Multi–GNSS Working Group Technical Report 2017

P. Steigenberger[1], O. Montenbruck[1]

[1] Deutsches Zentrum für Luft- und Raumfahrt (DLR)
German Space Operations Center (GSOC)
Münchener Straße 20
82234 Weßling, Germany
E-mail: peter.steigenberger@dlr.de

1 Introduction

The main activity of the Multi-GNSS Working Group (MGWG) is the Multi-GNSS Pilot Project (MGEX). MGEX finally aims at the integration of the evolving global and regional satellite navigation systems Galileo, BeiDou, QZSS, and NavIC (IRNSS) into the IGS data archives and operational products. Whereas the integration of the multi-GNSS observation data was already finished in 2016, improving the product quality of the emerging GNSS to achieve the same quality as for the legacy GPS and GLONASS is still an ongoing process. The membership of the MGWG has not changed in 2017. The members are representatives of the analysis and data centers as well selected specialists contributing to the goals of the MGWG.

2 GNSS Evolution

The satellite launches of the evolving systems Galileo, BeiDou, and QZSS in 2017 are listed in Table 1. Three 2nd generation QZSS satellites have been launched in 2017, two in inclined geosynchronous orbit like QZS-1 and one in geostationary orbit. Operational services of QZSS are expected to start in 2018.

The launch of a replacement satellite for NavIC (IRNSS-1H) failed in August 2017 as the heat shield of the launcher did not separate. This satellite should have replace IRNSS-1A suffering from a failure of all three rubidium clocks. The causes for problems with the Galileo rubidium as well as passive hydrogen maser clocks have been identified and the clocks still on ground have been refurbished prior to the launch in December 2017. This

Table 1: GNSS satellite launches in 2017.

Date	Satellite	Type
01 Jun 2017	QZS-2	IGSO
19 Aug 2017	QZS-3	GEO
09 Oct 2017	QZS-4	IGSO
05 Nov 2017	BeiDou-3 M1 and M2	MEO
12 Dec 2017	Galileo FOC FM-15/16/17/18	MEO

second Galileo launch with Ariane 5 delivered another four satellites into orbit. A further quadruple launch is planned for 2018.

Whereas five test satellites for BeiDou-3 (denoted as BeiDou-3S) have already been launched in 2015/6, 2017 marks the launch of the first two MEO satellites for the operational constellation. An ICD for the BeiDou-3 open service signals B1C and B2a has been published in August 2017 (China Satellite Navigation Office 2017).

3 Network

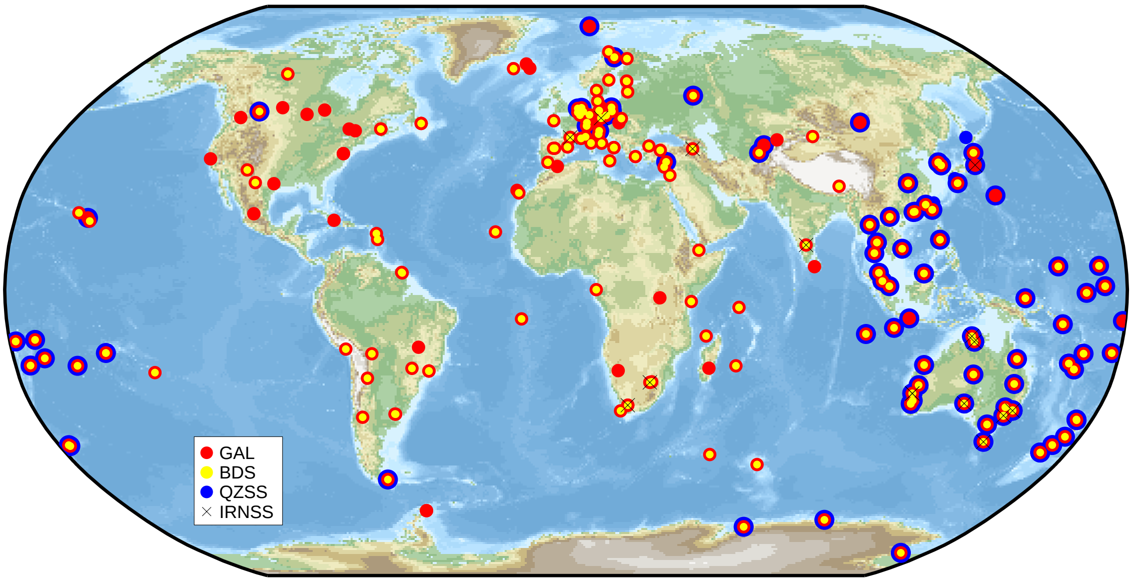

Figure 1: Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of December 2017.

