IGS-MGEX: PREPARING THE GROUND FOR MULTI-CONSTELLATION GNSS SCIENCE

O. Montenbruck[1], P. Steigenberger[2], R. Khachikyan[3], G. Weber[4], R.B. Langley[5], L. Mervart[6], U. Hugentobler[2]

[1] DLR/GSOC, Münchener Str. 20, 82234 Wessling, Germany, oliver.montenbruck@dle.de
[2] TUM/IAPG, Arcisstr. 21, 80333 München, Germany, steigenberger@bv.tum.de, urs.hugentobler@bv.tum.de
[3] JPL/IGS-CB, Pasadena, USA, robert.khachikyan@jpl.nasa.gov
[4] BKG, Richard-Strauss-Allee 11, 60598 Frankfurt a. M., Germany, georg.weber@bkg.bund.de
[5] University of New Brunswick (UNB/GGE), Fredericton, N.B., Canada E3B 5A3, lang@unb.ca
[6] TU Prague, Institute of Geodesy, Thákurova 7, 16629 Praha 6, Czech Republic, mervart@fsv.cvut.cz

ABSTRACT

With a total of four new and emerging constellations (BeiDou, Galileo, QZSS, IRNSS) as well as the ongoing modernization of GPS and GLONASS the world of satellite navigation presently experiences dramatic changes. Facing these challenges, the International GNSS Service (IGS) has initiated the Multi-GNSS Experiment (MGEX) to enable an early familiarization with the new systems and to prepare their incorporation into high-precision GNSS modeling and analysis. The paper reports on the status of the new constellations and the MGEX project as of September 2013. The offline and real-time segment of the multi-GNSS network built up so far are described and initial data products are presented. Recent results for individual systems are highlighted and necessary steps towards a comprehensive multi-GNSS service are identified.

1 INTRODUCTION

Over the past decade, the world of global positioning has experienced dramatic changes. Starting from just a single constellation (GPS), a set of six global or regional navigation satellite systems (GLONASS, BeiDou, Galileo, QZSS, IRNSS) has emerged that are already offering or at least preparing a position, navigation and timing (PNT) service. These independent navigation systems are further complemented by a variety of satellite-based augmentation systems to increase the availability, accuracy and reliability of PNT for safety-critical applications.

The potential merits of the new navigation systems have long been praised and often been used to justify the need for their build-up. Leaving aside the political arguments for an independent national PNT infrastructure, the new systems can indeed offer numerous advantages over stand-alone GPS navigation and the use of its legacy ranging signals. New signal structures will not only provide a greater robustness against interference and multipath but also enable more robust tracking at low signal levels. The availability of unencrypted signals on three frequencies enables new approaches to ambiguity resolution in carrier-phase-based relative positioning and can also contribute to the analysis of higher-order ionospheric path delays. Last, but not least, the simple increase in the number of available satellites will not only be of interest for navigation applications, but also offer an increased number of signals for ray tracing the neutral atmosphere and the ionosphere.

Given the remarkable contributions to science that GPS continues to make in geodesy, remote sensing, space and fundamental physics, similar and even larger benefits are commonly expected from the new navigation systems. Many of the quoted applications make direct or indirect use of the International GNSS Service (IGS), which has, over many years, set the gold standard for high-precision GPS and GLONASS measurement modeling and analysis. The IGS is a volunteer organization of more than 200 individual agencies and institutions that maintain a global network of monitoring stations and a long-term tracking data archive as well as products derived from the analysis of these measurements.

With the advent of modernized GPS signals and the rise of numerous new GNSS such as BeiDou, Galileo, QZSS and IRNSS as well as new augmentation systems such as SCDM and GAGAN, the IGS is fully committed to expand to a true multi-GNSS service. To pave the way for a future provision of high-quality data and products for all constellations, the IGS has initiated the Multi-GNSS Experiment (MGEX) under coordination of its Multi-GNSS Working Group. MGEX serves as a framework for increasing the overall awareness of multi-GNSS within the scientific and engineering communities, as well as to familiarize IGS participants and users with the new navigation systems.

The paper starts with a brief overview of new and modernized GNSS constellations and their transmitted signals as available in fall 2013. Thereafter, the MGEX network is described, which has been established by the IGS for multi-GNSS tracking and is operated in parallel to the legacy network in use for GPS and GLONASS. In the subsequent section initial MGEX data products are presented and their achieved performance is assessed along with a discussion of relevant processing standards. The paper concludes with a discussion of necessary steps and actions required for a full incorporation of new constellations and signals into the IGS service portfolio.

