The IGS MGEX Experiment as a Milestone for a Comprehensive Multi-GNSS Service

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ABSTRACT

The International GNSS Service (IGS), formerly the International GPS Service, is a voluntary federation of more than 200 worldwide agencies that pool resources and permanent GPS & GLONASS station data to generate precise GPS & GLONASS products. The IGS is committed to providing the highest quality data and products as the standard for Global Navigation Satellite Systems (GNSS) in support of Earth science research, multidisciplinary applications, and education. Currently the IGS includes two GNSSs: GPS and the Russian GLONASS. In view of the ongoing GPS modernisation and the build-up of new navigation systems such as BeiDou, Galileo and QZSS, the IGS has recently established the Multi-GNSS Experiment (MGEX). MGEX serves as a platform for early experimentation and familiarisation with the emerging new signals and constellations. Aside from collecting multi-GNSS tracking data from a global network implemented in parallel to the core IGS network, MGEX promotes the generation of dedicated multi-GNSS orbit and clock products and the development of advanced processing algorithms. The paper describes the current status of the MGEX project, discusses early achievements and presents the long-term vision for transitioning the IGS into a fully generic multi-GNSS service.

INTRODUCTION

Following three decades, during which the Global Positioning System GPS has evolved from a military navigation system into an indispensable tool for geodetic research and global monitoring of the Earth, the world of satellite navigation has experienced dramatic changes over the past years. With GLONASS, a second global navigation system has achieved full operational status, GPS is introducing modernised civil and encrypted navigation signals, and a variety of new navigation constellations are being built-up in Asia and Europe.

As of early 2013, Europe has successfully launched a total of four Galileo In-Orbit Validation (IOV) satellites which are presently undergoing testing in parallel to the build-up and verification of the ground segment [1]. The satellites routinely transmit signals in a total of four frequencies (E1, E5a, E5b, and E6) and offer a variety of publicly accessible pilot and data signals. As a unique feature, Galileo enables tracking of the AltBOC signal in the combined E5a+E5b band, which offers superior noise and multipath performance [2].

Meanwhile, the Chinese BeiDou Satellite Navigation System (BDS) has completed the first stage of it's system deployment and declared a regional navigation service for the Asia-Pacific region. A total of 14 operational satellites have been launched so far, which includes five satellites in geostationary orbit (GEO), five satellites in inclined geosynchronous orbit (IGSO) and four in medium-altitude Earth orbit (MEO). These transmit signals in a total of three frequency bands (B1, B2, B3) and tracking of the corresponding open service (O/S) signals is already supported by a variety of GNSS receivers [3]. With the release of a B1 O/S Interface Control Document (ICD, [4]) at the end of 2012, the BeiDou navigation message has become publicly accessible and users throughout the Asia-Pacific region can now benefit from BeiDou as a supplementary or stand-alone navigation system.

QZSS has, so-far, only launched a single satellite but recent political decisions have paved the way for the build-up of a complete constellation of IGSO and GEO satellites. Aside from a high level of compatibility with GPS, QZSS has introduced new signals such as the L1C signal and the LEX signal in the E6 band [5]. Along with this unique set of navigation signals, QZSS provides innovative service features such as the L1S (formerly the Submeter-class Augmentation with Integrity Function – SAIF) message and the L6b (formerly the L-band Experimental – LEX) real-time correction data message for high precision (sub-decimetre) point positioning. Also, QZSS precedes GPS in offering the new CNAV navigation message on L2C and L5, as well as the CNAV2 message on L1C. Long before their planned use in GPS these messages are now broadcast on a routine basis and contain novel information such as inter-frequency corrections and Earth orientation parameters.

Last, but not least, GPS has now a total of three Block IIF satellites in orbit that transmit an operational L5 signal for aviation users and which fly a new generation of highly stable Rubidium clocks. While neither L2C nor L5 are transmitted by a full constellation, users and investigators can gradually familiarise themselves with these new signals that will enable encryption-free dual-frequency navigation services for civil and aeronautical applications.

