Modern Satellite Navigation:
What is Beyond GPS L1 C/A?

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ABSTRACT

Global Navigation Satellite Systems (GNSS) have been changing significantly in the last decade. With the US GPS, the Russian GLONASS, the European Galileo and the Chinese BeiDou, four truly global satellite constellations are in operation. The increased number of available satellites as well as novel GNSS signals broadcast in different frequency bands will allow new GNSS applications and services in the future. This is often designated using the terms multi-constellation (MC) and multi-frequency (MF) GNSS. MC GNSS indicates the use of more than one satellite constellation, whereas MF GNSS indicates the parallel use of multiple signals in more than one frequency band per satellite.

Multi-constellation GNSS primarily benefits from the increased number of ranging sources for positioning and subsequently from a decreased dilution of precision. In addition, an MC GNSS user still can operate reliably in case of a system-wide malfunction of any GNSS constellation.

Multi-frequency GNSS benefits from having usable ranging signals from one satellite in more than one frequency band. By selectively combining multiple measurements, one can get hybrid measurements with characteristics tailored to the intended operation. This way, MF GNSS can help to increase the integrity or to allow for high-precision applications.

For primary aircraft navigation however, hardly any of these features of modern satellite navigation systems are in use today. Most certification documents focus on the legacy GPS L1 C/A signal only and thus currently impede the use of any other signal or constellation. Even though this is being addressed in various panels, the additional constellations and signals lack the operational experience that have been gained with GPS (and GLONASS) over the last decades.

This paper summarizes and explains the new GNSS constellations, signals, and capabilities, as well as their possible application, especially in the flight inspection domain.

INTRODUCTION

The US NAVSTAR GPS system became operational in 1993 and has been used in multiple domains ever since. As a military system developed and operated by the US Department of Defense, only a limited subset of services and signals was available for civil users. The basic GPS service was based on a single-frequency ranging code whose performance was even artificially degraded by a feature called “selective availability” (SA) until 2000.

During the cold war, the Soviet Union developed a similar (military) system called GLONASS, which became operational in 1993 (now operated by the Russian Federation). Due to Russia’s economic crisis in the following years, the number of usable satellites decreased to a minimum of six in 2001, but increased afterwards due to huge modernization efforts. In 2015, Russia officially declared GLONASS completed.

Both GPS and GLONASS have been included in ICAOs Standards and Recommended Practices (SARPs, Annex 10, [1]) as core constellations so that the use of their civil L1 signals is harmonized internationally. However, as most (western) regulators currently only allow the installation of GPS-only receivers, virtually all primary navigation equipment in the western hemisphere is currently using GPS only.

Aside from this, the overall GNSS landscape has been changing significantly over the last decade. New global navigation satellite systems like the European Galileo system and the Chinese BeiDou systems were introduced, using novel modulation types, orbit types and operational capabilities. This in turn also has led to significant modernization efforts for the legacy systems.

However, most of these new features cannot be used for primary aircraft navigation yet as the standardization etc. is not completed. This is why even today only the most traditional GPS signal (GPS L1 C/A) is used for primary aircraft navigation. Even when complemented with SBAS or GBAS, GPS L1 C/A is still the backbone for airborne radionavigation. All additional modernized features / signals / systems are currently unusable in most parts of the world for primary navigation. This will however most likely change in the future.

This could also lead to significant differences in the flight inspection domain in the future. On the one hand, if more systems and signals would be usable for primary aircraft navigation, flight inspection systems could also have to include additional checks in order to ensure the safety of a GNSS-based procedure. On the other hand, modern flight inspection systems also use GNSS for calculating a precise reference position that could benefit significantly from the modern GNSS capabilities available.

GNSS FREQUENCIES

The International Telecommunication Union (ITU) manages the use of the radio frequency spectrum all over the world, in order to ensure proper operation of all services using radio frequency signals. The ITU’s Radio Regulations [2] thus define specific frequency bands and allocate services to operate in these bands.

Table 1: Global Service Allocations for GNSS by ITU [2]

Frequency (MHz)	Allocation to Services
1164-1215	AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (space-to-Earth)
1215-1240	RADIONAVIGATION-SATELLITE (space-to-Earth)
1240-1300	RADIONAVIGATION-SATELLITE (space-to-Earth)
1300-1350	AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (space-to-Earth)
1559-1610	AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (space-to-Earth)
2483.5-2500	RADIODETERMINATION-SATELLITE (space-to-Earth)

In short, a GNSS may only transmit signals in the bands allocated to RADIONAVIGATION-SATELLITE (space-to-Earth)” or “RADIODETERMINATION-SATELLITE (space-to-Earth)”. In addition, only those frequency bands that are allocated to “AERONAUTICAL RADIONAVIGATION” are protected from other users and can be used for primary navigation.

