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MODERNIZATION OF THE GLOBAL NAVIGATION SATELLITE SYSTEMS: ISSUES OF COMPATIBILITY AND INTEROPERABILITY AMONG THEM

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ABSTRACT

During the last years, the incremental need of accurate Global navigation satellite systems (GNSSs) has led to rapidly growing changes in the operational status and practical exploitation of the systems, including the United States' Global Positioning System, Russian GLONASS, European Union's Galileo, Chinese BeiDou, and Satellite Based Augmentation Systems (SBASs). The status of these systems, as new satellites, new civil signals, and new monitoring stations, including the issues of compatibility and interoperability among them, are reviewed. Certainly, the modernized GNSS will provide the new possibility for the users' positioning, provided that all the satellite navigation systems coexist. The key requirements for this coexistence are compatibility and interoperability of these systems. Interoperability and compatibility are discussed at two different levels; system and signal. Considering signal interoperability; with identical center frequencies, reference stations can precisely measure the time offset between satellites of different systems and these differences can be communicated to user equipment as part of the satellite message. Given that every provider moves their internal reference coordinate system ever closer to the International Terrestrial Reference Frame (ITRF), the problem of interoperability of Satellite navigation systems, with respect to coordinate reference frame for majority users, does not exist. Following international cooperation, Signal In Space can be considered to not affect interoperability. International GNSS cooperation has improved radically so that users will experience the full benefits of compatible and interoperable signals. Because receivers will, without a glitch, combine signals with different digital characteristics, the user perception will be that all GNSS signals are completely identical. This study will be relevant to receiver manufacturers and space users.

Keywords: GNSS, Compatibility, Interoperability, and SBAS

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1. Introduction

During the last years, the incremental need of accurate Global Navigation Satellite System (GNSS) has led to rapidly growing changes (modernization) in the operational status and practical exploitation of the systems, including the United States' Global Positioning System (GPS), Russian GLONASS, European Union's Galileo, Chinese BeiDou (BDS), and Satellite Based Augmentation Systems (SBASs). (Mahashreveta, 2019). GNSS modernization implies provision of additional satellites and signals that enables productivity, quality, and efficiency benefits that would not otherwise be (O'Connor et al., 2019). Added satellites will provide for enhanced performance for all purposes, and especially where satellite signals can be obscured, such as in metropolitan gorge (United Nations Office for outer space affairs (UNOOSA), 2018). Also, the emergence and modernization of GNSS would lead GNSS industry to develop more flexible boards that are able to easily integrate any new system with minor modifications, resulting in a wide range of multi-constellation GNSS and SBAS receivers (European GNSS Agency (GSA), 2015).

The sense of GNSS is the technical interoperability and compatibility between various satellite navigation systems. Stupak (2015) defines compatibility to be the ability of the navigation satellite systems and augmentations to be used separately or together without causing any unacceptable interference and/or other harm to an individual system and/or service, whereas interoperability refers to the ability of 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 (UNOOSA, 2018). All global navigation satellite systems (GNSS) signals and services should be interoperable (UNOOSA, 2020). There are many benefits of employing interoperable, multi-constellation GNSS including increased resiliency due to multi-GNSS signal diversity, reduced reliance on ground support infrastructure, and the ability to utilize lower-cost components such as on-board clocks (UNOOSA, 2018).

Several new (and modernized) global and regional navigation satellite systems as well as various ongoing GNSS modernization programs have been extensively discussed by earlier scholars (Hein, 2020; Hennesey, 2018; Irene, Tony, & Bradley, 2018; Kriening, 2019; Pawel, Tomasz, Anna, & Jacek, 2019; Sun, 2019; Tholert, 2019). Some authors have recently attempted to examine the viability of Interoperability and compatibility among the GNSSs (Enderle, 2019a, 2019b; Guo, Xu, & Tian, 2018; Joel et al., 2018). While this report does not differ significantly from the previous works, and without claim for comprehensiveness, it tends to review the status of GNSSs (GPS, GLONASS, Galileo, BeiDou, and SBASs), with focus on extra signals to be broadcast by future GNSS satellites, improved ground controls, and issues of compatibility and interoperability among the GNSSs.

The readers of this article are assumed to have a basic of the principles and concepts associated with satellite based positioning. A broad introduction to the fundamentals of GPS and other Global navigation satellite systems can be found, e.g. in (Bhatta, 2010; Elliot & Christopher, 2017). This paper begins with introduction, and presents a brief summary of the GNSSs and their associated signals, SBAS, followed by the issues of compatibility and interoperability among them.

2. Global Navigation Satellite Systems

GNSS is composed of 3 operational systems; the United States' Global Positioning System (GPS), the Russian Federation's Global Navigation Satellite System (GLONASS) (Jerez & Alves, 2019), and with the successful launch of the last Geostationary Earth Orbit (GEO) satellite on 23rd June 2020, China's global navigation satellite system BeiDou (BDS) has completed the constellation (Stuart, 2020). One other GNSS is expected to be fully operational by 2020 at the earliest (Hein, 2020): the European Union's Galileo GNSS. Additionally, there are regional and global satellite based augmentation systems (SBAS) like WAAS, EGNOS, GAGAN, or QZSS that are available to enhance system performance to meet specific user requirements. Each of the systems consists mainly of three segments: (a) space segment, (b) control segment, and (c) user segment. These segments are almost similar in the three satellite technologies. Even so, within the systems, one can observe variations, modifications, and updates every year (Tholert, 2019). The orbital constellations of the GNSS as at 11/05/2020 are shown in table 2.1.

Table 2.1. GNSS orbital constellations (Hein, 2020).

GNSS constellation Status 11/05/2020	**GPS**	**GLONASS**	**Galileo**	**BDS-2**	**BDS-3**
Total satellites in constellation	32	27	24	15	34
Operational	31	24	22	15	28
Not included in orbital constellation					5
Under maintenance	1				
Spares		2			
In flight test phase		1	2		
IOV SV included in operational constellation			3		

2.1. Global positioning system (GPS)

The GPS space segment consists of a constellation of satellites, complete with computers and atomic clocks, transmitting radio signals to users. GPS satellites fly in medium Earth orbit (MEO) at an altitude of approximately 20,200 km (12,550 miles). Each satellite circles the Earth twice a day (Boeser, 2019). The satellites in the GPS constellation are arranged into six equally-spaced orbital planes surrounding the Earth. As of September 9, 2020, there were a total of 30 operational satellites in the GPS constellation, not including the decommissioned, on-orbit spares. They include (0) Block IIA (2nd generation, "Advanced"), (10) Block IIR ("Replenishment"), (7) Block IIR-M ("Modernized"), (12) Block IIF ("Follow-on"), and (2) GPS III/GPS IIIF ("Follow-on"). The GPS constellation is a mix of old and new satellites (Constellation arrangement, n.d; Current and Future Satellite Generation, n.d).

The generated GPS signals are controlled by atomic clock and consist of two carrier signals in the L-band, denoted L1=1575.42MHZ and L2=1227.60MHZ. The carriers L1 and L2 are biphase modulated by codes to provide satellite clock readings to the receiver and transmit information such as the orbital parameters. The modulation of L1 by Pcode, C/A-code and navigation message is done using the quadrature phase shift keying (QPSK) scheme (Hofmann-Wellenhof et al., 2001).

2.1.1. GPS modernization

GPS attained full constellation in 1995 and, since then has been modernized with new satellites and signals (Langley, Teunissen, & Montenbruck, 2017). GPS modernization involves the complete replacement of legacy GPS satellites and ground systems with newer, more capable ones, including system-wide improvements in interoperability with other GNSS constellations, and backward compatibility (Winternitz, 2017; GPS modernization, n.d).

