ESA ANTEX: A Consistent GNSS satellite Phase Centre Model Based on Galileo Ground Calibration Data

Erik Schoenemann[1], Florian Dilssner[2], Francesco Gini[1], Francisco Gonzalez[3], Manuela Seitz[4], Mathis Blossfeld[4], Tim Springer[2], Werner Enderle[1]

[1]ESA/ESOC, [2]PosiTim@ESA/ESOC, [3]ESA/ESTEC, [4]TUM-DGFI

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Background

- Information about satellite antenna phase centre offsets (PCO's) are indispensable for precise navigation.
- Due to the lack of manufacturer values in the past all GNSS PCO's have been estimated
  – drawback due to the correlation, GNSS cannot contribute to the ITRF scale
- In December 2016, Galileo as the first GNSS provider, Galileo published PCO's and PCV's
  via the European GNSS Service Centre of the European Union Agency for the Space Programme.
- The metadata is regularly updated - as soon as new Galileo satellites are declared operational.
- For the 3rd IGS reprocessing campaign Galileo calibrations for ground antennas have been made available
  – allowing for a consistent processing of Galileo observations
- IGS solution showed a scale offset of 0.68 ppb with respect to the ITRF2020 scale (Altamimi et al. 2022)

Background

- IERS decision to base the ITRF2020 scale purely on VLBI and SLR
  - excluding the Galileo ground calibrations
  - whilst fixing the estimated SLR range biases

- To maintain the consistency of IGS products with the ITRF2020 scale, the Galileo ground calibration values have been adjusted by 1-2dm. [IGSMAIL-8238]

- Considering the accuracy of the Galileo ground calibrations <1cm the adjustment is one order of magnitude above the uncertainty – the adjustment does not seem sensible.

- Considering further, the uncertainties in the ITRF scale and for the Ground antenna calibrations + their nearfield sensitivity the scale adjustment implemented via the GNSS PCO's is considered questionable.
  - The scale change between ITRF2014 and ITRF2020 is 0.4 ppb giving an idea of the significant uncertainty of the ITRF scale

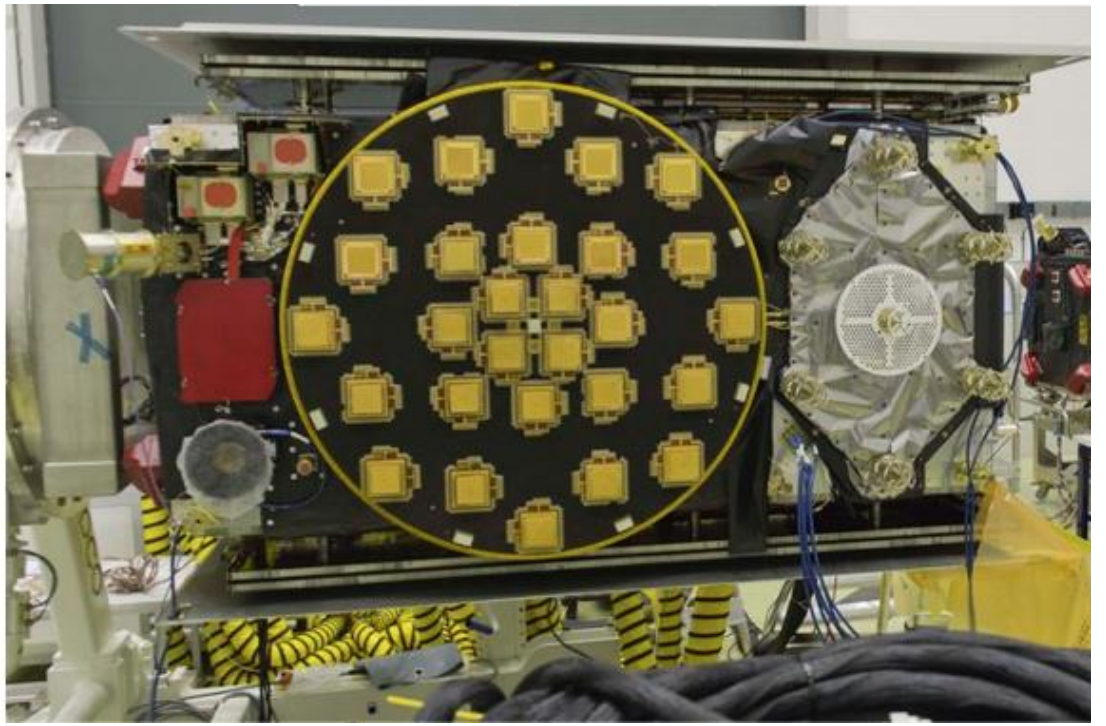
ESA's motivation for a consistent ANTEX
- considering all available calibration information