In the band between 1300 and 1350 MHz, GNSS is only a secondary user. This means GNSS may not cause any interference with the band’s primary users (ground-based radars and associated airborne transponders). This implies that GNSS signals in this band are not protected and must not be used for primary navigation.

In total, only the frequency bands between 1164 and 1215 MHz and between 1559 and 1610 MHz can be used for primary aircraft navigation. All GNSS constellations offer (or will offer) various navigation signals in different bands. As most frequency bands are relatively close to each other in the L-band, GNSS receivers and antennas can be designed to cover all usable frequencies with one common RF stage. This is why commercial (non-aviation) GNSS receivers and antennas often support more than one frequency/signal.

The term multi-frequency (MF) GNSS describes signals that simultaneously us more than one frequency. With MF GNSS it is for example possible to eliminate specific errors originating from the ionosphere (as this error is frequency-dependent). The threat due to ionospheric effects is one of the major unknowns and integrity risks for safety-critical GNSS applications. With two independent signals on different frequencies of the same satellite, a multi-frequency user can eliminate these frequency-dependent errors completely, effectively mitigating safety (integrity) impacts. This is why the use of multi-frequency GNSS also for primary navigation could enable more aviation use-cases in the future.

GNSS CONSTELLATIONS AND SIGNALS

In total, four different global navigation satellite systems are in operation at the moment: the Global Positioning System (GPS) operated by the United States, the Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) operated by the Russian Federation, the European Galileo system and the Chinese BeiDou system. In the scope of the ICAO, these four systems are referred to as “core constellations”.

In addition to these globally available systems, two regional systems provide coverage to a specific operation region only: the Indian NavIC system and the Japanese QZSS system. Even though these systems can be very beneficial to use in those regions, this paper will focus on the systems available globally.

Each of these global navigation satellite systems consists of a constellation of multiple satellites. Each satellite provides not only a ranging information but also additional navigation data (e.g. ephemeris data). A GNSS user has to receive the signals of multiple satellites in order to obtain its own position and the current time. The more satellite signals are received, the better the resulting positioning accuracy will be in most situations.

Global Positioning System (GPS)

The development of the Navstar Global Positioning System (GPS) started in the early 1970s. Initiated and operated by the U.S. Department of Defense (DOD), GPS was designed initially as a purely military system, with its civil-usable signals artificially degraded using a technology called Selective Availability (SA). The GPS was declared fully operational in 1995. Only after a presidential decision to allow for civil use in 2000, the artificial degradation of performance due to SA ceased and is no longer implemented for new satellite generations.

Traditionally, civil users could only use the GPS L1 C/A (for coarse-acquisition) signal as part of the standard positioning service (SPS), while military users could use dual-frequency signals for eliminating ionospheric effects as part of the precise positioning service (PPS). However, with the modernization of GPS, additional signals were introduced with new satellite generations. All currently broadcast signals are shown in Table 2. The civil signals are detailed in their corresponding interface control documents (ICD) [3] [4] [5].

Table 2: GPS Signals

Signal		Center Frequency	Civil (C) / Military (M)	Notes
GPS	L1 C/A	1575.42 MHz	C	Starting with Block I satellites (first launch in 1978)
	L1 P(Y)		M	Starting with Block I satellites (first launch in 1978)
	L1C		C	Starting with Block III satellites (first launch in 2018)
	L1M		M	Starting with Block IIR-M satellites (first launch in 2005)
	L2 P(Y)	1227.5 MHz	M	Starting with Block I satellites (first launch in 1978)
	L2C		C	Starting with Block IIR-M satellites (first launch in 2005)
	L2M		M	Starting with Block IIR-M satellites (first launch in 2005)
	L5	1176.45 MHz	C	Starting with Block IIF satellites (first launch in 2010)

The power spectral density (PSD) of all GPS signals in the different bands is shown graphically in Figure 1. The PSD of a signal indicates how the transmitted energy of a specific signal is distributed over the allocated bandwidth.

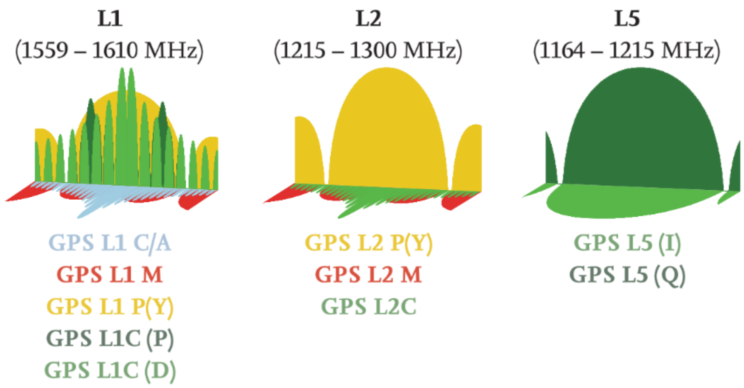

Figure 1: PSD of GPS Signals

Out of these signals, only the GPS L1 and L5 signals lie within the ITU's "AERONAUTICAL RADIONAVIGATION" bands. This means that – next to the GPS L1 C/A signal currently used dominantly – also GPS L5 and L1C could be used for primary aircraft navigation in the future.

