

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

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- 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 – GNSS cannot contribute to the ITRF scale
- In December 2016, Galileo as the first GNSS provider, 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 phase center calibrations for both satellite and ground receiver antennas were used, ensuring consistent processing of Galileo observations.
- IGS/GNSS solution showed a scale offset of 0.68 ppb with respect to the ITRF2020 scale (Altamimi et al. 2022)

- IERS decision to base the ITRF2020 scale purely on VLBI and SLR
  - rescaling the repro3 GNSS satellite z-offsets
  - 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 155.73mm [IGSMail-8238, IGS20.ATX]
- Considering the accuracy of the Galileo ground calibrations 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 in the Ground antenna calibrations, 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

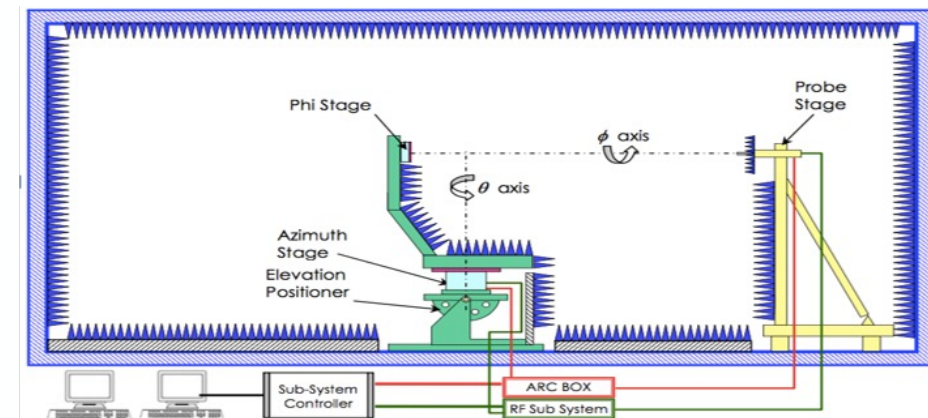
## - considering all available calibration information

- 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 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 [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 NAVANT – Anechoic chamber calibration

- IOV and FOC antennas individual calibrated by manufacturer
- Directional in azimuth ( $\Phi$ ) and nadir ( $\theta$ )
  - IOV:  $\theta = 0^\circ \dots 14^\circ$
  - FOC:  $\theta = 0^\circ \dots 20^\circ$
- Transformed onto far-field sphere
- Individual for each Galileo satellite
- Individual for each frequency band (E1, E5a, E5b, E5, E6)
- Good consistency between frequencies shown by ESA internal analysis and independently confirmed by [Steigenberger 2023].