Within the International GNSS Service (IGS, [6]), more than 200 worldwide agencies have, for many years, pooled resources and permanent GNSS station data to generate precise GNSS products in support of Earth science research, multidisciplinary applications, and education. So far, this service has been restricted to two systems, namely GPS and GLONASS. In recognition of the rapidly evolving GNSS landscape, the IGS has therefore setup a Multi-GNSS Experiment (MGEX, [7]) to explore and promote the use of new navigation signals and constellations. It shall enable an early familiarisation with new GNSSs, identify and overcome relevant challenges, and prepare use of emerging navigation systems in routine IGS products. MGEX comprises the build-up of a new network of sensor stations, the characterisation of the user equipment and space segment, the development of new concepts and data processing tools, and, finally, the generation of early data products for Galileo, QZSS, and BeiDou. MGEX is coordinated by the Multi-GNSS Working Group (MGWG), which interacts closely with other IGS entities, such as the RINEX Working Group, the Antenna Working Group, the Data Center WG and the Infrastructure Committee.

The paper starts with a description of the MGEX network that formed the starting point and initial focus of the overall MGEX project. Following a description of system characterisation activities, the current status of multi-GNSS data products and ongoing efforts for the development of new standards for multi-GNSS-related work within the IGS are presented.

NETWORK

Following a call-for-participation released in the summer of 2011, the build-up of a new network of multi-GNSS sensor stations has been initiated and has made substantial progress in a short time. By the end of 2012 the MGEX network comprises approximately 50 stations supporting at least one of the new navigation systems (Galileo, BeiDou, and QZSS) in addition to the legacy GPS, GLONASS and SBAS systems.

The bulk of stations is provided by IGS partners such as Bundesamt für Kartographie und Geodäsie (BKG), Centre National d'Etudes Spatiales (CNES), Deutsches GeoForschungsZentrum (GFZ), Geospatial Information Authority of Japan (GSI), Institut National de l'Information Géographique et Forestière (IGN), Swedish National Land Survey (Lantmaeteriverket, LMV), and Geoscience Australia (GA), that have upgraded/supplemented existing sites with new, multi-GNSS-capable receivers and antennas or started to deploy new multi-GNSS networks (such as CNES's REseau GNSS pour l'IGS et la Navigation (REGINA) network).

As shown in Fig. 1, the present set of MGEX stations exhibits an almost global coverage, even though a concentration in Europe and a reduced coverage in the Americas and the West Pacific are obvious. However, this situation is expected to improve soon with announced contributions from the COperative Network for GNSS Observation (CONGO) of the German Aerospace Center (DLR), the European Space Agency (ESA), the Multi-GNSS Monitoring Network (MGM-net) of the Japan Aerospace Exploration Agency (JAXA), and GA stations. While most MGEX sites support tracking of the Galileo satellites, only a subset of stations is presently providing data for QZSS and BeiDou. In particular, the regional BeiDou constellation (i.e. the GEO and IGSO) satellites are not well covered by the current network.

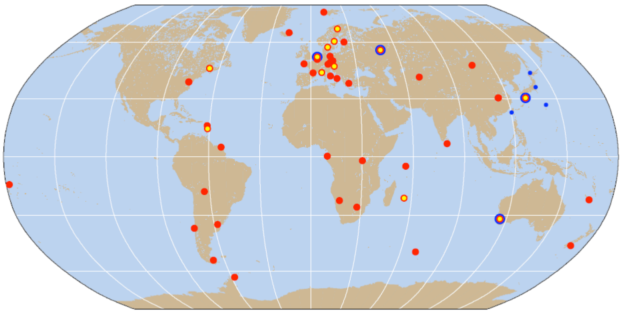

Figure 1 Distribution of MGEX stations supporting tracking of QZSS (blue), Galileo (red), and BeiDou (yellow) as of Feb. 2013.

Further MGEX sites are encouraged and the nomination of sites is still possible through the MGEX submission form (http://igs.geolinks.org/mgex) under the provision of relevant improvements to the capabilities, coverage and homogeneity of the overall network.

In terms of equipment, six basic receiver types and five basic antenna types are presently employed at the MGEX stations (Tables 1-2). Observation types provided by the individual receivers have been compiled from summary reports generated by the Astronomical Institute of the Unversity of Bern (AIUB) as part of their routine monitoring of RINEX 3 observation files from MGEX stations (see ftp://ftp.unibe.ch/aiub/mgex/odata2_receiver.txt).