GLONASS

GLONASS is the cold-war GPS equivalent developed by the (then) Soviet Union, providing initial operating capability in 1993. GLONASS struggled to maintain its required number of satellites following the collapse of the Soviet Union and the economic crisis in Russia. However, after receiving substantial funding in the late 1990s, GLONASS now provides a stable number of usable satellites. Despite being similar in its overall conception, it operates rather differently in detail compared to GPS.

Traditionally, GLONASS has been using Frequency Division Multiple Access (FDMA) since its initial conception. In contrast to Code Division Multiple Access (CDMA), FDMA ensures that each satellite transmits on a slightly different carrier frequency. In contrast to GPS, GLONASS has been allowing the parallel use of two civil signals (L1OF, L2OF) for years [6].

In recent years however, GLONASS initiated a system-wide modernization including additional CDMA signals [7]. Next to the L1 [8] and L2 [9] bands, these modernized signals will also cover the L3 band [10] with a center frequency of 1202.025 MHz.

All GLONASS signals are denoted by a four-character combination, like L1OF for the civil FDMA signal in the L1 band, or L2SC for the secured (military) CDMA signal in the L2 band. All signals currently broadcast are shown in Table 3.

Table 3: GLONASS Signals

Signal		Center Frequency	Civil (C) / Military (M)	Notes
GLONASS	L1OF	1598.0625 MHz - 1605.3750 MHz	C	FDMA, starting with GLONASS satellites (first launch in 1982)
	L1SF		M	FDMA, starting with GLONASS satellites (first launch in 1982)
	L1OC	1600.995 MHz	C	CDMA, starting with GLONASS K2 satellites (not launched yet)
	L1SC		M	CDMA, starting with GLONASS K2 satellites (not launched yet)
	L2OF	1242.9375 MHz - 1248.6250 MHz	C	FDMA, starting with GLONASS satellites (first launch in 1982)
	L2SF		M	FDMA, starting with GLONASS satellites (first launch in 1982)
	L2OC	1248.06 MHz	C	CDMA, starting with GLONASS-K1+ satellites (first launch in 2017)
	L2SC		M	CDMA, starting with GLONASS-K1+ satellites (first launch in 2017)
	L3OC	1202.025 MHz	C	CDMA, starting with GLONASS-L1 satellites (first launch in 2012)

The signals are distributed over the frequency bands as shown in Figure 2.

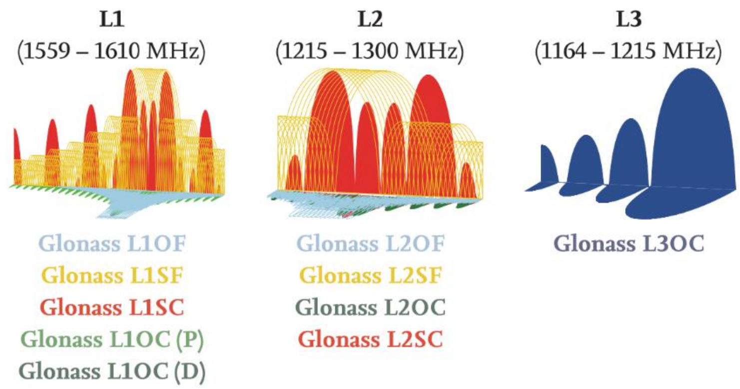

Figure 2: PSD of GLONASS Signals

For the legacy FDMA signals, each visible satellite transmits its signals on slightly different carrier frequencies in the L1 and L2 bands:

$$f_{L1} = (1602 + k \cdot 0.5625)\ MHz$$

$$f_{L2} = (1246 + k \cdot 0.4375)\ MHz$$

The factor k indicates the channel number, ranging currently between -7 and +6. Identical channel numbers are given to two antipodal satellites so that two satellites with the same frequency are never visible simultaneously. Due to the different carrier frequencies, the wavelengths of the received signals differ slightly, too. For example, this poses a challenge for using GLONASS FDMA signals in phase-differential position solutions like RTK.

