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# GNSS Satellite Orbit Validation Using Satellite Laser Ranging

**O. Montenbruck (1), P. Steigenberger (2), G. Kirchner (3)**
(1) DLR, German Space Operations Center, Wessling, Germany.
(2) Technische Universität München, Munich, Germany.
(3) ÖAW, Space Science Institute, Graz, Austria
oliver.montenbruck@dlr.de

**Abstract.** *With a total of four new regional and global navigation satellite systems that have launched first satellites or even started an operational service, the GNSS landscape has experienced major changes in recent years. As part of the Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS), a global network of multi-GNSS monitoring stations has been established and various analysis centers have started to determine orbits of selected GNSSs on a routine basis. As a key feature, all satellites of the new constellations (i.e. Galileo, BeiDou, QZSS and IRNSS) are equipped with laser ranging reflector arrays enabling high-precision two way ranging measurements. The paper illustrates the use of SLR observations collected by the ILRS for validation of precise and broadcast ephemerides of the new constellations. As an independent and unambiguous tracking system, SLR helps to gain a better understanding of the new satellites, which still lack a thorough characterization of their orbit and attitude dynamics. SLR tracking is thus considered an essential contribution for a future use of the new GNSSs in space geodesy. The paper also addresses operational aspects of SLR tracking of the new navigation satellites related to their specific orbits, regional distribution and continuously increasing number.*

## Introduction

Next to GPS and GLONASS, a total of four new navigation satellite systems has merged over the past five years, which will eventually triple the number of constellations available to the user. Among these, the Chinese BeiDou system has already launched a regional navigation service but pursues build-up of a global system over the years to come. Galileo has four satellites in orbit and is presently in the in-orbit validation (IOV) phase. Satellites for the full-operational constellation (FOC) are under construction, but the launch schedule has again been stretched and another 2-3 years will pass before an initial operational service will be provided. Japan, finally has one satellite of its Quasi-Zenith Satellite System (QZSS) in orbit since 2010 and has recently decided to proceed with the build-up of a comprehensive regional navigation system made up of 4-7 satellites in inclined geosynchronous orbits (IGSOs) and geostationary orbits (GEOs). Last but not least, India has successfully launched the first satellite of the Indian Regional Navigation Satellite System (IRNSS) in mid 2013. The system will ultimately comprise four IGSO and 3 GEO satellites and provide a standalone navigation service for India and adjacent regions. IRNSS-1A is currently in the commissioning phase but has already started signal transmission and navigation messages. However, the system is only barely accessible for common users at this stage due to the uncommon choice of signal frequencies (L5 and S-Band) and the lack of a public interface control document.

In response to the changing world of Global Satellite Navigation Systems (GNSS), the International GNSS Service (IGS) has established the Multi-GNSS Experiment (MGEX) to enable an early familiarization with new signals and systems as well as to prepare a future, full-featured multi-GNSS Service for the scientific community.

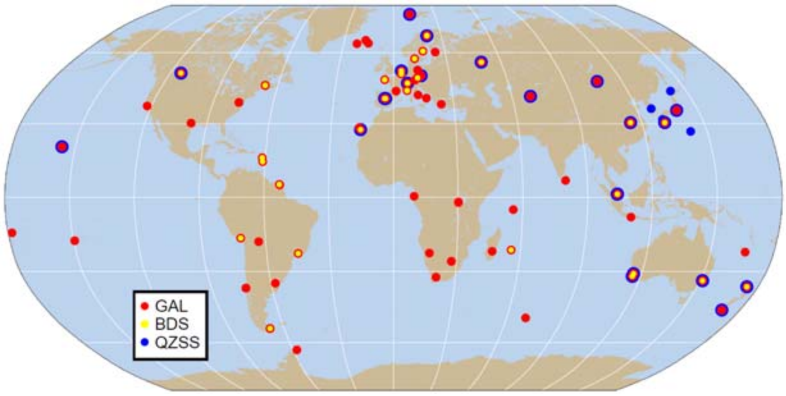

**Figure 1.** MGEX station distribution and supported constellations (Sep. 2013)

As a key achievement, a new network of monitoring stations tracking at least one of the new constellations has been established over the past two years (Figure 1). As of fall 2013, the MGEX network comprises some 90 stations around the globe, most of them enabling real-time data access in addition to offline archival data. Based on these observations, initial precise orbit and clock products have been released for Galileo and QZSS by various MGEX Analysis Centers (Montenbruck et al. 2013). In addition broadcast navigation data from the new (BeiDou, Galileo, QZSS) and legacy (GPS, GLONASS, SBAS) systems are routinely collected and merged into a cumulative multi-GNSS ephemeris product. As an exception, IRNSS is not yet supported by the MGEX project in view of lacking infrastructure and data provisions.

