# Multi-GNSS Pilot Project Technical Report 2023

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## 1 Introduction

In 2023, the IGS made further steps towards a full coverage of all GNSS in the IGS products: two MGEX ACs included additional constellations in their MGEX products. The Combination Task Force continued the development of a combined orbit and clock product, and with the latest generations of NavIC and GLONASS satellites, additional GNSS signals are on the air.

## 2 GNSS Evolution

Table 1 lists the GNSS satellite launches of the year 2023. GPS continued its modernization with the launch of the sixth GPS III satellite which was set healthy and available for use on February 16, 2023. China launched the fourth geostationary satellite of the BeiDou-3 system in May 2023. However, this satellite is not yet part of the operational constellation and still has the status *testing* as of early 2024. The latter is also true for the third BeiDou-3 GEO launched in June 2020. After a break of four years, a pair of BeiDou-3 MEO satellites transmitting as PRN C48 and C50 was launched at the end of 2023.

The first GLONASS K2 satellite was launched in August 2023 and started signal transmission on September 8, 2023 (IGS-ACS-MAIL #1599). In addition to the legacy L1 and L2 frequency division multiple access (FDMA) signals transmitted by all GLONASS satellites and the L3 code division multiple access (CDMA) signals of GLONASS M+ and K1 satellites, K2 adds CDMA signals in the L1 and L2 frequency band. As of early 2024, none of the IGS stations supports tracking of the new CDMA signals. Phase center offsets for the ionosphere-free linear combination of L1 and L2 FDMA signals by CODE, DLR and ESA have been added to the IGS antenna model in November 2023. A draft for the inclusion of L1OCd and L3OCd navigation messages in the RINEX 4.x navigation file format was prepared by the MGWG and is currently under discussion in the RINEX committee.

**Table 1:** GNSS satellite launches in 2023.

| Date | Satellite | Type |
|---|---|---|
| 18-Jan-2023 | GPS III-6 | MEO |
| 17-May-2023 | BeiDou-3 | GEO |
| 29-May-2023 | NVS-01 | GEO |
| 07-Aug-2023 | GLONASS K2 | MEO |
| 26-Dec-2023 | BeiDou-3 | MEO |
| 26-Dec-2023 | BeiDou-3 | MEO |

Launches of additional Galileo satellites are further delayed and now expected for 2024 following launching agreements with SpaceX. Several Galileo reference documents including interface control documents and service definitions have been updated or published in 2023 (European Union, 2023a,b,c,d).

The first generation of satellites of the Indian regional navigation system NavIC suffered from several failures of the onboard Rubidium clocks. Therefore, the Space Applications Centre (SAC) of the Indian Space Research Organisation (ISRO) developed its own Rubidium atomic frequency standard. This new type of clock is flown on NVS-01, the first second-generation NavIC satellite, launched in May 2023. NVS-01 started signal transmission on June 17, 2023 and was declared operational on July 4$^{th}$ of the same year (IGS-ACS-MAIL #1599). In addition to the L5 and S-band signals of the first generation NavIC satellites, NVS-01 also transmits a new signal in the L1 band which was added to the most recent RINEX version 4.01 published in July 2023 (Gini, 2023). A draft for the NavIC L1 navigation message prepared by the MGWG is currently under discussion within the IGS RINEX committee. Recent Javad receivers support tracking of the NavIC L1 starting with firmware 4.3.00 published in December 2023. However, none of the Javad receivers of the IGS tracking network runs that firmware as of early 2024.

## 3 Network

As of January 2024, the IGS multi-GNSS tracking network comprises 403 stations, see Figs. 1 and 2. Compared to 2022, this is an increase of nine stations. Unfortunately, another nine stations are completely dormant and did not provide any observations in 2023.

After a trial period, the RINEX 4 format (Gini, 2023) for observation, navigation, and meteorologial files was introduced in the operational data archives on July 19, 2023 (IGS-MAIL #8349). However, the number of stations providing RINEX 4 data is still very limited. Examples are GOP600CZE in Pecny, Czech Republic, and UNBD00CAN in New Brunswick, Canada.