2.1.1.1. Modernized GPS satellites

Launched on December 23, 2018 and August 22, 2019, GPS III SV01 and SV02 became part of today's operational constellation of 31 satellites, on January 13 and April 1, 2020 respectively (Clark, 2018; Atkinson, 2020). The U.S. Space Force and its mission partners successfully launched the GPS III SV03 satellite on June 30, 2020 from Space Launch Complex - 40 at Cape Canaveral Air Force Station, Florida (Cozzens, 2020b). Launch of the fourth GPS III satellite which was originally scheduled for Friday, October 2, was aborted two seconds before launch. As at the time of writing (06 October, 2020), neither a new launch window, nor the reason for the cancellation, had been stated (Cozzens, 2020a). GPS IIIF (Follow-On), approved in December 2017, is under development (Department of Defense United States of America, 2019). Once fully operational, GPS-III satellites will bring new capabilities to users, including three times greater accuracy and up to eight times the anti-jamming capabilities (Cameron, 2019).

2.1.1.2. New civil signals

A major focus of the GPS modernization program is the addition of new navigation signals to the satellite constellation. The GPS III satellites introduce a new L-band civilian signal, including L2C, L5, and L1C, which supports compatibility and interoperability with international satellite navigation systems (GPS World, 2020). Most of the new signals will be of limited use until they are broadcast from 18 to 24 satellites (New civil signals, n.d).

GPS-III will provide improved signal reliability, accuracy and integrity. The satellites will advance features included on the Block IIR-M and IIF satellites including (Dhande, 2020); (i) L2C signal on the 1227.6 MHz L2 frequency (ii) L5 "Safety of Life" signal on the 1176.45 MHz L5 frequency (iii) L1C signal on the 1575.42 MHz L1 frequency and (iv) Military M-code.

L2C is the second civilian GPS signal, and the first GPS satellite to transmit the signal is GPS Block IIR-M. The L2C signal features a radio Navigation Satellite Services (RNSS) radio band, modern signal design (CNAV), a bi-Phase Shift Key (BPSK) modulation, including a dedicated channel for codeless tracking. However, L2C remains pre-operational and should be employed at the user's own risk until it is declared operational (Winternitz, 2017; "New civil signals, n.d).

A new L5 is the third civil signal designed for safety of life applications in a highly protected Aeronautical Radio Navigation Services (ARNS) radio band. First transmitted by GPS Block IIF, it attained launching category in 2010. In addition, it features a bi-Phase Shift Key (BPSK) modulation, and a dedicated channel for codeless tracking. It is characterized by higher power, greater bandwidth, and an advanced signal design. When L5 is used in combination with L1 C/A and L2C, L5 will provide a highly robust service (Winternitz, 2017; New civil signals, n.d).

L1C is the fourth civilian GPS signal with signal structure designed to enable Aeronautical Radio Navigation Services (ARNS) radio band with modern signal design (CNAV-2). L1C features a Multiplexed Binary Offset Carrier (MBOC) modulation scheme that enables international cooperation while protecting U.S. national security interests. GPS III satellite was the first to transmit L1C, different from the legacy L1 C/A signal used nowadays. There are also two military signals at L1, as well as the legacy C/A signal. L1C broadcasts at the same frequency as the original L1 C/A signal, which will be retained for backwards compatibility (GPS World, 2020; Winternitz, 2017). L1C allows for the first time, GPS compatibility and full interoperability with signals from other satellite systems; it shares the same center frequency as Europe's Galileo GNSS, Japan's QZSS and China's BeiDou (Dhande, 2020). All these improvements will bring further benefits and developments to the GNSS market and civilian users in general (GPS World, 2020).

2.1.1.3. GPS modernized control segment

As part of the GPS modernization program, the Air Force has continuously upgraded the GPS control segment for many years. The ground upgrades are necessary to command and control all the newer GPS and legacy satellites and to enhance cyber security. The next generation Operational Control System (OCX) is the future version of the GPS control segment which will command, and manage all civil and military navigation signals, and provide improved resilience for the next generation of GPS operations. OCX will be ready for transitions to operations around first half of 2022. It will consist of (Next Generation Operational Control System, n.d): (i) A master control station and alternate master control station (ii) Dedicated monitor stations (iii) Ground antennas (iv) GPS system simulator and (v) Standardized space trainer.

2.2. GLONASS

The nominal baseline constellation of GLONASS comprises 24 GLONASS-M satellites (Information and analysis center for positioning, navigation and timing (IACPNT), n.d), that are uniformly deployed in three roughly circular orbital planes at an altitude of 19100-km. The longitude of ascending node differs by 120 deg from plane to plane and each plane comprises eight satellites, staggered by 45 deg in argument of latitude, and each satellite completes the orbit in approximately 11 hours 15 minutes (Langley, 2017).

2.2.1. GLONASS satellite generations

GLONASS satellite designs have gone through numerous improvements, and can be divided into generations (Pietrobon, 2018; Uragan Russian Space Web, 2016): the original GLONASS (since 1982, also called Uragan), GLONASS-M (since 2003), and GLONASS-K (since 2011). The true first generations of GLONASS, the Uragan satellites, were all three axis stabilized vehicles, equipped with a modest propulsion system to permit relocation within the constellation. Over time, they were upgraded to Block IIa, IIb, and IIv spacecraft. By the end of 2005, the Russians had deployed 60 Block IIvs. Each subsequent satellite generation contained equipment enhancements and also achieved longer lifetimes (Uragan Russian Space Web, 2016).

The second generation of satellites, known as GLONASS-M (for Modernized), was developed beginning in 1990 and first launched along with two Block IIvs. The new design offered many improvements, including better onboard electronics, a longer lifetime, an L2 civil signal, and an improved navigation message (Langley, 2017). A total of 14 second generation satellites were launched through the end of 2007. The last GLONASS-M launch took place on 16 March 2020 (Hein, 2020).

The third generation GLONASS-K is a substantial upgrade of the previous generation. The GLONASS-K satellite is expected to operate for 10 years, an improvement from the seven-year design life of previous satellites (Clark, 2020). It will transmit more navigation signals to improve the system's accuracy, including new CDMA signals in the L3 and L5 bands, which will use modulation similar to modernized GPS, Galileo, and Compass/Beidou satellites. GLONASS-K consists of 26 satellites having satellite index 65-98 and widely used in Russian Military space (Zak, 2020; GPS World, 2010). Enhanced GLONASS-K1 and GLONASS-K2 satellites, launched from 2018, feature a full suite of modernized CDMA signals in the existing L1 and L2 bands, which includes L1SC, L1OC, L2SC, and L2OC, as well as the L3OC signal (Graham, 2020). The launch of a GLONASS constellation next-generation K satellite is scheduled for October, 2020 (Inside GNSS, 2020b). Further GLONASS-K launches are expected in 2021 (Hein, 2020). Six additional GLONASS-V satellites, using Tundra orbit in three orbital planes, will be launched in 2023-2025; this regional high-orbit segment will offer increased regional availability and 25% improvement in precision over Eastern hemisphere, similar to Japanese QZSS system and Beidou-1 (Yury, 2018).

2.2.2. Legacy and modernized GLONASS Signals

Traditionally, GLONASS satellites transmit navigational radio signals in two frequency sub-bands of L-band: L1 ~ 1602 MHz and L2 ~ 1246 MHz. GLONASS L1 signals consist of L1OF, which is an open and unrestricted civilian signal, and L1SF, a more precise encrypted signal for military use. Similarly, L2 signals are separated into L2OF and L2SF, while the L3 signal only has a civilian edition, L3OC (Graham, 2020). One significant difference between GLONASS and GPS is that legacy GLONASS uses a frequency division multiple access (FDMA) in each band as opposed to the CDMA approach used by GPS. Comparable to GPS, the GLONASS signals utilize BPSK modulation and are transmitted out of a right-hand circularly polarized (RHCP) antenna. (Grewal, Andrews, & Bartone, 2020; Camacho-Lara, 2017).