- ESA advocates for considering all available calibration information (e.g., GNSS ANTEX) to improve the ITRF.
- ESA considers the adjustment of the Galileo z-offsets in the IGS processing approach as questionable.
- In view of the upcoming ESA GENESIS mission the adjustment of the Z-PCO's is considered inadequate.
  - statement support by outcome of [W. Huang 2020]
- The scientific community, including IGS, requested the publication of metadata from the GNSS service providers. Hence, ESA considers that, after all the efforts made to publish the requested metadata, these shall be used. The wrong message is sent to service providers, otherwise.
- Resolve inconsistency between PCO's in IGS ANTEX e.g., BeiDou values taken from igs14.atx.
- Preserve consistency of the GNSS products with GNSS providers using the existing ground calibrations.

Galileo Navigation Antennas (NAVANT)

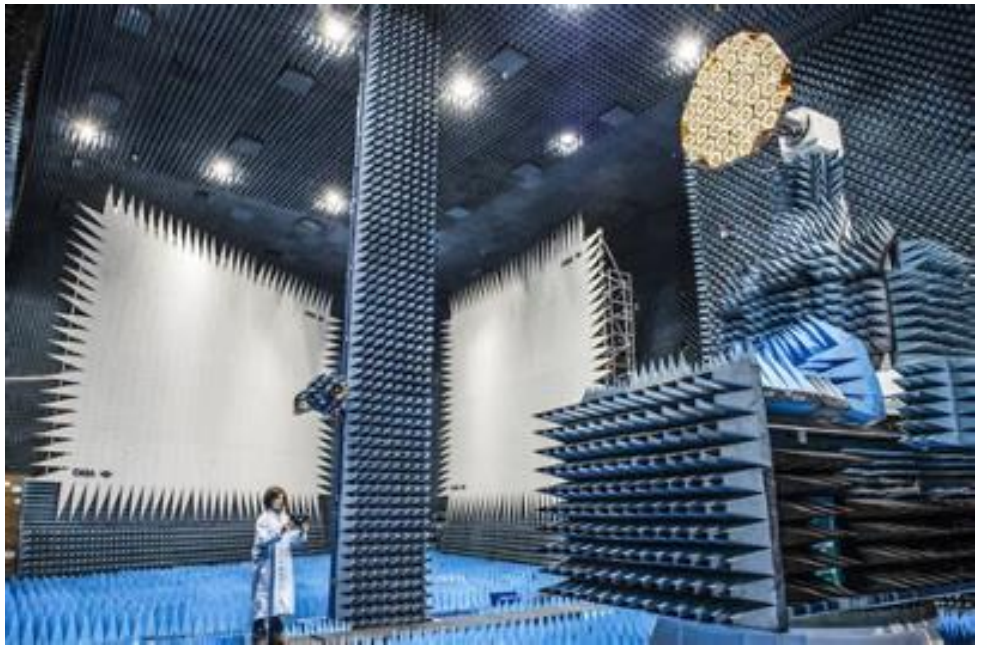
IOV - EADS CASA

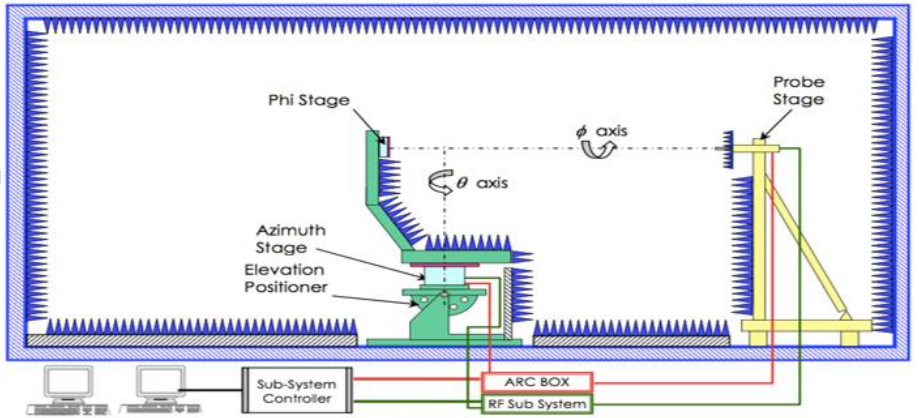
FOC - Thales Alenia Space



Galileo NAVANT – Anechoic chamber calibration

- IOV and FOC antennas individual calibrated by manufacturer
