orbits). Such attitudes pose a much bigger challenge for a kinetic attack. Nevertheless, Washington and

116 Steigenberger, Thoelert, Montenbruck 2017: 9.
117 Tkachev (Ткачёв), Slopov (Солопов) 2019.
118 Elliott 2018.
119 Bowman 2018.
120 Musil 2018.
121 Symantec 2018.
122 Gettleman, Kumar 2019.
123 Smith 2019.

Moscow[124] were already in possession of weapons able of anti-satellite (ASAT) warfare, missiles as well as co-orbital[125] tools during the cold war and are now working on newer and advanced systems. China, too, is supposedly working on co-orbital weapons, while it tested a missile able to reach MEO in 2013.[126] Especially after this test officials from the US army remarked on several occasions that the GPS system will be one of the primary targets of Washington's space opponents, referring to People's Liberation Army reports stressing the importance of destroying enemy's communications satellites.[127] It can also be assumed that Washington would target Russian and Chinese GNSS' as well in a case of conflict.

Although not all experts agree on the possibility and reasonability of an ASAT attack for now[128], in order to lower the risks in the near future a high demand for countermeasures arises. Besides possible on-orbit defense systems, making "the GPS constellation part of a far broader plan that will likely include modular satellites with common interfaces and reprogrammable payloads as well as on-orbit system defense capabilities […] integrating space activities across American and allied programs, across US civil and military agencies and across government and commercial satellites"[129] is considered.[130] Here, the American position seems to be most advanced for now, since the country operates over 40% of a total of almost 2000 satellites totally in earth's orbit.[131]

However, since there is no absolute reliability of GNSS, in a search for alternatives a quantum accelerometer, a stand-alone device that allows navigation without any outside signal or support, was recently presented by British researchers.[132] However, it is not likely to be suitable for civil use anytime soon due to the size and the cost of the device. Hence, navigation without GPS may be needed to be reintroduced, like at the US Naval Academy, where a celestial navigation course is back on the syllabus after a hiatus of ten years.[133]

CONCLUSION

To answer the question of which power leads the international competition for the global navigation satellite system, this study examined and compared five aspects that contribute significantly to the quality of GNSS: geospatial coverage, accuracy of positioning, smartphone application of GNSS, mutual compatibility, and also reliability and resilience.

Being the oldest system in the orbit, the US' GPS is with regard to the most former aspect still ahead of its competitors. Due to being most widely used, having full global

124 Harrison et al. 2019: 20ff.

125 Other than the direct-ascent missiles, co-orbital weapons are placed into the same or close orbit as the potential target and will be maneuvered to strike its target when needed. Hence, such ASAT satellites may remain inactive and undetected for longer periods in orbit before being activated. - Harrison et al. 2019: 10-13.

126 Harrison et al. 2019: 10-13.

127 Divis 2019.

128 Shankaran 2014: 26ff.

129 Divis 2019.

130 Accordingly the establishment of space warfare service branches, e.g. Russian Aerospace Forces (reestablished 2015) or now proposed United States Space Force and French Space Force.

131 RFE/RL's Infographics 2019.

132 Dunning 2018.

133 Bowman 2018.

operationality and providing slightly better coverage than the other systems. GPS is just in the lead in geospatial coverage. Neverthe-less, BeiDou and Galileo are supposed to achieve their full operational ability in 2020 and with 35 and 32 satellites respectively will then have greatly increased their coverage, thus bringing both to the top level and equating GPS's advantage. However, for significantly extended coverage, especially from satellites in higher altitudes, inter-compatibility of the competing system is trump. Alongside availability, continuity, and integrity, accuracy accounts for one of the four major parameters to determine GNSS performance. Concerning the leadership in terms of accuracy of location, BeiDou and especially Galileo, once they are fully operational, hold out the highest levels of precision among the four major GNSS examined (up to 0.01 m for Galileo). With the launch of its new Vespucci satellites in December 2018, GPS has recently sought to increase its accuracy and meet present-day needs in an increasingly competitive environment. As figures show, and as is confirmed by the Russian System for Differential Correction and Monitoring (SDCM), accuracy levels of GLONASS are somewhat lower than the ones reached by GPS. However, after years of lagging behind at larger margins, due to poorer atomic clocks and other factors, recent modernizations have allowed GLONASS to catch up.

All four GNSS investigated here not only share their basic functions as well as the challenges posed to them with respect to attainable accuracy, they also share the existence of open/un-authorized and closed/authorized channels of operation. This distinction is crucial in determining respective levels of accuracy since the authorized (and encrypted) channels of operation regularly provide much higher levels of accuracy than attainable to every-day private or commercial users. While in this category Gali-leo and BeiDou seem to be slightly ahead of their competitors by now, the Galileo system also differs from other national GNSS in that it is not only a multinational project but also a civil one. This aspect represents a considerable trust advantage for Galileo. The advantage may be especially of value with regard to the BeiDou system, which currently has a similar level of accuracy like GPS and Galileo, but which will probably exceed the accuracy of GPS in the future due to new specifications. Yet it remains uncertain for its users as to their confidence in the consistent and reliable functionality of BeiDou.