One of the concerns with an FDMA GNSS arrangement is the inter-frequency phase bias and inter-frequency code bias that can arise within the FDMA GNSS receiver. These error sources come up because the various navigation signals pass through the components within the receiver at slightly different frequencies. GLONASS receiving equipment is prone to experiencing both biases (Zhu, Liu, Wang, & Ye, 2018). But the inter-frequency biases are relatively abridged with CDMA-based navigation systems because all of the signals are transmitted at the same frequency.

GLONASS-K continues to transmit the legacy FDMA signals in the L1 and L2 bands. They introduce new, interoperable code division multiple access (CDMA) signals in the L3 Band that will be extended to L1 and L2 CDMA signals, with two civilian signals and two military signals with higher accuracy (Inside GNSS, 2020b). CDMA signals fully interoperable with GPS, Galileo and BeiDou will be implemented in the 2020s when a modernized GLONASS-K satellite, GLONASS-KM is introduced. GLONASS-KM, may also transmit on the L5 frequency at 1176.45 MHz, the same as the modernized GPS signal L5 and Galileo signal E5a (Langley, 2017). The L3 CDMA signal allows an easy and low-cost implementation of multi-standard GNSS receivers. The L3OC signal is centered at 1,202.25MHz using BPSK (10) modulation for the data and pilot components (Inside GNSS, 2020a).

2.2.3. GLONASS Control Segment

The GLONASS control segment consists of the system control center and a network of command tracking stations across Russia. The GLONASS control segment, similar to that of GPS, monitors the satellites health, determines the ephemeris corrections, as well as the satellite clock offsets with respect to GLONASS time and UTC (Coordinated Universal Time). Twice a day, it uploads corrections to the satellites (Sanz Subirana, Juan Zornoza, & Hernández-Pajares, 2013).

On March 6th, 2017, a new GLONASS station was officially commissioned in South Africa. That station will monitor GLONASS and GPS satellites' navigation signals, measurements of current navigation parameters of their travel, and receipt of navigation messages from the satellites (GPS World, 2017).

2.3. Galileo Global navigation satellite system

Galileo is the global navigation satellite system (GNSS) created by the European Union (EU) through the European GNSS Agency (GSA) (Council of the European Union, 2020). The European navigation system Galileo is on its final stretch to become a fully operational capability (FOC) Global Navigation Satellite System (GNSS).

The current Galileo satellite constellation consists of 30 satellites placed in Medium Earth Orbit (MEO), at orbital altitude of 23,222 km, with 10 satellites placed in each of 3 orbital planes (at 56 º nominal inclinations (Bury, Sosnica, Zajdel & Strugareck, 2020; European GNSS Agency (GSA), 2019), and since late 2016 is considered as an operational system. The active constellation comprises of 24 satellites, including 6 spare satellites, which can be moved to replace any failed satellite within the same plane. Each satellite broadcasts navigation timing signals together with navigation data providing the clock and ephemeris correction data which are essential for navigation (European GNSS Service Center (GSC), 2019).

2.3.1.Galileo satellites

The first Galileo test satellite, the GIOVE-A, was launched 28 December 2005, and was followed by a second test satellite, GIOVE-B, launched in April 2008; both are now decommissioned. The first satellite to be part of the operational system was launched on 21 October 2011 (Galileo GNSS, 2016). The constellation of Galileo satellites is nearly complete, and recent launches have put satellites into orbit four at a time with the Ariane 5 launch vehicle. It is expected that the next generation of satellites will begin to become operational by 2025 to replace older equipment (Benedicto, 2018). All the Galileo satellites are equipped with Laser Retro reflector Arrays (LRA) for Satellite Laser Ranging (SLR). As a result, a number of Galileo satellites are tracked by laser stations of the International Laser Ranging Service (ILRS) (Bury et al., 2020).

2.3.2. Galileo Signals

Probably, the most significant discriminator of Galileo compared to other GNSS is its capability to broadcast three independent CDMA multi-frequency Right-Hand Circularly Polarized (RHCP) (E5, E6, E1) signal components on all operational satellites (Benedicto, 2019). The wide band Galileo E5 signal is centered on a frequency of 1191.795 MHz. The E5 signal is further sub-divided into signals denoted E5a and E5b. The E5a and E5b are centered on frequencies of 1176.45 MHz and 1207.14 MHz respectively. The Galileo E1 is centered at 1575.42 MHz. The E1 carrier is modulated with a CBOC (6, 1, 1/11) (following the MBOC spectrum) code for the open source and a BOCcos (15, 2, 5) code for the public regulated service. The Galileo E6 signal is transmitted on a center frequency of 1278.75 MHz and comprises commercial service and public regulated service signals, which are modulated with a binary phase shift keying (BPSK)(5) and BOCcos(10,5) code, respectively (Camacho-Lara, 2017; European Union (EU), 2016). Corresponding carrier frequencies and receiver reference bandwidths for the Galileo signals are shown in table 2.2. Significant details on the Galileo signals in space, can be found, e.g. in (European Union, 2015).

Table 2.2. Carrier frequencies and receiver reference bandwidths corresponding to the Galileo signals (EU, 2016).

Signal	Carrier Frequency (MHz)	Receiver Reference Bandwidth (MHz)
E1	1575.420	24.552
E6	1278.750	40.920
E5	1191.795	51.150
E5a	1176.450	20.460
E5b	1207.140	20.460

2.3.3. Galileo Ground segment

Galileo's ground segment is essential to keeping Galileo services running dependably. The ground segment comprises a set of four Medium-Earth Orbit Local User Terminals serving Galileo's search and rescue service, at the corners of Europe and facilities for testing Galileo service quality and security (Cozzens, 2018). The core of the Galileo ground segment, are 2 Galileo Control Centers (GCC). Each control centre manages control functions supported by a Galileo Control Segment (GCS) and mission functions, supported by a dedicated Galileo Mission Segment (GMS). The GCS handles spacecraft organization and constellation maintenance while the GMS handle navigation system control. The GCS and GMS interface the satellites with a worldwide ground station network implementing control and monitoring functions (Galileo GNSS, 2019).

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2.4. BeiDou Global Navigation Satellite System

China formulated a three-step development plan to actualize the construction of the BeiDou satellite navigation system. The various phases of BDS are referred to as BDS-1, BDS-2, and BDS-3. Each BDS phase has supported a mix of satellites in various orbits: MEO, geostationary Earth orbit (GEO), and inclined geosynchronous orbit (IGSO) (China Satellite Navigation Office (CSNO), 2019b).

The first phase involved building the BeiDou-1 system. The service began in 2000 with the launch of two satellites for BeiDou-1; it became "operational" with the launch of the third spacecraft, BeiDou-1C, in 2003 (Yang, 2010). It was originally made up of two geostationary orbit satellites (GEO), followed by an additional GEO satellite for backup in 2003 (Yang, Tang, & Montenbruck, 2017).

On December 27, 2012, the phase 2, BeiDou regional navigation satellite system (BDS-2), was established with a constellation of 14 satellites: five GEO satellites, five inclined geosynchronous orbit (IGSO) satellites, and four medium Earth orbit (MEO) satellites(Yang et al., 2014).

Following the continuous and stable regional service of BDS-2, a GNSS (BDS-3), to complete BDS and provide services around 2020 (Yang et al., 2018, 2019, 2020), began to be developed. Before the construction of BDS-3 commenced, a demonstration system was built in 2015 (Yang, Xu, Li, & Yang, 2018). With the successful launch of the last Geostationary Earth Orbit (GEO) satellite on 23rd June 2020, BDS has completed the constellation. This is the third iteration of the BDS system and consists of 24 medium Earth orbit satellites, 3 inclined geostationary satellites and 3 geostationary satellites (Stuart, 2020). Overall, 55 BDS satellites are currently launched into orbit, providing more continuous, stable, reliable, positioning, navigation and timing services to world (Lu, Guo, & Su, 2020). The implication of this development is the associated expansion of the coverage area and a significant change of the provided signals and services to achieve better interoperability with other existing GNSS systems.

