ESA's New Operational GNSS Processing Approach for Precise IGS Products

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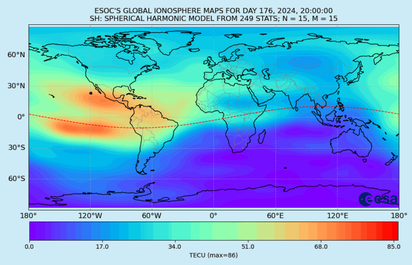
Introduction

The Navigation Support Office at the European Space Agency has developed a novel GNSS processing concept called CHAMP, *Consolidated High Accuracy Multi-GNSS Processing*. Based on constellation-wise data processing and normal equation stacking, the method is used to efficiently generate GNSS products for all five navigation systems: GPS, Galileo, GLONASS, BeiDou, QZSS. CHAMP's modular design allows the different projects within the Navigation Support Office to combine the necessary constellation results in a flexible manner, leading to substantial savings in CPU power and storage requirements. Data consistency is enhanced by aligning satellite orbits and station coordinates to IGN's latest cumulative ITRF-IGS20 realization and aligning the clock products to UTC based on ESA's UTC realization *UTC(ESA)*.
ESA's data processing for the IGS is among the activities benefiting from CHAMP. As the transition to the new setup approaches in the coming months, ESA, as a long-standing IGS Analysis Center (AC), will routinely deliver Final products encompassing, for the very first time, all GNSS. Additionally, in its role as an IGS Ionosphere Associate AC, ESA employs CHAMP to routinely produce ionospheric maps for the IGS. Since March 2024, these maps have been based on the Galileo, GPS, GLONASS, and BeiDou observations.

The primary objectives of the CHAMP processing setup are:
- Optimized processing, limiting redundancy
- Efficient resources usage (RAM and CPU)
- Improved reliability, maintainability and timeliness

CHAMP's products support many of the Office's activities:
- ESA's Earth Orientation and Reference Service
- ESA Space Weather programme
- ESA Ground Observation Network and Tracking Site Monitoring
- ESA UTC realization
- Galileo Space Segment
- LEO POD processing
- IGS AC ESA & IGS Ionosphere AC ESA



Conclusions for the IGS ESA Analysis Center

The *Consolidated High Accuracy Multi-GNSS Processing* CHAMP is the new operational approach adopted by the Navigation Support Office. The modular method is utilized to generate the ESA precise GNSS products. This method offers a variety of cross-constellation analyses that can be performed to assess and improve the products quality.

All ESA CHAMP products are based on the fully consistent satellite antenna phase centre offsets for all systems, based on calibrations where available, and provided in the ESA ANTEX.

ESA's CHAMP-based products include the following constellations: GPS, GLONASS, Galileo, BeiDou, QZSS.

In addition to the routine operations, the team has already conducted a complete reprocessing from 2017.

The CHAMP clock products are now all aligned to UTC within 5ns, thanks to ESA's UTC realization.

CHAMP's products show a remarkable high quality of GPS, Galileo and BeiDou MEO orbits, particularly thanks to the PCOs alignments and the accurate non-gravitational force models. These are based, where possible, on satellite properties published by the system providers, or tuned by the Office's POD experts.

There is still margin of improvement for QZSS and BEI-IGSO's, as the orbit determination is challenged by the higher orbit and short estimation arc of 'only' 24h, compared to the longer orbital period.

All ESA/ESOC internal POD operations smoothly transitioned to the CHAMP products and confirmed their excellent quality.

ESA already switched to the multi-GNSS CHAMP-based products for its contribution to the IGS ionospheric AC.

ESA is planning to switch soon to the multi-GNSS CHAMP-based products in its role of IGS AC.

CHAMP Design

CHAMP *Consolidated High Accuracy MGNSS Processing* is the key system of the ESA/ESOC Navigation Support Office for the routine GNSS-based POD and geodetic products.
It is designed to be flexible, efficient and easier to maintain.