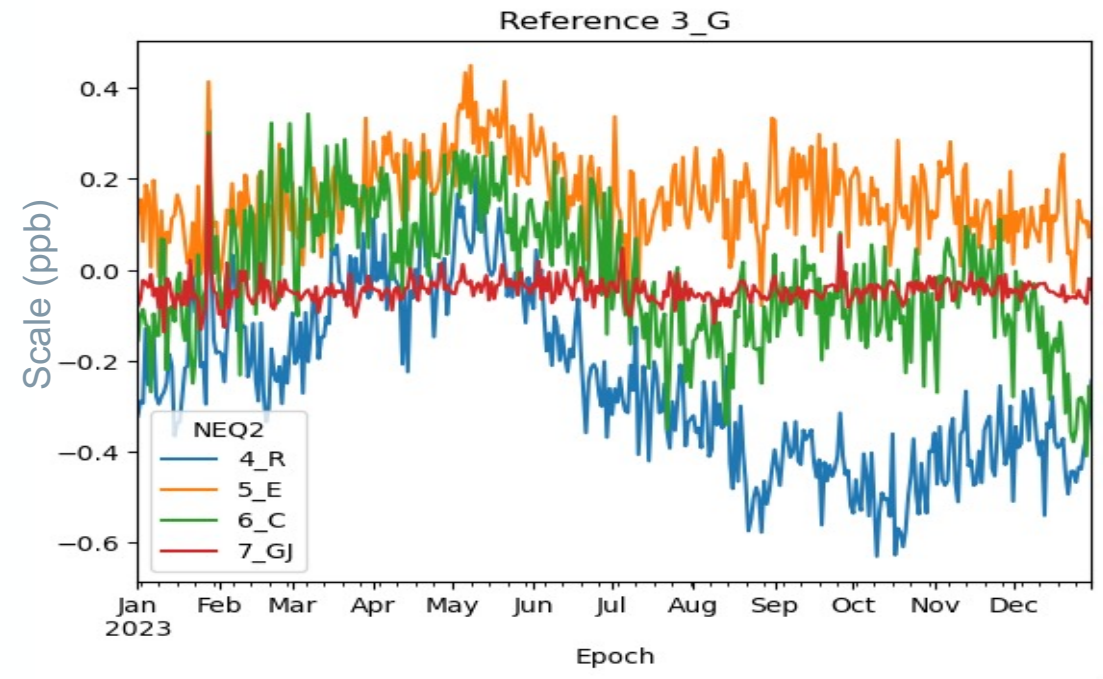


## ESA ANTEX processing setup

- 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

- Small differences in estimated GPS III z-offsets compared to Lockheed [NAVCEN 2021] values show deltas of:

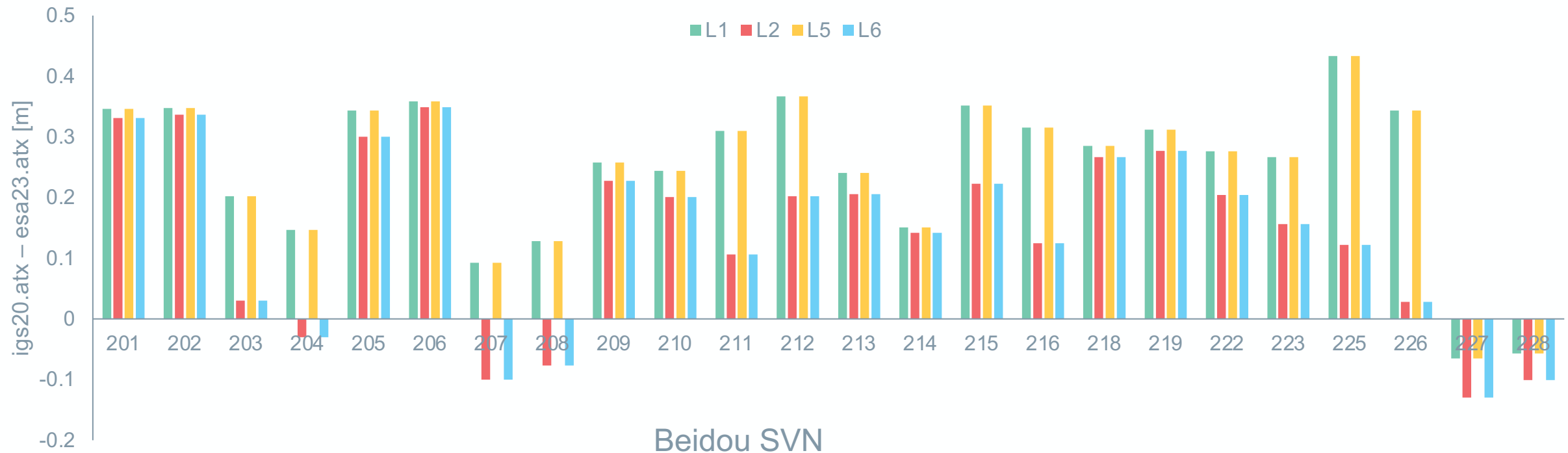
- -24 mm (GPS-74)
- -52 mm (GPS-75)
- +15 mm (GPS-76)
- -5 mm (GPS-77)
- -26 mm (GPS-78)
- -8 mm (GPS-79)



- These 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 ESA’s single constellation runs (CHAMP) show a mean difference between GPS and Galileo of 0.16 ppb (1.0 mm).

