Latest GNSS Signal in Space Developments – GPS, QZSS & the new Beidou 3 under examination

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Abstract

Nowadays one can use four global navigation satellite systems (GNSS). Two of them are complete constellations (GPS, Glonass) and two (Beidou, Galileo) are already usable and will be finish in the near future. Additionally satellite based augmentation systems (SBAS) like WAAS, EGNOS, GAGAN or QZSS complement the GNSS service. However, within all systems one can observe changes, modifications, and updates every year. This can be related to satellite renewables leading to signal property changes. Especially, for safety critical applications using GNSS, like advanced receiver autonomous integrity monitoring (ARAIM) or ground-based augmentation systems (GBAS) the new or changed signal properties are of high interest. With the help of detailed information about the signal deformation and the received signal power it is possible to calculate realistic error bounds and consequently realistic protection level for these kinds of safety critical applications.

This paper presents an overview of the findings according new signals or signal configurations of GPS, Beidou and QZSS of the last two years. After a brief introduction of the measurement facility the paper will introduce basic analysis about the quality of the signal shape in spectral and modulation domain. Using our precise calibrated measurement facility, we will also present an analysis of the transmitted satellite signal power including estimates about the power sharing among individual signal components within each band. Considering the measured power in relation to the boresight angle of the satellite one can derive a cut through the antenna pattern of the satellite and can assess the antenna symmetry properties. Examples for different satellites will be presented. Finally, we will end with a conclusion regarding the considered signal developments and its impact on GNSS users.

Introduction

Global navigation satellite systems (GNSS) are used in thousands of applications all over the globe. Thus, it is not surprising that they are constantly modernized, supplemented and developed further. In the focus of this paper are the L-band signal transmissions of GPS, Beidou and QZSS. Changes in the signal transmission can vary from simple changes in signal power up to the entire signal structure or the frequency range. Even completely new signals can be added or signal components are turned off.

The Chinese Beidou navigations system (BDS) is one of the most rapidly growing satellite navigation systems of the last years. Started as a local navigation system, it is currently expanding into a global one with a launch frequency of approximately two satellites every two months. This development to a global system implies not only the expansion of the coverage but also a significant change of the transmitted signals and services to serve a wider range of applications and to achieve better compatibility to existing GNSS and consequently less implementation effort at manufacturer side, and therefore better competitiveness.

Approved information about all of the provided Beidou 3 signals and services are still not available. The paper will fill this lack of knowledge vis-à-vis the expectations in the navigation community e.g. collected and presented in Betz (2015) and the released interface control documents (ICDs) which have been published within the last 12 month.

While Beidou and QZSS have evolved over the past few years to their expansion plan, GPS has been a long established system. But even in a fully developed system, changes in the radiated signal can also be observed. This happened for instance in 2017 for all GPS-IIR-M satellites as reported in Szilàgyi et al. (2017) and Thoelert et al. (2018).

Usually common GNSS receivers are used for monitoring of signals. But typically they provide only information about the legacy signals for GPS for instance L1 C/A and P(Y) pseudo code tracking. Neither information about the M-code nor the interplex signals are available from receiver measurements to assess e.g. for GPS the complete overview about the new power sharing of the IIR-M satellites.

Therefore, a special measurement facility is used to gather data for the analysis of the latest constellation updates. The German Space Operations Center (GSOC) of the German Aerospace Center (DLR) operates a 30 m dish antenna at its ground station in Weilheim (Germany). This antenna is regularly used by DLR's Institute of Communication and Navigation (IKN) for the analysis of GNSS signals [e.g., Thoelert et al. 2009, Steigenberger et al. 2018a]. The antenna provides a gain of about 50 dB and supports spectrum, inphase/quadrature (IQ), and calibrated power measurements covering the lower and upper L-Band. A detailed summary of the current measurement setup is given in Thoelert et al. (2013). Using such an instrument, the GNSS signals are raised above the noise floor and the gathered data provide a suitable basis for precise signal analysis.

GPS

GPS Block IIR-M and Block IIF satellites have the capability to redistribute transmit power between individual signal components. This so-called flex power can be used for increased protection against jamming and was already demonstrated in September 2010.