CHAMP's main characteristics are:
- It runs with the *ESA Precise Navigation System* (EPNS) software, in the ESOC Mission Operational infrastructure
- It processes 24h-long arcs with simultaneously 200 stations and 5 GNSS constellations
- It enforces that only stations with good calibrations are included in the process
- It aligned its products to the latest IGS20 cumulation
- It provides products with 3 different latencies: Ultra-Rapid, Rapid, and Final solutions
- It allows flexibility to combine different constellation selections depending on the needs
- It enables cross-constellation comparisons for better products monitoring, analysis, and investigations to continuously improve the models and products' quality

Signal Selection

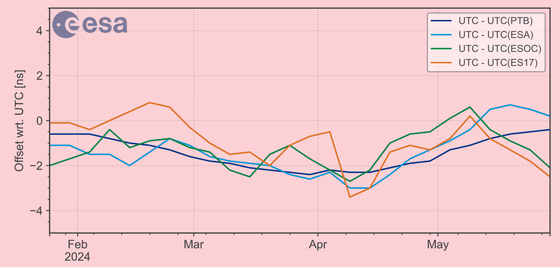
Constellation	GPS	GLO	GAL	BEI	QZS
Signal selection	L1W L2W	L1P L2P	E1C E5Q	L1P L5P	L1C L2L

CHAMP building blocks

Section	Description
Leaves	Product Generation and secondary processes such Ionosphere estimation
Branches	NEQ stacking of selected constellation solutions. ITRF-IGS20 alignment. Estimation of 30s clocks and Inter-System biases
Trunk	Constellation-wise Processing: Data pre-processing and screening, integer ambiguity resolution, ambiguity fixed solution.
Roots	Compilation of input data such as RINEX, ANTEX, EOP

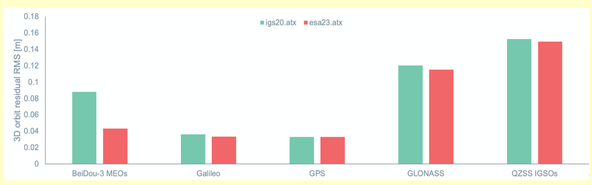
UTC clock alignment

UTC Alignment
ESA is realizing its own timeseries and contributes to UTC as a BIPM approved laboratory, using an ensemble of H-Masers at ESOC and ESTEC. The ESOC GNSS stations located in Darmstadt are connected to these and are used to align the CHAMP clock estimates to UTC. It is hence guaranteed that the offset between the CHAMP-based clock solution and UTC is kept below the 5 ns level. The figure shows the performance of the UTC realization at ESA, PTB, and the two ESOC redundant chains.



ESA ANTEX

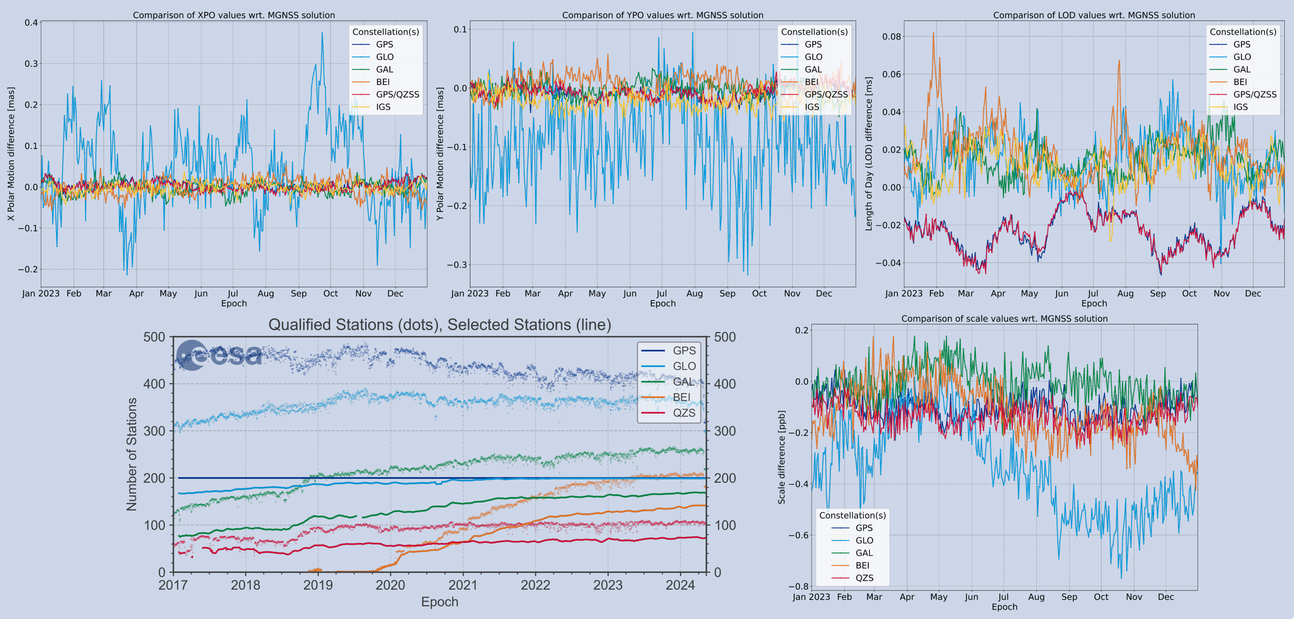
ESA's new operational products are based on ESA's Multi-GNSS ANTEX:
- It provides a consistent set of Phase Center Offsets and Variations for Galileo, GPS, GLONASS, BeiDou, and QZSS
- It is based on all publicly available GNSS ground-calibrated data to ensure consistency with the GNSS providers
- It resolves the inconsistencies of the igs20 ANTEX, between the PCOs of the different constellations
- ESA's results based on the ESA ANTEX show a significant orbit accuracy improvement for all constellations, and by a factor of two for the BeiDou constellation, from 89 mm to 43 mm.
- The ESA ANTEX is publicly available on our webpage, under the metadata section