As of December 2017, 218 out of 505 IGS tracking network stations were multi-GNSS stations providing their observations in RINEX 3 format. 13 of these stations were dormant,

Table 2: Analysis centers contributing to IGS MGEX.

Institution	Abbr.	GNSS
CNES/CLS	grm	GPS+GLO+GAL
CODE	COD0MGXFIN	GPS+GLO+GAL+BDS+QZS
GFZ	gbm	GPS+GLO+GAL+BDS+QZS
JAXA	JAX0MGXFIN	GPS+GLO+QZS
TUM	tum	GAL+QZS
Wuhan University	wum	GPS+GLO+GAL+BDS+QZS

i.e., data are missing since more than three weeks. In addition, data of five MGEX experimental stations are available that did not meet the requirements of the IGS site guidelines but are still important for experimental applications. Real-time data are available from the BKG MGEX and IGS-IP casters for 127 multi-GNSS stations.

Triple-frequency BeiDou-3S observations are currently only provided by Javad TRE_3 receivers, whereas Septentrio PolaRx5 receivers provide dual-frequency (B1/B3) tracking of these satellites. However, implementation of the new BeiDou-3 signals in the RINEX 3 format definition is still pending.

4 Products

The MGEX analysis centers and the GNSS covered by their products are listed in Table 2. The number of analysis centers has not changed compared to 2016. However, JAXA included GLONASS starting with the switch to a new product line in April 2017. Since GPS week 1962, CODE provides a 30 s clock solution. These new CODE and JAXA products are indicated with long file names which are discussed in Sect. 5. In addition to the well established data centers at CDDIS and IGN, MGEX products are also available from the new IGS data center of the European Space Astronomy Centre (ESAC) of the European Space Agency (ESA).

In the following, selected publications based on MGEX data and products or relevant for multi-GNSS processing are discussed. Sośnica et al. (2017) validated the CODE MGEX Galileo orbits with satellite laser ranging (SLR). They found systematic biases in the order of 2 – 5 cm and RMS values between 4 and 5 cm.

Xie et al. (2017) show first results of the precise orbit and clock determination of BDS-3. They could achieve an orbit accuracy evaluated by SLR of 1 – 3 dm. Zhang et al. (2017) analyzed the BDS-3 navigation signals and demonstrate that BDS-3 does not suffer from satellite-induced elevation-dependent code variations like the BDS-2 satellites (Wanninger and Beer 2014). An alternative correction model for these BDS-2 pseudorange variations was developed by Zou et al. (2017) with model coefficients for each individual satellite and frequency. Zhao et al. (2018) showed that BDS-3 satellites do not enter orbit normal mode for elevations of the Sun above the orbital plane $|\beta| < 4°$. Dilssner (2017) used the reverse PPP technique for attitude analysis of the latest BDS-2 satellite, namely BeiDou IGSO-6, that does also not enter orbit normal mode. Dilssner (2017) developed a simple yaw attitude model for IGSO-6 and identified two other BDS-2 satellites not utilizing orbit normal mode since October 2016 and March 2017, respectively.

Dedicated box-wing models for QZS-1 were developed by Montenbruck et al. (2017) and Zhao et al. (2017). Both models provide a RMS consistency with SLR better than 10 cm. Rajaiah et al. (2017) developed a dedicated orbit model for for the Indian Regional Navigation Satellite System (IRNSS) which is currently not covered by the MGEX products. Based on C-band ranging, they could achieve a few meter orbit precision and SLR residuals on the few decimeter level.

Steigenberger et al. (2017) measured the transmit power of GPS, GLONASS, Galileo, and BeiDou-2 satellites with a 30 m high-gain antenna. The transmit power is required for the computation of the antenna thrust that can alter the orbital radius by up to 3 cm depending on transmit power, mass, and orbital radius of the satellite. The transmit power of current IGS model (IGS 2011) that covers only GPS was found to be too large by about 40 %.

Li et al. (2017) estimated Differential Code Biases (DCBs) for Galileo and found an agreement on the 0.22 ns level with the corresponding MGEX estimates. For BeiDou, the RMS of the DCBs determined by Fan et al. (2017) and the MGEX DCB product is with 0.39 ns significantly higher.