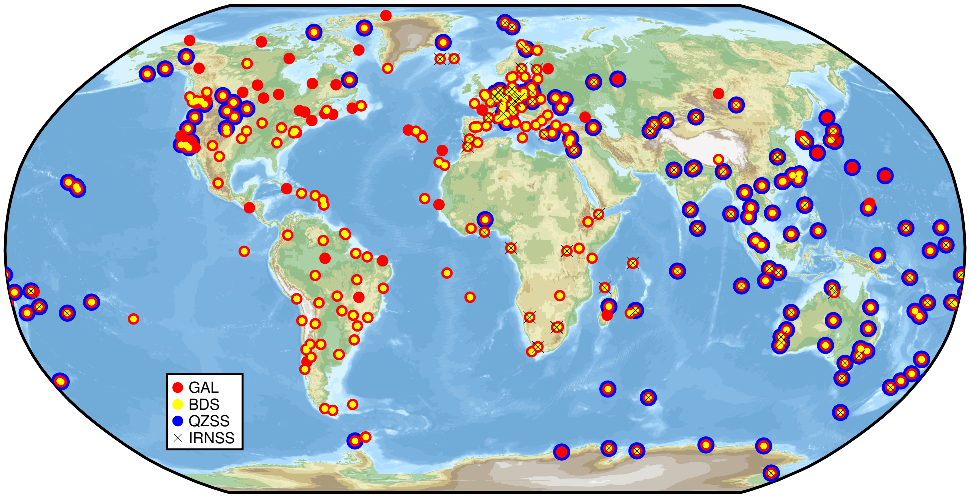


**Figure 1:** Distribution of IGS multi-GNSS stations supporting tracking of Galileo (red), BeiDou (yellow), QZSS (blue), and IRNSS (black crosses) as of January 2024.

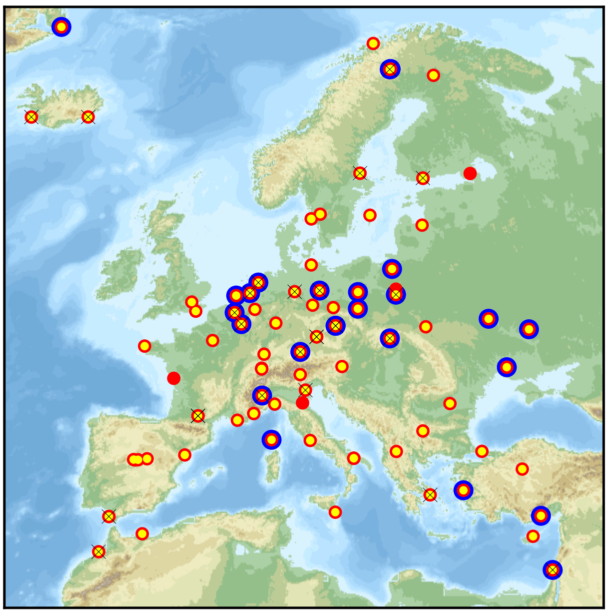

**Figure 2:** Distribution of European IGS multi-GNSS stations as of January 2024. See Fig. 1 for explanation of individual station labels.

# 4 Products

Table 2 lists the analysis centers (ACs) contributing orbit and clock products to the IGS Multi-GNSS Pilot Project. Two MGEX ACs made progress to cover more constellations in their products: JAXA started to include Galileo on 1 August 2023 and BeiDou is included in the CNES/CLS products since GPS Week 2288 (IGS-ACS-MAIL #1610).

**Table 2:** Analysis centers contributing to IGS MGEX as of December 2023.

| Institution | Abbr. | GNSS |
|---|---|---|
| CNES/CLS | GRGOMGXFIN | GPS+GLO+GAL+BDS2+BDS3 |
| CODE | CODOMGXFIN | GPS+GLO+GAL+BDS2+BDS3+QZS |
| GFZ | GFZOMGXRAP | GPS+GLO+GAL+BDS2+BDS3+QZS |
| IAC | IACOMGXFIN | GPS+GLO+GAL+BDS2+BDS3+QZS |
| JAXA | JAXOMGXRAP | GPS+GLO+GAL+QZS |
| SHAO | SHAOMGXRAP | GPS+GLO+GAL+BDS2+BDS3 |
| Wuhan University | WUMOMGXFIN | GPS+GLO+GAL+BDS2+BDS3+QZS |

Multi-GNSS differential code bias (DCB) products are generated by CAS and GFZ (daily rapid products) as well as DLR (quarterly final product). The transition of the MGEX DCB products to operational (OPS) IGS products was decided and prepared in late 2023 and is planned for 23 January 2024. Wuhan University started to provide a rapid MGEX phase bias product, for details see IGSMAIL #8409.