- Directional in azimuth (Φ) and nadir (θ)
  - IOV: θ = 0º … 14º
  - FOC: θ = 0º … 20º
- Transformed onto far-field sphere
- Individual for each Galileo satellite
- Individual for each frequency band (E1, E5a, E5b, E5, E6)
- Calibration accuracy <1cm
- Good consistency between frequencies [P. Steigenberger 2023]





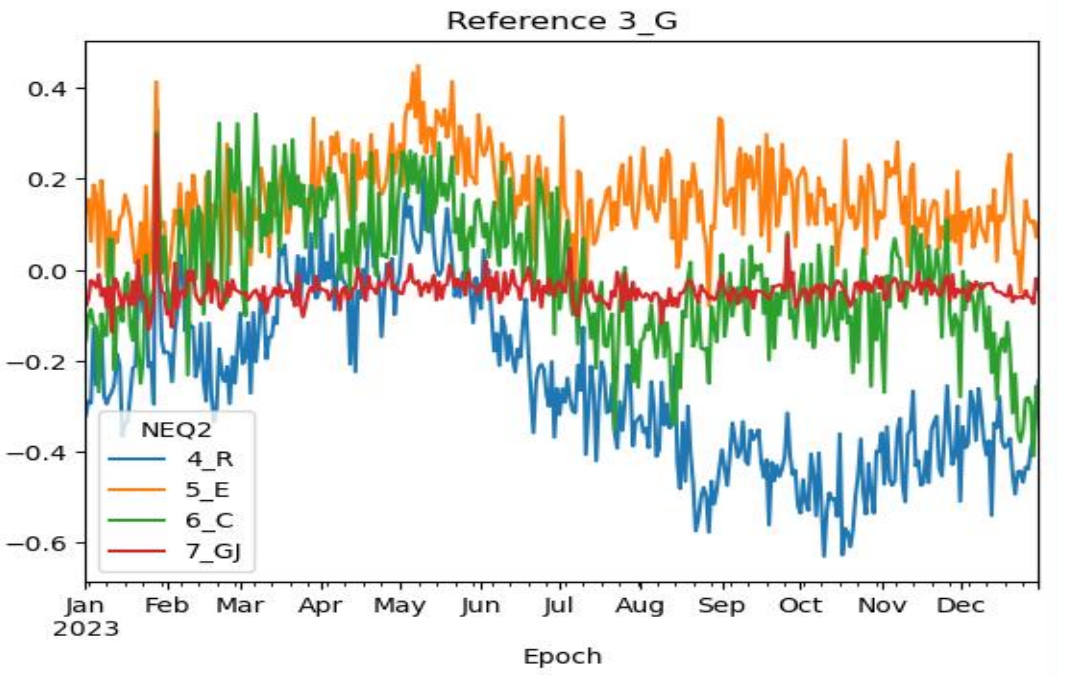
ESA ANTEX Processing strategy

ESA ANTEX processing setup

- Dual-frequency ionosphere free (IGS like) reprocessing of IGS data from all GNSS constellations
- 9.8 years of GPS L1/L2, Galileo L1/E5a, GLONASS L1/L2, BeiDou L2/L6, QZSS L1/L2
- 4.0 years of BeiDou L1/L5
- Rigorous combination of daily normal equations (NEQ)
- PCO's and PCV's for Galileo, GPS III and QZSS fixed to ground calibration values (CAO 2017, Dilssner et al. 2023, EUSPA 2016, NAVCEN 2021)
- Horizontal PCO's for BeiDou fixed to ground calibration values (CSNO 2020)
- BeiDou PCV's adopted from earlier estimation (Dilssner et al. 2014, 2020)
- Horizontal PCO's and PCV's for GPS Block II adopted from igs20.atx
- Free estimation of remaining satellite z-offsets relative to "Galileo scale"
- Network scale left free to adjust