Table 1 Receiver types in use within the MGEX network (status Feb. 2013). Observation types for Galileo (E), BeiDou (C), and QZSS (J) are based on RINEX 3 observation codes as reported in the submitted data files (frequency bands: 1=L1/E1, 2=L2/B1, 5=L5/E5a, 6=E6/B3, 7=E5b/B2, 8=E5ab; signals: c=C/A-code, I=data, Q=pilot, X=data+pilot). They do not necessarily indicate the full tracking capabilities supported by the receivers but rather the observations presently made available to MGEX users from the respective stations.

Receiver Type	Stations	Observations
IFEN SX_NSR_RT_800	1	E: 1X,5X,7X,8X,6X C: 2I, 7I
JAVAD TRE_G3TH DELTA	14	E: 1X,5X
LEICA GR10 and LEICA GR25 and LEICA GRX1200+GNSS	9	E: 1X,5X,7X,8Q
NOV OEM6	1	E: 1C,5Q
SEPT POLARX4TR and SEPT POLARXS	3	E: 1C,5Q,7Q,8Q C: 2I,7I
TRIMBLE NETR9	26	E: 1X,5X,7X,8X C: 2I,7I,6I J: 1C,1X,2X,5X,6X

It may be noted that no common standard has yet evolved in terms of supported signals and observation types. This causes certain restrictions for data analysis and product generation. As an example, Galileo orbit and clock products will (at least initially) be based on E1/E5a observations due to a limited coverage of E5b and E5ab tracking.

Table 2 Antenna types currently employed within the MGEX network (status Feb. 2013)

Antenna Type		Stations
AOAD/M_T	NONE	2
JAV_RINGANT_G3T	NONE	12
JAVRINGANT_DM	SCIG	1
LEIAR10 LEIAR25 LEIAR25.R3 LEIAR25.R4	 NONE and LEIT and LEIT	16
TRM55971.00 TRM57971.00 TRM57971.00	NONE and NONE TZGD	8
TRM59800.00 TRM59800.00	NONE and SCIS	15

Selected sites (such as UNB and USNO) offer multiple receivers in short- or zero-baseline configuration to facilitate equipment characterisation. Further such installations will be added to the MGEX network during proposed extensions.

While all stations contribute data to offline archives hosted by CDDIS, IGN, and BKG for the MGEX project, a selected subset is also supporting real-time analyses (Fig. 2). All real-time streams utilise NTRIP, the Networked Transport of RTCM via Internet Protocol [8], which has emerged as a standard for real-time GNSS data exchange. A dedicated MGEX caster (http:// http://mgex.igs-ip.net/) is hosted by BKG in Frankfurt, where native raw data streams received from the individual sites are converted and encoded in a prototype of the RTCM3 Multiple-Signal-Message (MSM) format.

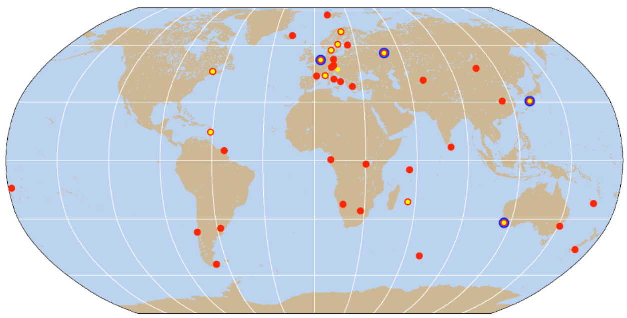

Figure 2 Distribution of MGEX real-time stations supporting tracking of QZSS (blue), Galileo (red), and BeiDou (yellow) as of Feb. 2013.

Following the recent acceptance of the proposed format specification [9], RTCM3-MSM will enable a harmonised framework for multi-GNSS real-time operations and ensure a seamless conversion to the RINEX 3 offline data format. The new MGEX NTRIP caster provides a basis to gain early experience with the new MSM format and facilitates a timely adaptation of user software. This is further supported through free-ware software modules for data conversion provided by BKG.

