

**REFINEMENT OF GRAVIMETRIC QUASIGEOID MODELLING IN
THE GULF OF FINLAND USING SWOT-DERIVED GEOIDAL HEIGHT
CONSTRAINTS: CONTRIBUTION TO THE NKG2026 PROJECT**

MOTIVATION

- Lack of gravity observations in the eastern portion of the Gulf of Finland
 - A patch generated for the NKG2015 project using GO_CONS_GCF_2_DIR_R5 evaluated up to degree 240
 - Previous gravity- and geoid-related studies in the region have hinted at geoid modelling problems:

Varbla S, Ellmann A, Delpeche-Ellmann N (2020) Validation of marine geoid models by utilizing hydrodynamic model and shipborne GNSS profiles. Mar Geod 43:134–162. <https://doi.org/10.1080/01490419.2019.1701153>

Saari T, Bilker-Koivula M, Koivula H, Nordman M, Häkli P, Lahtinen S (2021) Validating geoid models with marine GNSS measurements, sea surface models, and additional gravity observations in the Gulf of Finland. Mar Geod 44:196–214. <https://doi.org/10.1080/01490419.2021.1889727>

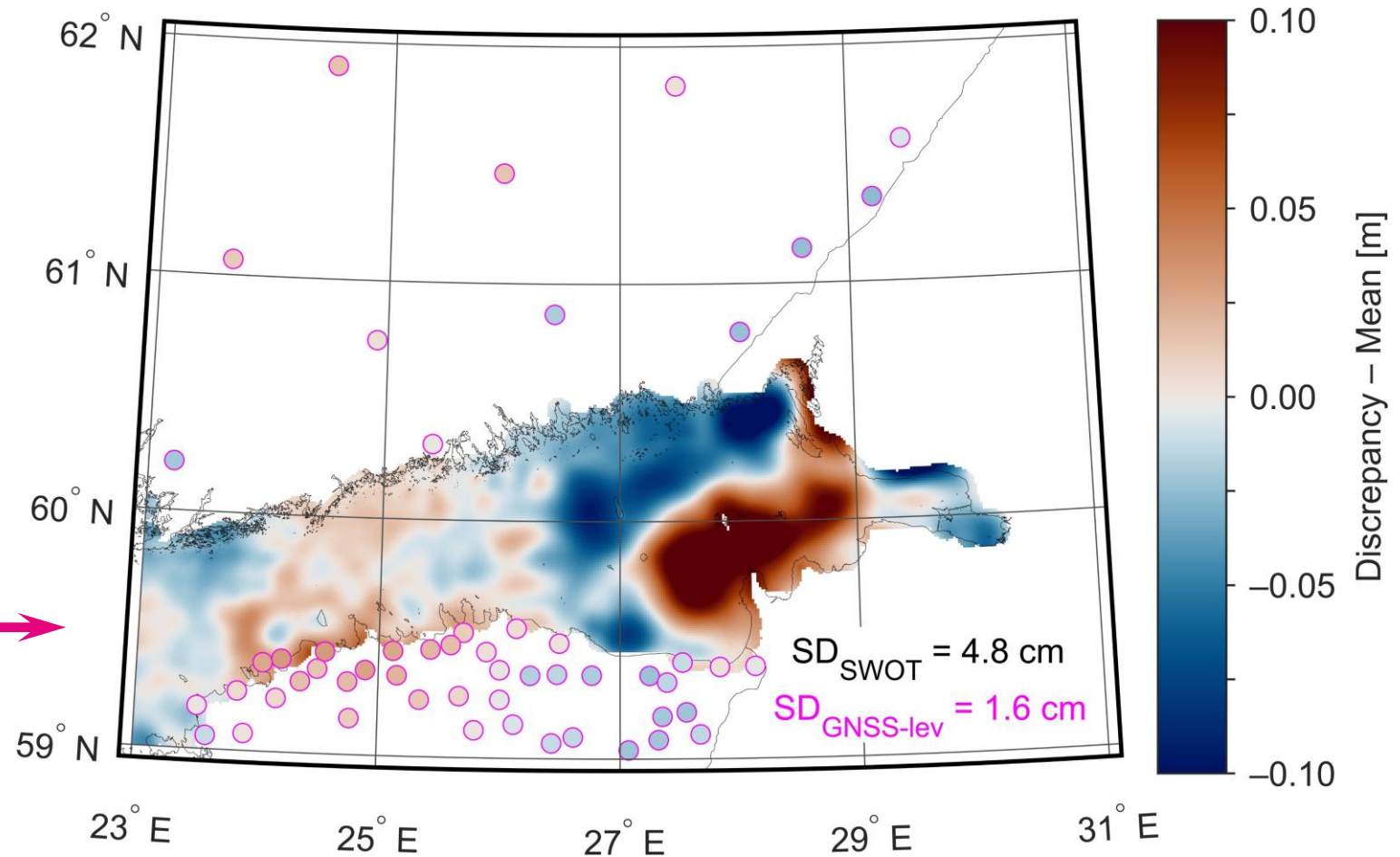
Varbla S, Ellmann A, Delpeche-Ellmann N (2021) Applications of airborne laser scanning for determining marine geoid and surface waves properties. Eur J Remote Sens 54:558–568. <https://doi.org/10.1080/22797254.2021.1981156>

Jahanmard V, Delpeche-Ellmann N, Ellmann A (2022) Towards realistic dynamic topography from coast to offshore by incorporating hydrodynamic and geoid models. Ocean Model 180:102124. <https://doi.org/10.1016/j.ocemod.2022.102124>

MOTIVATION

- SWOT-based geometric geoidal heights can now provide a detailed look into potential gravimetric geoid modelling errors