2 NAVIGATION SYSTEMS STATUS

A summary of current navigation systems and satellites is given in Tab. 1 based on information in [1]. With the most recent launch of IRNSS-1A, a total of six navigation satellite systems have so far become available. Among these, the legacy systems GPS and GLONASS have long achieved their full operational capability and provide navigation signals on at least two frequencies that can be accessed by civil users. A third frequency (L5 or L3) has been added on the latest generation of GPS IIF and GLONASS-K satellites, but remains still limited to a very small number of spacecraft. In June 2013, the GPS Directorate started a first test campaign with life broadcasts of the new L2C and L5 CNAV navigation message. This offers enhanced navigation information and improved positioning capabilities but will only be transmitted on a routine basis once the new GPS control segment (OCX) has been put into operation.

Table 1. Deployment Status of Global and Regional Navigation Satellite Systems in Sep. 2013. Satellites marked in brackets have not been declared operational.

System	Blocks	Signals	Sats
GPS	IIA	L1 C/A, L1/L2 P(Y)	8
	IIR-A/B	L1 C/A, L1/L2 P(Y)	12
	IIR-M	+L2C	7
	IIF	+L5	4
GLONASS	M	L1/L2 C/A + P	24
	K	+L3	(1)
BeiDou	GEO	B1, B2, B3	5
	IGSO	B1, B2, B3	5
	MEO	B1, B2, B3	4
Galileo	IOV	E1, (E6), E5a/b/ab	(4)
QZSS	n/a	L1 C/A, L1C, SAIF L2C, E6 LEX, L5	1
IRNSS	n/a	L5, S	(1)

Next to GPS and GLONASS, a standalone navigation service for China mainland and the Asia-Pacific area is now offered by the BeiDou system. The build-up of a global service is targeted for about 2020. Even though only the B1 Open Service is presently covered by the BeiDou Open Service Interface Control Document (ICD), signals on up to three frequencies can in fact be tracked by a variety of multi-GNSS receivers. BeiDou is thus the first constellation enabling a systematic assessment of triple-frequency positioning techniques.

Galileo has presently four In-Orbit Validation (IOV) satellites in orbit. These satellites support early testing and experimentation, but have not yet been declared healthy. An initial operational service with global coverage is target for a few years from now. While access to the E6 signals is still not fully defined, users can freely access signals with advanced multi-path performance in the E1 and E5a/E5b bands. As a unique feature, the Galileo satellites are equipped with passive hydrogen masers. These offer exceptional clock stability with many potential benefits for real-time navigation, precise positioning and science applications.

Japan has validated the concept of a Quasi-Zenith Satellite System (QZSS) with its “Michibiki” satellite for more than two years. The build-up of a fully operational system comprising at least three satellites in inclined geosynchronous orbit (IGSO) and one in geostationary orbit (GEO) has now been announced and a completion within the present decade is envisaged. The QZSS system supports a unique portfolio of navigation signals on four distinct frequency bands and offers various types of correction data for medium and high-accuracy users.

Finally, a first satellite for the Indian Regional Navigation Satellite System (IRNSS-1A) has been launched in July 2013 and is currently undergoing testing. The system will ultimately comprise four IGSO and two GEO satellites. IRNSS-1A transmits signals in both the L5 and S band but cannot presently be tracked by common GNSS receivers due to lacking information on the employed L5 ranging codes and the unique choice of the second signal frequency. It is unclear, at present, whether addition of an L1 signal is considered for upcoming IRNSS satellites to improve interoperability with existing systems.

The six navigation satellite systems mentioned above are complemented by a total of thirteen Satellite Based Augmentation System (SBAS) satellites in geostationary orbit. While not in the immediate focus of the IGS and the scientific community, a growing number of SBAS satellites already offer dual-frequency (L1/L5) ranging signals that can be tracked by modern GNSS receivers and may become of interest for future precise positioning applications.

An up-to-date overview of the GNSS system status with focus on new constellations is maintained at the web site of the IGS Multi-GNSS project [1] along with supporting information for the data processing.

3 THE IGS MULTI-GNSS NETWORK

As a backbone of MGEX project, a new network of multi-GNSS monitoring stations has been deployed around the globe in parallel to the legacy IGS network for GPS and GLONASS. Building up on contributions from various national agencies, universities and other volunteer institutions, the MGEX network has grown to almost 90 stations by September 2013 and a continued expansion is expected within the last quarter of this year (Fig. 1).

The network largely builds on institutions that have modernized their legacy networks in recent years or established new multi-GNSS-capable monitoring stations. Overall, about two third of all MGEX stations are contributed by the Centre National d'Etudes Spatiales (CNES) and the Deutsches GeoForschungsZentrum (GFZ) as well the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the European Space Agency (ESA), and the Bundesamt für Kartographie und Geodäsie (BKG). An up-to-date map and list of all MGEX stations along with links to station-specific sitelog files is provided at the MGEX website [2].

