Multi-GNSS Working Group
Technical Report 2016

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1 Introduction

In the beginning of 2016, the status of the Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) was changed to a Pilot Project by the IGS Governing Board. Nevertheless, the name "MGEX" will be retained due to the high recognition received so far. A comprehensive overview of the status of MGEX as of October 2016 is given in the review paper of Montenbruck et al. (2017).

A few changes of membership of the Multi-GNSS Working Group (MGWG) occurred during the reporting period:

- Andrea Stürze succeeded Axel Rülke as representative of Bundesamt für Kartographie und Geodäsie (BKG)
- Zhiguo Deng succeeded Mathias Fritsche as representative of Deutsches GeoForschungsZentrum (GFZ)
- Satoshi Kogure moved from the Japan Aerospace Exploration Agency (JAXA) to the Cabinet Office but is still member of the MGWG
- Inga Selmke joined the MGWG representing Technische Universität München (TUM)

2 GNSS Evolution

This section is limited to the evolving systems Galileo, BeiDou, and IRNSS. The satellite launches of these systems in 2016 are listed in Table 1. The year 2016 marks several important milestones, in particular for Galileo. In November, an Ariane-V launched four

Table 1: GNSS satellite launches in 2016.

Date	Satellite	Type
20 Jan 2016	IRNSS-1E	IGSO
01 Feb 2016	BeiDou M3-S	MEO
10 Mar 2016	IRNSS-1F	GEO
29 Mar 2016	BeiDou IGSO 6	IGSO
28 Apr 2016	IRNSS-1G	GEO
24 Mai 2016	Galileo FOC FM-10/11	MEO
12 Jun 2016	BeiDou GEO 7	GEO
17 Nov 2016	Galileo FOC FM-07/12/13/14	MEO

Galileo satellites at the same time (GPS World Team, 2016) increasing the number of Galileo satellites in orbit from 14 to 18. Galileo Initial Services were officially declared by the European Commission on 15 December 2016 (GSA, 2016) based on a constellation of 11 satellites for the Open and the Public Regulated Service and 12 satellites for the Search and Rescue service. An update of the Galileo Open Service Signal In Space Interface Control Document was also published in December 2016 (European Union, 2016). The two Galileo satellites in eccentric orbit (GSAT-201/2) started an experimental transmission of broadcast messages in August 2016. The satellites are not included in the almanac and the initial update rate was limited to three hours. Starting with November 2016, the update rate was in general increased to 10 min.

Galileo IOV metadata were published by the European Global Navigation Satellite Systems Agency (GSA) on 16 December 2016 (European GNSS Service Center, 2016). These data include amongst others information about attitude, transmit antenna phase center corrections, geometry and optical properties, as well as group delays. An important task of the MGWG for 2017 will be the consolidation and exploitation of these data for the generation of the MGEX products.

BeiDou moved forward in completing its constellation with the launch of two second generation (BDS-2) and one third generation (BDS-3) BeiDou satellites (Tan et al., 2016). Version 2.1 of the BeiDou Interface Control Document (China Satellite Navigation Office, 2016) was published in November including several clarifications, e.g., for the ionospheric delay model parameters, but not yet covering the BDS-3 signals.

With the launch of the 3rd GEO satellite, the 7-satellite constellation of the Indian Regional Navigation Satellite System (IRNSS) was completed in April 2016. Along with this, the system was renamed to “Navigation with Indian Constellation” (NAVIC).