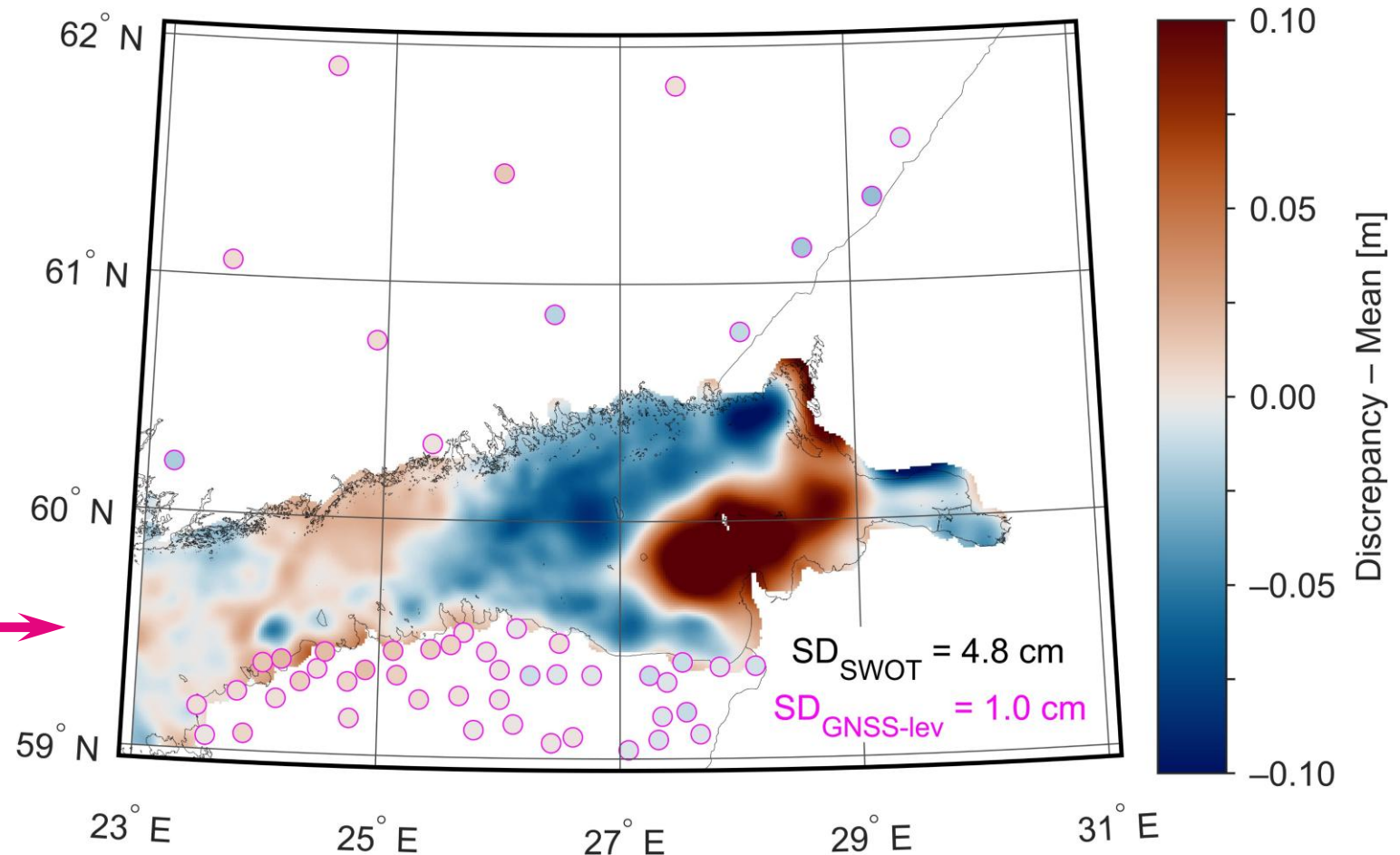
Discrepancies of the
NKG2015 quasigeoid model



MOTIVATION

- The more recent BSCD2000 quasigeoid model uses the same patch as the NKG2015 model
 - Discrepancies are a bit more constrained due to new shipborne gravity observations that were not available during the NKG2015 project

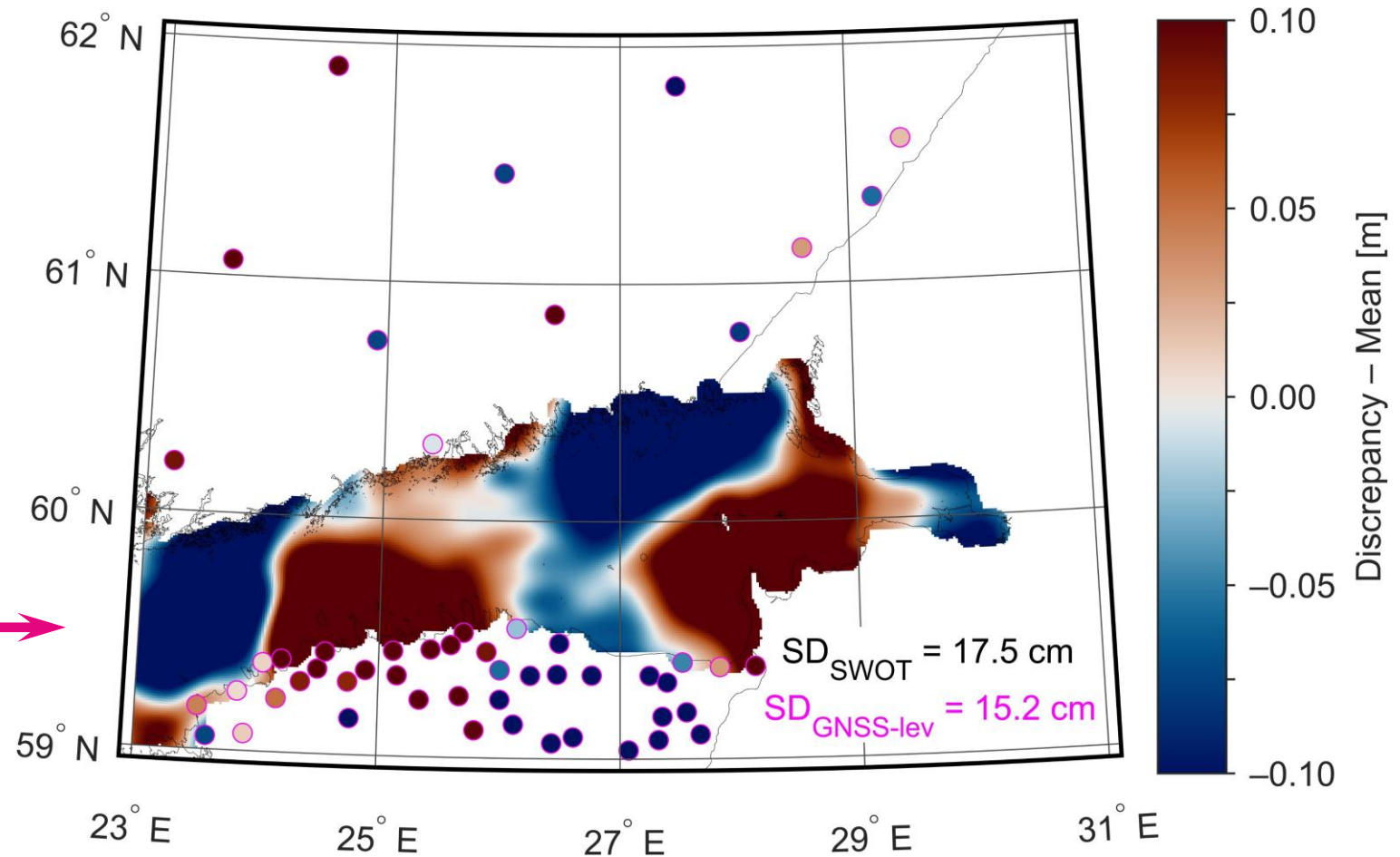
Discrepancies of the
BSCD2000 quasigeoid model



MOTIVATION

- Discrepancies in the eastern portion of the Gulf of Finland replicate those of the GO_CONS_GCF_2_DIR_R5
- A new patch should be derived for the NKG2026 project

Discrepancies of
GO_CONS_GCF_2_DIR_R5₂₄₀



VALIDATION DATA

- GNSS-levelling
 - nkg2026_v01_gnsslev_Common_B
 - Ellipsoidal heights: ETRF2014, zero-tide, epoch 2000.0
 - Levelled heights: national EVRS realisations, zero-tide, epoch 2000.0
- SWOT-based geoidal heights
 - Refer to the poster: **An LSC-based framework for geoid-consistent geometric height reference surface determination in the Baltic Sea using SWOT altimetry**
- Gravity observations
 - ~~NKG2026: release01tmp~~
 - FAMOS/BSCD2000: the final release + processing
- All comparisons consider the region 59...62° N and 23...31° E