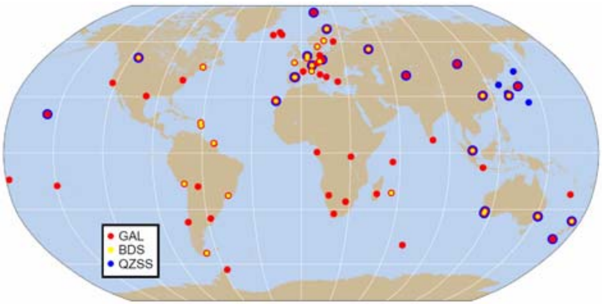

Figure 1. MGEX station distribution and supported constellations (Sep. 2013)

As a minimum, all MGEX stations support tracking of GPS as well as one of the new BeiDou, Galileo, or QZSS constellations. While not a prerequisite, GLONASS is likewise supported by the majority of stations and a large fraction also offers L1 or L1/L5 SBAS tracking. However, no stations with IRNSS tracking capability have, so far, become available for the MGEX project due to the lacking signal specification and the very early project status.

MGEX builds on a highly heterogenous network comprising a wide range of end user equipment (Fig. 2.). Most widely used receiver types include the Trimble NetR9, Javad Delta-G3TH, Leica GR10/25 and Septentrio PolaRx4 receivers. Most sites employ choke ring antennas (such as Leica AR25R3/4, Trimble 59800, or Javad Ringant G3T) but surveying-grade antennas with conventional ground-planes (e.g.., Trimble Zephyr GII) are likewise employed at many stations. Even though the variety of employed receivers and antennas imposes a significant challenge for a consistent data processing, it is, at the same time, a valuable asset. The diversity of available tracking techniques and observation types assists a thorough understanding and assessment of new navigation signals, Also, the cross-comparison of different equipment contributes to a continued evolution and improvement by the manufacturers.

Figure 2. Commonly employed antennas (top) and receivers (bottom) within the MGEX network

Six MGEX sites presently host multiple receivers of different types connected to a common antenna (Table 2). This enables a direct comparison of the tracking behavior and assists the assessment of receiver specific differential code and carrier phase biases for individual GNSS signals.

Table 2. Colocated MGEX stations with common antennas

Site	Station	Receiver
Concepcion	CONX	Javad TRE_G3TH Delta
	CONZ	Leica GRX1200+GNSS
Singapore	SIN0	Javad TRE_G3TH Delta
	SIN1	Trimble NETR9
Univ. New Brunswick	UNBD	Javad TRE_G2T Delta
	UNBS	Septentrio PolaRxS
Univ. New South Wales	UNX2	Javad TRE_G3TH Delta
	UNX3	Septentrio AsteRx3
US Naval Observatory	USN4	Septentrio PolaRxTR4
	USN5	NovAtel OEM6
Wettzell	WTZ2	Leica GRX1200+GNSS
	WTZ3	Javad TRE_G3TH Delta

Observation data and broadcast ephemerides collected by the MGEX network are archived and distributed by data centers at CDDIS, IGN, and BKG. The RINEX 3 format [3] has consistently been adopted throughout the MGEX project. Implementation of the latest version 3.02 is in progress, but legacy DOS-style (7+3) filenames are currently retained for compatibility with existing processing infrastructure. Introduction of new filenames with extended information fields as foreseen in the new RINEX 3.02 standard is planned at a later stage in coordination with MGEX users and the IGS Infrastructure Committee. As a minimum, daily RINEX observation files at a 30-s sampling rate are provided for all stations, but hourly and/or 15-min highrate observations files are likewise offered for selected sites through the individual data centers. Links to the MGEX data archives can again be found at the MGEX web site [2].

In addition to offline data, a large subset of stations also provides real-time data streams with multi-GNSS observations to the MGEX project (Fig 3). A dedicated caster (http://mgex.igs-ip.net/) for the MGEX project is hosted by BKG, Frankfurt, where streams from roughly 70 stations can presently be accessed by interested users following a free registration. The NTRIP protocol [4] and the RTCM3-MSM Multi-Signal Message format [5] have been adopted for the MGEX project to ensure a consistent interface irrespective of the employed receivers and their native binary data formats.

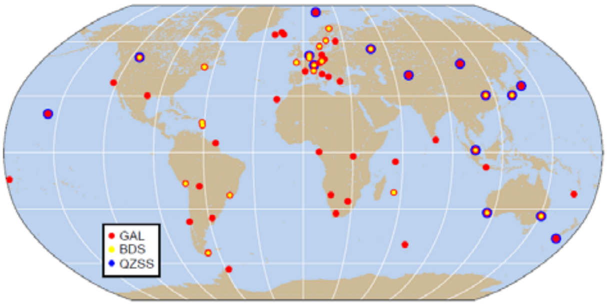

Figure 3. MGEX real-time network (Sep. 2013)

Other than legacy RTCM 3.1 messages, the new MSM messages are designed to handle all constellations, signals and observation types thus as to ensure full compatibility with the information content of RINEX observation files [6]. Following release of the new RTCM 3.2 standard, implementation of MSM support is under preparation by major receiver manufacturers, but MSM-capable firmware versions have not yet been publicly released. As a substitute BKG and NRCan have started to generate prototype MSM data streams for the MGEX project by converting native data formats in real-time. The resulting streams are made available at the BKG MGEX caster and facilitate an early familiarization and utilization of this format.