2.4.1. BeiDou Signal Plan

The BeiDou System (BDS) provides triple-frequency (B1, B2 and B3) measurements and operates in the frequency bands (Chu & Yang, 2018; Editorial Team, 2017), as shown in table 2.3. The frequency of the B1I signal is centered at 1561.098 MHz. The B1I signal is Right-Hand Circularly Polarized (RHCP). The signal multiplexing mode is Code Division Multiple Access (CDMA). The bandwidth of the B1I signal is 4.092MHz (centered at carrier frequency of the B1I signal) (CSNO, 2019a).

Table 2.3. Frequency bands of the BeiDou system

Signal	Frequency (MHz)	Bandwidth (MHz)	Band (MHz)
B1	1561.098	4.092	1559.05-1563.15
B2	1207.140	24	1195.14-1219.14
B3	1268.520	24	1256.52-1280.52

BDS-3 defines three open service signals (Hunter-Spirent, 2018; CSNO, 2017); (i) B1C: 1575.42 MHz with a bandwidth of 32.736 MHz (ii) B2a: 1176.45 MHz with a bandwidth of 20.46 MHz and (iii) B3I: 1268.52 MHz with a bandwidth of 20.46 MHz. In addition to the legacy B1I and B3I signals, new open service signals, B1C and B2a/B2b, as well as some new authorized service signals, will be broadcast by BDS-3 satellites. Among them, B1C and B2a are compatible and interoperable with GPS and Galileo (Lu, Li, Yao, & Cui, 2019).

Interoperable with GPS and Galileo, the carrier frequency of B1C, 1575.42 MHz, is the same as the carrier frequency of GPS L1 C/A and L1C, and the Galileo E1 OS signal. The QMBOC (6, 1, 4/33) modulation (Yao, Lu, & Feng, 2010) is applied to B1C. The Beidou B1C components; frequencies and modulations, are shown in table 2.4a.

Table 2.4a.Beidou B1C components: frequencies and modulations

Signal	**Signal component**	**Carrier frequency (MHz)**	**Modulation**	**Symbol rate (sps)**
B1C	Data component B1C_data	1575.42	BOC(1,1)	100
	Pilot component B1C_pilot		QMBOC(6, 1, 4/33)	0

BeiDou B2a Band describes the signal characteristics corresponding to the B2a signal contained within the 20.46 MHz bandwidth with a center frequency of 1176.45 MHz. B2a signal is interoperable with GPS L5 and Galileo E5a. Table 2.4b indicates the Beidou B2a components; frequencies and modulations (CSNO, 2017; Li, Shivaramaiah, & Akos, 2019; Lu, 2018).

Table 2.4b. Beidou B2a components: frequencies and modulations

Signal	**Signal component**	**Carrier frequency (MHz)**	**Modulation**	**Symbol rate (sps)**
B2a	Data component B2a_data	1176.45	BPSK(10)	200
	Pilot component B2a_pilot			0

The B3I open service B3I signal is transmitted by the BDS-2 and BDS-3 satellites. The frequency of the B3I signal is centered at 1268.520MHz. The B3I signal is Right-Hand Circularly Polarized (RHCP).The signal multiplexing mode is Code Division Multiple Access (CDMA). The bandwidth of the B3I signal is 20.46 MHz (centered at carrier frequency of the B3I signal). The Binary Phase Shift Keying (BPSK) modulation is applied to B3I (CSNO, 2018).

2.4.2. BeiDou Ground Segment

The BeiDou Ground Segment consists of (Shen, 2016; Lu, 2018):

- A Master Control Station: responsible for satellite constellation control and processing the measurements received by the Monitor Stations to generate the navigation message.
- Upload Stations: responsible for uploading the orbital corrections and the navigation message to BeiDou satellites;

- Monitor Stations, which collect BeiDou data for all the satellites in view from their locations.

Currently, the Ground Segment includes one Master Control Station, two Upload Stations and 30 Monitor Stations. In addition, the system supports a short message communication service that can be exchanged between the station and the users.

2.5. Satellite Augmentation

Satellite-Based Augmentation Systems (SBASs) is a regional network of ground and geosynchronous (GEO) satellite systems that brings extra satellites and signals to augment GNSS Position, Navigation and Timing (PNT) capabilities. SBAS uses GEO satellites to broadcast ranging, integrity, and correction information to GNSS users or to add a signal source. The augmented correctness is crucial for aviation and is widely used by the geospatial industry for increased accuracy in navigation and mapping (Li et al., 2018; Hexagon, 2020b).

SBAS setup (Hexagon, 2020b), as shown in figure 2.1, includes reference stations, master stations, uplink stations and GEO satellites. Reference stations, which are geographically distributed throughout the SBAS service area, receive GNSS signals and forward them to the master station. Since the locations of the reference stations are accurately known, the master station can accurately calculate wide-area corrections. Corrections are uplinked to the SBAS satellite then broadcast to GNSS receivers throughout the SBAS coverage area. User equipment, e.g., GNSS receivers in a vehicle or airplane, receives the corrections and applies them to range calculations (Augmentation system, n.d). To calculate GNSS position errors, GNSS data from satellites are compared against the precisely documented locations of each reference station. These SBAS corrections – called deviation corrections – allow GNSS receivers to more accurately and reliably determine their position (Murphy, 2018).

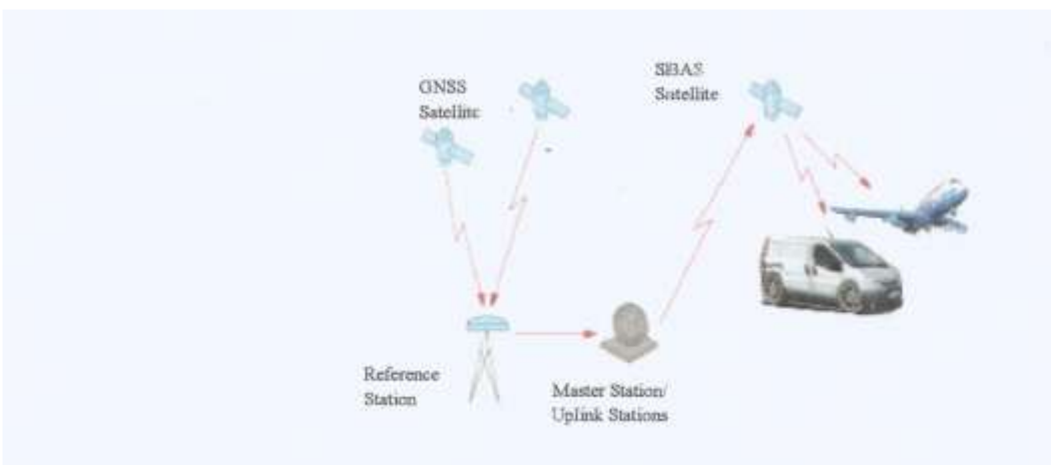

Figure 2.1: Showing SBAS-setup (Hexagon, 2020b)

Several countries have implemented SBAS, or are in various stages of developing their own SBAS. The U.S. has the Wide Area Augmentation System (WAAS); the EU has the European

Geostationary Navigation Overlay Service (EGNOS); Russia has the System for Differential Correction and Monitoring (SDCM); Japan has the Multi-functional Satellite Augmentation System (MSAS); India has launched the Geo-Augmented Navigation system (GAGAN); Nigeria deployed NIGCOMSAT geostationary satellite; and South Korea has approved and is developing its Korean Augmentation Satellite System (KASS). Also, China, Australia and New Zealand, South Africa and South America are currently inthe developmental stages for their own systems (European GNSS Agency (GSA), 2020).