VALIDATION NOTES

- Standard deviation of discrepancies between SWOT-based geoidal heights and a model being evaluated is weighted using standard uncertainties of SWOT-based geoidal heights
 - Near-coast discrepancies are downweighted due to coastal effects and extrapolation uncertainties
- Estimated accuracy of a global geopotential model is derived as:

Adopted as patch accuracy $\rightarrow$

$$\sigma_{GGM} = \sqrt{\sigma_{discrepancies}^2 - \frac{1}{n} \sum_{i=1}^n \sigma_i^2}$$

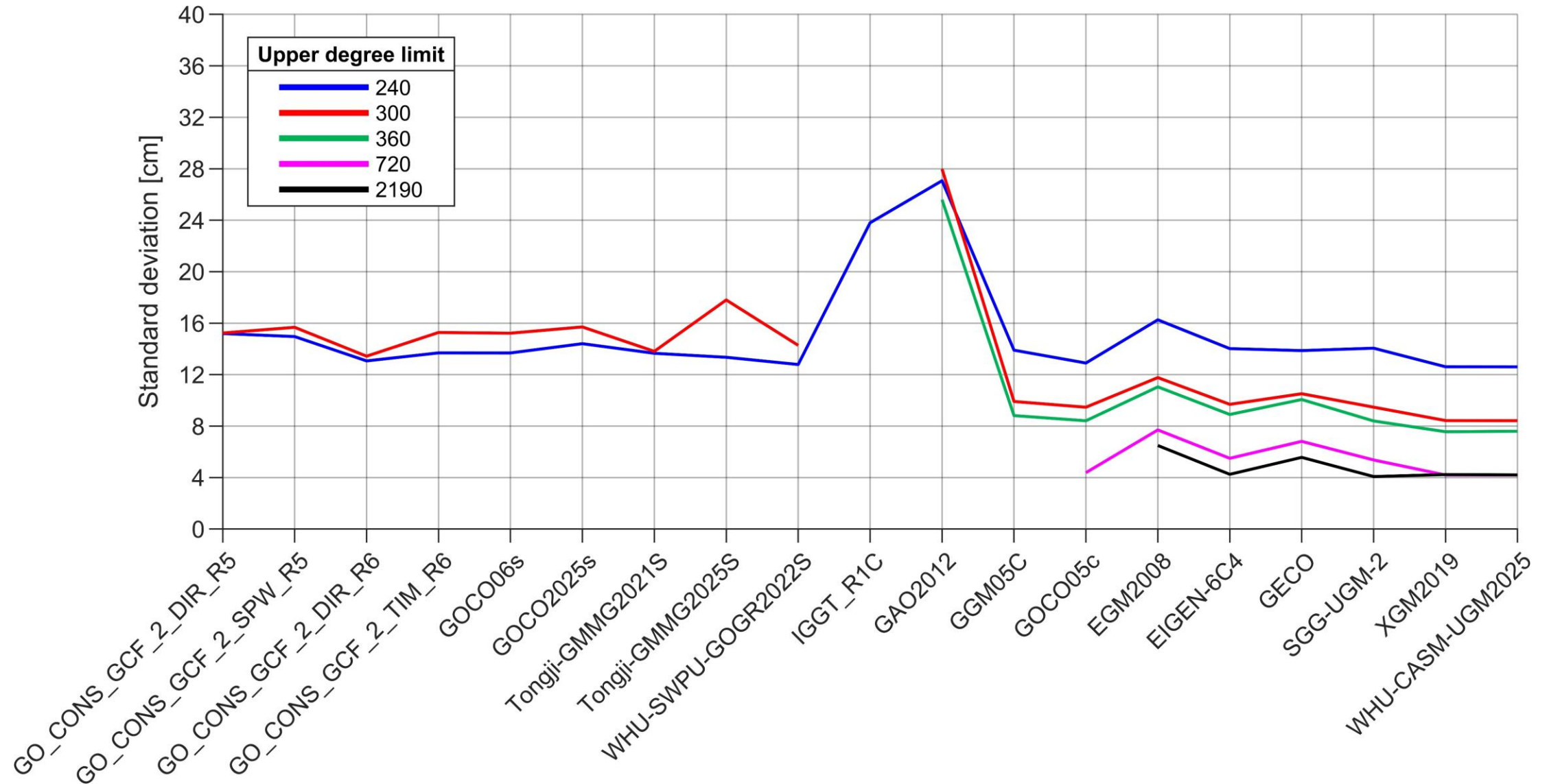
Variance of discrepancies

Contribution from observations **0.98 mGal²**

Any observation with an a priori accuracy of <0.1 mGal had its accuracy reduced to 0.1 mGal