4 PRECISE ORBIT AND CLOCK PRODUCTS

As a first step towards the incorporation of new constellations into an IGS multi-GNSS service, various analysis centers compute precise orbit and clock products for Galileo and QZSS based on observations of the MGEX network and, optionally, other proprietary stations. The data are publicly available for interested users at the MGEX product archive maintained by the CDDIS [7].

4.1 Galileo

Orbit and clock products for the four Galileo IOV satellites (PRN E11, E12, E19 and E20) are routinely provided by the Technische Universität München (TUM) and Centre National d'Etudes Spatiales (CNES/CLS) with latencies of 3-6 days. These are complemented by various batches of reprocessed ephemeris contributed by the Center for Orbit Determination in Europe (CODE) and GeoForschungsZentrum Potsdam (GFZ). Overall, the MGEX orbit and clock products of Galileo presently cover a time span of almost 1.5 years (Fig. 4), which enables a long-term performance assessment under a wide range of conditions.

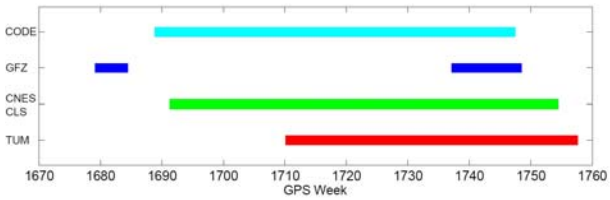

Figure 4. Availability of Galileo precise orbit and clock products in mid Sep. 2013

In the absence of published values for the GNSS antenna offset from the center-of-mass, conventional values of

$$(x, y, z) = (+0.2, 0.0, +0.6)\ \text{m}$$

have been adopted for the MGEX project and are recommended for the observation modeling when working with the MGEX orbit and clock products. The above values refer to the Galileo spacecraft coordinate system illustrated in Fig. 5.

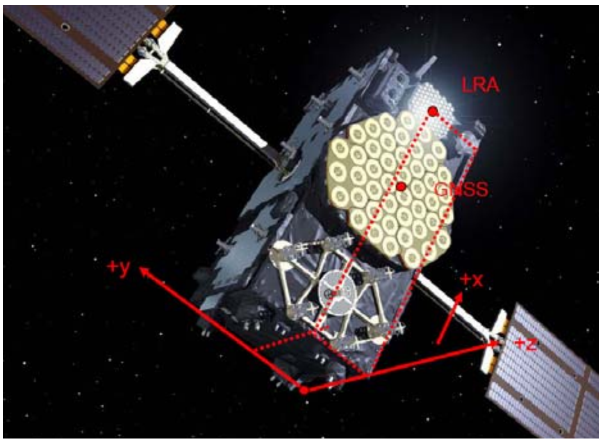

Figure 5. Orientation of the Galileo-IOV spacecraft coordinate system and location of the GNSS antenna and the laser retroreflector (artist's drawing © ESA)

Similar to GPS, the IOV satellites employ a yaw-steering about the Earth-pointing z-axis to maintain the solar panel axis y perpendicular to the Sun-direction. Other than for GPS, however, the Sun is always maintained in the $-x$ hemisphere, while the $+x$-panel carrying the atomic frequency standard is oriented towards the deep space [8].

All MGEX analysis centers make use of a ionosphere-free combination of E1 (Open Service) and E5a observations in their Galileo processing and the resulting satellite clock offsets apply specifically for this set of observations. For single-frequency processing or use of E5b and E5AltBOC observations, appropriate group delay parameters need to be considered. These can, for example, be obtained from the Galileo broadcast ephemeris message.

A comparison of Galileo IOV precise orbit estimates from TUM and CODE is given in Fig. 6. On average over all satellites and the 8-month analysis period, the two products exhibit a consistency of about 16 cm (3D rms position difference). This contributes an orbit-only uncertainty of roughly 5 cm to the user range error. CNES/CLS orbit products currently show a roughly three times larger error, which can largely be attributed to the use of 1-day data arcs (as opposed to 3-day or 5-day solutions provided by the other analysis centers)

For an independent performance assessment, satellite laser ranging (SLR) measurements collected by the International Laser Ranging Service (ILRS, [9]) have been used. On average, some 50 normal points are collected per day for each of the four Galileo IOV satellites. Residuals of the SLR measurements with respect to the GNSS-based orbit solutions provide a direct measure of the line-of-sight orbit errors. These are illustrated in Fig. 7 for satellite pairs IOV-1/2 (PRN E11/E12) and IOV-3/4 (E19/E20) which are placed in orbital planes B and C, respectively. Aside from a mean radial bias of about 5 cm, which is as yet unexplained, the residuals show a distinct bow-tie pattern with peak amplitudes of about 20 cm and a standard deviation of about 8 cm. These values clearly exceed the self-consistency of the CODE and TUM orbit products and indicate the presence of highly correlated common errors in both solutions.