All satellites of the aforementioned new constellations are (and will be) equipped with laser retro-reflector arrays (LRAs) that enable satellite laser ranging (SLR) measurements. Other than GNSS code- and carrier phase measurements, laser ranging is based on a two-way principle and provides (essentially) unbiased distance observations irrespective of the satellite clock. As such, SLR tracking provides an important complement to purely radiometric observations of the new constellations. Support requests for laser tracking have been filed with the International Laser Ranging Service (ILRS) by BeiDou, Galileo, QZSS, and IRNSS and ILRS is already tracking the respective satellites on a routine basis or as part of dedicated campaigns.

The use of these observations enables a fully independent validation of GNSS-only orbit products and provides key information on the quality of dynamical models for the individual constellations. Relevant results for each of the four new constellations are discussed in the next section. Subsequently, operational aspects concerning the tracking of a large number of high altitude satellites with a limited ILRS ground network are addressed, before providing a summary and conclusions.

**BeiDou**

Following the release of a public B1 Open Service ICD, the MGEX project started to collect broadcast ephemerides of the BeiDou satellites on a routine basis in early 2013. Using SLR observations, the radial position accuracy of this orbit information can be validated. Typical root-mean-square (RMS) errors of 0.5-0.7 m have been derived by Montenbruck & Steigenberger (2013) for the four satellites currently tracked by the ILRS (Figure 2). Their results confirm a proper quality of the broadcast information in consistence with the achieved performance for real-time users.

Even though BeiDou observations are already provided from various MGEX stations, the number of sites in view of the regional (GEO and IGSO) system is still quite limited and the generation of precise orbit and clock products by MGEX Analysis Centers has so far been confined to selected

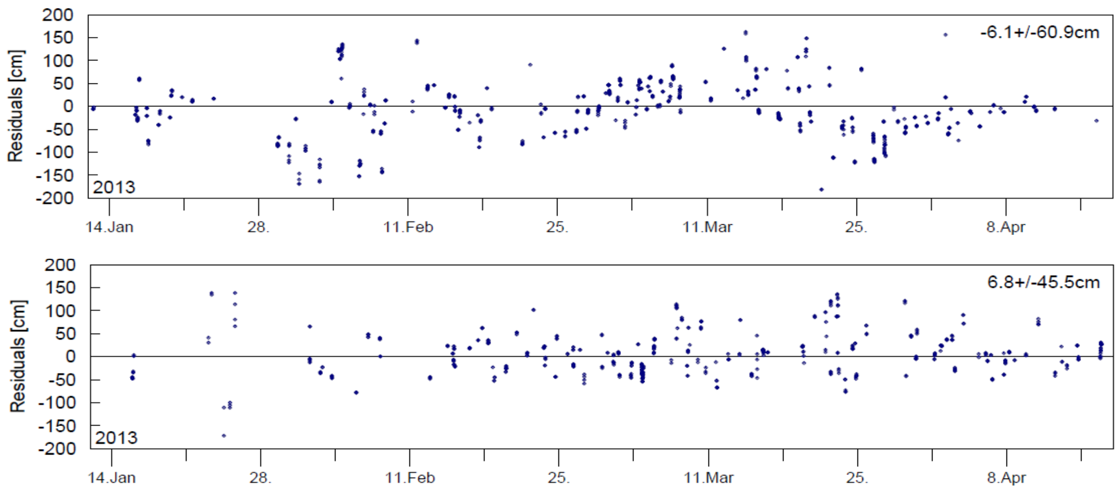


**Figure 2.** SLR Residuals of BeiDou broadcast ephemerides for an inclined geosynchronous satellite (I5/C10; *top*) and a satellite in medium altitude Earth orbit (M3/C11; *bottom*) (Montenbruck & Steigenberger 2013)

trials (Steigenberger et al. 2013). Even though routine products are known to be generated by various Chinese institutions (such as Wuhan University and Shanghai Observatory) making use of a proprietary station network as well as MGEX observations, neither measurements nor derived products are presently made available to MGEX and the IGS community. Following Zhao et al. (2013) the Wuhan orbit solutions match the observed SLR ranges to better than 10 cm RMS, however, an independent validation could not yet been performed by other researchers.