Since February 2017 GPS has changed the configuration of the transmit power of the L1 signal components (C/A-, P(Y)-, M-code) of the GPS IIR-M satellites [Thoelert et al. 2018]. Nearly at the same time, since January 2017, a geographically driven flex power mode is enabled on ten Block IIF satellites [Szilàgyi et al. 2017]. This is visible in carrier-to-noise density ratio observations of ground-based GPS receivers as well as differential code bias estimates between the L1 C/A- and P(Y)-code signals [Steigenberger et al. 2018c].

The signals of the GPS IIF satellites were also measured at the DLR ground station at Weilheim, Germany with a high gain antenna and a connected L-band measurement system. For the present work, L1/L2 signal spectra of GPS satellites have been obtained to highlight the presence or amplitude variation of different modulations in the course of flex power tests. These are complemented by in-phase and quadrature (IQ) measurements, which are the basis for the evaluation of the relative power distribution among individual signal components. Various calculation methods are described in detail in Thoelert et al. (2018).

Figure 1 shows the L1 spectral flux density of the Block IIF satellite G065 with and without flex power mode. The blue curve recorded on 25 March 2018 at 10:34 UTC represents the nominal signal transmission including C/A-, P(Y)-, and M-code. The sharp peak at 1575.25 MHz represents the 1 MHz C/A-code whereas the smaller broader dome at the same center frequency is caused by the 10 MHz P(Y)-code. The BOC(10,5) binary offset carrier modulation of the M-code introduces the two lobes at 1565 and 1585 MHz.

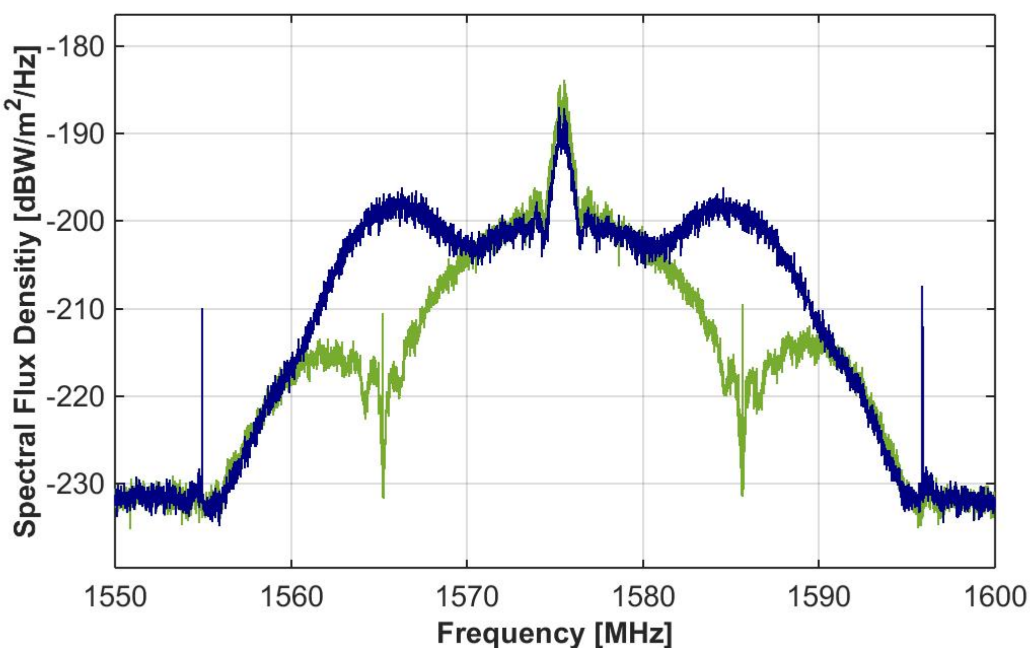

Figure 1: L1 spectral flux density of the GPS Block IIF satellite G065 (NAVSTAR 67) on 25 March 2018. Blue: nominal transmission including M-code at 10:34 UTC. Green: flex power mode without M-code transmission at 10:42 UTC

The green curve was acquired 5 minutes later after the switch to flex power mode. Obviously, the M-code lobes have disappeared and the smaller sidelobes of the P(Y)-code at 1560 and 1590 MHz become visible. Clearly, one can see that the C/A- code flux density is slightly increased. The question is, how was the power redistributed in this frequency band? Figure 2 depicts the equivalent isotropic radiated power (EIRP) measured over the complete frequency range from 1550 MHz until 1605 MHz. At the switch over from nominal to flex power mode the band power drops about 0.6 dB. Thus not the complete M-code power was transferred to the C/A-code. The reason for this might be a constraint regarding the constant envelope condition, which is a common goal for an effective power amplifier operation.