As may be recognized from a comparison of SLR residuals for individual satellites, the error amplitude is primarily related to the Sun angle above the orbital plane (i.e., the β-angle). The residuals are smallest whenever the Sun achieves its maximum elevation above the respective plane. However, a secondary minimum can be noted in the vicinity of the eclipse season, when the β-angle vanishes.

The radial orbit errors evidenced by the SLR residuals indicate a subtle error in the modeled accelerations. In view of their obvious correlation with the Sun aspect angle, a deficiency of the solar radiation pressure modeling presently appears as the most plausible cause of these errors. Indeed both CODE and TUM employ the same 5-parameter ECOM model [10], which is well

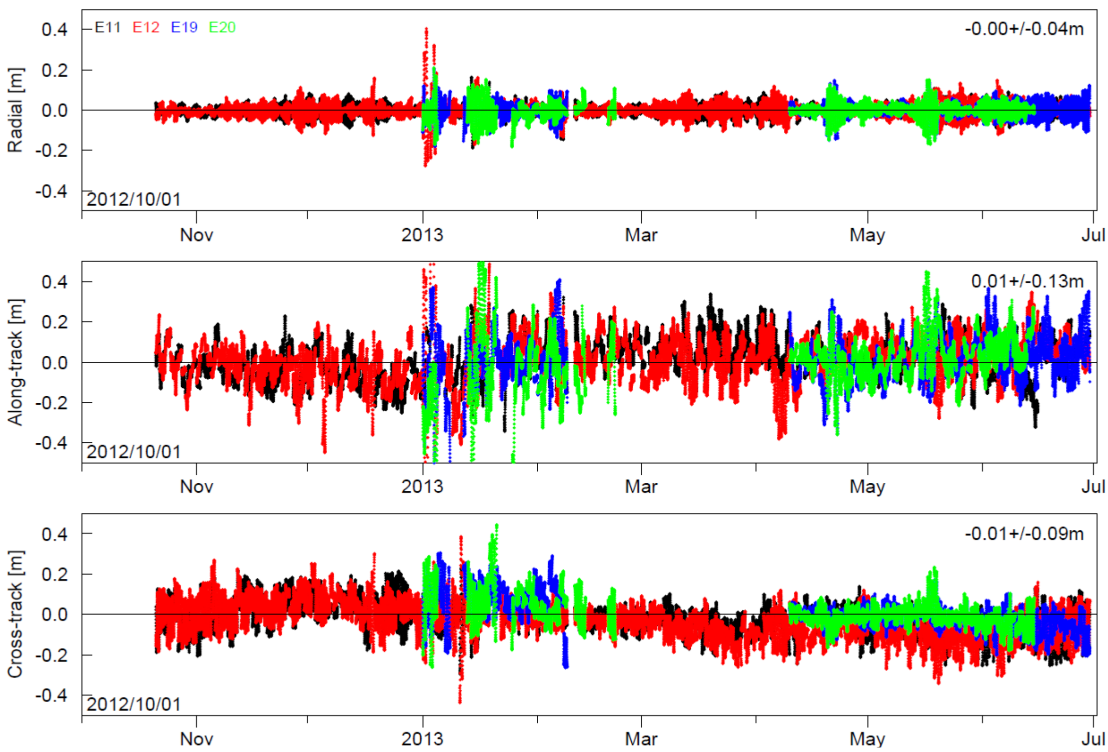

Figure 6. Difference (TUM-minus-CODE) of MGEX precise orbit products for the Galileo IOV satellites