Out of all GLONASS signals, L1OF, L1OC and L3OC are protected for primary aviation use. However, only L1OF is currently included in the ICAO SARPs.

Galileo

Galileo is a global navigation satellite system operated by the European Union via its "European Union Agency for the Space Programme" (EUSPA). Despite being developed as a purely civilian system, Galileo nowadays also provides military (encrypted) signals. All Galileo signals are shown in Table 4 and are broadcast by all operational Galileo satellites.

Table 4: Galileo Signals

Signal		Center Frequency	Civil (C) / Military (M)	Notes
Galileo	E1-BC	1575.42 MHz	C	Part of the Open Service (OS).
	E1-A		M	Part of the Public Regulated Service (PRS).
	E6-BC	1278.75 MHz	C	Part of the High Accuracy Service (HAS).
	E6-A		M	Part of the Public Regulated Service (PRS).
	E5b	1207.14 MHz	C	Part of the Open Service (OS). The E5 (altboc) signal consists of the E5a and E5b sub-components. Galileo-capable receivers can track both components either individually or jointly.
	E5 (altboc)	1191.795 MHz	C	
	E5a	1176.45 MHz	C	

The resulting power spectrum distribution of the Galileo signals is shown in Figure 3.

Figure 3: PSD of Galileo Signals

Galileo provides different services for its users, each of them incorporating different signals:

- The Open Service (OS) [11] is a civil-usable service using the E1-BC and E5a/b signals.
- The Public Regulated Service (PRS) is an encrypted service for (mostly) military users, which is especially robust against jamming. It uses the E1-A and E6-A signals and is not described publically.
- The High-Accuracy Service (HAS) [12] is intended to provide precise point positioning (PPP) services in the future. For this, it will use the E6-BC signal. The HAS will offer two service levels with slightly different levels of performance. While a basic service will be offered globally, the high accuracy service will be limited to Europe only.

With its development, Galileo actually triggered the modernization of both GPS and GLONASS. Galileo tries to continue to be on the forefront of GNSS development, for example by its message authentication mechanism allowing to ensure that navigation data originates from the Galileo system itself and is not spoofed by a third party.

BeiDou

The BeiDou Navigation Satellite System (BDS) is a GNSS operated by the People's Republic of China. The BeiDou system is being implemented in three stages. The first stage, called BDS-1, was an experimental testbed providing regional service in China only. The first of four BDS-1 satellite launched in October 2000. BDS-1 ceased operation in 2012.

The second stage, called both BDS-2 and Compass, provides worldwide service with a special regional focus. It operates totally independent of BDS-1 and incorporates in total 20 satellites launched between 2007 and 2019. These satellites are placed in different orbits; besides medium-earth orbit (MEO) satellites (as with the other constellations), inclined geo-synchronous orbit (IGSO) and geo-stationary (GEO) satellites are part of the BDS-2 constellation. BDS-2 included signals in three frequency bands [13] and was declared fully operational in 2012.

The third stage is called BDS-3 and is an evolution of BDS-2, offering a global positioning service. While most of the signals transmitted in BDS-2 are also transmitted, BDS-3 features additional signals [14, 15, 16, 17, 18] as shown in Table 5. BDS-3 similarly uses satellites on different orbits and includes 24 MEO satellites, 3 IGSO satellites and 3 GEO satellites launched between 2017 and 2020.

Table 5: BeiDou Signals

Signal		Center Frequency	Civil (C) / Military (M)	Notes
BeiDou	B1C	1575.42 MHz	C	BDS-3, SBAS from GEO satellites
	B1A		M	BDS-3
	B1-I	1561.098 MHz	C	BDS-2 and BDS-3
	B1-Q		M	BDS-2 and BDS-3
	B3-I	1268.52 MHz	C	BDS-2 and BDS-3
	B3-Q		M	BDS-2 and BDS-3
	B3-A		M	BDS-3
	B2-I	1207.14 MHz	C	BDS-2 only
	B2-Q		M	BDS-2 only
	B2b		C	BDS-3, PPP from GEO satellites
	B2a	1176.45 MHz	C	BDS-3

The resulting power spectrum distribution of the BeiDou signals is shown in Figure 4.

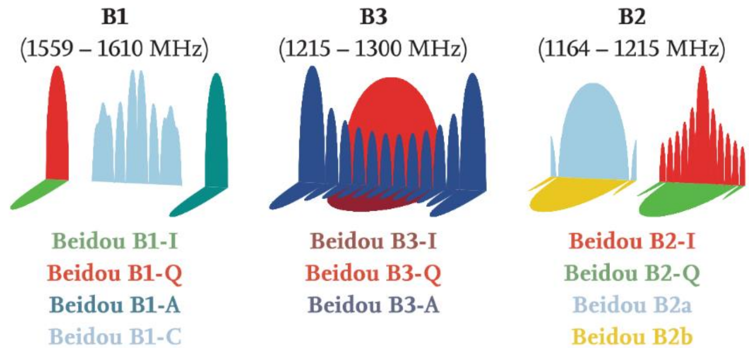

Figure 4: PSD of BeiDou Signals

An interesting feature of BDS-3 is that the GEO satellites will provide a PPP service for China [19] via the B2b signal.