With support from the IGS Central Bureau, the analysis section of the MGEX website (`https://igs.org/mgex/analysis/`) was updated to cover all BDS-3 MEO satellites. Clock time series analysis is now based on one selected AC (currently GFZ).

# 5 SLR tracking of BeiDou-3 MEO satellites

Satellite laser ranging (SLR) is a valuable tool for the validation of GNSS orbits obtained from microwave observations (e.g., Sosnica et al., 2015). So far, SLR tracking of the BeiDou-3 constellation was limited to two CAST and two SECM MEO satellites. In February 2023, the International Laser Ranging Service (ILRS) added the remaining 20 BeiDou-3 MEO satellites to the general pool of satellites where station operators are free to decide to track these targets. Orbit predictions for these satellites in CPF format are generated by SHAO on a routine basis.

Figure 3 shows the number of SLR normal points per BeiDou-3 MEO satellite. Most satellites have between 1000 and 1500 normal points. The four satellites previously recommended for SLR tracking (CAST MEO-3/4 and SECM MEO-9/10) have still a signif-

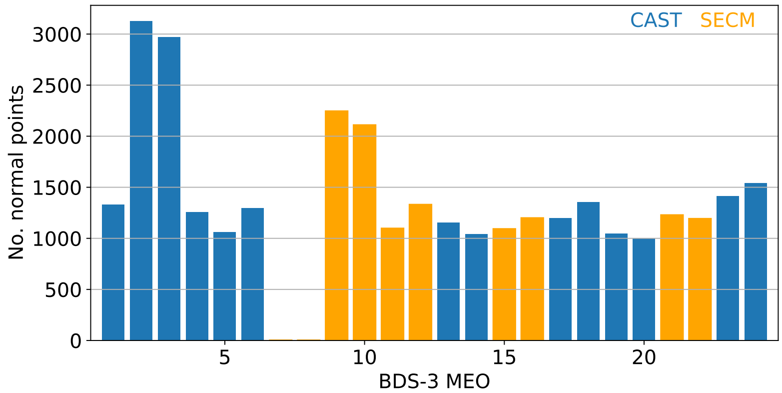


**Figure 3:** Number of SLR normal points obtained in 2023 for the BeiDou-3 MEO satellites.

icantly higher number of up 3000 observations. For the MEOs 7 and 8, no normal points are available due to missing orbit predictions.

## 6 Satellite Metadata

The new GNSS satellites discussed in Sec. 2 as well as other changes in the constellations are continuously incorporated into the IGS satellite metadata file (Steigenberger and Montenbruck, 2022) available at https://files.igs.org/pub/station/general/igs_satellite_metadata.snx. On request of the combination task force (Sec. 7) a new SATELLITE/PLANE block is currently under discussion to provide information about the orbital plane and slot of individual GNSS satellites.

Additional satellite metadata were published in 2023 by the system providers: Boeing provided antenna gain and phase patterns of the GPS Block IIF satellites (Igwe, 2023). A characterization of these phase patterns and a comparison with estimated patterns is given in Montenbruck et al. (2023). Band-specific transmit antenna gain patterns for all active QZSS satellites as well as the future QZS-5/6/7 satellites are described in Cabinet Office (2023) and available at https://qzss.go.jp/en/technical/antenna-patterns.html

## 7 Combination Task Force

The IGS Combination Task Force (CTF) has been established as an independent entity next to the MGWG in order to coordinate and advance the combination of multi-GNSS orbit clock and bias users. The CTF currently comprises the following 17 members from nine institutions:

- DLR: Oliver Montenbruck, Peter Steigenberger
- GA: Salim Masoumi
- GFZ: Andreas Brack, Gustavo Mansur
- JAXA: Kyohei Akiyama, Toshitaka Sasaki, Hiroshi Takiguchi
- SHAO: Bin Wang
- TUM: Bingbing Duan, Urs Hugentobler, Dhruv Upadhyay
- Université Paris-Cite: Paul Rebischung, Pierre Sakic
- Wuhan University: Guo Chen, Jianghui Geng
- UPWR: Radoslaw Zajdel

and held a total of six virtual meetings throughout the year 2023. Following an initial decision to focus on the orbit/clock/bias combination process in support of multi-GNSS Precise Point Positioning (PPP) users, the CTF has targeted the multi-GNSS orbit combination process. Use of python and the pandas data analysis library was adopted for the development and integration of a new orbit combination software. To facilitate cross exchange of software and study results, a github repository was created and populated with software modules and demo utilities (e.g., file reading, Helmert transformation, basic combination steps). As a starting step, a consolidated SP3 reader for loading orbit files from different analysis centers and processing chains as well as associated metadata into a pandas object was developed.