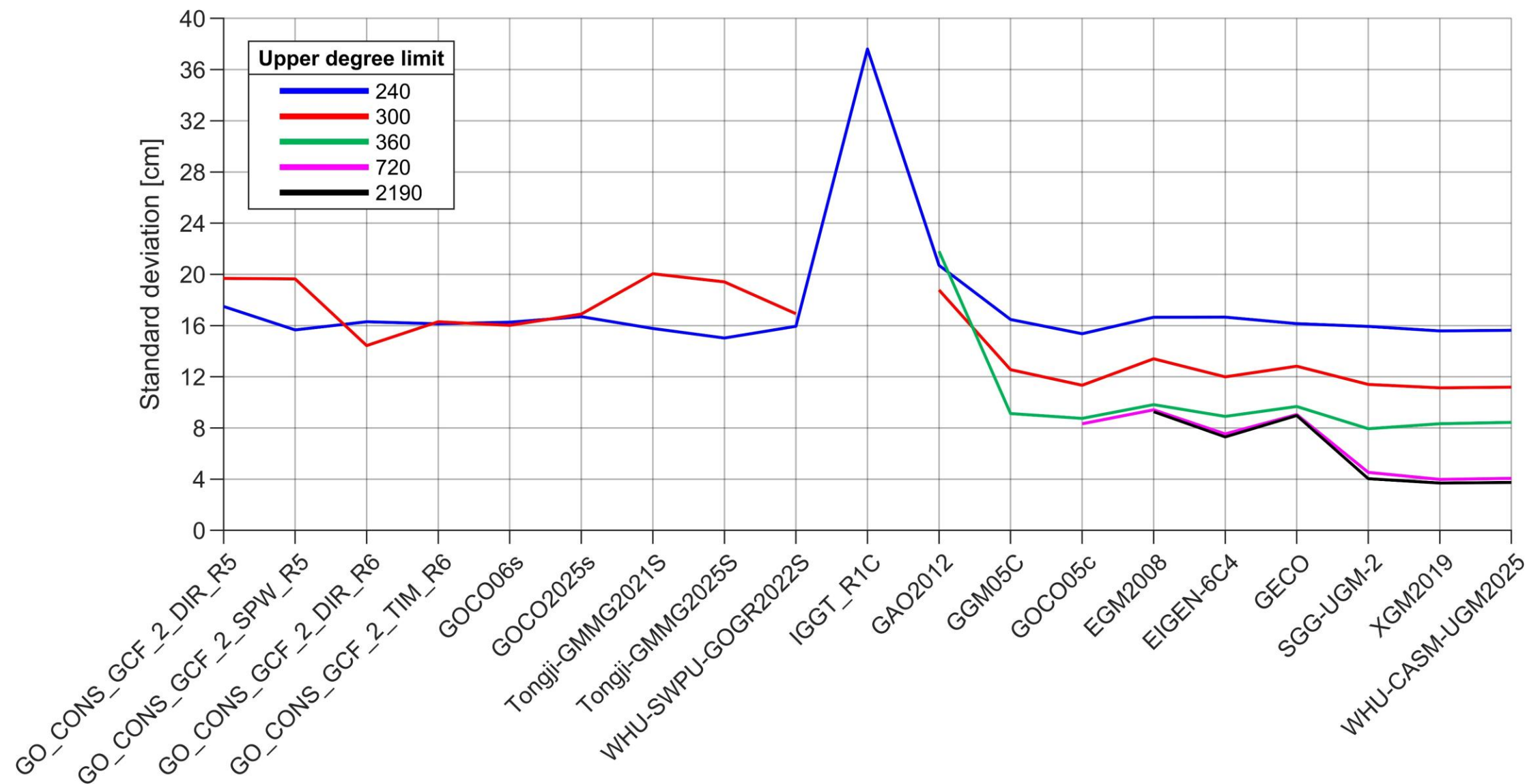
EVALUATION OF HEIGHT ANOMALIES

GNSS-LEVELLING

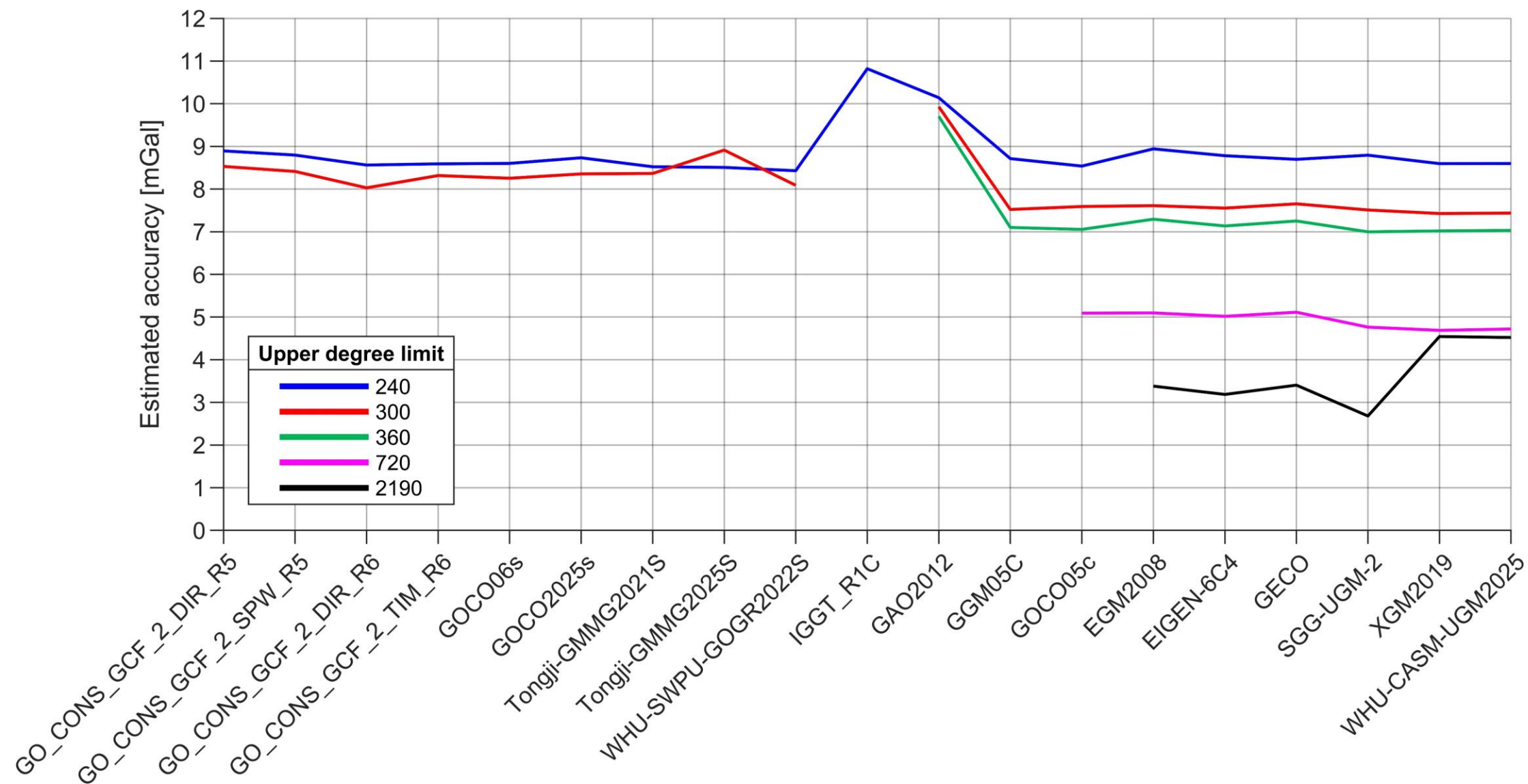


EVALUATION OF HEIGHT ANOMALIES

SWOT-BASED GEOIDAL HEIGHTS



EVALUATION OF GRAVITY ANOMALIES



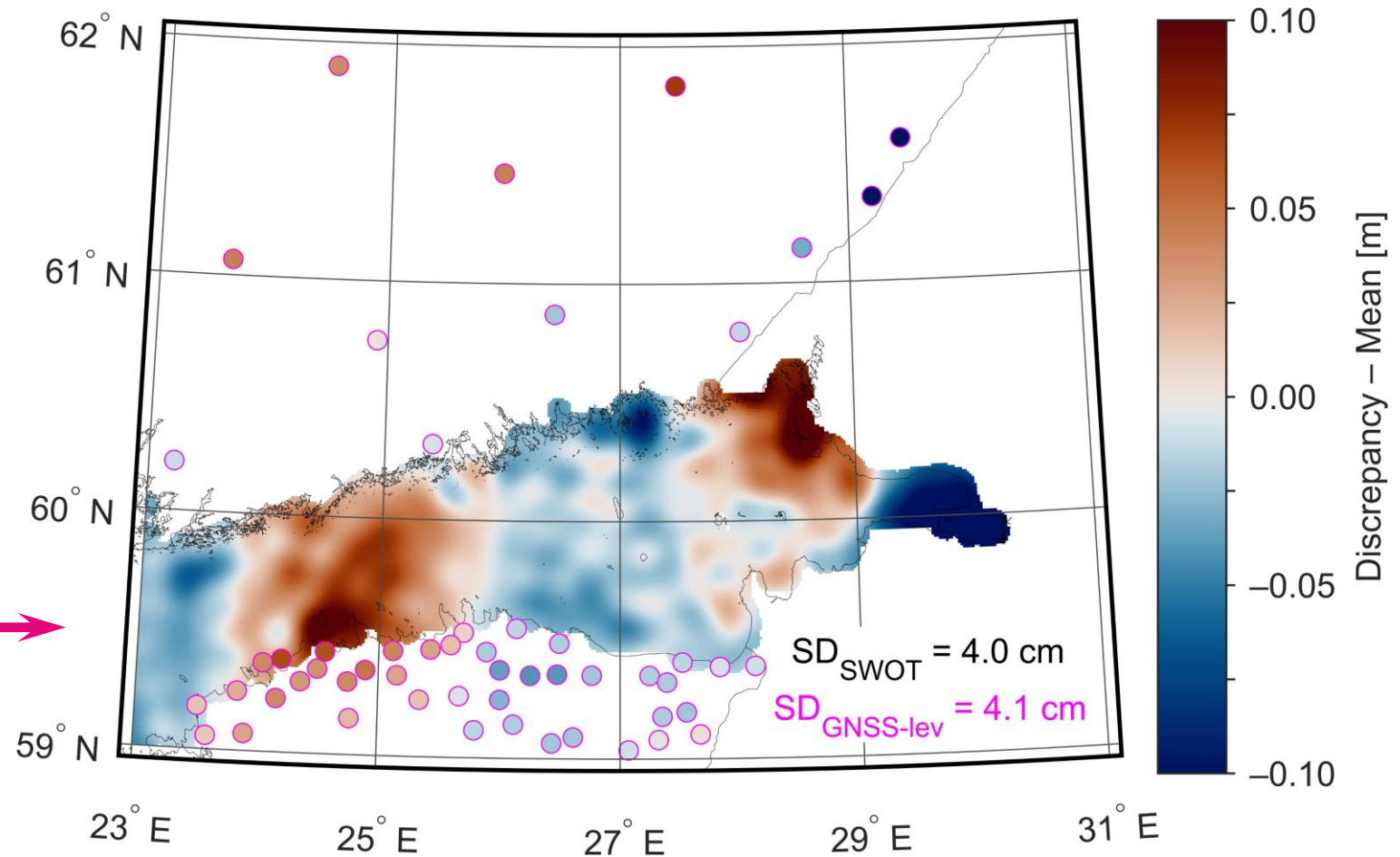
EVALUATION NOTES

- Using a satellite-only model, there would be no significant improvement over the current GO_CONS_GCF_2_DIR_R5₂₄₀ patch
 - The distinct discrepancy signature remains