SYSTEM CHARACTERISATION

While a systematic quality control of the MGEX data has not yet started, first performance assessments of both the ground and space segment have been reported in [10], [2] and other publications. Overall, the measurement quality of the employed multi-GNSS receivers is found to be comparable or even superior to established GPS reference stations. A high performance is, in particular, obtained for unencrypted signals with high chipping rates and bandwidths such as the GPS/QZSS L5 and Galileo AltBOC.

By way of example, Fig. 3 illustrates the elevation-dependency of pseudorange errors for BeiDou tracking with a Trimble NetR9 receiver as used at numerous MGEX stations. Aside from the expected variation of receiver noise, the analysis reveals a systematic code bias that varies by 0.4-0.6 m from horizon to zenith and can best be attributed to spacecraft internal multipath ([11], [12]).

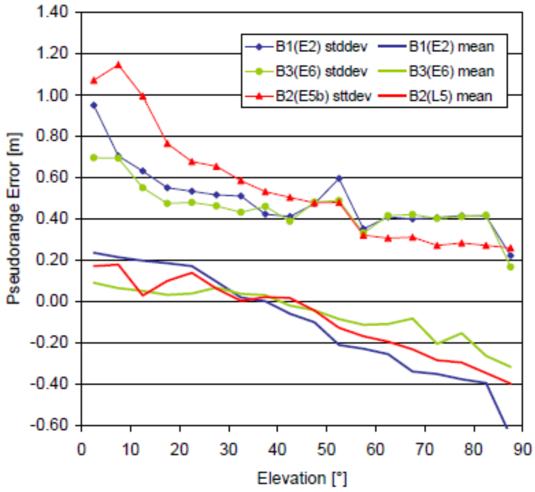

Figure 3 Code noise and elevation-dependent biases for BeiDou tracking (from [11]).

An interesting opportunity for system characterisation is provided by triple-frequency observations (GPS+QZSS L1/L2/L5, BeiDou B1/B2/B3, Galileo E1/E5a/E5b) made available by a subset of the MGEX network. While a thermal variation of inter-frequency biases has earlier been identified for the GPS Block IIF satellites, a high level of consistency is demonstrated for QZSS, BeiDou, and Galileo (Fig. 4).

PRODUCTS

While the newly established MGEX network forms a mandatory prerequisite for multi-GNSS work within the IGS, the MGEX experiment supports a wider range of activities, that are presently being established. Foremost, the generation of orbit and clock products for the new constellations is promoted in coordination with new and established IGS analysis centres.

Initial Galileo IOV products are already provided by CNES/CLS [13], CODE [14], and GFZ [15] since mid-2012, and a combined Galileo+QZSS product has recently been added by Technische Universität München (TUM; [16], [17]). Aside from the MGEX network, some of these solutions make complementary use of proprietary multi-GNSS networks to compensate existing coverage limitations and achieve an improved product quality.

Table 3 Inter-comparison of selected MGEX orbit products for the Galileo IOV satellites (here: IOV-1,DOY

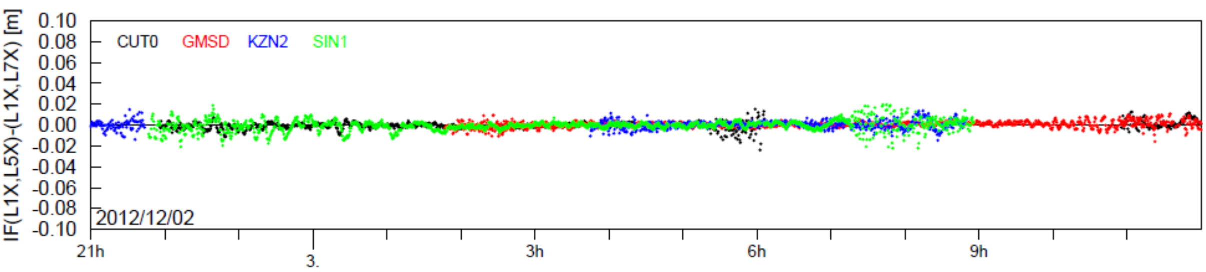

Figure 4 Triple-frequency combination of Galileo IOV-3 observations from various MGEX stations demonstrating a high coherency of E1, E5a, and E5b carrier-phase measurements for the new European navigation satellites [2].