Constellation-specific characteristics

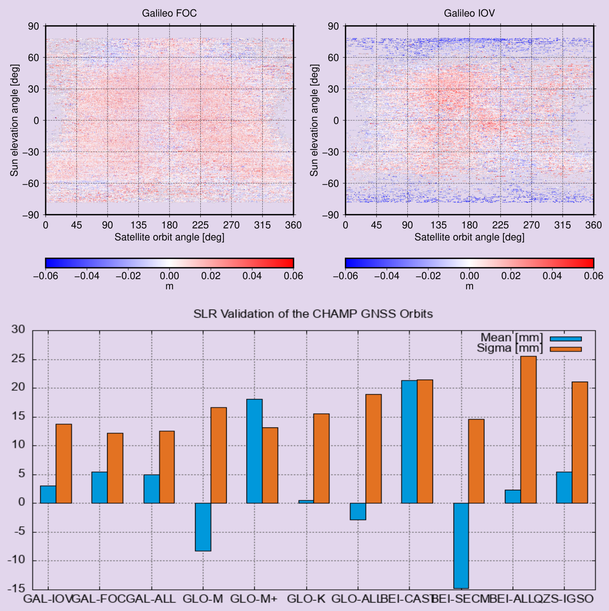
The CHAMP processing yields individual constellation solutions that are subsequently combined into a single Multi-GNSS solution, or a subset of it, if needed. This setup allows internal comparisons between individual constellation solutions and the combined Multi-GNSS solution, uncovering unique constellation characteristics and the impact of their combination.
Some examples of these comparisons are displayed in the plots on the right, where the single-constellation EOP estimates (Pole and LOD) are compared against the stacked Multi-GNSS solution and the IGS Finals.
For the pole values XPO, YPO and their rates (not shown), the fluctuations of the GLONASS satellites evidence the lower accuracy provided by this constellation, while all other constellations' estimates match quite well the combined and IGS values, although some minor inter-constellations differences can still be observed.
For the Length of Day (LOD), the GPS constellation, standalone or combined with QZSS, behaves differently from all other single constellations, the combined solution, and the IGS one. This shows a very clear constellation-specific characteristic for the analyzed period. This is a very interesting pattern that is currently object of investigation at the Navigation Support Office.
Additionally, the scale difference of the various constellations is compared against the Multi-GNSS one. Good agreement is found between the various constellations' scales and the combined one, also for BeiDou. Once again, GLONASS stands out with a higher scale difference and a periodic annual signal, which is also under investigation.
All these elements, along with others under investigation such as CODE parameters and clocks, are of significant interest for the Office and require attention. They offer clear insights and guidance for identifying and potentially resolving constellation-specific modelling issues. This is viewed as a critical step towards achieving the ultimate POD accuracy, enabling interoperability among GNSS systems.