ESA ANTEX - GPS/Galileo scale consistency

- Small differences in estimated GPS III z-offsets compared to Lockheed values show deltas of:
  - -24 mm (GPS-74)
  - -52 mm (GPS-75)
  - +15 mm (GPS-76)
  - -5 mm (GPS-77)
  - -26 mm (GPS-78)
  - -8 mm (GPS-79)

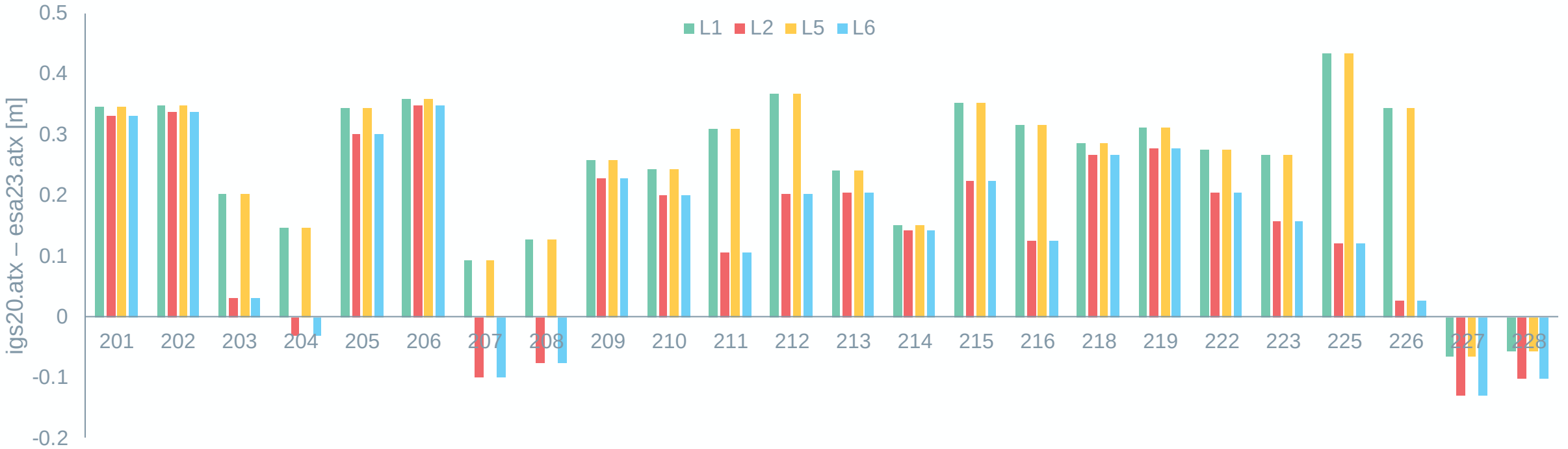


- The small differences (one order of magnitude below adjustment) increases the confidence in both Galileo and GPS III ground calibrations.

- Good consistency between “Galileo scale” and “GPS scale” One-year comparison of CHAMP single constellation runs show a mean difference between GPS and Galileo of 0.16 ppb (1.0 mm).