GNSS Augmentation

The performance of GNSS is sufficient for a variety of applications. Aircraft navigation however requires for every phase of flight an integrity (i.e. a certain measure of trust a pilot can have in the correctness of any given information) that cannot be met by any GNSS constellation. This is why any kind of augmentation is always required. Three different augmentation systems are used in aviation.

Firstly, aircraft based augmentation systems (ABAS) are used. ABAS ensure a certain level of integrity without information from outside the aircraft. The most common ABAS implementation is the receiver autonomous integrity monitoring (RAIM) which uses the redundant satellite measurements in order to detect a possible failure in a GNSS satellite. This way, GNSS receivers with RAIM allow for en-route and non-precision approach guidance.

Secondly, in a space based augmentation system (SBAS), geostationary satellites provide corrections for GNSS measurements. An SBAS user receives the SBAS data next to the GNSS data, and uses it to correct the raw GNSS measurements in order to achieve a significant improved performance. SBAS-based receivers allow for performance levels sufficient to enable localizer performance with vertical guidance (LPV) approaches down to a decision height of 200 ft. Different SBAS implementations are available, each of them covering a certain region. In regular operation are the Wide Area Augmentation System (WAAS, USA) since 2003, the MTSAT Satellite Augmentation System (MSAS, Japan) since 2007, the European Geostationary Overlay System (EGNOS, Europe) since 2011, and the GPS Aided Geo Augmented Navigation (GAGAN, India) since 2013. All of them allow for LPV approaches using GPS L1 C/A. Various other implementations as well as enhancements to the current systems are currently planned and under development. One example for this is BeiDou, which will include SBAS compatible messages via their B1-C signal [20] from the geostationary BDS-3 satellites.

Thirdly, the ground based augmentation system (GBAS) allows to perform precision approaches using differential corrections generated at an airport and broadcast via a VHF data broadcast (VDB). GBAS ground stations are installed at certain airports worldwide and allow precision approaches for GBAS equipped aircraft down to CAT-I visibility minima. Western GBAS equipment currently only supports GPS L1 C/A as underlying GNSS signal. However, Russian ground installations also allow for the use of GLONASS L1OF in addition. Most standardization has also been completed for a GBAS Approach Service Type (called GAST-D) that will support low-visibility operations in CAT-II/III minima.

MODERN SATELLITE NAVIGATION

Compared with GPS-only navigation, the parallel use of all available GNSS constellations and signals can enable completely new or significantly improved navigation services. The parallel use of satellites of more than one constellation is denoted multi-constellation GNSS (MC GNSS), while the parallel use of signals in more than one frequency band is denoted multi-frequency GNSS (MF GNSS). Both principles can be used to improve accuracy, integrity and/or availability of positioning.

Compared to the use of just one constellation (e.g. GPS) and one signal (e.g. GPS L1 C/A), the parallel use of different constellations and signals can help to improve the overall positioning performance significantly. This section will describe different techniques made possible by the availability of modern GNSS constellations and signals.

Multi-Constellation GNSS

The parallel use of measurements of more than one core constellation has several positive effects on GNSS positioning. Firstly, the number of usable satellite is vastly increased. More usable satellites mean better geometries and thus less dilution of precision (DOP), resulting in an improved positioning accuracy. Secondly, MC GNSS can also protect users from constellation-wide faults if enough satellites for each GNSS constellation are used. An autonomous integrity check comparing the overall multi-constellation solution with the individual single-constellation solutions can detect and exclude such failure conditions, improving the positioning integrity.

For multi-constellation GNSS it is crucial to consider inter-system biases due to slight differences between the constellations' individual time references. As GNSS is based on precise timing, even tiny differences between the constellations' time reference frames can lead to significant positioning errors. Even though most constellations transmit inter-system bias parameters as part of their navigation data, multi-constellation GNSS users usually estimate the inter-system biases along with the receiver time error within the position calculation. This implies that multi-constellation GNSS users have to extend the (to be estimated) state vector by a system-clock offset for each additional GNSS constellation. This also means that, instead of one time dilution of precision (TDOP) parameter, multiple TDOP parameters exist when using multiple constellations. If for example only one satellite of a specific constellation is used, this does not contribute to an improved positioning accuracy but only to the estimation of the inter-system bias for this constellation.