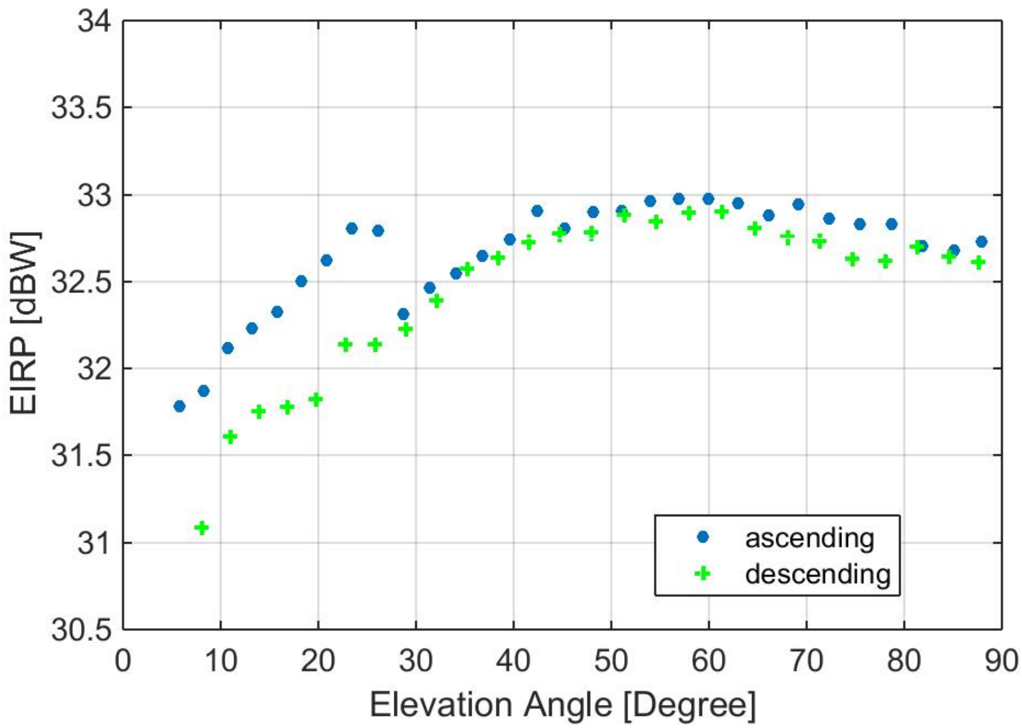

Figure 2: L1 Equivalent Isotropically Radiated Power (EIRP) of G065. 23 March 2018: nominal transmission including C/A-, P(Y)-, and M-code until approximately 27 degree elevation, then switch to flex power mode resulting in an EIRP reduction of about 0.6 dB

A different flex power setting was observed in April 2018. In contrast to the permanent installation of the geographically driven flex power mode described above, the configuration of the transmit power between the GPS components changed not only in L1 and also in L2 frequency band. Figure 3 and Figure 4 illustrate the change within the L1 band and L2 band based on calibrated spectral representations of the acquired data, respectively.