Following a literature and software review, a consolidated formulation for Helmert transformations was agreed within the group and applied in subsequent studies. Independent analyses by various CTF members suggest that Helmert transformations have become of limited relevance for the quality of the combination process. A good frame consistency was found among the MEO constellations in the various AC solutions. Even though constellation-specific transformations appear to be of benefit (in terms of more consistent combined orbits) at first sight when including IGSOs and GEOs, the specific GNSS-specific Helmert transformations are likely to mask systematic orbit errors in this case. As such, Helmert transformations in the combination process should be determined on a per-AC basis considering all available constellations but excluding IGSO and GEO satellite. Even though the resulting Helmert transformations of individual ACs with respect to a mean or combined orbit are typically small for the current operational and MGEX products, the Helmert transformation may still be kept as a quality check and indicator of possible occasional misalignments.

Concerning the combination technique itself, Variance Component Estimation (VCE) was identified as a promising alternative to the L1-norm based (non-iterated) weighting in the legacy combination software. GFZ is already using least-squares VCE (LS-VCE) successfully in their existing multi-GNSS combination software (Mansur et al. 2022). As an alternative with lower computational complexity, the VCE scheme of Förstner (1979) was discussed and tested with promising results. Compared to the LS-VCE, the latter approach will protect against negative weights that may occasionally arise in LS-VCE in case of unfavorable data. Further tests are ongoing at GFZ and UPWR to assess use of

Förstner's scheme for orbit computation on a larger set of test cases.

As an additional activity, the CTF provided inputs to the IGS Governing Board for the upcoming transition of the Analysis Center Coordinator. A phased transition was recommended, in which the prospective new ACC would start exercising full multi-GNSS orbit, clock, and, optionally, bias combinations parallel to a continued generation of GPS products by the current/old ACC. While the CTF is not expected to come up with a fully consolidated combination software in the near future, various software tools have already been developed outside the immediate CTF work. These include the multi-GNSS orbit and clock combination of GFZ (Mansur et al., 2022), the multi-GNSS orbit combination software of GA used for the Repro3 combination and, more recently, for operational GPS/GLO/GAL orbit products (Zajdel et al., 2023), as well as clock and bias combination software of Wuhan University (Chen et al., 2022; Lin et al., 2023). While the CTF does not provide a specific recommendation for the ACC, it proposes the above software tools as candidates for the next ACC prior to the completion of a dedicated IGS-internal combination software development.

Concerning the introduction of new constellations into combined GNSS orbit and clock products, initial studies performed within and outside the CTF suggest that the combined GPS products are not contaminated by the incorporation of other GNSSs. As part of the Repro3 campaign and IGS20 refence frame development, it was furthermore demonstrated that the latest igs20.atx antenna model enables a fully consistent processing of GPS, GLONASS, and Galileo. On the other hand multi-GNSS PPP results may still be contaminated when adding BeiDou and possibly QZSS due to a lacking compatibility of the manufacturer transmit antenna calibrations with the IGS20 reference frame. A dedicated campaign for BDS/QZSS antenna calibration was therefore initiated by the reference frame coordinator and will be conducted in 2024. This campaign was joined by multiple MGEX ACs and will closely be followed by the CTF.

## Acronyms

**CAS** Chinese Academy of Sciences

**CLS** Collecte Localisation Satellites

**CNES** Centre National d'Etudes Spatiales

**CODE** Center for Orbit Determination in Europe

**DLR** Deutsches Zentrum für Luft- und Raumfahrt

**ESA** European Space Agency

**GA** Geoscience Australia

**GFZ** Deutsches GeoForschungsZentrum

**IAC** Information and Analysis Center for Positioning, Navigation and Timing

**JAXA** Japan Aerospace Exploration Agency

**SHAO** Shanghai Observatory
**TUM** Technische Universtität München
**UPWR** Wroclaw University of Environmental and Life Sciences
**WU** Wuhan University

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