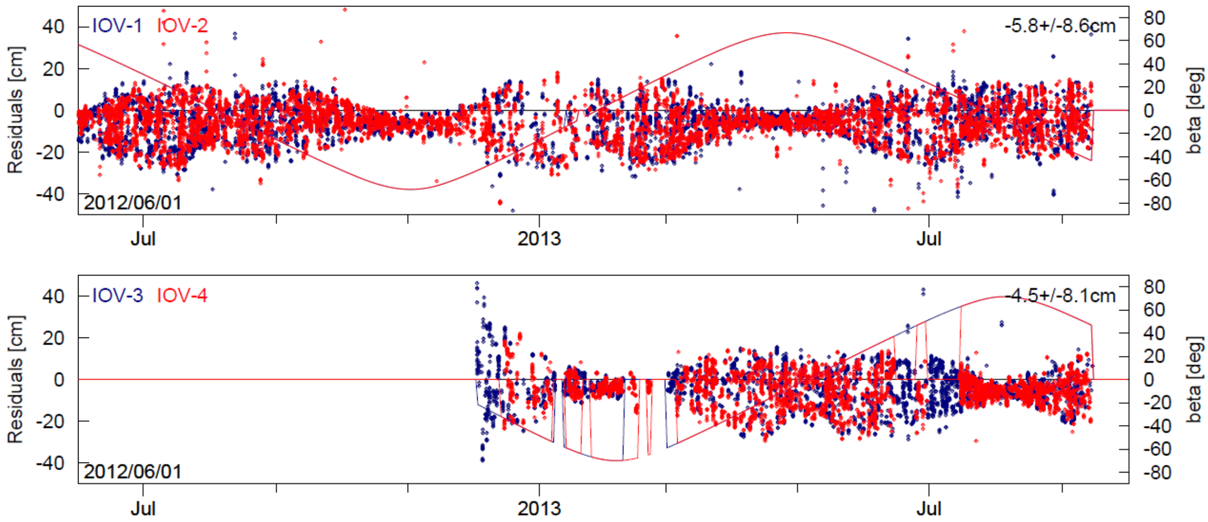

Figure 7. Satellite laser ranging residuals of CODE and TUM orbit products for the first (*top*) and second (*bottom*) pair of Galileo IOV satellites. Solid lines indicate the sun angle above the orbital plane (β-angle).

proven for GPS but appears to be less adequate for the Galileo satellites. Further analyses will be required to assess the potential benefits of a full-featured box-wing model or a ROCK-type a priori model as proposed in [11].

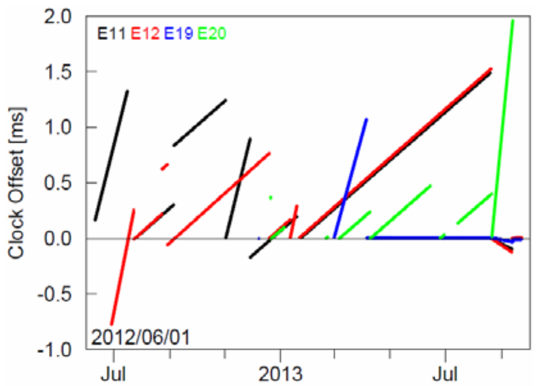

Figure 8. Clock Offsets of the Galileo IOV satellites from GPS Time as derived by MGEX analysis centers

An overview of the Galileo IOV clock offset and drift based on MGEX precise ephemeris products is shown in Fig. 8. Over the past year the clock offset have mainly been confined to less than 1.5 ms with typical drifts of 5-20 µs/d relative to the GPS time scale.

Both hydrogen masers and Rubidium clocks have been operated in an alternating manner on the individual satellites. While MGEX observations and clock products can be used to characterize the Allan deviation over a wide range of timescales a detailed clock analysis is beyond the scope of this paper and left to other publications [12,13].

4.2 QZSS

Next to Galileo, QZSS is the second emerging navigation satellite system for which precise ephemeris products are generated within the MGEX project. As of fall 2013, only one MGEX analysis center (TUM) determines precise QZSS orbit and clock data based on observations of the MGEX network. However, final QZSS products generated by the JAXA control segment based on a mission specific monitoring network are provided as a complement to the TUM products since August of this year. The contribution of a new multi-GNSS ephemeris product generated by JAXA with the new MADOCA software [14] is foreseen in 2014 following dedicated inter-agency comparisons and completion of the software validation.

A comparison of TUM and JAXA orbits solutions for QZSS is shown in Fig. 9 for a 1-month period in July/August 2013. The two products exhibit a consistency of about 0.7 m (3D position difference), while the radial component agrees to roughly 0.1 m. This is essentially consistent with satellite laser ranging residuals of about 0.15 m for each of the two products in the same time period.

While the above comparison demonstrates a good performance of MGEX QZSS products during phases of high β-angle, a degraded quality may be noted when QZSS attains an orbit-normal attitude for |β|<20°. Here, the standard IGS yaw-steering attitude model is no longer applicable and the parameterization of the radiation pressure must be adapted to account for the actual orientation of the spacecraft body and the solar panels [16].