# ESA ANTEX – Estimated BeiDou 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 satellite-specific offset
- Beneficial for integer ambiguity fixing as internal consistency is preserved

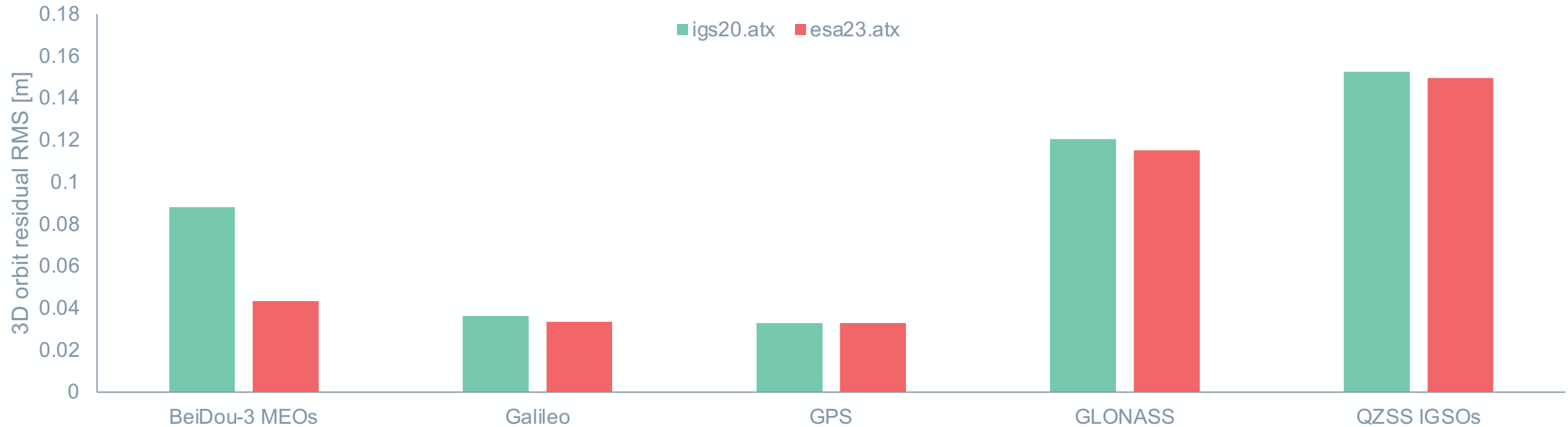




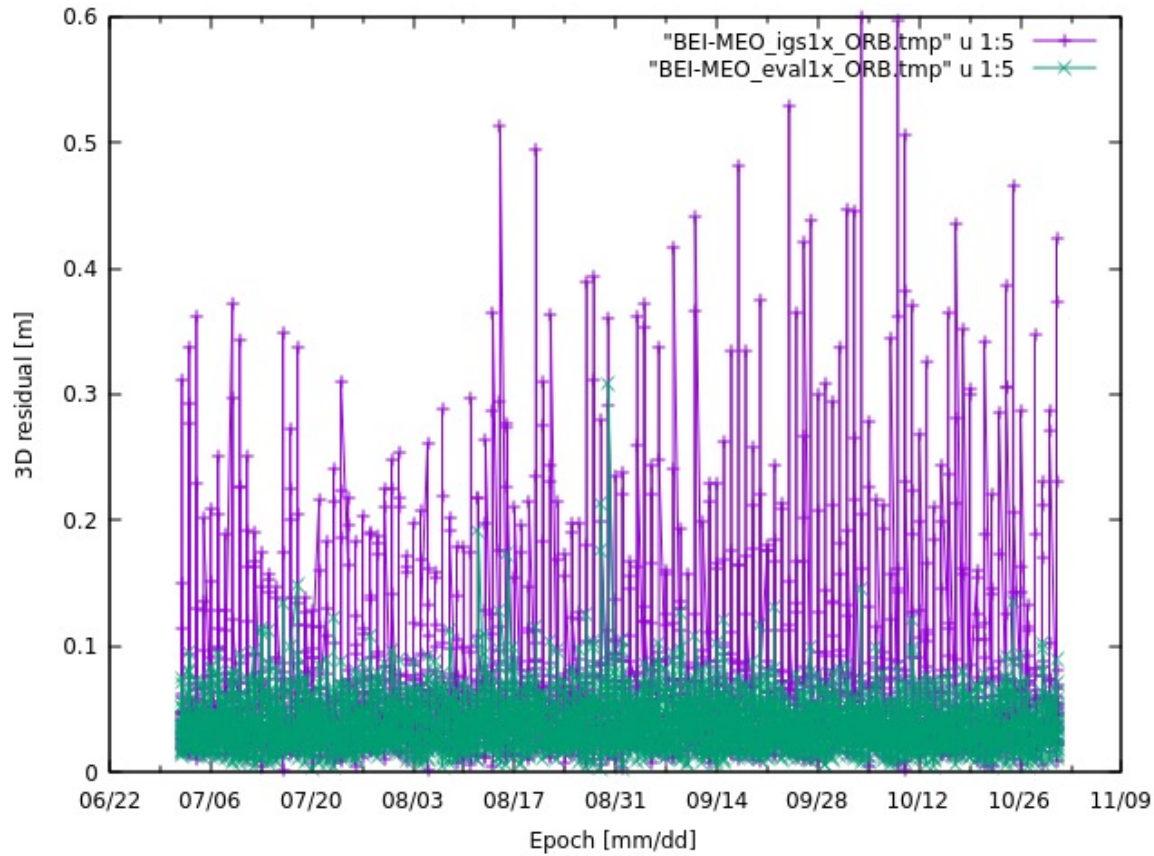
# ESA ANTEX – Orbit improvements

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