## Galileo

GNSS measurements of the Galileo IOV-1/2 satellites have been collected from the very beginning of the MGEX network and precise orbit and clock products for these satellites are now available for more than 1.5 years. IOV-3 and 4 have been tracked essentially since signal activation in late 2012 and a long record of precise products is likewise available by now.

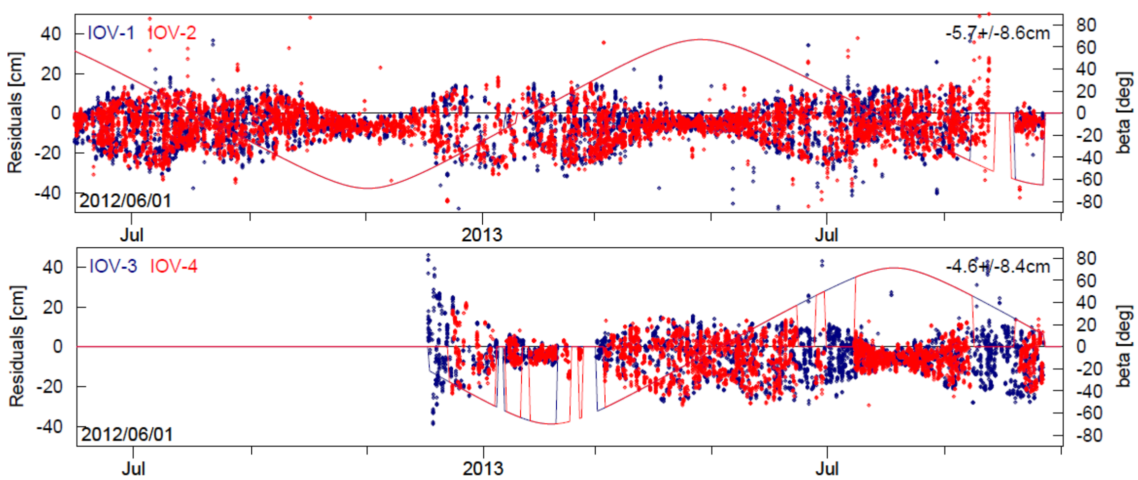


**Figure 3.** SLR residuals of Galileo IOV satellites

Based on SLR observations the MGEX products can be shown to exhibit a radial orbit error of about 10 cm (RMS). Aside from a systematic bias of about -5 cm that is almost identical for all four spacecraft, the radial orbit errors exhibit an orbital periodicity, but a pronounced seasonal variation of their amplitude may be recognized (Figure 3). In fact, the amplitude is strongly related to the Sun's elevations above the orbital plane (also known as β-angle). Error amplitudes are generally least for high elevations but grow up to 20 cm near the eclipse season. Further investigation shows that the SLR residuals (and thus the radial orbit errors) depend primarily on the elongation of the Sun, i.e. the Sun-spacecraft-Earth angle. The pronounced correlation is illustrated in Figure 4 and corresponds to a similar dependence identified by Svehla et al (2013) in the analysis of periodic variations in the apparent clock solutions of the Galileo H-maser as evidenced in the MGEX products.

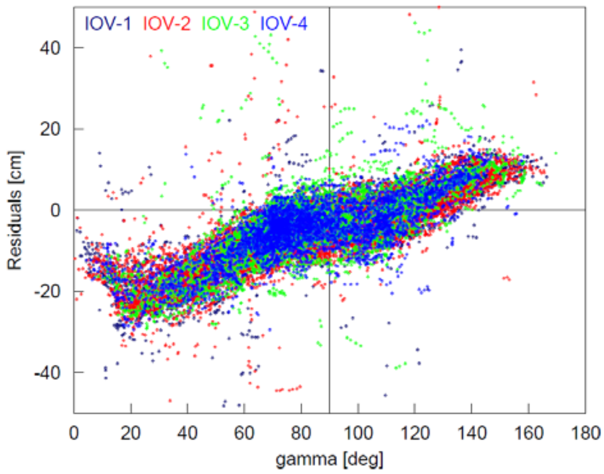


**Figure 4.** SLR residuals of Galileo IOV satellites as a function of the Sun-spacecraft-Earth angle (γ)

The presence of 1/rev orbit errors indicates an error in the modeled accelerations and is commonly attributed to deficiencies in the empirical CODE solar radiation pressure (SRP) model used within the IGS. Apparently this model does not properly capture the true variation of the SRP accelerations with gamma angle and a box-wing or ROCK-type base model is therefore recommended (Svehla et al. 2013). However, the observed radial errors $\Delta R$ and their time variations cannot be used directly to infer the unmodelled radial acceleration $\Delta a_R$ since the radial (R) and along-track (T) motion are coupled via the Hill-Clohessy-Wiltshire equations