The use of multiple constellations in ABAS receivers using RAIM is not simply possible as this algorithm can detect a single failure of a GNSS satellite only. With more than one constellation, an ABAS implementation would need to check for more than this single cause of error. Thus, all certified ABAS receivers only use GPS L1 C/A at the moment. Enhanced concepts like Advanced RAIM (ARAIM) are currently under development addressing this.

Current operational SBAS implementations also support GPS L1 C/A only. However, most systems plan to incorporate differential corrections for other GNSS constellations in the future in order to achieve an improved level of performance in the future. Examples for this are EGNOS v3 (GPS + Galileo), BDSBAS (GPS + BeiDou) or SDCM (GPS + GLONASS).

On the ICAO level, GBAS is designed to support both GPS and GLONASS ranging sources. However, GBAS systems in the western world are limited to GPS L1 C/A only. In contrast, Russian GBAS ground installations already support GPS and GLONASS in parallel. This allows approaching aircraft to use GPS only, GLONASS only, or both systems in parallel. Aside from this, development is ongoing to also include other constellations for GBAS, too. This however is constrained by the data capacity offered by the VHF data broadcast.

Multi-Frequency GNSS

The availability of range and phase measurements on different frequencies for a single satellite allows for the construction of linear combinations of measurements. Such virtual GNSS measurements can be tailored to specific characteristics and can be used instead of the original measurements to certain extend.

One example for a linear combination of multi-frequency GNSS measurements is the ionosphere-free combination (IFree). The ionosphere can be a significant source of errors as it affects the GNSS signal between the satellite and a user. Ionospheric effects influence code and phase measurements diametrically. However, most ionospheric errors are proportional to the carrier frequency. If multi-frequency GNSS users have raw measurements on different frequencies for a specific satellite available, an ionosphere-free linear combination can be calculated. This artificial (combined) measurement still contains the range between satellite and receiver, but eliminates the majority of ionospheric effects. This significantly improves the integrity as certain ionospheric effects can hardly be predicted. The drawback is the increased noise of the ionosphere-free linear combination.

A multi-frequency GNSS user can calculate several other linear combinations with different characteristics in parallel, which can be used to monitor specific errors in subsequent processing. Multi-frequency GNSS is however not necessarily a mitigation against radio-frequency interference (RFI). Even if interference occurs only in one frequency band directly, other frequency bands can be affected if the antenna's amplifier is driven into saturation by the interference. Strong interferers can thus deny GNSS positioning in all bands even if only one band is affected.

For airborne navigation, MF-GNSS is advantageous as it can be used to eliminate the effects of the ionosphere (which is a major source of uncertainty for the overall integrity) almost completely, but suffers from a significantly increased measurement noise. However, as none of the augmentations currently implemented supports MF-GNSS, only single-frequency GNSS is currently used. ARAIM (as a future ABAS implementation) however will be based not only on MC-GNSS, but also on dual-frequency (L1 & L5) measurements.

In the field of space based augmentation systems, many SBAS implementations experiment with L1/L5 broadcasts. Such a future SBAS service will provide correction data on and for both signal bands, allowing its users to either use L1 signals, L5 signals, or the combination of L1/L5 signals. All operational SBAS broadcasts however only support L1 measurements at the moment.

GBAS currently only supports L1 signals, even though the extension of L5 signals is being researched in order to provide a future GAST-F service. However, as the VDB capacity is severely limited, the transmission of the additional corrections is particularly challenging [21].

Real Time Kinematics (RTK)

Real Time Kinematics (RTK) is commonly used as a high-precision reference solution, especially in the flight inspection domain. It uses differential correction data uploaded to the user from a nearby ground reference station for a phase-based position solution (thus, it is also called phase-differential GNSS or PDGNSS). This way it is possible to eliminate most errors and to fix the integer ambiguities of the phase measurements in the vicinity of the reference station. RTK can achieve sub-centimeter accuracy when all ambiguities are fixed correctly.

Historically, most RTK implementations used only GPS. The GPS L1 C/A signal was used primarily, and the (encrypted) GPS L1 P(Y) signal was tracked using code-less correlation techniques. This allowed to use the pseudorange (code) and phase measurements of the GPS L1 C/A signal, as well as the phase measurements of the GPS L2 P(Y) signal. Due to these constraints, the usability of RTK is rather constrained, as this technique requires long convergence times and works best very close to the reference receiver. With the addition of additional civil-usable GPS signals (GPS L2C and L5), the resulting performance can be increased.

GLONASS has been offering dual frequency signals for decades now (GLONASS L1OF and L2OF). However, as these signals use FDMA, the carrier frequencies are not constant over all satellites, which generates additional constraints.