ESA ANTEX – Estimated MEO z-offsets

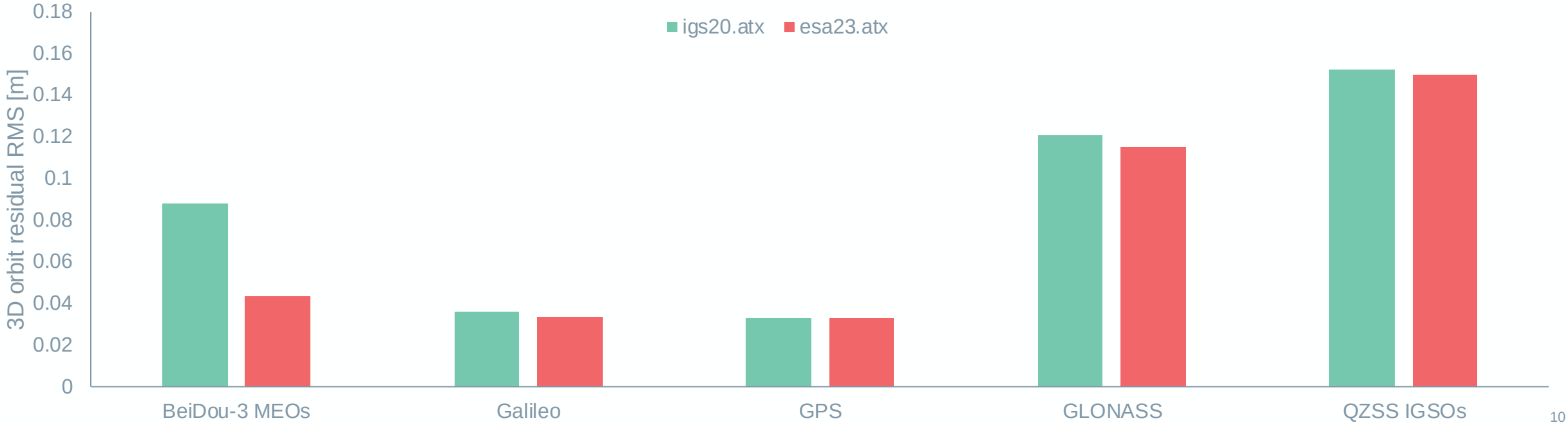
- BeiDou-3 MEO z-offsets differ by up to 0.4 m from igs20.atx values
- Substantial impact on satellite orbits, especially in along-track
- Ground calibrations for L2/L6 and L1/L5 modified by common SV-specific offset
- Beneficial for integer ambiguity fixing as internal consistency is preserved



ESA ANTEX – Orbit improvements

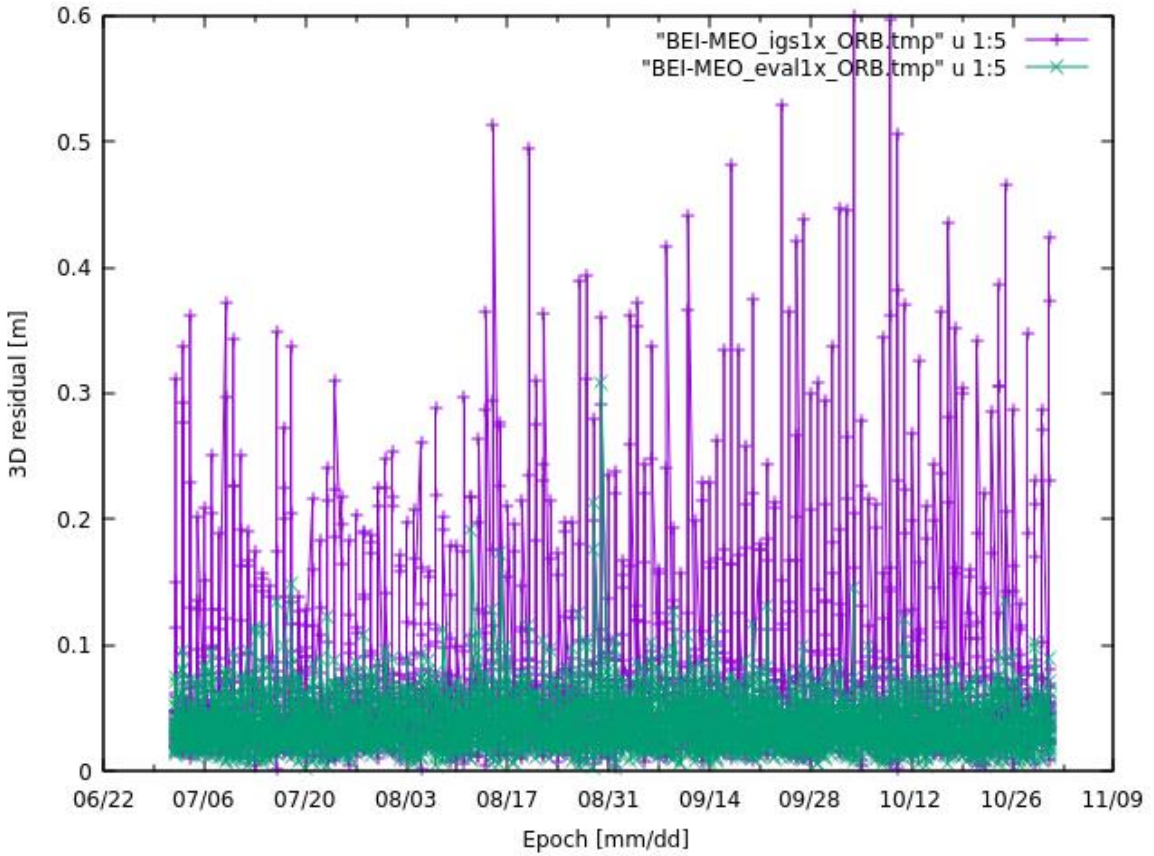
Test setup:

- 4-months IGS like reprocessing
- Calculation of day-boundary orbit residuals as measure for orbit precision
- 3D RMS reduction for BeiDou MEOs by factor two, from 89 mm (igs20.atx) to 43 mm (ESA ANTEX)
- Galileo orbits benefiting as well; 3 mm improvement in 3D RMS
- Minor improvements for other GNSS satellite orbits



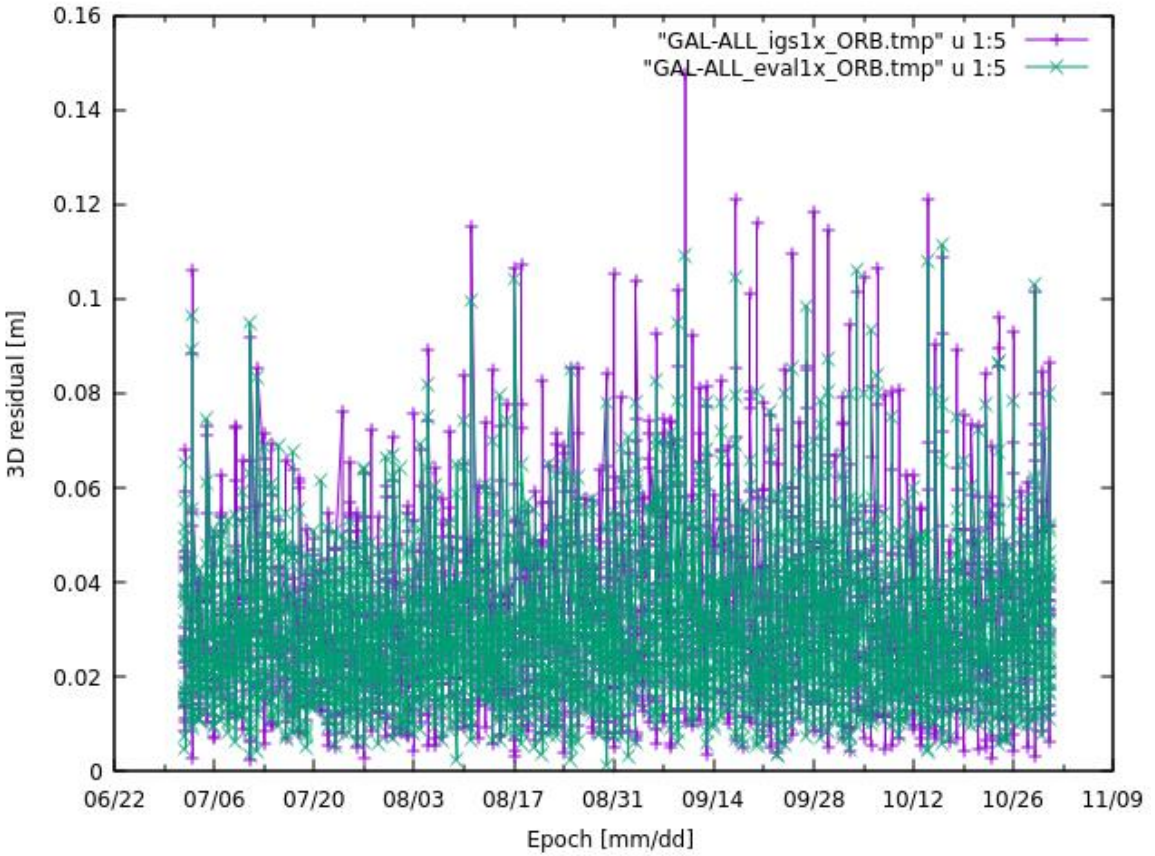
ESA ANTEX – Orbit improvements for BeiDou & Galileo