- Focusing on the eastern portion of the Gulf of Finland and the area east of Finland, the most viable models for the patch seem to be **XGM2019** and WHU-CASM-UGM2025
 - The latter is essentially an augmented XGM2019, with primary contribution to the very high degrees

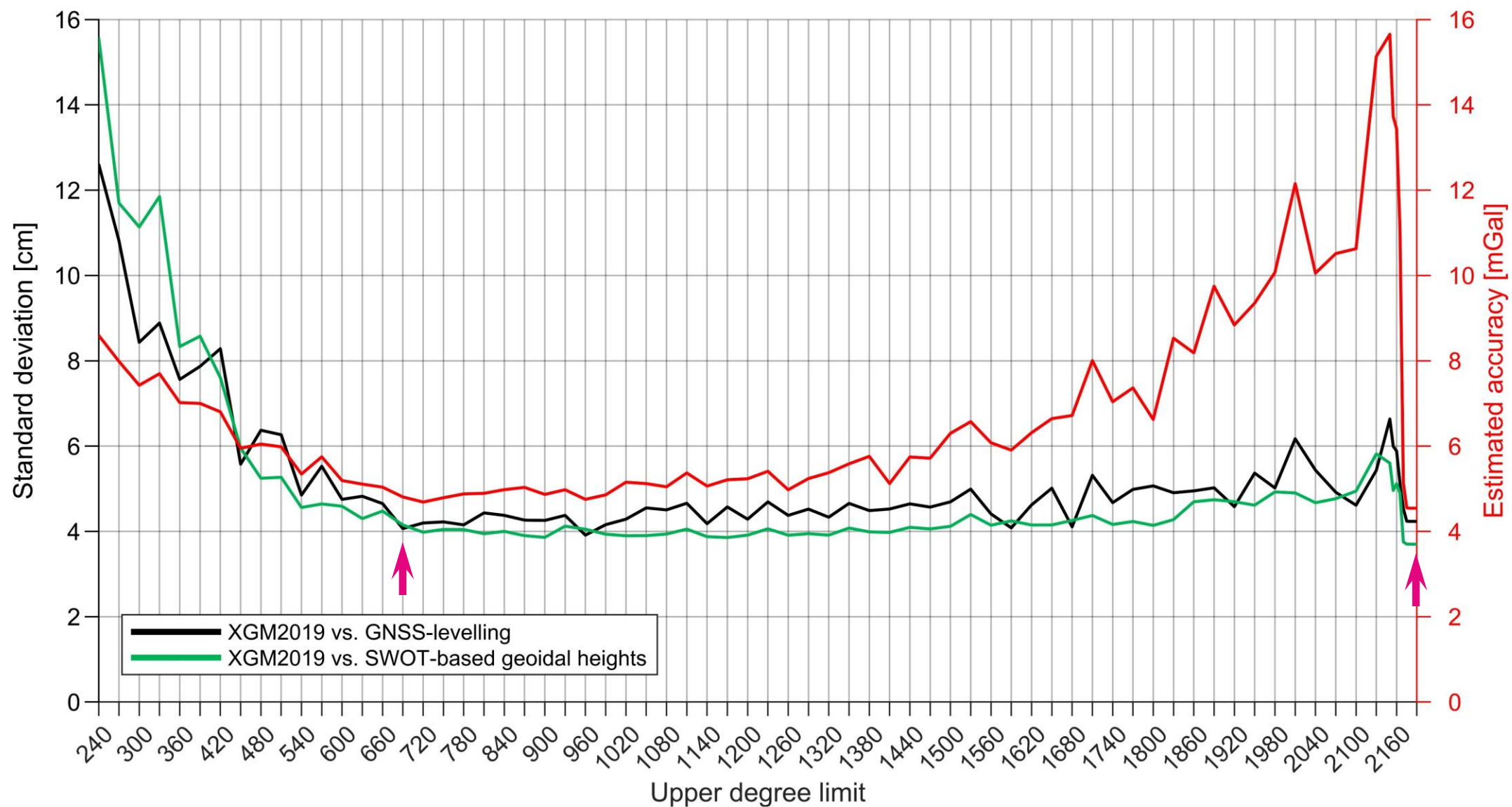
EVALUATION NOTES

- Although SGG-UGM-2 agrees well with validation data, it does not perform as well as XGM2019 in the eastern portion of the Gulf of Finland