SBAS GEO satellites transmit an L1, modulated with a Coarse/Acquisition Pseudo-Random Noise (PRN) code, and L5 frequencies which share similar design to the GPS-like L1 (1574.42 MHz) and L5(1176.45 MHz) signals (Hexagon, 2020a). For example, WAAS will broadcast ionospheric corrections and integrity data on both L1 and L5. The SBAS L1 radio frequency characteristics are described in (Choy, Kuckartz, Dempster, Rizos, & Higgins, 2017).

2.6. Issues of compatibility and interoperability among the GNSS

The issues of compatibility and interoperability arise because different GNSS signals are not inherently well-matched. Each of these systems is separately owned, developed and operated. They employ different signal structures, geodesy, and system time (Rita, Powell Thomas, & Stansell Thomas, 2012). These differences limit the user's ability to tap the navigation resources from different GNSSs.

Interoperability can be discussed at two different levels (Hein, 2006), system and signal. At system level, a GPS, GLONASS, Galileo or BeiDou user's receiver should be able to provide same navigation solution when used standalone. In this scope, GPS, GLONASS, Galileo or BeiDou can be said to be interoperable at system level (Hein, 2006), while bringing the advantage of being independently operated thus providing redundancy to the GNSS user community -hence increasing the market confidence on the technology.

Signal Interoperability is achieved when the signal provided by the different satellite navigation system and SBAS are similar enough to allow a GNSS integrated receiver to use all those signals with minor modification. For GNSS, signal interoperability considers the following factors (Hein, 2006), including geodetic reference frame, time difference, use of the same carrier frequency, and international cooperation.

2.6.1. Geodetic Reference frame

Each GNSS has its own reference frame, but the international civil coordinate reference standard remains the International Terrestrial Reference Frame (ITRF). For two GNSS to be declared interoperable from the standpoint of a reference frame, the difference between frames should be within 3 cm, the target accuracy (Galileo GNSS, 2019). Given that every provider moves their internal reference coordinate system ever closer to ITRS, most systems already agree with ITRS to within a few centimeters (Rita et al., 2012). This implies that the difference between frames will be within tolerance limit, hence guaranteeing interoperability for most applications. For example, Galileo Terrestrial Reference Frame (GTRF) is specified to always be in harmony with the international terrestrial reference frame (Galileo GNSS, 2019). The GTRF is specified to differ from the latest version of ITRF by no more than 3 centimeters (Groves, 2008). The GLONASS coordinate reference frame is

Parametry Zemli 1990 (PZ–90.020), and this version is coordinated to ITRF. This shows that there are agreements between ITRF, GTRF, and WGS84, the GPS coordinate reference frame. This suggests that the problem of interoperability of Satellite navigation systems, with respect to reference frame for majority users, does not exist.

2.6.2. Time difference

Universal Time Coordinated/Atomic Time (UTC/ TAI), the international civilian time standard, is the Time reference frame. While most clocks in the world are synchronized to UTC, the atomic clocks on the satellites are set to own satellite navigation system time. For example, the GPS system uses its own particular, continuous time scale, GPS System Time (GPST) referenced to UTC (US Naval Observatory – USNO), and GLONASS time is based on the national time scale of Russian Federation- UTC (SU). With identical center frequencies and signal spectra, reference stations can precisely measure the time offset between satellites of different systems and these differences can be communicated to user equipment as part of the satellite message (Wang & Knight, 2011). For example, the Galileo System provides the "Galileo to GPS Time Offset" (GGTO) as part of the navigation messages. Although providers could use this information to drive their own system clocks to agree with any one of the other systems, it would be preferable to establish an international GNSS time standard against which each system could measure its time and drive any difference toward zero.

2.6.3. Use of the same carrier frequency and Signals in Space

Compatibility and interoperability of GNSS are the key requirements for integrated multi GNSS navigation and positioning. For example, the OS carrier frequencies (in particular E1 and E5a) and their modulation characteristics simplify the combined use of Galileo with other constellations (GPS, GLONASS and BeiDou). GPS and Galileo can be considered interoperable at signal level among themselves in some frequency bands (e.g. L1 and L5/ E5a), but not with the legacy GLONASS signals which use FDMA technique. Inside GNSS (2020b) explains that GLONASS-K will transmit additional civilian CDMA signals in the L1, L2, L3 and L5 bands, becoming interoperable with Galileo and GPS, while, according to Langley (2017), GLONASS-KM, may also transmit on the L5 frequency at 1176.45 MHz, the same as the modernized GPS signal L5 and Galileo signal E5a. Though GPS and Galileo may be compatible, they may be considered as not interoperable among themselves in frequency-bands that have no correspondence, such as E5b or L2.

Aspects of the design of the Signals in Space, such as modulation, signal structure or selection of the codes that require only "software modifications" at the receiver can be considered to not affect interoperability (Hein, 2006). Furthermore, several working groups have been formed at international level in order to coordinate during the design of the signals design in order to ensure compatibility and signal interoperability.

2.6.4. International Cooperation

International cooperation is intended to ensure among other things, compatibility and interoperability (Turner, 2010). Since each of the GNSS is separately owned, developed and operated by different countries, the issue of signal design affects directly compatibility and interoperability among the systems. To assure compatibility and interoperability among the systems, cooperation at international level at the outset of development has been done. Bilaterally or multilaterally, different parties have taken on several cooperation venues. For example, a multilateral dialog in 2005 led to the formation of International Committee on Global Navigation Satellite Systems (ICG) by the United Nations, as the needed forum where discussion and coordination on issues, including global compatibility, and interoperability of space-based position, navigation, and timing services (PNT) could be held (Inside GNSS, 2019). Compatibility, interoperability, and transparency in civil service provision are priorities, pursued through bilateral and multilateral dialogues (Auerbach, 2020; Inside GNSS, 2019). Also, a Providers' Forum established at the second meeting of the International Committee on Global Navigation Satellite Systems (ICG) in 2007, in Bangalore, India, aims to promote greater compatibility and interoperability among current and future providers of the Global Navigation Satellite Systems (UNOOSA, 2020; Inside GNSS, 2019). The U.S. Government has engaged European Union and a number of other countries in cooperative activities related to space-based PNT (Positioning, Navigation, and Timing) systems.

Conclusion

This paper reviews the status of the various satellite navigation systems, as new satellites, new civil signals, and new monitoring stations, including the issues of compatibility and interoperability among them. Obviously, this is a very dynamic period, with the last satellite of the BDS launched on June 23, 2020; a fully global system is now deployed by the Chinese to provide full services to the world, the Russian GLONASS system now restored to a very high level of worldwide performance, and the US GPS system with the (GPS) III SV03 satellite successfully launched on June 30, 2020, is, along with the Wide-Area Augmentation System (WAAS), the most widely used system. In addition, the European Galileo initiative is also moving swiftly ahead. These GNSSs are bringing new or modernizing elements into the world. The modernized GNSS will provide the new possibility for the users' positioning, provided that all the satellite navigation systems coexist. The key requirements for this coexistence are compatibility and interoperability of these systems.

At system level of interoperability, a GPS, GLONASS, Galileo or BeiDou user's receiver should be able to provide same navigation solution when used standalone. Considering signal interoperability as a factor of time reference, with identical center frequencies, reference stations can precisely measure the time offset between satellites of different systems and these differences can be communicated to user equipment as part of the satellite message. However, it would be preferable to establish an international GNSS time standard against which each system could measure its time and drive any difference toward zero. Given that every provider moves their internal reference coordinate system ever closer to ITRS, the problem of interoperability of Satellite navigation systems, with respect to coordinate reference frame for majority users, does not exist. Signal in Space can be considered to not affect interoperability, since several working groups have been formed at international level in order to coordinate during the design of the signals so that compatibility and signal interoperability are guaranteed.