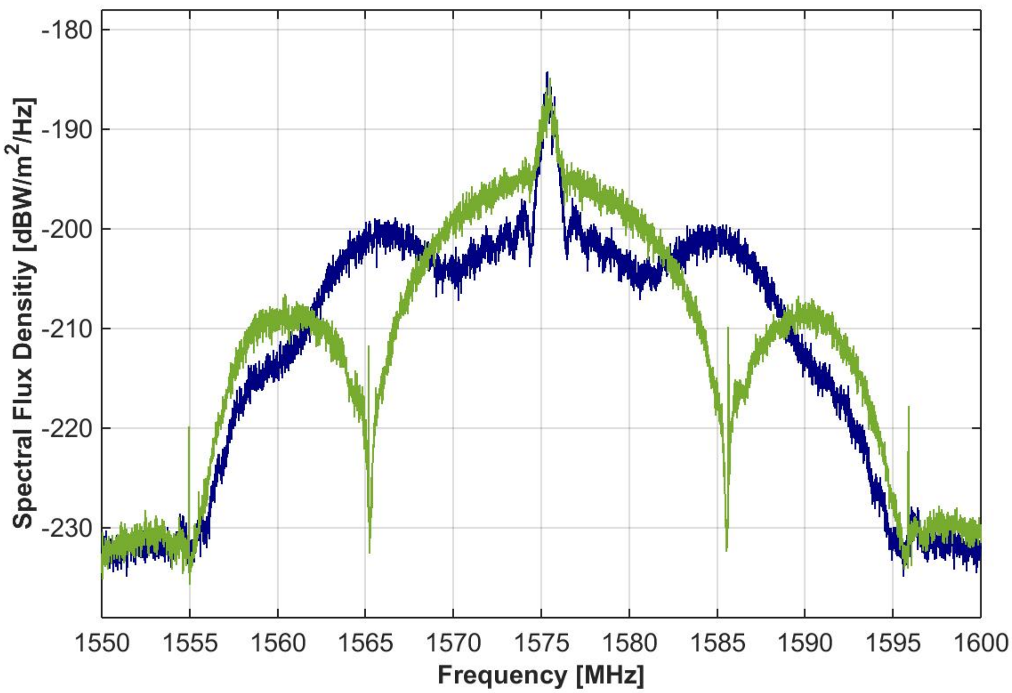

Figure 3: L1 spectral flux density of the GPS Block IIR-M satellite G055 (NAVSTAR 60). Blue: nominal transmission including M-code on May 11, 2018 at 05:06 UTC. Green: flex power mode without M-code transmission on April 17, 2018 at 09:01 UTC

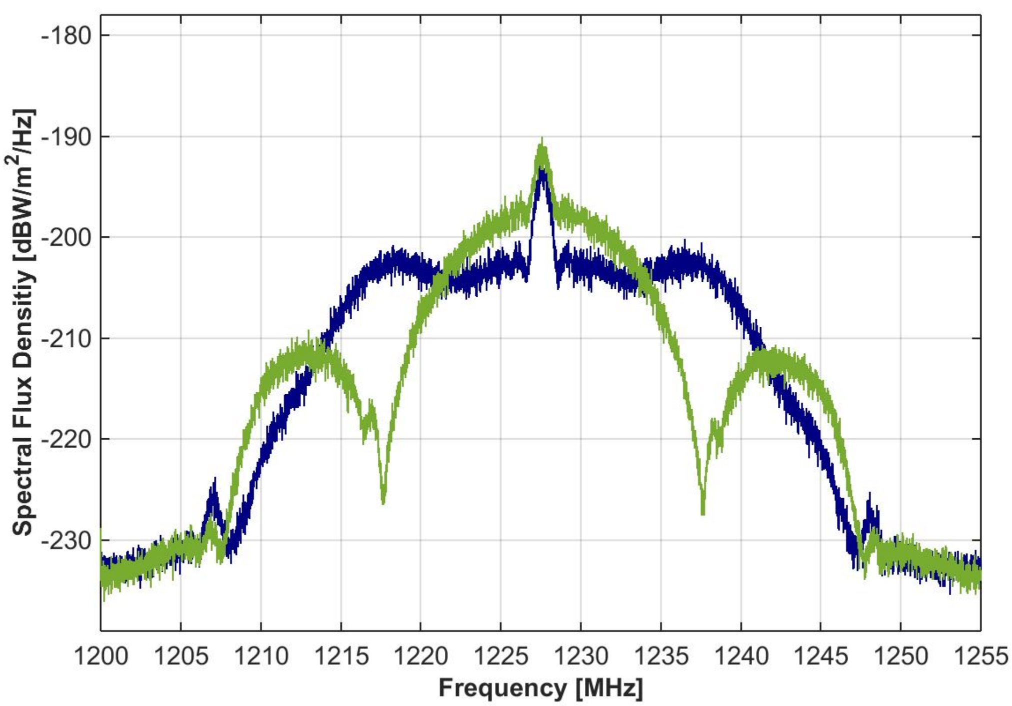

Figure 4: L2 spectral flux density of the GPS Block IIR-M satellite G055 (NAVSTAR 60). Blue: nominal transmission including M-code on May 11, 2018 at 05:07 UTC. Green: flex power mode without M-code transmission on April 17, 2018 at 09:02 UTC

Similar to the first flex power mode the M-code has been switched off. But in contrast to the first flex power mode the focus of the redistribution of the power was obviously to increase the P(Y)-code instead of the C/A-code. While the power of the P(Y)-code have been increased by approximately 6 dB in L1 and 5 dB in L2 the C/A-code respectively L2C-code remain nearly constant.