With the availability of more GNSS constellations and signals, RTK positioning has the potential to increase its usability significantly by a superior availability of service.

Precise Point Positioning (PPP)

In contrast to RTK, Precise Point Positioning (PPP) does not require a reference ground station in the vicinity for determining a high-accuracy reference solution. Instead, PPP service providers use networks of GNSS reference stations to model the remaining GNSS errors to an amount that the resulting position solution is highly accurate.

PPP is not a new technology and has been in widespread use for years now, mostly for post-processing. However, with the availability of multiple GNSS constellations and signals, closely-spaced global receiver networks, and the ubiquitous availability of internet connectivity, PPP has evolved to support real-time operations down to an accuracy level allowing for ambiguity resolution (AR), resulting in a similar performance to RTK. However, most real-time PPP services are not royalty-free and require constant data reception (e.g. via satellite links or internet connectivity). Furthermore, it has to be considered that some GNSS providers (e.g. Galileo and BeiDou) plan to implement free-of-charge global or regional PPP-based services in the future.

In flight inspection, PPP can serve as a flexible alternative to RTK for some operators. Without the need for a local GNSS base station, PPP can help to reduce the time necessary for performing a flight inspection. One significant disadvantage compared to RTK is due to the continental drift. RTK (with its known position of the GNSS ground station) relates the user position to this known position. As the reference point moves along with the runway, the influence of the continental drift on RTK is limited as long as all coordinates were surveyed at the same time. PPP on the other hand provides an absolute accuracy globally, which could result in significant errors if the relevant coordinates were surveyed too long ago.

STANDARDIZATION DOCUMENTS

Prior to being usable for primary aircraft navigation, any global navigation satellite system has to be included in multiple different documents created by various organizations.

On ICAO level, a global navigation satellite system has to be accepted as a core constellation as part of its Annex 10 (Standards and Recommended Practices – SARPS). As this is an annex to the original Chicago Convention, any change to the SARPs has to be accepted by the ICAO navigation system panel (NSP). Thus, even after a proposed change has been developed technically, the process to legally include these changes into the SARPs can take several years. Compared to the legacy systems, one particular challenge of the new systems (Galileo and BeiDou) is the lack of long-term operational experience. For this reason, the official ICAO SARPs still do not include Galileo and BeiDou, even though preliminary proposals towards the addition of these constellations already exist on a working paper level.

The approval of corresponding equipment however is done under the authority of a national regulator (like the Federal Aviation Administration (FAA) in the US or the European Aviation Safety Agency (EASA) in Europe). In order to ease the approval of new equipment, the regulators define (European) Technical Standard Orders (TSO / ETSO) for specific devices. In turn, these TSOs are usually based on certification documents (e.g. Minimum Operational Performance Specifications – MOPS) issued by technical organizations like the "Radio Technical Commission for Aeronautics" (RTCA) or the "European Organization for Civil Aviation Equipment" (EUROCAE). TSOs are available for GNSS antennas and for GNSS sensors using ABAS (Aircraft Based Augmentation Systems), SBAS or GBAS. ABAS is usually implemented using a Receiver Autonomous Integrity Monitoring (RAIM) function. Table 6 represents the current state of these documents in the field of global navigation satellite systems.

Table 6: GNSS-Related Documents and Technical Standard Orders

Document	(E)TSO	Description
RTCA DO-228	C144a	Passive GNSS antenna
RTCA DO-301	C190	Active L1 GNSS antenna
RTCA DO-373	-	Active L1/L5 GNSS antenna
RTCA DO-316	C196b, C206	ABAS with L1 GPS
RTCA DO-368	-	ABAS with L1 GPS & GLONASS
RTCA DO-229E	C145e, C146e, C204a, C205	SBAS with L1 GPS
EUROCAE ED-259	-	SBAS with L1/L5 GPS & Galileo
RTCA DO-246E	C162b	VDB receiver for GBAS
RTCA DO-253D	C161b	GBAS with L1 GPS

It is clearly visible that valid technical standard orders only exist for equipment using GPS in the L1 band. Even if additional documents describing additional GNSS applications (e.g. for L1&L5 or Glonass / Galileo) already exist, no straight-forward certification of such equipment is possible as no TSO exists yet.

Thus, in order to include any new GNSS constellations or signals, the harmonization on the ICAO level must be finalized, the technical standardization documents by RTCA or EUROCAE must exist, and the national regulator must have issued a corresponding TSO.

Consequently, only GPS L1 C/A is used operationally for primary aircraft navigation at the moment. This might change in the future as soon as other systems and signals are covered by corresponding TSOs, certification documents, and the ICAO SARPS.