The outcome of the international bilateral and multilateral cooperation has resulted in the recognition of the gains of GNSS compatibility and interoperability. Through the different meetings, the parties have taken major steps to ensure that the aims and objectives of the cooperation are achieved. This effort has led to radical improvements in the International GNSS cooperation, with the intention that users will experience the full benefits of compatible and interoperable signals. Because receivers will, without a glitch, combine signals with different digital characteristics, the user perception will be that all GNSS signals are completely identical. This study will be relevant to receiver manufacturers and space users.

REFERENCES

Atkinson, I. (2020, June 30). SpaceX launches third GPS Block III satellite. *Spaceflight.* Retrieved from https://www.nasaspaceflight.com/2020/06/spacex-launch-third-gps-block-iii-satellite/

Auerbach, J. (2020, September). *U.S. GPS/GNSS International Activities Update*. Paper presented at the Civil GPS Service Interface Committee Meeting. Retrieved from https://www.gps.gov/cgsic/meetings/2020/auerbach.pdf

Augmentation system. (n.d.) McGraw-Hill Dictionary of Scientific & TechnicalTerms, 6E. Retrieved October 18 2020 from https://encyclopedia2.thefreedictionary.com/augmentation+system

Benedicto, J. (2018, December). Directions 2019: Galileo moves towards FOC. *GPS World*. Retrieved from https://www.gpsworld.com/galileo-moves-toward-foc

Benedicto, J. (2019, December 14). Directions 2020: Galileo moves ahead. *GPS World*. Retrieved from https://www.gpsworld.com/directions-2020-galileo-moves-ahead/

Bhatta, B. (2010). *Global navigation satellite systems: Insights into GPS, GLONASS, Galileo, Compass, and others.* Retrieved from https://books.google.com.ng/ books?id=22NdJ_jTxTUC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false

Boeser, S.M. (2019). Global Positioning Systems (GPS). In: C.W. Finkl, C. Makowski (Eds.), *Encyclopedia of Coastal Science.Encyclopedia of Earth Sciences Series*. Springer, Cham. https://doi.org/10.1007/978-3-319-93806-6_154

Bury, G., Sośnica, K., Zajdel, R., & Strugarek, D. (2020). *Precise Galileo orbit determination using combined GNSS and SLR observations*. Retrieved from https://meetingorganizer.copernicus.org/EGU2020/EGU2020-340.html

Camacho-Lara S. (2017). Current and future GNSS and their augmentation systems. In: J. Pelton, S. Madry, & S. Camacho-Lara (Eds.), Handbook *of Satellite Applications*. Springer, Cham. https://doi.org/10.1007/978-3-319-23386-4_25

Cameron, Alan. (2019, April 1). Benefits coming from GPS III constellation. *GPS World*. Retrieved from https://www.gpsworld.com/benefits-coming-from-gps-iii-constellation/

China Satellite Navigation Office (CSNO). (2017). BeiDou *Navigation Satellite System Signal in space interface control document open service signal B2a*(version 1.0), December 2017.19-0853-z

China Satellite Navigation Office (CSNO). (2018). *BeiDou navigation satellite system signal in space interface control document open service signal B3I.* (version 1.0). Retrieved from http://en.beidou.gov.cn/SYSTEMS/ Officialdocument/201806/P020180608525869304359.pdf.

China Satellite Navigation Office. (2019a). *BeiDou Navigation Satellite System Signal In Space Interface* Control *Document Open Service Signal B1I* (Version 3.0). Retrieved from http://en.beidou.gov.cn/ SYSTEMS/ ICD/201902/P020190227702348791891.pdf

China Satellite Navigation Office (CSNO). (2019b). *Development of the BeiDou Navigation Satellite System* (Version 4.0). Retrieved from http://www.beidou.gov.cn/xt/gfxz/ 201912/ P020191227430565455478.pdf

Choy, S., Kuckartz, J., Dempster, G. A., Rizos, C., Higgins, M. (2017). GNSS satellite-based augmentation systems for Australia. *GPS Solutions, 21*, Pp. 835–848. https:// doi.org/ 10.1007 /s10291-016-0569-2

Chu, F., & Yang, M. (2018). BeiDou system (BDS) triple-frequency ambiguity resolution without code measurements. *Remote Sensing, 10*, Pp. 675-692. Doi: 10.3390/rs10050675

Clark, S. (2018, December 23). SpaceX closes out year with successful GPS satellite launch. *Spaceflight Now*. Retrieved from https://spaceflightnow.com/2018/12/23/spacex-closes-out-year-with-successful-gps-satellite-launch/

Clark, S. (2020, October 26). Russia launches Glonass navigation satellite. *Spaceflight Now*. Retrieved from https://spaceflightnow.com/2020/10/26/russia-launches-glonass-navigation -satellite/

O'Connor, A.C., Gallaher, M.P., Clark-Sutton, K., Lapidus, D., Oliver, Z.T., Scott, T.J., Wood, D.W., Gonzalez, M.A., Brown, E.G., & Fletcher, J. (2019). *Economic Benefits of the Global Positioning System (GPS)*. (RTI Report Number 0215471). Retrieved from https:// www.rti.org/sites/default/files/gps_finalreport.pdf

Constellation arrangement (n.d). GPS.Gov. Retrieved August 07, 2020, from http://www.gps.gov/systems/gps/ space

Council of the European Union (2020). *On a Civil Global Navigation Satellite System (GNSS) between the European Community and its Member States and Ukraine*.Retrieved from https://www.europeansources.info/record/ proposal-for-a-council-decision-on-the-signing-of-the-protocol-to-the-cooperation-agreement-on-a-civil-global-navigation-satellite-system-gnss-between-the-european-community-and-ukraine/

Cozzens, T. (2018, March 28). Galileo ground segment keeps constellation on track. GPS World. Retrieved from https://www.gpsworld.com/galileo-ground-segment-keeps-constellation-on-track/

Cozzens, T. (2020a, October 1). GPS III launch aborted with 2 seconds to spare. *GPS World*. Retrieved from https://www.gpsworld.com/fourth-gps-iii-satellite-poised-to-launch/

Cozzens, T. (2020b, June 30). SMC and SpaceX launch third GPS III satellite. *GPS World*. https://www.gpsworld.com/smc-and-spacex-poised-for-third-gps-iii-falcon-9-launch/

Current and Future Satellite Generation. (n.d). GPS.Gov. Retrieved August 07, 2020, from http://www.gps.gov/ systems/gps/space

United States of America, Department of Defense (2019, December). *Global Positioning System Ill Follow-On Production (GPS IIIF)*. (RCS: DD-A&T(O&A)823-590). Retrieved from https://www.esd.whs.mil/ Portals/54/Documents/FOID/Reading%20Room/Selected_Acquisition_Reports/FY_2019_SARS/20-F-0568_DOC_36_GPS_IIIF_SAR_Dec_2019_Full.pdf

Dhande, M. (2020, September 27). What is GPS III & how capable it is? *Geospatial World*. Retrieved from https://www.geospatialworld.net/blogs/what-is-gps-iii-and-what-are-us-gps-iii-capabilities/

Editorial Team, (2017, March 27). BeiDou Frequency Bands. *EverythingRf*. Retrieved from https://www.everythingrf.com/community/beidou-frequency-bands

Enderle, W. (2019a, March 26). Development of an Interoperable GNSS Space Service Volume–The GNSS SSV Booklet. *European Space Agency*. Retrieved from http://navigation-office.esa.int/attachments_ 54919608_1_2019-03-27_-_Munich_Summit_2019_-_ICG_GNSS_SSV_Presentation_-_Final.pdf

Enderle, W. (2019b, November 20). Interoperable GNSS Space Service Volume –Update on ESA Activities. *European Space Agency*.Retrieved from http://navigation office.esa.int/attachments_ 549196 04_1_2019 - 11-20_-_GPS_PNT_Board_-_Interoperable_GNSS_SSV_-_Update_on_ESA_activities_Final.pdf