$$\begin{aligned} \Delta\ddot{R} - 2n\Delta\dot{T} - 3n^2\Delta R &= \Delta a_R \\ \Delta\ddot{T} + 2n\Delta\dot{R} &= \Delta a_T \end{aligned} \tag{1}$$

(Vallado 1997)
Despite this limitation, the analysis of SLR radial errors provides a crucial tool for validating SRP models and refined orbit determination techniques that are currently under study.

**QZSS**

Precise orbit and clock products for the MGEX project are routinely provided by Technische Universität München (TUM) and the Japan Aerospace Exploration Agency (JAXA). While the former are based on a limited subset of MGEX stations, the JAXA's products make use of a proprietary monitoring network and achieve a factor of-two performance improvement on average. The TUM products are, furthermore, limited by an incomplete modeling of solar radiation pressure throughout the "orbit normal" mode employed by QZSS for β-angles of less than 20°. Irrespective of their better performance, systematic biases with a clear dependence on the Sun elevation above the orbital plane may still be recognized in JAXA's solution. These biases vary between about ±20 cm (Figure 5) and are potentially related to deficiencies in the QZSS solar radiation pressure modeling. As an alternative to empirical SRP models, use of a box-wing model has therefore been suggested for JAXA's new multi-GNSS orbit determination software MADOCA that is currently under qualification for GPS+QZSS+Galileo product generation (Ikari et al. 2013).

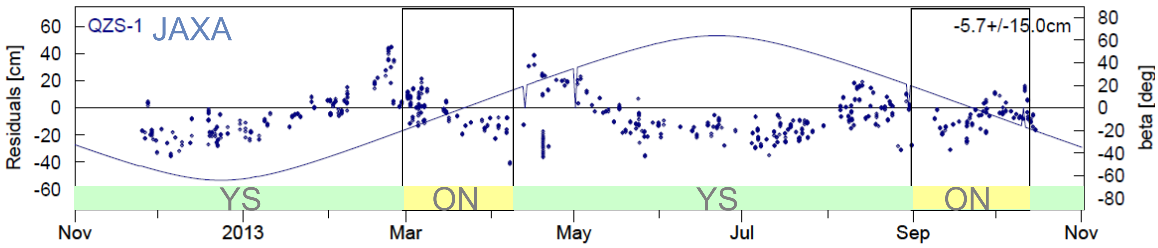


**Figure 5.** SLR Residuals of QZSS (Jaxa final orbit product; YS= yaw-steering mode, ON = orbit normal mode)

**IRNSS**

Even though more than four months have passed since launch of IRNSS-1A, no ICD is presently available and only limited signal analyses have become available so far (Thoelert et al. 2014). Commercial IRNSS-capable GNSS receivers are not available so far and GNSS-based precise orbit determination solutions cannot presently be performed. As such, SLR tracking provides the only means for independent orbit determination at this mission stage. A goodness of fit at the few cm level is presently achieved for orbit determination arcs covering 7-10 days outside maneuver arcs, which enable a preliminary assessment of the IRNSS-1A clock stability from one-way carrier phase analyses as well as a coarse validation of the IRNSS-1A navigation message.

**Operational Aspects**

While the number of operational GPS and GLONASS satellites with laser retro-reflectors will remain essentially constant over the rest of this decade , the overall number of GNSS satellites equipped for laser ranging is expected to double or triple with upcoming launches of BeiDou, Galileo, QZSS and IRNSS. A substantial fraction of these satellites will be geosynchronous/ geostationary satellites with orbital periods of 24 h and altitudes well above the common MEO constellations. In view of their large distance and limited visibility (mainly from the Asia-Pacific region) these satellites can only be tracked by a small subset of ILRS stations and their increasing number posed a notable challenge for comprehensive support by the current laser tracking network.