Table-1: Transmit power changes due to flex power on 17 April 2018. Average values of G052 and G065 are given.

SVN	Mode	L1				L2			
		C/A	P(Y)	M	IM	L2C	P(Y)	M	IM
G052	Normal	35%	18%	30%	17%	25%	27%	23%	25%
	Flex II	32%	68%			23%	77%		
G065	Normal	31%	16%	34%	19%	30%	24%	25%	21%
	Flex II	31%	69%			29%	71%		

Consequences of these transmit power changes are not only the power variation itself, but also an influence on the pseudorage and consequently the resulting differential code bias (DCB). Further information about the observed flex power activities on GPS and the effect according the differential code bias can be found in Steigenberger et al. (2018c).

Beidou 3

The Chinese Beidou navigations system (BDS) is one of the most rapidly growing satellite navigation systems of the last years. It starts 2000 with a demonstration phase with 3 geostationary test platforms. In a second step it has been expanded to a local navigation system with 16 space crafts in total [Y. Yang GNSS Handbook Chap. 10, Page 280]. In 2015 the Chinese have been started updating their system from a regional to a global one with the launch of their first Beidou 3 satellite. This development to a global system implies not only the expansion of the coverage but also a significant change of the provided signals and services to achieve better compatibility to existing GNSS and consequently less implementation effort at manufacturer side and therefore better competitiveness.

Until mid of 2017 the information about the Beidou 3 signals and services were very fragmentary. From official statements and information circulated in the navigation community draft overviews according to service type, frequency and spreading modulations were collected and presented in Betz (2015) and Teunissen and Montenbruck (2017).

Within the last 10 month interface control documents (ICDs) regarding the new signal components B1C, B3I and B2a have been released, which provide detailed information about signal structure, modulation, coding, message types and structure etc.

The first satellite, which has been transmitting the new signals, was BDS I2-S. The transmission was started on August 10, 2015. Researcher from different research entities like JRC, Italy and DLR, Germany and from China as well as commercial company JAVAD GNSS observed and analyzed the signal of that particular satellite [Bravaro et al. 2015, Cameron et al. 2015]

Based on their analysis they confirmed the presence of a time multiplexed binary offset carrier (TMBOC) signal and its power sharing between its individual components and an additional BOC(14,2) and a legacy B1I signal (Beidou phase 2) at L1-14 Mhz. The researchers at JAVAD GNSS have validated not only signals on L1 but also at E5a and E5b frequencies and gave a first impression on the signal strength which users can expect on ground. This first satellite transmitting the new Beidou 3 signal belongs to a group of test satellites for validation purposes [Betz 2015, page 262] but with operational capability.

However, even at this time there are no complete information about the capabilities and the provided signals as well as services of the final Beidou 3 system and its satellites are available. Therefore, the DLR captured spectral and I-Q-data from the latest Beidou satellites to provide information about the currently transmitted signals of the Beidou 3 system. Figure 5 provides a spectral overview, recorded at our measurement facility at Weilheim, Germany on October 1, 2018.