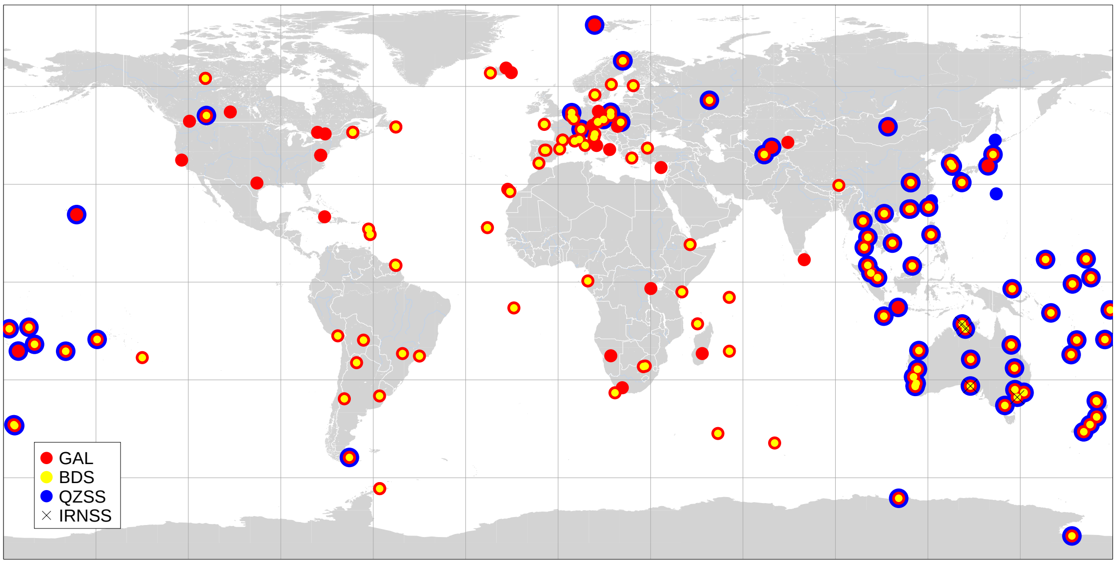

Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2017.

3 Network

In 2016, the number of IGS multi-GNSS stations increased from almost 130 to about 180, see Fig. 1. About half of the stations also provide real-time streams, mainly via the dedicated MGEX caster (`http://mgex.igs-ip.net/`) but also via the IGS-IP caster (`http://igs-ip.net`). Both casters are operated by BKG and provide the real-time streams in different versions of the RTCM-3 MSM format. First Galileo E6- and IRNSS L5-capable receivers were installed at several locations by Geoscience Australia. The signals of the BDS-3 satellites (Xiao et al., 2016) can only be tracked on the B1 frequency by selected receivers of the IGS network.

4 Products

Six analysis centers (ACs) contribute orbit and clock products to MGEX as listed in Table 2. A detailed review of the MGEX product quality is given in Montenbruck et al. (2017). Recent results of individual ACs are given in Prange et al. (2016) for the Center for Orbit Determination in Europe (CODE) and in Guo et al. (2016b) for Wuhan University. Guo et al. (2017) evaluated the MGEX Galileo, BeiDou, and QZSS orbit and clock products and found an orbit consistency of 10 – 25 cm for Galileo, 10 – 20 cm for BeiDou MEOs, 20 – 30 cm for BeiDou IGSOs, and 20 – 30 cm for QZSS.

Table 2: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
Centre National dEtudes Spatiales/ Collecte Localisation Satellites (CNES/CLS)	grm	GPS+GLO+GAL
Center for Orbit Determination in Europe (CODE)	com	GPS+GLO+GAL+BDS+QZS
Deutsches GeoForschungsZentrum (GFZ)	gbm	GPS+GLO+GAL+BDS+QZS
Japan Aerospace Exploration Agency (JAXA)	qzf	GPS+QZS
Technische Universität München (TUM)	tum	GAL+QZS
Wuhan University	wum	GPS+GLO+GAL+BDS+QZS

Steigenberger et al. (2016) estimated satellite antenna phase center offsets (PCOs) for the Galileo satellites. They proposed rounded PCO values for three different groups of Galileo satellites: In-Orbit Validation (IOV) satellites, Full Operational Capability (FOC) satellites in nominal orbit, and FOC satellites in eccentric orbit (FOCe, i.e., GSAT-201 and -202). These PCO values are given in Table 3 and included in the IGS antenna model starting with the release `igs08_1915.atx` (Schmid, 2016). They are used by the MGEX ACs since September 2016.

Table 3: Galileo satellite antenna PCOs as used within the IGS since September 2016. IOV: In-Orbit Validation; FOCe: Full Operational Capability in eccentric orbit; FOC: Full Operational Capability in nominal orbit.

Satellite group	x [cm]	y [cm]	z [cm]
IOV	-17	$+3$	$+95$
FOCe	$+16$	-1	$+105$
FOC	$+12$	-1	$+110$

Version d of the SP3 format (Hilla, 2016) was released in February 2016 but none of the MGEX ACs currently uses this format. Major advantage of this format is the increased number of 999 satellites compared to 85 in SP3-c.