Discrepancies of
SGG-UGM-2₂₁₉₀

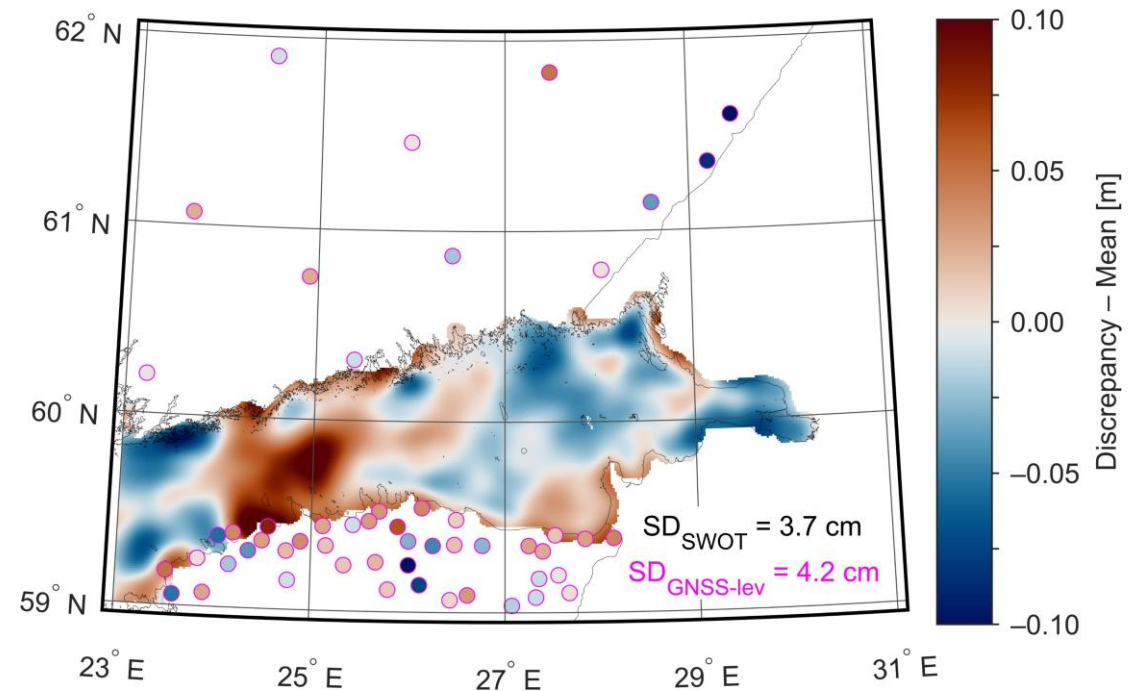
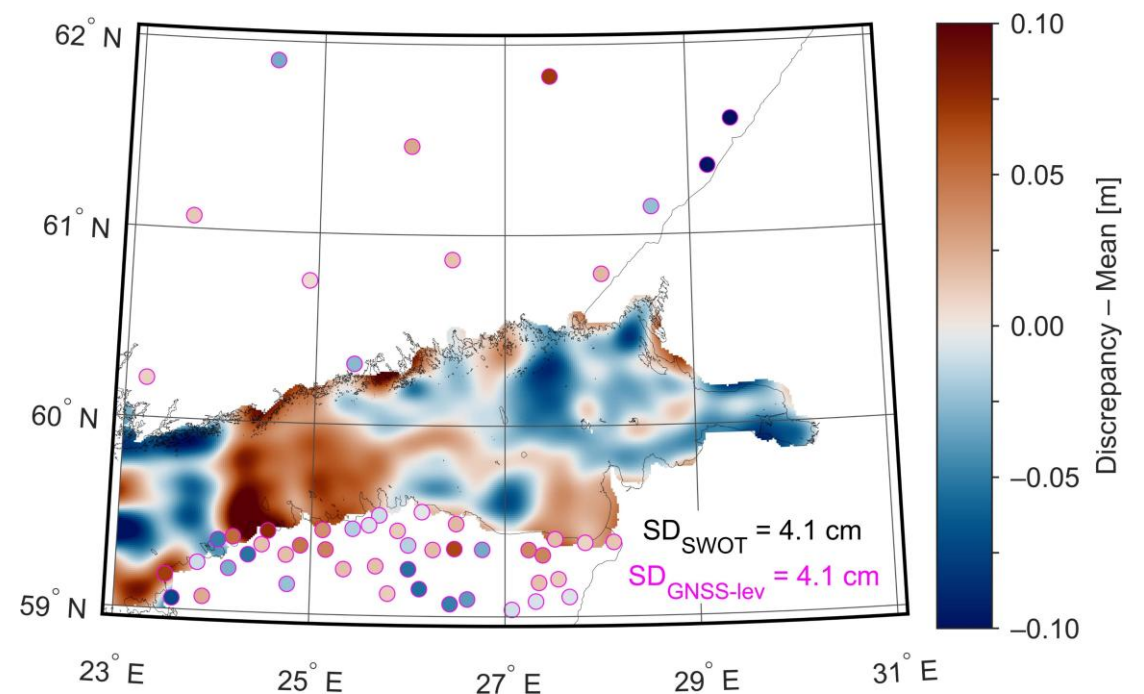


EVALUATION OF XGM2019



EVALUATION OF XGM2019

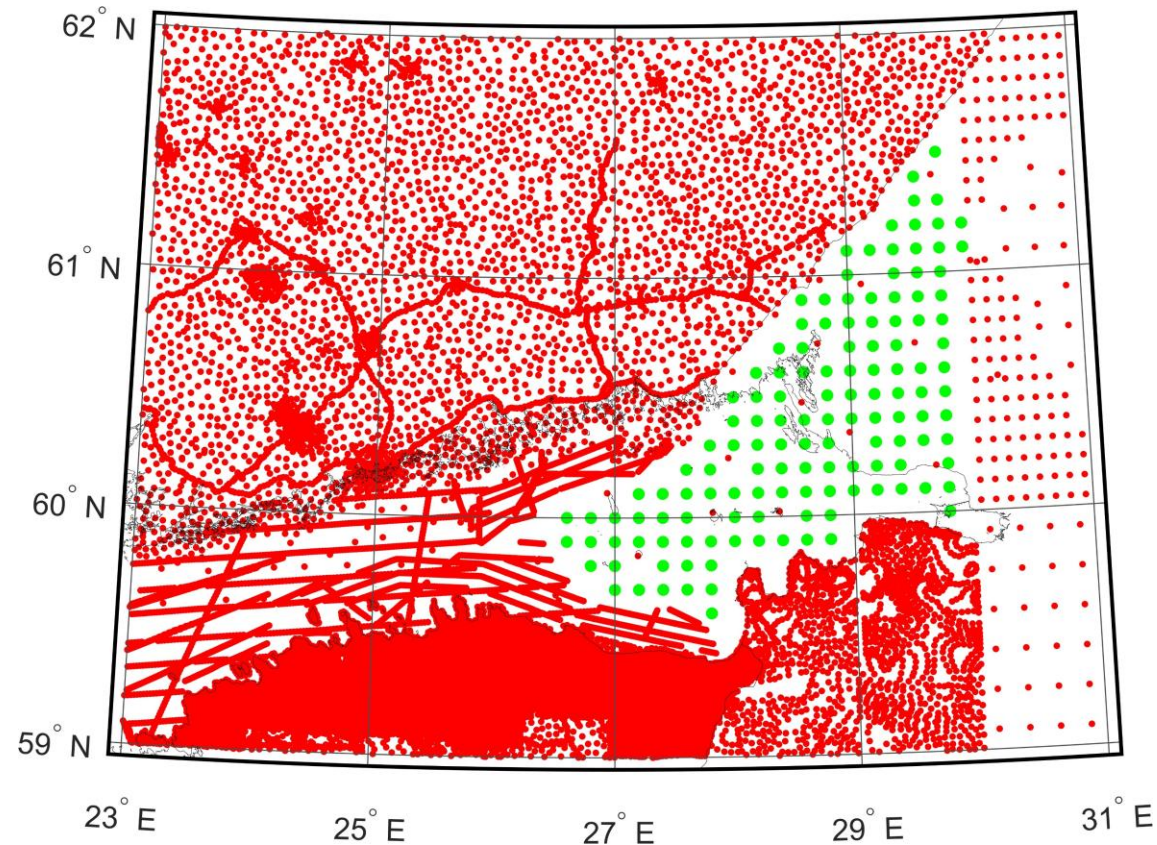
- The use of XGM2019 evaluated up to degree **690 (up)** or **2190 (down)** seems most optimal
 - $\sigma_{XGM2019_{690}} = 4.80$ mGal
Patch minus 0.42 mGal bias
 - $\sigma_{XGM2019_{2190}} = 4.54$ mGal
Patch minus 0.52 mGal bias