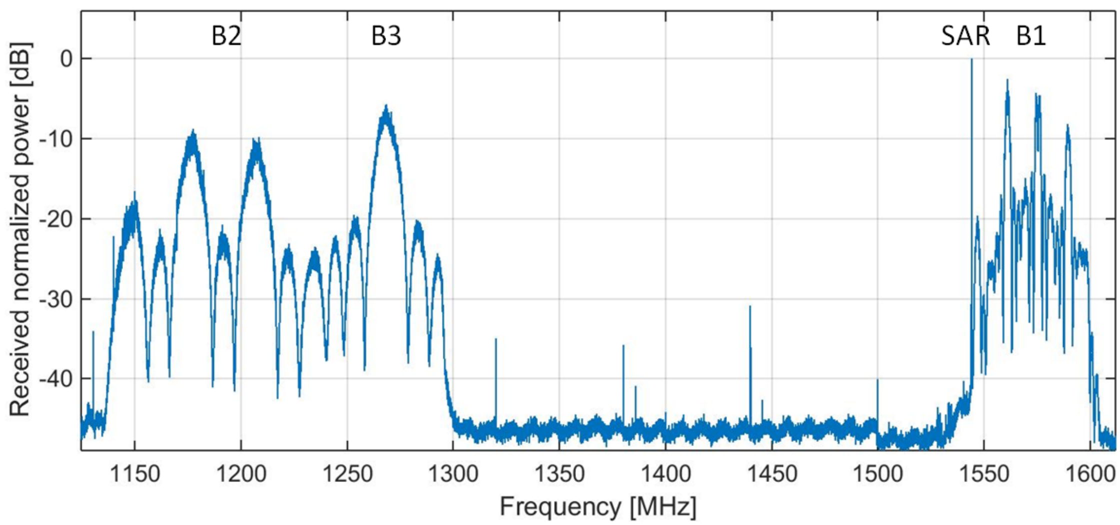

Figure 5: Pwer Spectra of Beidou 3 M13 captured October 1, 2018.

Based on the captured spectra one can see signal transmissions in B1, B2 and B3 band within the L-band. Clearly on can also observe a sharp peak at around 1544 MHz. This represents a signal of a search and rescue (SAR) transmitter. Further, analysis of the recorded IQ data show that the B1 signal contains transmissions of a BOC(1,1) data + pilot complemented by a BOC(6,1,4/33) in a QMBOC version which is in line with the published ICDs as expected. Furthermore BOC(14,2) components on I and Q channel were identified and the legacy B1I signal from Beidou 2.

Aside the identification about the provided signals of the new Beidou 3 satellites, the transmitted signal power is of interest for users. Especially, for the usability analysis of applications in areas with degraded receive signal strength it is important that there is still enough signal power remaining for receiver operation. Within the existing literature no information about the transmitted signal power can be found. Figure 6 shows the equivalent isotropic radiated power (EIRP) of two Beidou 3 satellites. The BDS-3 M1-S is one satellite of the mentioned test satellite series labeled with the “-S” in the end and the other curve is obtained from a final Beidou 3 series, the BDS-3 M1. The EIRP is calculated using the calibrated sum over the complete B1 frequency band and the free space loss based on the geometric distance between satellite and ground station. The curves within the figure represent the full overflight of each satellite according the measurement station, separated by different markers in the ascending and descending part. This is helpful to assess the symmetry of the satellite antenna pattern. For a symmetric pattern the ascending and the descending curve has to be overlaid, which is the case for the BDS-3 M1 satellite. Regarding the BDS-3 M1-S satellite a pattern asymmetry is obviously.