Throughout the years, IGS has excelled in expanding both the station network and the Multi-GNSS tracking capabilities. The graphics on the right offer a comprehensive overview of the available stations for each constellation, as well as the number of stations chosen for our processing. Thanks to the CHAMP's constellation-wise parallel processing, a network of 200 stations can be selected. This extensive station network of well-calibrated stations directly contributes to enhancing the quality of the GNSS products.

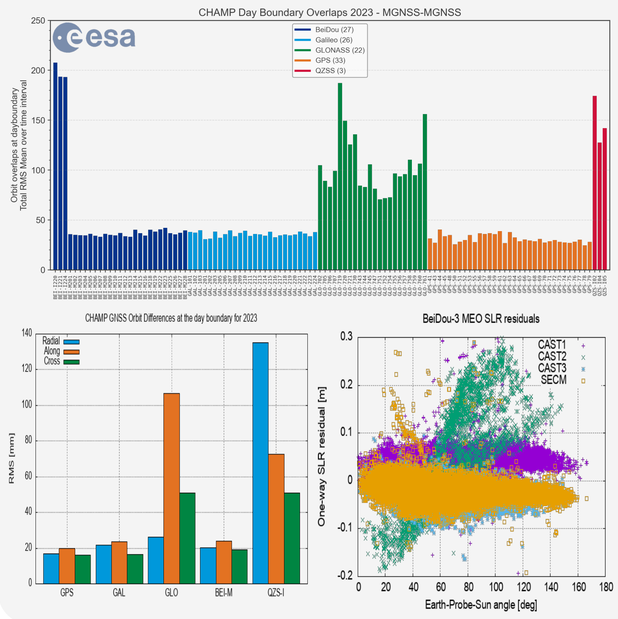


Satellite Laser Ranging Validation

- Satellite Laser Ranging (SLR) tracking data allows for a completely independent validation of GNSS orbits that are derived from microwave data; particularly the radial component. Unfortunately, currently none of the active GPS satellites can be tracked by SLR.
- The quality of the GNSS orbits is so high that the range biases of the SLR sites must be considered. In its contribution to the ITRF2020 the ILRS has started to estimate biases for its tracking stations. These biases are made public in the ILRS Data Handling File (DHF).
- The DHF contains the estimated range biases for the stations for LAGEOS-1, LAGEOS-2, and a combined bias for both ETALON satellites. It also contains information regarding stations for which biases shall be estimated. Consequently, in the analysis the Office followed the information as given in the DHF to estimate biases for the indicated stations and used the ETALON bias where available for all the GNSS targets.
- The ETALON based biases work very well except for two stations (7110 and 7825). Both stations also show significant issues in our ILRS processing. The estimated biases are below the 20 mm level but for station 1886 a huge bias of ~90mm was found.
- The plots show the excellent agreement of our CHAMP GNSS orbits with the SLR observations. It is at the 15mm level for Galileo which is very close to the noise of the SLR observations and comparable to the results obtained with LAGEOS.
- The residuals as function of the solar angles show hardly any signature which is good!



Orbit Quality



- An important part of the GNSS operations is the monitoring of the quality of the solutions. For the orbit quality assessment, the day boundary orbit differences is adopted as criterium. With the 24h-arc solutions this is the "worst" point for comparison. Two plots show the overlap statistics, per satellite (top) and per constellation (bottom left)
- The constellation-wise plot shows the very good performance of GPS, Galileo and BeiDou(!). The GLONASS performance is clearly lower mainly due to the lack of integer ambiguity resolution and accurate orbital models. Additionally, several GLONASS satellites are suffering from different hardware failures. The performance of the BeiDou and QZSS IGSO and GEO satellites is also lower, given by the very different observation geometry due to their different altitude. The 24h arcs are considered sub-optimal for these satellites given that this period matches one orbital period of the satellite.
- Additionally, the Satellite Laser Ranging (SLR) data are adopted as routine validation of the orbit quality for those GNSS satellites that carry a laser reflector.
- The figure on the lower right show the SLR residuals of the BeiDou satellites. The BeiDou satellites are built by two different manufacturers and those satellites are clearly very different and thus separate models are needed. Within these classes there are significant differences between the satellites. Some seem to have been equipped with an extra panel containing the search and rescue (SAR) antenna (e.g., CAST2, SECM). The two CAST2 satellites also look very different in the SLR residuals, showing there is still margin of improvement.

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