As shown by Kirchner and Koidl (2012), the tracking of high altitude satellites in general (and GNSS satellites in particular) may, however, benefit substantially from the use of kHz laser systems. The high pulse rate enables the collection of adequate normal points in much less than a 5 min interval currently allocated for this distance range. This enables faster switching between objects and thus a substantially increased turn-around in terms of tracked objects and collected SLR normal points. By way of example, tracking of up to 20 LEO satellites and 14 HEO objects has successfully been demonstrated by the Graz laser station in a single night of 7 h duration.

**Summary and Conclusions**

As shown by the examples of Galileo and QZSS, SLR tracking offers an indispensable tool for validation of GNSS orbit products and its availability is gratefully acknowledged by the GNSS community. SLR tracking has demonstrated a radial orbit accuracy at the level of 10 cm (Galileo, BeiDou) to 20 cm (QZSS). Mean biases between GNSS-based orbits and SLR observations are presently at the 5 cm level for the aforementioned constellations. SLR tracking will also help to assess future improvements from refined orbit dynamics models, improved GNSS tracking coverage and refined processing concepts (e.g., ambiguity resolution). The diversity of orbits and spacecraft models within even a single GNSS constellation suggests a need for comprehensive SLR tracking of "all" new GNSS satellites until the GNSS only orbit determination accuracy is compatible with that of existing systems (GPS, GLONASS). Beyond this immediate goal, SLR tracking of GNSS satellites will contribute to the harmonization of GNSS- and SLR-based reference frames. The development of a consolidated SLR tracking concept for GNSS satellites within the ILRS is therefore encouraged. As part of this, special consideration should be given to the potential increase in overall tracking capacity provided by high-rate kHz laser systems. Build-up of such systems appears of particular interest for the Asia-Pacifica region, which hosts a large number of geosynchronous GNSS satellites that are less well covered than the more common GNSS satellites in medium Earth orbit.

Aside from the use of SLR tracking for the sole purpose of GNSS orbit validation the systematic exploration of combined GNSS+SLR orbit determination techniques shall be promoted by the respective analysis centers. This combination can help to better constrain the radial position than a GNSS-only solution and thus to reduce the impact of solar radiation pressure modeling errors. For geostationary satellites, SLR tracking can likewise help to constrain the orbital longitude, which is only weakly determined from GNSS-data due to the static observation geometry and unknown carrier phase ambiguities.

**References**


Ikari S., Ebinuma T., Funase R., Nakasuka S.; *An Evaluation of Solar Radiation Pressure Models for QZS-1 Precise Orbit Determination*; ION-GNSS-2013, 17-20 Sep. 2013, Nashville, TN (2013).

Kirchner G., Koidl F.; *Graz Experience with HEO SLR*; Joint ITLW-12 and ETRUSCO-2 Workshop, 5-9 Nov. 2012, Frascati (2012).

Montenbruck O., Steigenberger P.; *The BeiDou Navigation Message*; IGNSS Symposium 2013, 16-18 July 2013, Outrigger Gold Coast, Qld, Australia (2013).

Montenbruck O., Steigenberger P., Khachikyan R., Weber G., Langley R.B., Mervart L., Hugentobler U.; *IGS-MGEX: Preparing the Ground for Multi-Constellation GNSS Science*; 4th Int. Colloquium on Scientific and Fundamental Aspects of the Galileo System, 4-6 Dec 2013, Prague (2013).

Steigenberger P., Hugentobler U., Hauschild A., Montenbruck O.; *Orbit and Clock Analysis of Compass GEO and IGSO Satellites*; Journal of Geodesy 87(6):515-526 (2013). DOI 10.1007/s00190-013-0625-4

Svehla D., Rothacher M., Hugentobler U., Ziebart M.; *10 Years of Precise Geometrical Positioning in Space: Geometrical Model of Solar Radiation Pressure Based on High-Performing Clocks Onboard new GNSS Satellites*; IAG Scientific Assembly , Potsdam (2013)

Thoelert S., Montenbruck O., Meurer M.; *IRNSS-1A - Signal and Clock Characterization of the Indian Regional Navigation System*; GPS Solutions (2014). ; DOI 10.1007/s10291-013-0351-7

Vallado, DA.;. *Fundamentals of astrodynamics and applications*. Vol. 12. Springer, 2001.

Zhao Q., Hu Z., Guo J., Li M., Shu X., Chen G., Shi Ch., Liu J.; *Positioning Performance of BeiDou Navigation Satellite System*; IGNSS Symposium 2013, 16-18 July 2013, Outrigger Gold Coast, Qld, Australia (2013).