The TUM AC switched to a more recent version of the Bernese GNSS Software and implemented the a priori solar radiation pressure (SRP) model of Montenbruck et al. (2015) as well as the "dynamic yaw steering attitude" model of Ebert and Oesterlin (2005) for the Galileo satellites in November 2016 (Selmke, 2016). Whereas the original model of Montenbruck et al. (2015) is limited to Galileo IOV, Steigenberger and Montenbruck (2016) provide updated coefficients for the Galileo FOC satellites. Guo et al. (2016a) developed an adjustable box-wing model for BeiDou MEO and IGSO satellites that in particular improves the orbit quality during orbit-normal (ON) mode.

Fritsche (2016) adopted the IGS orbit and clock combination software to include Galileo, BeiDou, and QZSS. They report weighted root-mean square differences with respect to

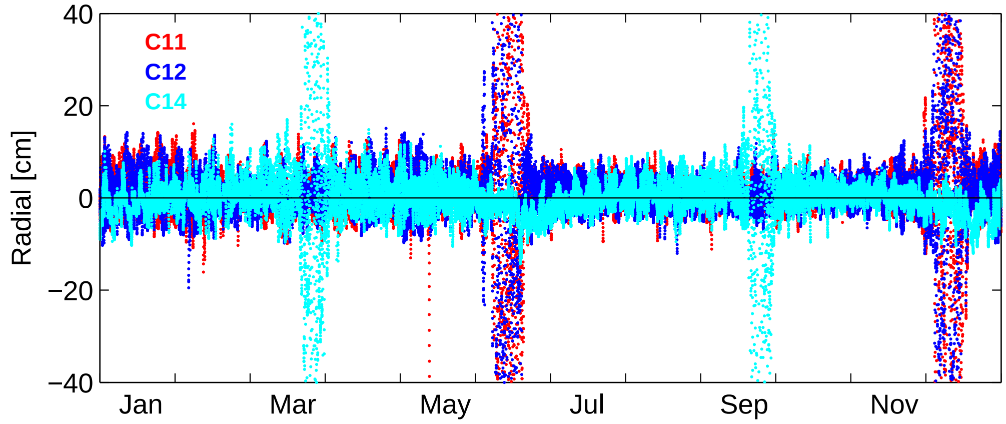

Figure 2: Radial differences for CODE and GFZ BeiDou MEO satellite orbits.

the combined orbit of 5 cm for Galileo, 3 – 5 cm for BeiDou MEOs, 10 – 20 cm for BeiDou IGSOs and QZSS in yaw-steering (YS) mode. During ON mode, these values can be exceeded by far, see Fig. 2.

In April 2016, an *Analysis* section was established on the MGEX webpage (`http://mgex.igs.org/analysis/index.php`). It is updated on a weekly basis and includes information on

- MGEX product availability;
- GNSS satellite signal transmission for GPS, GLONASS, BeiDou, Galileo, IRNSS, and SBAS;
- Clock time series of individual BeiDou and Galileo satellites;
- SLR residuals for GLONASS, BeiDou, Galileo, and QZSS;
- Orbit comparisons between the various ACs for GPS, GLONASS, BeiDou (separately for MEO, IGSO, GEO), Galileo, and QZSS.

An example for the comparison of BeiDou MEO satellite orbits of CODE and GFZ is given in Fig. 2. Large differences can be seen during ON mode as this attitude mode is not yet considered by CODE.

Two ACs contribute Differential Code Bias (DCB) products to MGEX. Whereas the Chinese Academy of Sciences (CAS) DCB product (Wang et al., 2016) is updated on a daily basis, the Deutsches Zentrum für Luft- und Raumfahrt (DLR) product has a quarterly update rate. Since the second quarter of 2016, the DLR DCB product is provided in version 1.00 of the Bias SINEX format (Schaer, 2016a). Please note that the December 2016 version of the Bias SINEX format (Schaer, 2016b) uses a 4-digit year whereas the version of February 2016 (Schaer, 2016a) which is implemented by DLR uses a 2-digit year for specifying validity intervals.

Acronyms

BKG Bundesamt für Kartographie und Geodäsie

CAS Chinese Academy of Sciences

CLS Collecte Localisation Satellites

CNES Centre National dEtudes Spatiales

CODE Center for Orbit Determination in Europe

DLR Deutsches Zentrum für Luft- und Raumfahrt

GFZ Deutsches GeoForschungsZentrum

JAXA Japan Aerospace Exploration Agency

TUM Technische Universität München

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