Elliott, D. K., & Christopher, H. (Ed.). (2017). *Understanding GPS/GNSS: Principles and Applications.* Retrieved from https:// books.google.com.ng/ books?id =y4Q0D wAAQBAJ&printsec=frontcover&source=gbs_ book_other_versions#v=onepage&q&f=false

European GNSS Agency. (2015, March). GNSS Market Report (Issue 4). Retrieved from http://www.gsa.europa.eu/ system/files/reports/GNSS-Market-Report-2015-issue4_0.pdf

European GNSS Agency (GSA). (2019). *Latest batch of Galileo satellites enters service*. Retrieved from https://www.gsa.europa.eu/newsroom/news/latest-batch-galileo-satellites-enters-service

European GNSS Agency (GSA). (2020). *What is SBAS?* Retrieved from https://www.gsa.europa.eu/european-gnss/what-gnss/what-sbas

European GNSS Service Centre (GSC). (2019). *Constellation information*. Retrieved from https://www.gsc-europa.eu/system-service-status/constellation-information

European Union (EU). (2015). *Satellite Navigation, Galileo Open Service Signal-In-Space Interface Control, OS SIS ICD* (Issue 1.2), November 2015. Retrieved from https://galileognss.eu/wp-content/ uploads/2015/12/Galileo_OS_SIS_ICD_v1.2.pdf

European Union (EU). (2016). *Galileo Open Service (OS) Signal In Space (SIS) Interface Control Document* (Issue 1.3), December, 2016. Retrieved from https://www.gsc-europa.eu /sites / default/files/sites/all/files/Galileo-OS-SIS-ICD.pdf

Galileo GNSS. (2016). *Galileo space segment*. Retrieved from https://galileognss.eu/giove

Galileo GNSS. (2019). Galileo-Open Service-Service Definition Document, Issue 1.1, May 2019. Retrieved from https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-OS-SDD_v1.1.pdf

GPS modernization (n.d). GPS.Gov. Retrieved August 08, 2020, from https://www.gps.gov/systems/gps/ modernization/

GPS World. (2010, October 1). *GLONASS forecast bright and plentiful.* Retrieved from https://www.gpsworld.com/the-system-glonass-forecast-bright-and-plentiful/

GPS World. (2017). *GLONASS ground station goes live in South Africa*. Retrieved from https:// www.gpsworld.com/glonass-ground-station-goes-live-in-south-africa/

GPS World. (2020, January 21). *4th GPS civilian signal goes live*. Retrieved from https://www.gpsworld.com/4th-gps-civilian-signal-goes-live/

Graham, W. (2020, October 25). Russia launches Soyuz with next-generation navigation satellite. *Spaceflight*. Retrieved from https://www.nasaspaceflight.com/2020/ 10/russia-launches-soyuz-with-next-generation-navigation-satellite/

Grewal, S. M., Andrews, P. A., & Bartone, G. C. (2020). *Global Navigation Satellite Systems, Inertial Navigation, and Integration* (Fourth edition). Retrieved from https: //online library.wiley.com/doi/pdf/ 10.1002/9781119547860

Groves D.P. (2008).*Principles of GNSS, Inertial, and Multisensor integrated navigation Systems*. Retrieved from http://read.pudn.com/downloads614/ebook/2502316/Principles%20of%20GNSS,%20Inertial,%20and%20 MultiSensor%20Integrated%20Navigation%20Systems.pdf

Guo, C., Xu, B., & Tian. (2018). Research on multi-constellation GNSS compatible acquisition strategy based on GPU high-performance operation. *EURASIP Journal on Wireless Communications and Networking.* Retrieved from https://www.researchgate.net /publication/325047946_Research_on_multi-constellation_GNSS_compatible_ acquisition_strategy_based_on_GPU_high-performance_operation

Hein, G. (2006). GNSS Interoperability: Achieving a Global System of Systems or Does everything has to be the same? *Inside GNSS*. Retrieved fromhttps://www.insidegnss.com/auto/ 0106_Working_Papers_IGM.pdf

Hein, G.W. (2020). Status, perspectives and trends of satellite navigation. *Satellite Navigation, 1(*22). https:// doi: 10.1186/s43020-020-00023-x

Hennesey, R. M. (2018, March 20). GNSS receiver demonstration. *National Mapping and Resource Information*. Retieved from https://unstats.un.org/unsd/geoinfo/UNGEGN/docs/Training/Manila/day%202/08_MAR OHOM_GNSS_Demo.pdf

Hofmann-Wellenhof B., Lichtenegger H., and Collins J. (2001), *Global Positioning System:Theory and Practice*. Retrieved from https://www.springer.com/gp/book/9783211835340

HEXAGON. (2020a). *GNSS Frequencies and Signals*. Retrieved from https://novatel.com/support/known-solutions/gnss-frequencies-and-signals

HEXAGON. (2020b). *Satellite Based Augmentation Systems*. Retrieved from https:// novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/satellite-based-augmentation-systems

Hunter-Spirent, M. (2018, September 18). BeiDou Frequency Bands. Newsletter. *EverythingRf*. Retrieved from https://www.everythingrf.com/community/beidou-frequency-bands

Information and analysis center for positioning, navigation and timing (IACPNT), (n.d). GLONASS Constellation Status. Retrieved on November 10, 2020, from https://www.glonass-iac.ru/en/GLONASS/

Inside GNSS. (2019). *International Committee on GNSS-13 Focuses on PNT in High Earth Orbit and Beyond*. Retrieved from https://insidegnss.com/international-committee-on-gnss-13-focuses-on-pnt-in-high-earth-orbit-and-beyond/

Inside GNSS. (2020a, August 4). *Ready, Steady, Go — Here at Last Comes GLONASS-K*. Retrieved from https://insidegnss.com/ ready-steady-go-here-at-last-comes-glonass-k/

Inside GNSS. (2020b, September 8). *Third GLONASS-The First in Six Years — to Launch in October*. Retrieved from https://insidegnss.com/third-glonass-k-the-first-in-six-years-to-launch-in-october

Irene, K., Tony, O., & Bradley, P. (2018). *The rise of new navigation satellites.Aviation Week & Space Technology*. Retrieved from https://aviationweek.com/defense-space/space/rise-new-navigation-satellites

Jerez, G. O., & Alves, D. B. M. (2019). Generation and performance analysis of GPS and GLONASS virtual data for positioning under different ionospheric conditions. *Boletim de Ciências Geodésicas*, 25(2). https://doi.org/10.1590/s1982-21702019000200007

Joel J. K. P., Frank H. B., Benjamin W.A., James J. M., Enderle, W., & Blonski, D. (2018). Development of an Interoperable GNSS Space Service Volume. *European Space Agency*. Retrieved from http://navigation-office.esa.int/attachments _38502812_1_Paper ___ Development _of_an_Interoperable_GNSS _Space_Service _Volume ___ Parker.pdf

Kriening, T. (2019, January 23). Japan prepares for GPS failure with Quasi-Zenith. *SpaceWatch.* Retrieved from https://spacewatch.global/2019/01/japan-prepares-for-gps-failure-with-quasi-zenith-satellites/

Langley, B. R. (2017, November 1). Innovation: GLONASS-past, present and future. *GPS World.* Retrieved from https://www.gpsworld.com/ innovation-glonass-past-present-and-future/

Langley R. B., Teunissen P.J., Montenbruck O. (2017) Introduction to GNSS. In: P.J. Teunissen, O. Montenbruck (Eds.), *Springer Handbook of Global Navigation Satellite Systems* (pp. 3-33). https://doi.org/10.1007/978-3-319-42928-1_1

Li, Y., Shivaramaiah, N.C. & Akos, D.M. (2019). Design and implementation of an open-source BDS-3 B1C/B2a SDR receiver. *GPS Solution 23*(60). https://doi.org/10.1007/s10291-0

Li, R., Zheng, S., Wang, Z., Tang, Y., Sun, S., & Huang, Z. (2018). Evaluation of GNSS signal-in space continuity: A Weibull-distribution-based method. *Chinese Journal of Electronics*, *27*(3). Pp. 634–640.