323-329, 2012). Orbit differences (mean±std.dev.) in radial (R), along-track (T) and cross-track (N) direction are provided in the upper right cells, 3D rms position differences in the lower left. All values in units of m.

	COD	CNES/CLS	TUM
COD	-	R +0.05±0.09 T -0.00±0.29 N +0.04±0.15	R +0.00±0.03 T +0.06±0.09 N -0.04±0.07
CNES/CLS	0.34	-	R -0.05±0.10 T +0.06±0.30 N -0.09±0.13
TUM	0.14	0.36	-

Table 4 Satellite laser residuals (mean±std.dev.) for Galileo IOV-1/2 orbit products (DOY 323-329, 2012).

	COD	CNES/CLS	TUM
Residuals	-6.8±3.6	+0.7±8.4	-6.8±5.6

Based on inter-agency comparisons (Table 3) and satellite laser ranging measurements (Table 4) collected by the International Satellite Laser Ranging Service (ILRS; [18]), a user equivalent range error (UERE) of a few decimetres is presently achieved by MGEX orbit products of the Galileo IOV satellites. For CODE and TUM products, which are both based on 3-day data arcs rather than 1-day arcs, an even better accuracy of about 10cm can be inferred from the inter-comparison and the SLR residuals analysis.

For QZSS only a single MGEX analysis centre (TUM) is presently generating orbit and clock products. However, precise ephemerides are also provided by the JAXA control segment. As shown in Fig. 6 for a sample data arc in Jan./Feb. 2013, a consistency at the level of 10-20cm is presently achieved for each axis by these products.

Concerning the Chinese BeiDou system, which has now reached the initial operational capability for a regional service, early orbit and clock determination results have been reported by various Chinese [19] and European [20] researchers using data from dedicated regional sensor station networks. An effort will be made to promote the extension of the BeiDou tracking capabilities within the MGEX network and to make MGEX-only or mixed-network-based orbit and clock products for BeiDou accessible to a wider user community through the MGEX data centres.

In the absence of publicly available broadcast navigation data for Galileo (and prior to 2013 also for BeiDou), the MGEX orbit and clock products constitute a significant promotion for the early use of all available navigation systems. Aside from initial positioning experiments they provide a basis for the in-depth characterisation of both the space and user segment, and – hopefully – help facilitate an improved interaction with system providers. Early applications of MGEX multi-GNSS products and observations have, for example, been reported in [21], [22], and [11].

STANDARDISATION

In support of MGEX, the MGWG interacts closely with other IGS working groups to coordinate data formats, processing standards and applicable models for use in

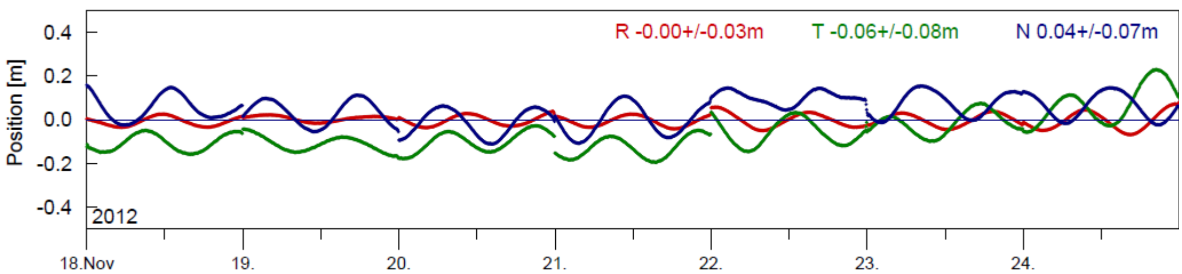

Figure 5 Difference of MGEX Galileo IOV-1 (E11) orbit products from TUM and CODE for DOY 232-239, 2012 (R: radial direction, T: along-track direction, N: cross-track direction)