Guo et al. (2017) assessed the performance of MGEX products for precise point positioning (PPP). They achieved RMS values of kinematic PPP position estimates of 2.0 cm for the North, 4.9 cm for the East, and 5.3 cm for the height component utilizing GPS, GLONASS, Galileo, and BeiDou. In a study of Wuhan University, the long-term variation of signal-in-space range errors of the BeiDou-2 system was assessed based on MGEX cumulative broadcast ephemerides and precise orbit clock products (Wu et al. 2017).

5 Long Product File Names

Starting with 2017, two analysis centers (CODE and JAXA) provide their products with long file names which are inherited from the RINEX 3 naming scheme. The DCB products of CAS and DLR are already provided with long file names since 2015. This new file naming allows for a proper distinction of legacy and MGEX products for the different product lines (ultra-rapid, rapid, and final products). The file name is composed of different fields providing information about analysis center, product version, campaign/project, product type, start epoch, sampling, content type, and format:

```
AAAVPPPTTT_YYYYDDDHHMM_LEN_SMP_CNT.FMT[.*]
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Field	length	content
AAA	3 characters	analysis center abbreviation
V	1 character	version/solution identifier
PPP	3 characters	campaign/project specification
TTT	3 characters	type specification, e.g., ULT, RAP, FIN
YYYYDDDHHMM	11 digits	product start epoch
LEN	3 characters	intended (nominal) product period
SMP	3 characters	temporal resolution
CNT	3 characters	content type
FMT	3 characters	file format
	1 or 2	compression method extension, Z or gz

So far, only the version identifier 0 is used within MGEX whose project specification is MGX. The following content types are currently provided within MGEX

CLK receiver and/or satellite clock parameters
DCB differential code biases
ERP Earth rotation parameters
ORB satellite orbits
OSB observable-specific signal bias
SOL variance/covariance information or normal equations

using these file formats:

BIA bias SINEX
BSX bias SINEX
CLK clock RINEX
ERP IGS ERP format
SNX Solution INdependent EXchange (SINEX) format
SP3 Special Product 3 (SP3) orbit format

As an example, CODOMGXFIN_20173360000_01D_05M_ORB.SP3 denotes a final MGEX orbit file in SP3 format of the CODE analysis center covering one day (day of year 336/2017) with 5 min sampling.

6 GNSS Satellite Metadata

Knowledge about satellite metadata like antenna phase center position is crucial for a full exploitation of GNSSs. An IGS white paper on satellite and operations information for generation of precise GNSS orbit and clock products has been published by Montenbruck

(2017) and passed to the International Committee on Global Navigation Satellite Systems (ICG).

Galileo FOC metadata were published by the European Global Navigation Satellite Systems Agency (GSA) on 6 October 2017 (European GNSS Service Center 2017) following the earlier publication of IOV metadata. The Cabinet Office (CAO), Government of Japan, published QZSS satellite information (Cabinet Office 2017a, b, c, d) for all QZSS satellites in orbit. CAO is also the first provider publishing operational history information for QZS-1 (Cabinet Office 2017e) including date and time of attitude mode changes, date of reaction wheel unloading, date, time, duration and velocity change of orbit maintenance maneuvers as well as the post-maneuver mass. Publication of optical properties as well as operational history information for the other QZSS satellites is planned for 2018. Metadata not published so far for Galileo or QZSS include transmit antenna gain pattern, which are essential for the determination of the transmit power (Steigenberger et al. 2017).

In order to be able to store and exchange the GNSS satellite metadata in a standardized format, an extension of the solution independent exchange (SINEX) format Rothacher and Thaller (2006) has been developed. A first draft of this satellite metadata extension was distributed within the MGWG in November 2017 and covers the following new SINEX blocks:

- Satellite designations (static): SVN, COSPAR ID, satellite catalogue number, Block
- PRN assignment
- GLONASS frequency channel
- Spacecraft mass
- Center-of-mass position
- Equipment positions: GNSS transmit antennas, laser retroreflector array, ...
- Transmit power
- Yaw angle information for GPS satellites

Consolidation of the format and the content is currently in progress.

Acronyms

BKG Bundesamt für Kartographie und Geodäsie

CAS Chinese Academy of Sciences

CDDIS Crustal Dynamics Data Information System

CLS Collecte Localisation Satellites

CNES Centre National d'Etudes 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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