PATCH GENERATION

- A **new patch** is generated (using the *harmonic_synth* FORTRAN program) analogously to the old one:
 1. Rescale to zero-tide and GRS80
 2. Compute height anomalies and then geodetic heights on a $0.01^\circ \times 0.02^\circ$ grid
 3. Compute gravity anomalies on a $0.01^\circ \times 0.02^\circ$ grid
 4. Average gravity anomalies to a $0.10^\circ \times 0.20^\circ$ grid
 5. Retain gravity anomalies that are no closer to **observations** than 0.05° latitude and 0.10° longitude
 - Considering also longitude $< 30^\circ$ E
 6. Remove the (~ 0.5 mGal) bias

The generated patches consist of 134 data points

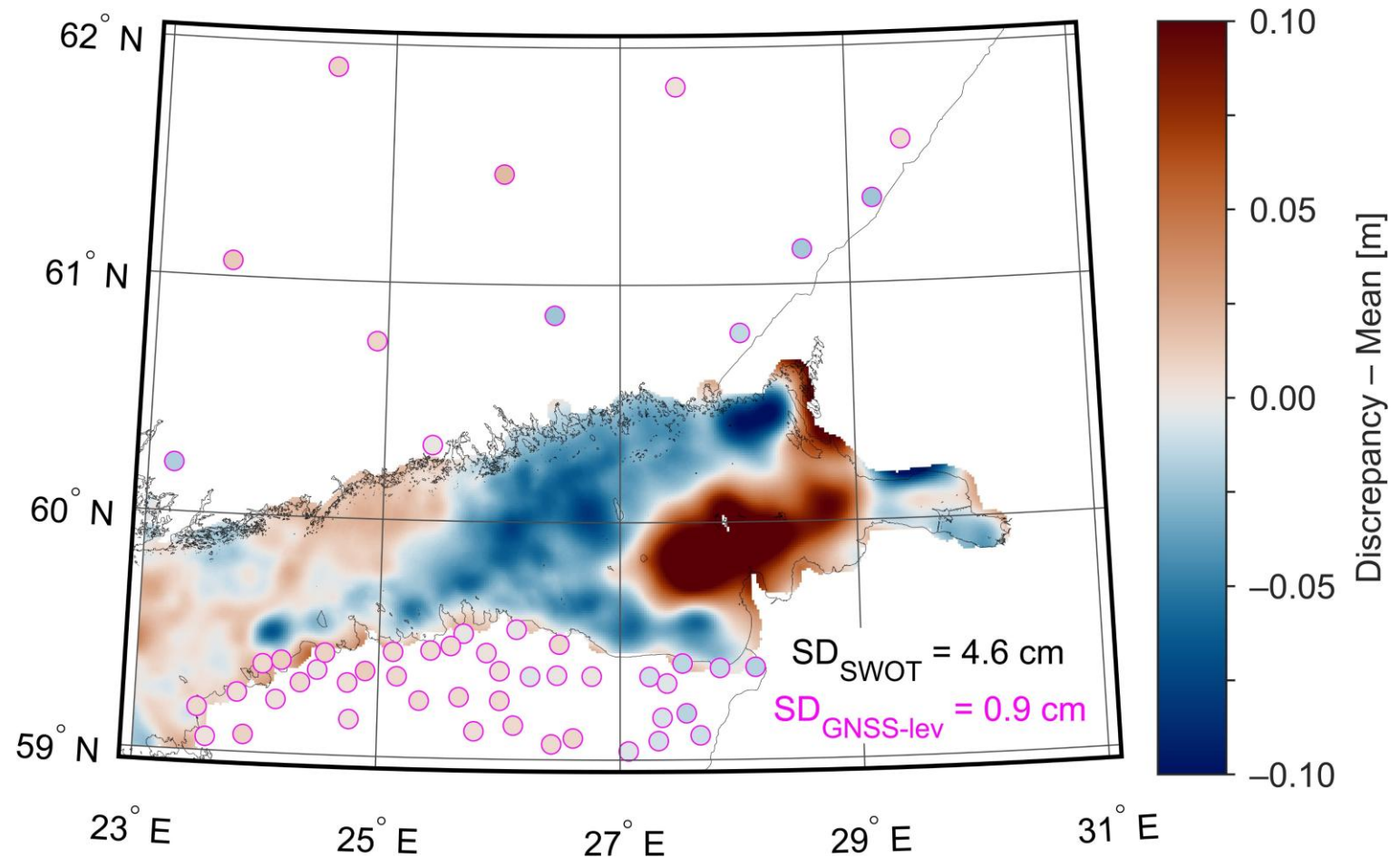


QUASIGEOID MODELLING

REFERENCE SOLUTION

- The reference solution is computed analogously to TUT3A BSCD2000 solution with a minor adjustment of some parameters
 - Use of the original DIR_R5₂₄₀ patch

For details on TUT3A, refer to Schwabe et al. (2026):
<https://doi.org/10.1007/s00190-026-02096-z>