FLIGHT INSPECTION IMPLICATIONS

The availability and operational use of several additional GNSS constellations and signals could directly affect typical flight inspection missions in the future. This paper will address three different possible implications of modern GNSS for flight inspection operations in the future.

MC/MF Primary GNSS Navigation

As stated before, additional GNSS constellations and signals (next to GPS L1 C/A) could become usable for aircraft primary navigation in the future. The ICAO foresees that multiple GNSS core constellations will be usable in the future, and that it will be up to an airborne receiver to decide which signal(s) it will use. This is in line with the concept of “Performance Based Navigation” (PBN) in which operational procedures will no longer require a specific implementation, but will only require a certain level of performance to be met.

This means that – in theory – aircraft flying a specific procedure will not ultimately use the same satellite navigation signals, but could choose out of a variety of different processing options. This could result in additional requirements for inspections. In part, flight inspections ensure that the overall performance required by a procedure is met. In order to deal with different GNSS-based positioning implementations, a flight inspection would also need to receive all possible GNSS signals, to calculate all possible processing options and to alert the operator in case any of these solutions fail to meet the required performance.

Due to this, flight inspecting a certain GNSS-based procedure might become technically more challenging. However, as long as this is not part of the ICAO DOC 8071 [22], the availability of additional GNSS constellations and signals will not have any direct effect on flight inspecting GNSS-based procedures.

Radio Frequency Interference Monitoring

With the ubiquitous use of modern GNSS in various applications, radio frequency interference (RFI) affects more and more GNSS users – not only in aviation, but also throughout all domains. This is why handling GNSS interference has become a very challenging but important task over the last years.

Radio frequency interference can be caused both intentionally (e.g. by so-called Personal Privacy Devices (PPD) or other kinds of jammers) and unintentionally (e.g. by defective or misconfigured equipment). As any user receives the GNSS signals at very low power levels, even small jammers can affect GNSS positioning in a large area.

Ensuring that used frequency bands are free of interference is one key task of the so-called spectrum monitoring. The International Telecommunication Union (ITU) requires its member states to implement spectrum monitoring as part of the national spectrum management. For this, specifically equipped flight inspection aircraft could fill monitoring gaps by providing an airborne analysis of detected RFI events [23].

This could be particularly challenging as flight inspection aircraft nowadays primarily rely on the presence and usability of GNSS signals. For analyzing GNSS-RFI, they would need to use others sensors (e.g. inertial technology [24]) to remain operational even in case of strong GNSS interference.

GNSS Reference Positioning

Most flight inspection systems use GNSS as the basis for their reference position. The required accuracy of the reference position in flight inspection usually depends on the type of procedure or navigation aid that is being evaluated.

For flight inspecting approaches into an airport, real-time kinematics (RTK) is often used. This works by placing a reference receiver at a precisely metered point on the airport and transmitting this receiver’s data to the flight inspection aircraft. RTK allows for accuracies in the centimeter range. This is achieved by using dual-frequency measurements as well as relative phase information.

Historically, most RTK implementations focus on the use of GPS L1 C/A and the code-free tracking of GPS L2 P(Y) phase. However, by using modernized signals and additional GNSS constellations, RTK could result in a significantly improved availability and accuracy, even in challenging situations (e.g. due to signal masking from nearby buildings or mountains).

Another interesting application of modern GNSS for reference positioning in flight inspection is the use of real-time precise point positioning (PPP). With more and more GNSS systems and signals becoming available, most PPP providers already allow incorporating them into a high-precision position solution. This results in significantly faster convergence times, an improved accuracy and a better availability of PPP-based solutions. The requirement of having all relevant points on the aircraft surveyed within a certain period is however not affected by this at all.

CONCLUSIONS

Driven by the possibility to determine the position, velocity and time accurately, global navigation satellite systems are used increasingly in various domains. With the addition of novel systems (Galileo and BeiDou) and the modernization of the existing systems (GPS and GLONASS), global navigation satellite systems nowadays offers great flexibility and an unprecedented overall performance.

However, due to the high complexity and stringent certification requirements of systems for primary aircraft navigation, the new possibilities of modern satellite navigation cannot be used in aviation currently. This is why the use of satellite navigation is limited to GPS L1 C/A in the majority of aircraft, augmented with either ABAS/RAIM, SBAS or GBAS. This will change in the future as soon as the regulatory documents are in place.

In the flight inspection domain, modern satellite navigation allows for a better reference positioning, either via PPP or via RTK. The availability of more usable satellites and signals allows for a better availability, shorter convergence times and improved stability. Once more than just GPS L1 C/A is usable for flying a specific procedure, flight inspection systems might have to include additional checks in order to ensure that this procedure can be used safely under all conditions.

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