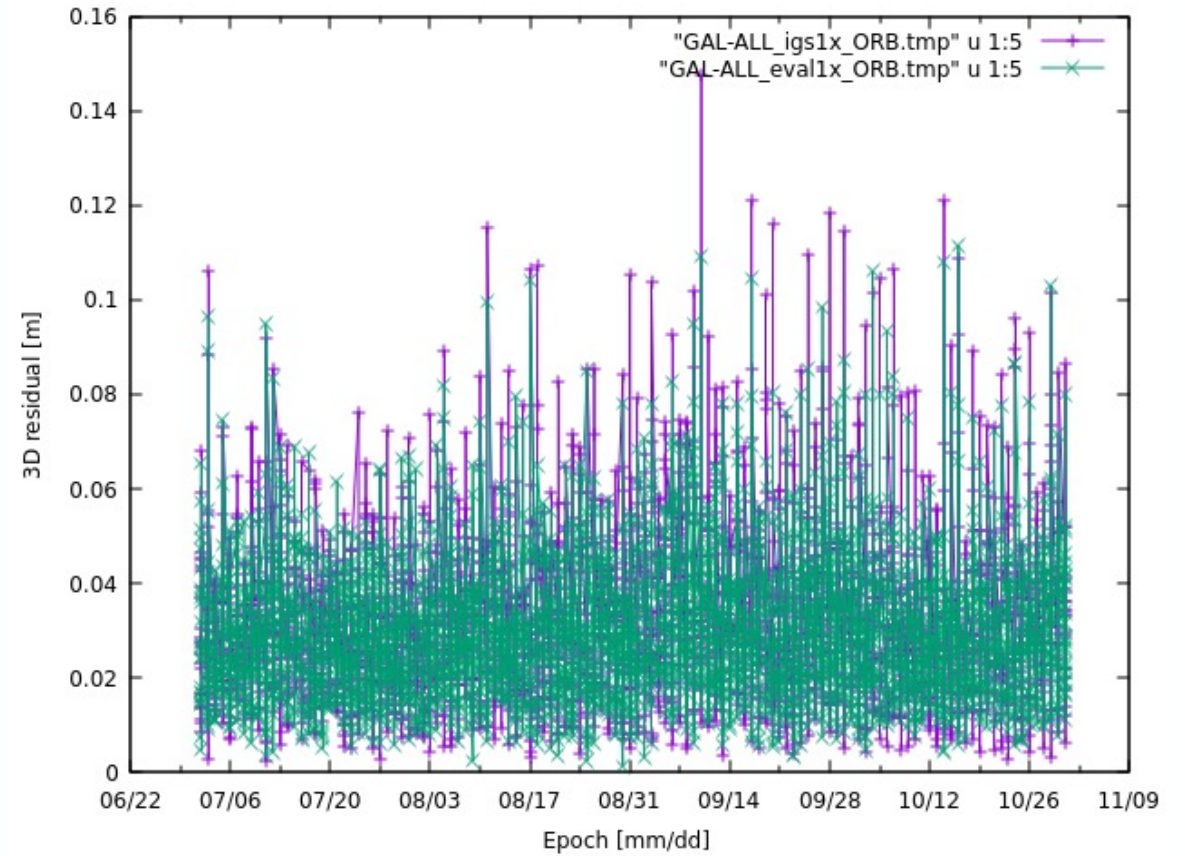


BeiDou-3 MEO residuals with igs20.atx (purple) and ESA ANTEX (green)



Improvement: factor 2 – 46 mm 3D

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



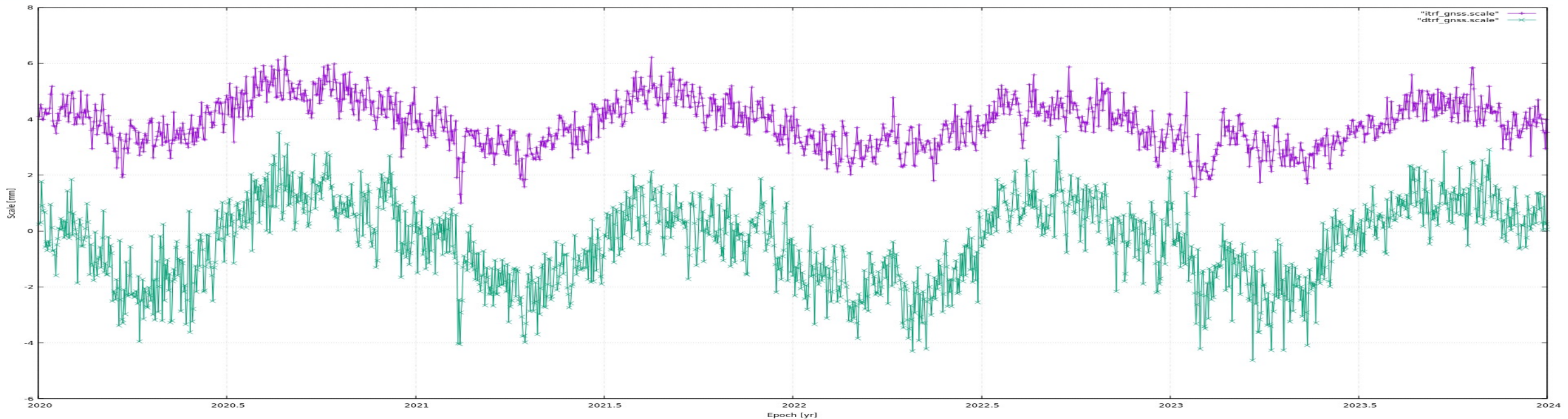
Improvement: 3 mm 3D

# 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  $-0.4 \pm 1.5$  mm (DTRF2020) and  $+3.9 \pm 0.8$  mm (ITRF2020)



- 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 “perfect” satellite antenna offsets – parameters can be included considering their associated uncertainties, similar local site-ties.

**Thank you for your attention!**

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