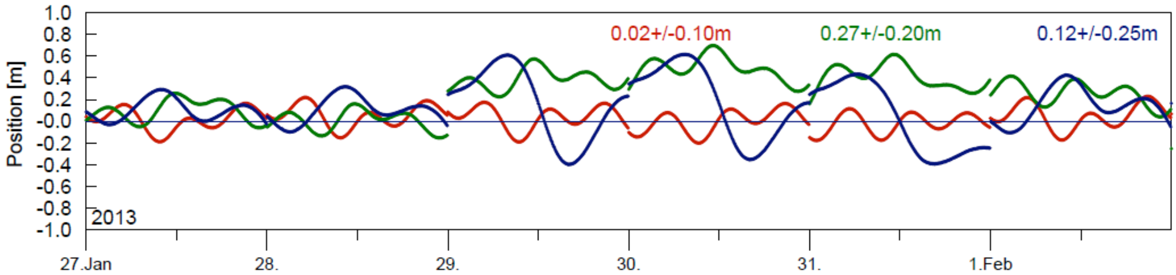

Figure 6 Comparison of TUM MGEX orbit products of QZS-1 with precise ephemerides of JAXA for DOY 027-033, 2013

multi-GNSS work. Examples include necessary RINEX 3 and RTCM3 extensions for full support of new GNSS signals and tracking modes as well as the rapidly growing set of diverse broadcast navigation data.

Table 5 Conventional antenna offsets from the spacecraft centre of mass for processing of Galileo IOV and BeiDou observations as recommended by the MGEX project. All values refer to the spacecraft coordinate system.

	$x_{s/c}$	$y_{s/c}$	$z_{s/c}$
Galileo IOV	+0.2 m	+0.0 m	+0.6 m
BeiDou	+0.6 m	+0.0 m	+1.1 m

Another focus of current work addresses the proper moelling of antenna offsets and phase patterns for receiver and satellite antennas, along with a documentation of constelation-specific spacecraft coordinate systems and attitude modes. This work is performed in close coordination with the IGS Antenna Working Group. Among others, conventional antenna phase centre offsets (Table 5) have been agreed upon that shall enable a consistent processing of MGEX observations up to the release of official information by the Galileo and BeiDou program offices.

PUBLIC OUTREACH

As a central point for exchange of MGEX-related information with the user community, a dedicated website has been established at the IGS Central Bureau (Figure 7). The new web site provides an overview of available MGEX data and products with direct links to the respective archives at IGS data and product centres. Furthermore, users are provided with up-to-date information on the status of emerging navigation satellite systems as well as recommended parameters (e.g. antenna offsets) for a harmonised and consistent processing of MGEX observations.

Figure 7 Homepage of the IGS multi-GNSS Experiment at http://igs.org/mgex

Through individual members, the Multi-GNSS Working Group is furthermore represented in other boards and bodies such as the International Committee on GNSS (ICG), the IAG, and the Multi-GNSS Asia (MGA) project.

SUMMARY AND CONCLUSIONS

As part of its continued effort to provide highest-quality data and products for all satellite navigation systems, the International GNSS Service has initiated the IGS Multi-GNSS Experiment. MGEX supports early work with new signals and constellations. It enables a timely preparation of IGS analysis centres as well as the user community to expand from GPS/GLONASS towards full multi-GNSS processing.

Within the first year of MGEX, substantial progress has already been made. In particular a global network of muti-GNSS receivers has been established in parallel to the existing core network or by upgrading existing sites with new multi-GNSS equipment. The MGEX network forms the backbone for all other activities, such as system characterisation and product generation. Aside from offline data provisions, a substantial fraction of MGEX stations are already offering real-time data streams which paves the way for a rapid extension of the upcoming IGS real-time pilot service to Galileo and possibly other constellations. A limited number of analysis centres has already started to provide orbit and clock products for Galileo and/or QZSS as a basis for precise positioning applications. Aside from initial positioning experiments they will provide a basis for the in-depth characterisation of both the space and user segment, and – hopefully – help facilitate an improved interaction with system providers.

Upcoming activities will focus on the systematic incorporation of the BeiDou navigation satellite system. While BeiDou is the third constellation that has reached an operation system status after GPS and GLONAS, it is presently not well covered by the MGEX tracking network. Along with the targeted incorporation of BeiDou-capable reference stations (particularly in the Asia-Pacific area) the generation and provision of related orbit and clock products will be promoted to facilitate a timely use of BeiDou by the geodetic community.

Subject to active participation by a sufficient number of analysis centres, the MGEX project will eventually transition into a Pilot Project offering operational data products of Galileo, QZSS and BeiDou within the next few years.

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