Lu, J., Guo, X. & Su, C. (2020). Global capabilities of BeiDou Navigation Satellite System .*Satellite Navigation, 1*, 27. https://doi.org/10.1186/s43020-020-00025-9

Lu, M., Li, W., Yao, Z., & Cui, X. (2019). Overview of BDS III new signals. *Navigation, 66*(1), Pp. 19-35. Retrieved from https://doi.org/10.1002/navi.296

Lu, (2018, November). *Overview of the BDS III Signals*. Symposium conducted at the 13th Stanford PNT meeting of the Tsinghua University. Retrieved from http://web.stanford.edu/group/scpnt/pnt /PNT 18

Mahashreveta, C. (2019, November 20). What are various GNSS systems? *Geospatial World*. Retrieved from https://www.geospatialworld.net/blogs/what-are-the-various-gnss-systems/

Murphy, J. (2018, September 19). What is SBAS and how does it work? *Official blog of Juniper systems.* Retrieved from https://blog.junipersys.com/how-does-sbas-improve-gps-free-sbas-coverage-map/

New civil signals. (n.d). GPS.Gov. Retrieved August 08, 2020, from https://www.gps.gov/systems /gps/ modernization /civilsignals

Next Generation Operational Control System (OCX). (n.d). *GPS.Gov.* Retrieved August 08, 2020, from https://www.gps.gov/systems/gps/control/OCX/

Pawel, W., Tomasz, H., Anna, K., Jacek, P. (2019). Research on GNSS positioning and applications in Poland in 2015-2018.*Geodesy and Cartography, 68*(1), 87-119. doi:10.24425/gac.2019.126089

Pietrobon, S. (2018, June 18). *Russian launch manifest.* Retrieved from https://www.sworld.com.au/steven/space/russia-man.txt

Rita, M. L., Thomas, D. [Powell], and Thomas, A. [Stansell]. (2012). The Interchangeability Problem: Signals, Coordinate Frames, and Time. *Global Navigation Satellite Systems: Report of a Joint Workshop of the National Academy of Engineering and the Chinese Academy of Engineering*. Washington, DC: The National Academies Press. https://www.nap.edu/read/13292/chapter/9

Sanz Subirana, J., Juan Zornoza, J. M., & Hernández-Pajares, M. (2013). *GNSS data Processing: Volume I: Fundamentals and Algorithms*. Retrieved from: https://gssc.esa. int/navipedia/ index.php/ GLONASS_Space_Segment#cite_ref-GNSS-Book_1-1

Shen, J. (2016). *Update on Beidou navigation satellite system.* Paper presented at the 56th Meeting of the Civil GPS Service Interface Committee at the ION GNSS+ 2016 Conference, Portland, Oregon, USA. Retrieved from https://www.gps.gov/cgsic/meetings/2016/shen.pdf

Stuart, C. (2020, June 23). China launches last Beidou to rival GPS. *Spacewatch*. Retrieved from https://www.theguardian.com/science/2020/jun/25/spacewatch-china-launches-final-beidou-satellite-rival-gps-navigation-system

Stupak, G. (2015, November). *Compatibility and interoperability of GNSS.* Paper presented at the tenth meeting of the International Committee on GNSS, Boulder (USA). Retrieved from https://www.unoosa.org/pdf/ icg/2015/icg10/wg/wga12.pdf

Sun, Y. (2019). GNSS brings us back on the ground from ionosphere. *Geoscience Letters, 6*(14). https:// doi.org/10.1186/s40562-019-0144-0

Tholert, S. (2019). Latest GNSS signal in space developments – GPS, QZSS & the new Beidou 3 under examination. *E3S Web of conferences, 94*(6):03016. https://doi:10.1051/e3sconf/20199403016

Turner, D. A. (2010). GNSS Interoperability through International Cooperation. *Institute of Navigation*. https://www.gps.gov/multimedia/presentations/ 2010/ 09/ION/ turner.pdf

United Nations Office for Outer Space Affairs (UNOOSA). (2018). *The Interoperable Global Navigation Satellite Systems Space Service Volume* (ST/SPACE/75). Retrieved from http:// navigationoffice.esa.int/ attachments_38503197_1_The_Interoperable_Global_Navigation_Satellite_Systems_Space_Service_ Volume___UnitedNations_SSV_booklet_2018.pdf

United Nations Office for outer space affairs. (2020). *International Committee on Global Navigation Satellite Systems (ICG): Providers' Forum.* Retrieved from https://www.unoosa.org/oosa/en/ourwork/icg/providers-forum.html

Uragan, Russian Space Web. (2016, May 28). Retrieved from http://www.russianspaceweb.com /uragan.html

Wang, J., & Knight, L. N. (2011). Impact of the GNSS Time Offsets on Positioning Reliability. *Journal of Global Positioning Systems*, *10*(2). Doi:10.5081/jgps.10.2.165

Winternitz, L. (2017, June). *Introduction to GPS and other Global Navigation Satellite Systems*. Paper presented at the 42nd annual time and frequency metrology seminar. Retrieved from http://www.spaceflightfans.cn/ wp-content/uploads/2017/12/Introduction-to-GPS-and-other-Global-Navigation-Satellite-Systems.pdf

Yang Y. (2010).Progress, contribution, and challenges of COMPASS/BeiDou satellite navigation system. Acta *Geodaeticaet Cartographica Sinica, 39*(1), pp.1-6.https://doaj.org/article/adc121ac6a454fed 8b2a5a 284ca3fc1e

Yang, Y. X., Gao, W., Guo, S., Mao, Y., & Yang, Y. (2019). Introduction to Bei-Dou-3 navigation satellite system. *Navigation, 66*(1), 7–18.https://onlinelibrary.wiley.com/doi/abs/10.1002/navi.291

Yang, Y., Li, J., Wang, A., Xu, J., He, H., Guo, H., et al. (2014). Preliminary assessment of the navigation and positioning performance of BeiDou regional navigation satellite system. *Science China: Earth Sciences, 57*(1), 144–152. https://doi.org/10.1007/s11430-013-4769-0.

Yang, Y., Mao, Y., & Sun, B. (2020). Basic performance and future developments of BeiDou global navigation satellite system. *Satellite Navigation*, *1*, 1–8. https://doi.org/10.1186/s43020-019-0006-0.

Yang, Y. X., Tang, J., & Montenbruck, O. (2017). Chinese satellite navigation system. In P. Teunissen & O. Montenbruck (Eds.), *Handbook of global navigation satellite system* (pp. 273–304). New York: Springer.

Yang, Y., Xu, Y., Li, J., & Yang, C. (2018). Progress and performance evaluation of BeiDou global navigation satellite system: Data analysis based on BDS-3 demonstration system. *Science China: Earth Sciences, 61*(5), 614–624.https://link.springer.com/article/10.1007/s11430-017-9186-9

Yao Z, Lu, M. (2011, September). *Optimized modulation for compass B1-C signal with multiple processing modes.* Paper presented at the 24th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2011), *Portland*.

Yury, U. (2018, December 12). Direction 2019: High-orbit GLONASS and CDMA signal. *GPS World*. Retrieved from https://www .gpsworld.com/directions-2019-high-orbit-glonass-and-cdma-signal/

Zak, A. (2020, October 28). *Deployment of the GLONASS constellation*. Retrieved from http://www.russianspaceweb.com/glonass_deployment.html

Zhu, J., Liu, Y., Wang, B., & Ye, S. (2018). Improved method for glonass long baseline ambiguity resolution without inter-frequency code bias calibration. *Remote Sensing*, 10. doi:10.3390/rs10081223