BeiDou-3 MEO residuals with igs20.atx (purple) and ESA ANTEX (green)



Improvement: factor 2 – 46 mm 3D

Galileo residuals with igs20.atx (purple) and ESA ANTEX (green)



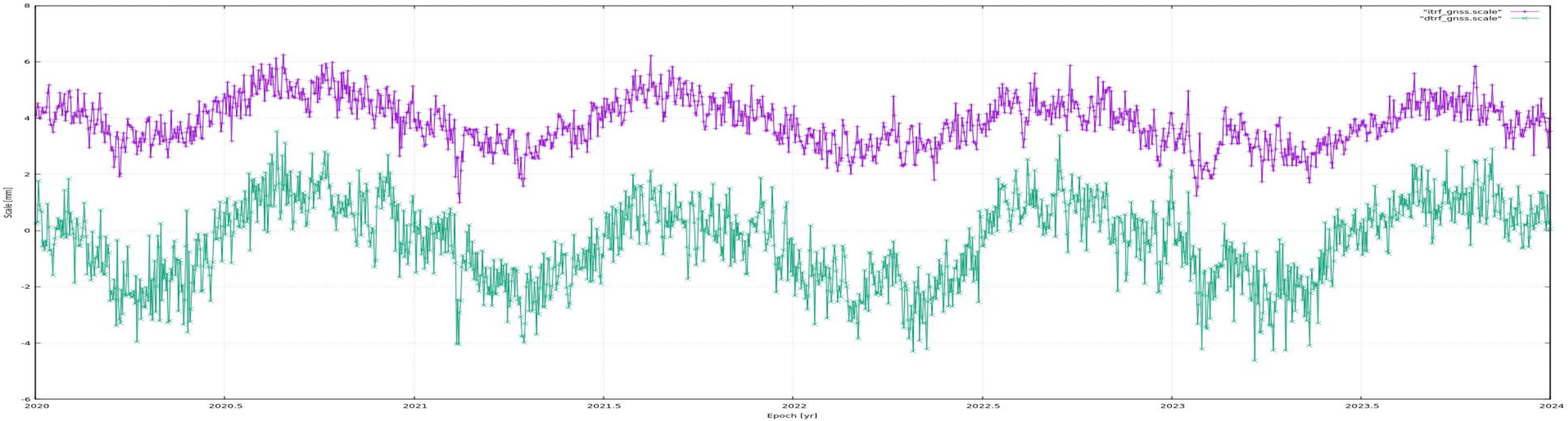
Improvement: 3 mm 3D

ESA ANTEX – DTRF2020 scale consistency

Testing of DTRF2020 alignment with GNSS scale-based ESA ANTEX

Parameters:

- Station coordinates only (note velocities and PSDs are still taken from ITRF2020)
- Helmert comparison against 4 years of MGNSS daily NEQs from CHAMP
- Scale and origin free, orientation aligned to ITRF or DTRF
- Scale difference of -0.4 ± 1.5 mm (DTRF2020) and +3.9 ± 0.8 mm (ITRF2020)



Summary/Conclusions

- Accurate Phase Centre Offsets and Variations have been published first by Galileo and are now also available for satellites from other constellations e.g. GPS III, QZSS.

- The IGS scale alignment implemented via the GPS block III and Galileo Z-PCO adjustment is questionable.

- ESA ANTEX scale is well aligned with DTRF2020
- ESA ANTEX is fully consistent across all constellations
- ESA ANTEX https://doi.org/10.57780/esa-q8jgzrf is publicly available and updated regularly

- **ESA advocates that future ITRF realisations consider the GNSS contributions for the terrestrial scale, and therefore the Galileo / GNSS ground calibration values shall be used for the generation of the scale**

- No need for error-free satellite antenna parameters – parameters can be included considering their associated uncertainties, similar local site-ties

Thank you for your attention!

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