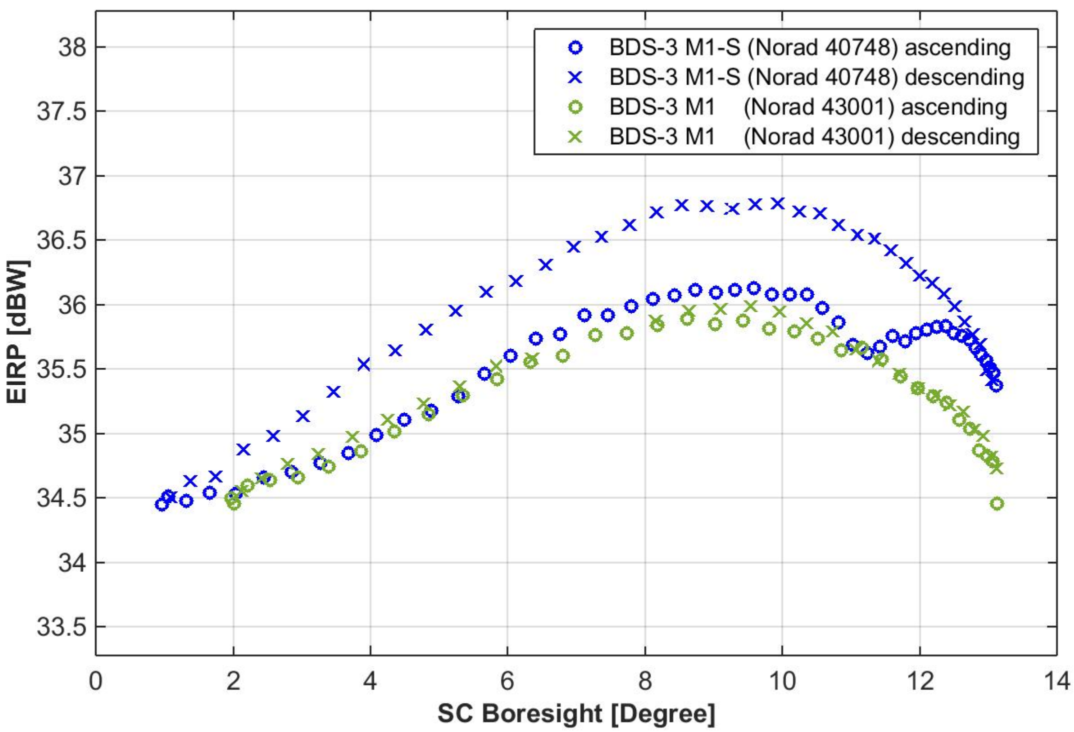

Figure 6 EIRP measurements of Beidou 3 satellites in the B1-band

Note that the pattern of the BDS-3 M1 is not necessarily fully symmetric. However, the measured cut through the satellite`s pattern provide symmetry. The total transmit power within the B1 band is similar, just slightly higher for the M1-S considering the average over the complete path.

QZSS

The Japanese Quasi-Zenith Satellite System (QZSS) is a regional augmentation system to provide highly precise and stable positioning services in the Asia-Oceania region, which is compatible with GPS. The first QZS satellite “Michibiki” was launched in 2010. In June 2017 the second satellite QZS-2, or Michibiki-2, was launched and started transmitting signals since June 27. Followed by QZS-3 and QZS-4 in August and October the same year the planned constellation has been completed. All 4 satellites have been placed into inclined geosynchronous, elliptical orbits, which enable extended satellite visibility periods over Japan and are characteristic features for this regional navigation system.

Similar to Beidou 3 the Japanese QZSS experienced an update with the implementation of new signals since the launch of the QZS-2 satellite. Figure 7 show the spectral overview of transmitted signal within the L-band.

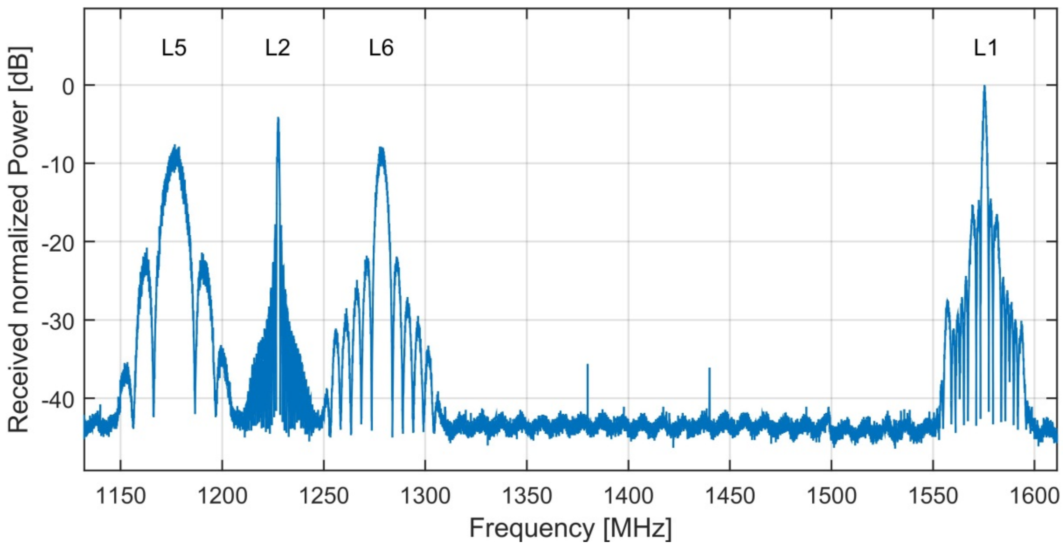

Figure 7: QSZ-2 L-band normalized power spectra recorded at Weilheim, Germany, on August 17, 2017.

A first measurement of the signals shows a good spectral shape, appropriate band filtering and no out-of-band unwanted spurious emissions of the satellite. For further analysis, we looked closer at each signal-band spectrum and the performed IQ-sample recordings.

Comparing the QZS-2 spectra to that of QZS-1, we see differences in the signal structure for the L1 frequency band. Figure 8 shows the L1 spectra of both satellites. The additional signal component at 6 x 1.023 MHz and 18 x 1.023 MHz can be clearly seen. This is the result of the new L1C-pilot modulation, which is based on the time-multiplexed binary offset carrier (TMBOC) modulation technique using a mixture of BOC(1,1) and BOC(6,1).