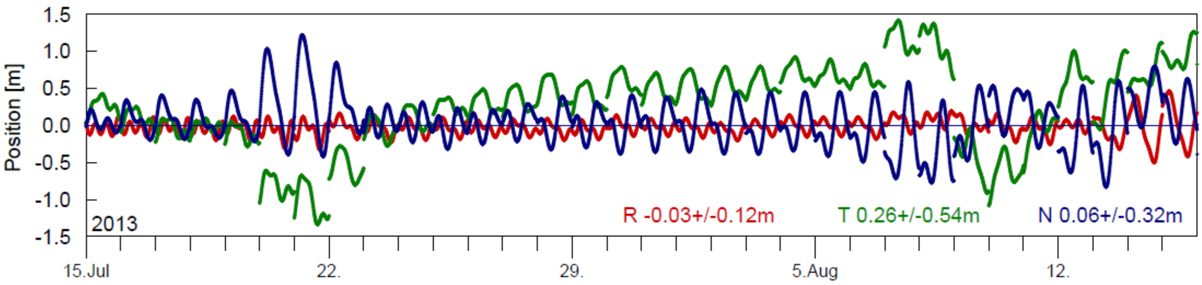

Figure 9. Difference of TUM and JAXA orbits solutions for QZSS over a one-month period in mid 2013

4.3 BeiDou

The BeiDou system has declared an operational regional navigation service at the beginning of this year and provides broadcast ephemerides of good accuracy to its users. Precise orbit and clock products are computed by various Chinese institutions (such as Wuhan university) making use of proprietary networks as well as MGEX monitoring stations. For BeiDou satellites in medium Earth orbit (MEO) and inclined Geosynchronous Orbit (IGSO), overlap accuracies at the 10 cm level (3D position) and SLR residuals of similar order have been reported in [15]. For geostationary (GEO) satellites a degraded performance with along-track errors of about 0.5 m is achieved as a result of the static observation geometry.

Within the MGEX project, the generation of precise orbit an clock products for BeiDou has not yet started, but efforts are made to provide first such products in early 2014.

5 BROADCAST EPHEMERIDES

In an effort to provide users with orbit and clock information for all GNSS satellites presently tracked by the MGEX network, a cumulative broadcast ephemeris file with GPS, GLONASS, Galileo, BeiDou, and SBAS information is generated on a daily basis by TUM and DLR for the MGEX project. Overall, the file provides ephemerides of more than 80 satellites and this number will increase as more satellites are deployed. For improved compatibility with existing s/w packages, that may not have full-featured implementation of the broadcast orbit models for all constellations, an SP3 version of the ephemeris file will also be provided. In this context, an extension for the SP3c format accommodating more than 85 satellites has been initiated and is under review within the IGS.

Even though the accuracy of the broadcast orbit and clock information is not fully competitive with precise data products, the broadcast ephemerides are well suited for numerous applications such as visibility analysis, quality control of observation data or relative navigation. In case of BeiDou, for which precise ephemerides are not yet available within the MGEX project, the broadcast ephemerides achieve a typical user range error at the 1.5 m level [17]. The broadcast ephemerides also provide access to group delay parameters (TGD, BGD) and inter-constellation system time offsets for new constellations for which no alternative products are currently available in the MGEX project.

In view of the current limitation of the RINEX 3.02 navigation message format [3], the cumulative broadcast file is limited to legacy (L1 C/A-code) navigation messages for GPS and QZSS, but does not support CNAV and CNAV2 messages broadcast with the new L2C, L5 and L1C signals. An effort has, nevertheless, been made within the MGEX project to collect CNAV broadcast ephemerides during the first GPS CNAV test transmission in June 2013 with a limited set of receivers [18,19]. Aside from binary raw navigation data frames transmitted by the Block IIR-M and IIF satellites during the campaign, the decoded navigation and auxiliary data have been archived in a RINEX-style format and are made available to interested users through the CDDIS [20].

6 FUTURE WORK

The build-up of the MGEX network has laid the foundation for an early familiarization with new GNSS signals and systems. Even though first steps have been made to provide precise ephemeris products for individual constellations, a major effort still needs to be made before a comprehensive multi-GNSS service can be offered within the IGS. Key activities to be pursued by the Multi-GNSS Working Group in cooperation with other IGS entities over the next year include

- the expansion of multi-GNSS tracking capabilities within the frame of an overall IGS network,
- the consideration of additional constellations (BeiDOu, IRNSS and, optionally SBAS) in the precise ephemeris generation,
- the development of a new multi-GNSS/multi-signal differential code bias product and its generation within the ionospheric data processing

- the characterization of the new GNSS satellites (antenna offsets and phase pattern, attitude modes, solar radiation pressure models, maneuvers) and the development of common processing standards for orbit and clock products,
- the development of multi-GNSS/multi-signal quality control tools (noise, multipath, cycle slips, etc.) and their routine application for monitoring of the overall network.

These tasks will help to pave the way for a comprehensive consideration of new navigation satellite systems in engineering and science and strengthen the role of IGS as a leading provider of free GNSS data and products of highest quality.