With regard to the smartphone application of GNSS two aspects are crucial. First, which of the four major GNSS is supported by most smartphone models and second, which of the current smartphone vendors provides its users with the broadest service in terms of navigation precision. Being the only GNSS supported by all 40 reviewed smartphone models (100 percent), GPS takes the lead in this cate-gory. GLONASS reaches a score of 92.5 percent mainly due to the lacking support of Alcatel. BeiDou ranks third with 72.5 percent, which is especially due to the lack of support from Apple and Alcatel, but also to some missing points among Chinese vendors. With a score of 57.5 percent, Galileo ranks last within the four ready-to-use GNSS when it comes to smartphone support, but it offers great potential, particularly regarding dual-frequency positioning. Among the ten reviewed smartphone vendors only Samsung and Xiaomi support all four GNSS. Here it is to be kept in mind that the more GNSS a smartphone vendor supports the better since the combination of different positioning satellite systems accelerates the positioning process and increases the accuracy of position determination. A wider range of GNSS support could also possibly protect the user against possible failures (or even deliberate shut-downs), as the smartphones can use the satellites of another system.
Furthermore, the study also points out the very importance of compatibility and

interoperability for GNSS. These criteria are both, intertwined and inseparable. Three technical factors - the signal-in-space, the geodetic coordinate reference system, and the time reference system - mainly determine the compatibility and interoperability between systems. In comparison to the other three GNSS, GPS is far ahead in the development of navigation satellite systems. The technical advantage of GPS guarantees its leadership in terms of compatibility and interoperability, also promoted by its cooperation with other countries and international organizations. Although Galileo also has some technical advantages, finan-cial problems limit its development in reciprocal compatibility. The cooperation of GLONASS with GPS and Galileo has decelerated due to political crises, while China and Russia are promoting the compati-bility between their systems. Besides, the present compatibility and interoperability of different GNSS show different levels of development.

Finally, a look at the reliability and resilience of GNSS is indispensable. As a quality of any infrastruc-ture, especially of one as crucial as GNSS, reliability stands out if it is about the decision for one or another provider. Moreover, the resilience to extern disruptions of the system in terms of functionality and availability is a major point. This applies to both, the military and civil dimensions. Out of the many possibilities to disrupt positioning signals, GNSS will stay vulnerable to jamming due to the enormous distances between the transmitting and receiving devices. To avoid disruption and increase reliability, countermeasures can be taken on both sites of the signal, the receiver and the transmitter. Hereby ad-vances in transmitting and encryption technology compete with sophisticated countermeasures, espe-cially engaged by state actors. Furthermore, major players are developing multiple technologies for the physical destruction of satellites, posing an additional threat to GNNS in case of a conflict. Accordingly, all four systems are vulnerable due to the similar transmitter to receiver proximity. Hence we cannot identify a clear leader in this field. On the other hand, USA, Russia and by now to a lesser degree China is ahead of European Union in terms of capability to disrupt and destroy GNSS-infrastructures in case of a conflict.

Altogether GPS is still the leading GNSS according to the most criteria. Having said that, its leadership rests upon the early presence on the stage and is shrinking now. Galileo and BeiDou are catching up fast in terms of technological advance and availability. Also GLONASS will narrow the gap with the new stage of modernization of its satellite infrastructure. Still, GPS enjoys the widest level of trust by the civil users and will probably stay in front in the middle run, particularly when Washington launches the next generation of GNS-satellites in the next years.

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Full Form
ABAS	Aircraft-based augmentation systems
ASAT	Anti-satellite weapons
BDS	BeiDou
BDT	BeiDou Navigation Satellite System Time
BSCS	BeiDou Coordinate System
C4ADS	Center for Advanced Defense Studies
CDMA	Code division multiple access
CGCS2000	China Geodetic Coordinate System 2000
CHA	Channel of High Accuracy
CSA	Channel of Standard Accuracy
ECEF	Earth-Centered Earth-Fixed
FDMA	Frequency division multiple access
GBAS	Ground-based augmentation system
GGTO	GPS to Galileo Time Offset
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPST	GPS Time
GSA	Global Navigation Satellite Systems Agency
GST	Galileo System Time
GTRF	Galileo Terrestrial Reference Frame
ICG	International Committee on Global Navigation Satellite Systems
ICG	United Nations International Committee on GNSS
IERS	International Earth Rotation and Reference System Service
ITRF	International Terrestrial Reference Frame
ITU	International Telecommunication Union
LEO	Low Earth orbit
MBOC	Multiplexed binary offset carrier
MEO	Medium Earth Orbit
MOD	Maximum continuous outage duration
NATO	North Atlantic Treaty Organization

NavIC	Navigation with Indian Constellation
OS	Open Service
PPS	Precise Positioning Service
PRS	Galileo Public Regulated Service
QZSS	Quasi-Zenith Satellite System
RNP	Required Navigation Performance
SAR	Search & Rescue
SBAS	Satellite-based augmentation systems
SDCM	System for Differential Correction and Monitoring
SI	International System of Units
SPS	Standard Positioning Service
SSV	GNSS Space Service Volume
USNO	US Naval Observatory
UTC	Universal Coordinated Time
UTC-SU	Universal Coordinate Time, Soviet Union Standard
WGS84	World Geodetic System 1984

Publisher:	Center for Global Studies (CGS) Chair for International Relations Rheinische Friedrich-Wilhelms-Universität Bonn
ISSN:	2698-976X

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Design Editor:	Andrej Pustovitovskij
Graphics source:	©colourbox.com
Published:	October 2019