Other differences are present in the L5 and L6 band. More details can be found in Thoelert et al. (2017) and Steigenberger (2018b). Summarizing the new facts, within L5 an additional L5S signal has been transmitted by QZS-2 and the following spacecrafts, while in the L6 band a new component has been transmitted on the Q-component. On QSZ-2-4, an additional L6 signal component (Centimeter-Level Augmentation Message for Experiments, L6E) is implemented.

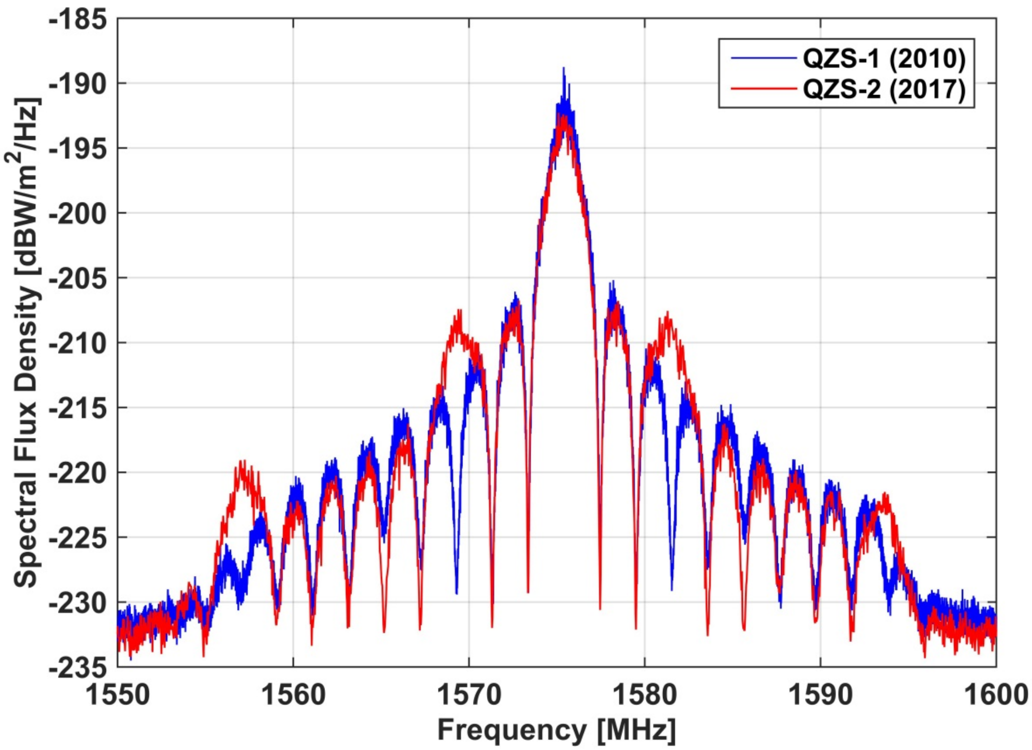

Figure 8: QZS-1 and QZS-2 L1 spectral flux density [Thoelert 2017].

Summary and Conclusions

The paper collected new as well as previously published information about signal in space developments of GPS, Beidou and QZSS over the last two years. We focused on flex power activities of GPS and the latest system implementations and updates of Beidou and QZSS. The presented examples show that signal changes respectively modifications can occur not only in the course of the implementation or modernization of a GNSS (like within Beidou and QZSS) but also within long-established systems, as described for the GPS signal power modifications in 2017 and 2018. The goal according the GPS activity can be just a test of the capability of the spacecrafts or to establish a new power sharing between the individual signal components within a frequency band for a more efficient energy consumption of the satellite payload, e.g. implemented for all GPS IIR-M satellites in 2017 [Thoelert et al. 2018]. Further aims can also be a system updates to provide more service variety, positioning accuracy or better compatibility with other system which may be able to relate to Beidou 3 or QZSS.

The presented examples for new or modified signals respectively signal power within the paper show that regular monitoring of the GNSS satellites could be beneficial to detect these changes and provide compensation if necessary. This is essential especially for safety-critical applications or for applications using prior knowledge of satellite properties, for instance in GNSS reflectometry applications like bi-static radar for calibration purposes. The presented events also indicate that modifications can be temporary or permanent.

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