7 SUMMARY AND CONCLUSIONS

The status of the MGEX project has been reported and current achievements have been highlighted. Over the past 1-2 years a global multi-GNSS network has been established and initial products are delivered to the scientific community. Future work within the MGEX project focuses on the incorporation of additional constellations, the improved characterization of the space and ground segment, and the provision of new product types. Subject to active participation by MEGX analysis centers and a timely build-up of the necessary processing chains, the MGEX project is expected to transition into a multi-GNSS Pilot Project within the next couple of years.

REFERENCES

1. Langley, R. (2013). The Almanac, *GPS World* 13(8), 47-50.
2. Homepage of the IGS Multi-GNSS Experiment. URL http://igs.org/mgex (alternate URL for access from China: http://igsws.unavco.org/mgex/)
3. IGS (2013); *RINEX – The Receiver Independent Exchange Format;* Version 3.02; IGS RINEX WG and RTCM-SC104, 3 April 2013.
4. Weber, G., Dettmering, D., Gebhard, H. & Kalafus, R. (2005); Networked Transport of RTCM via Internet Protocol (Ntrip)—IP-Streaming for real-time GNSS applications. *ION-GPS-2005*; 13–16 Sep. 2005, Long Beach, CA.
5. RTCM (2013). *RTCM Standard 10403.2 Differential GNSS (Global Navigation Satellite Systems) Services – Version 3 with Ammendment 1*. RTCM, Arlington, VA, 12 July 2013.
6. Boriskin, A., Kozlov, D. & Zyryanov, G. (2012). The RTCM Multiple Signal Messages: A New Step in GNSS Data Standardization, *Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2012)*, Nashville, TN, Sep. 2012, pp. 2947-2955.
7. MGEX Product Archive. URL . ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/
8. Konrad, A., Fischer, H.-D., Müller, C., Oesterlin, W. (2007). Attitude & Orbit Control System for Galileo IOV; *17th IFAC Symposium on Automatic Control in Aerospace*. DOI 10.3182/20070625-5-FR-2916.00006
9. Pearlman, M.R., Degnan, J.J., and Bosworth, J.M. (2002). The International Laser Ranging Service, *Advances in Space Research*, 30(2):135-143. DOI:10.1016/S0273-1177(02)00277-6
10. Springer, T. A., G. Beutler, and M. Rothacher (1999). A New Solar Radiation Pressure Model for GPS Satellites. *GPS Solutions* 2(3):50-62.
11. Svehla D., Rothacher, M., Hugentobler, U., Steigenberger P., Ziebart M. (2013). Geometrical Model of Solar Radiation Pressure Based on High-Performing Clocks Onboard new GNSS Satellites; IAG Scientific Assembly, 1-6 Sep. 2013, Potsdam.
12. Hauschild A., Montenbruck O., Steigenberger P. (2013). Short-Term Analysis of GNSS Clocks; *GPS Solutions* 17(3):295-307 DOI 10.1007/s10291-012-0278-4
13. Hackel, S., Steigenberger, P., Hugentobler, U., Uhlemann, M., Montenbruck, O. (2013). Galileo Orbit Determination using Combined GNSS and SLR Observations; *GPS Solutions*.
14. Miyoshi, M., et al. (2012). The orbit and clock estimation result of GPS, GLONASS and QZSS by MADOCA; 23rd Int. Symposium on Space Flight Dynamics, 29 Oct – 2 Nov. 2012, Pasadena.
15. Zhao, Q., Hu, Z., Guo, J., Li, M., Shu, X., Chen, G., Shi, C., Liu, J. (2013). Positioning Performance of BeiDou Navigation Satellite System; IGNSS Symposium 2013, 16-18 July, 2013, Gold Coast, Australia.
16. Ikari, S., Ebinuma, T., Funase, R., Nakasuka S. (2013) An Evaluation of Solar Radiation Pressure Models for QZS-1 Precise Orbit Determination: ION-GNSS-2013, 17-20 Sep. 2013, Nashville, TN.
17. Montenbruck, O., Steigenberger, P. (2013).; *The BeiDou Navigation Message*; IGNSS Symposium 2013, 16-18 July 2013, Gold Coast, Qld, Australia.
18. GPS Directorate (2013). *Global Positioning System Modernized Civil Navigation (CNAV) Live-Sky Broadcast Test Plan*, 30 May 2013. URL http://www.navcen.uscg.gov/Content/GPS/CNAV Testing/L2C_L5_CNAV_Test_Plan.pdf
19. Montenbruck, O., Langley, R.B., Steigenberger, P.; First Live Broadcast of GPS CNAV Messages; *GPS World*, Vol. 24, No. 8, August 2013, pp. 14-15; URL http://www.gpsworld.com/2c-or-not-2c-the-first-live-broadcast-of-gps-cnav-messages/
20. June 2013 CNAV Campaign Directory. URL ftp://cddis.gsfc.nasa.gov/gnss/data/campaign/cnav/2013/06/