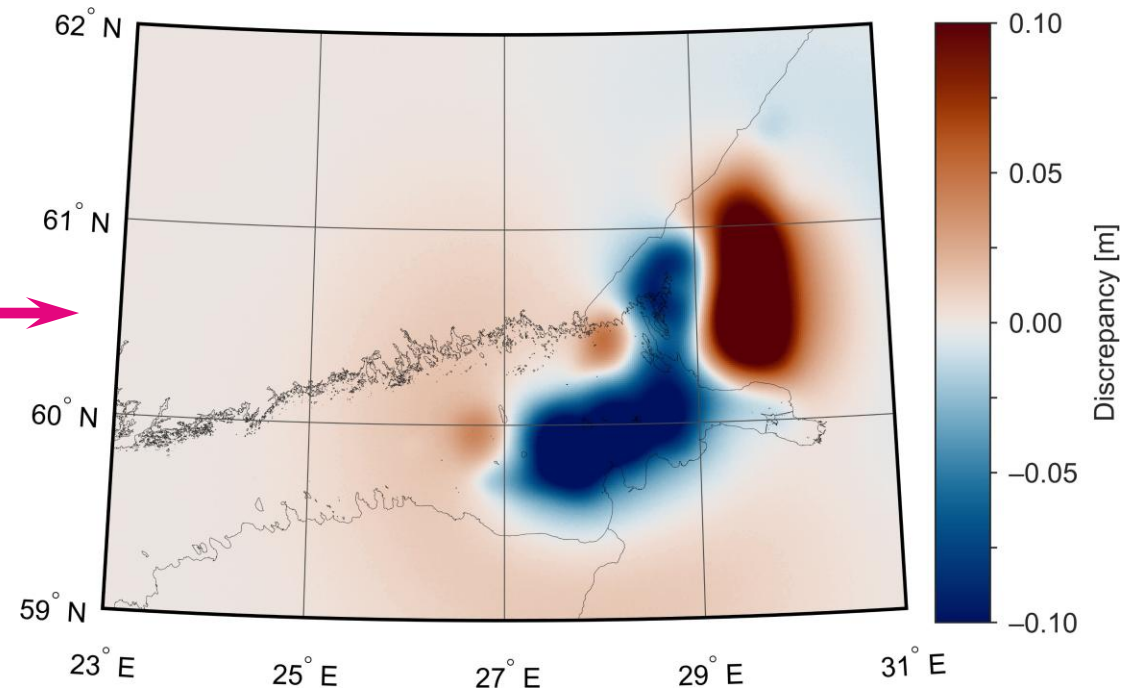
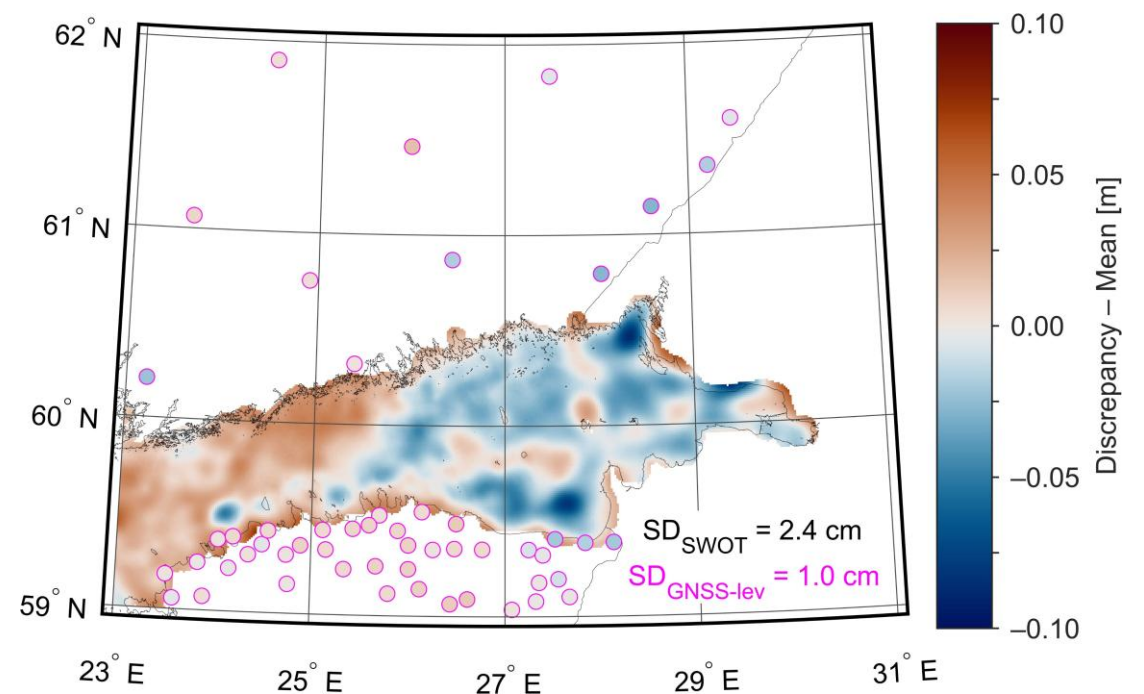


QUASIGEOID MODELLING

XGM2019₆₉₀ PATCH

- The only difference with respect to the reference solution's processing is that the used patch has been swapped

Test solution (XGM2019₆₉₀ patch)
minus the reference solution

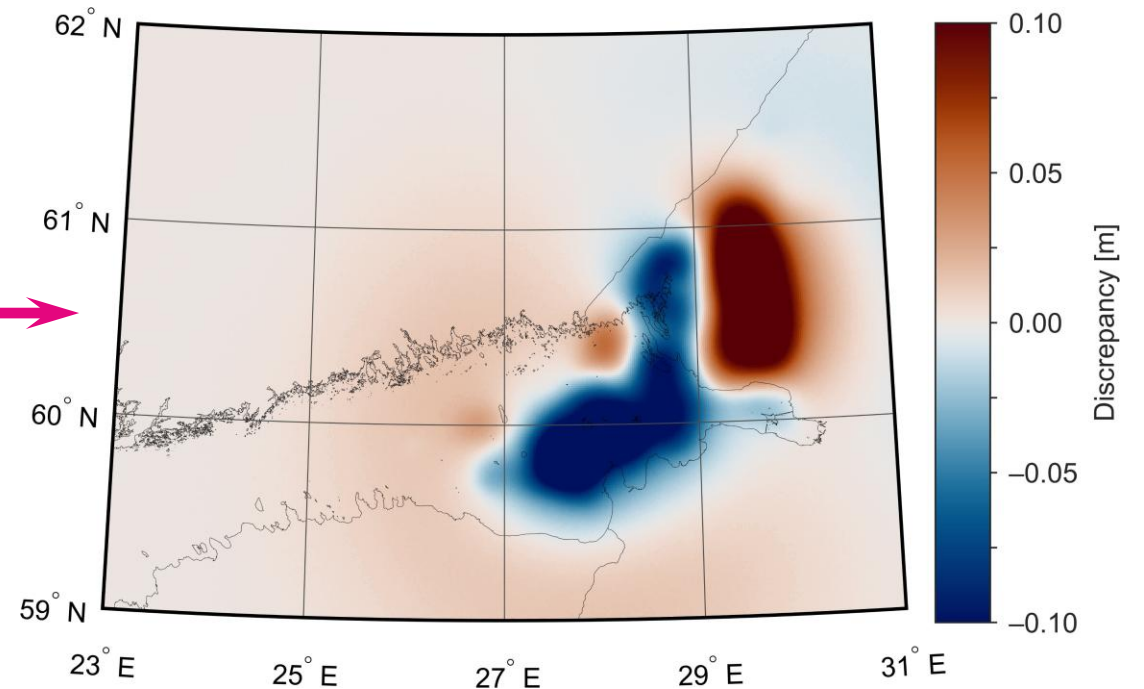
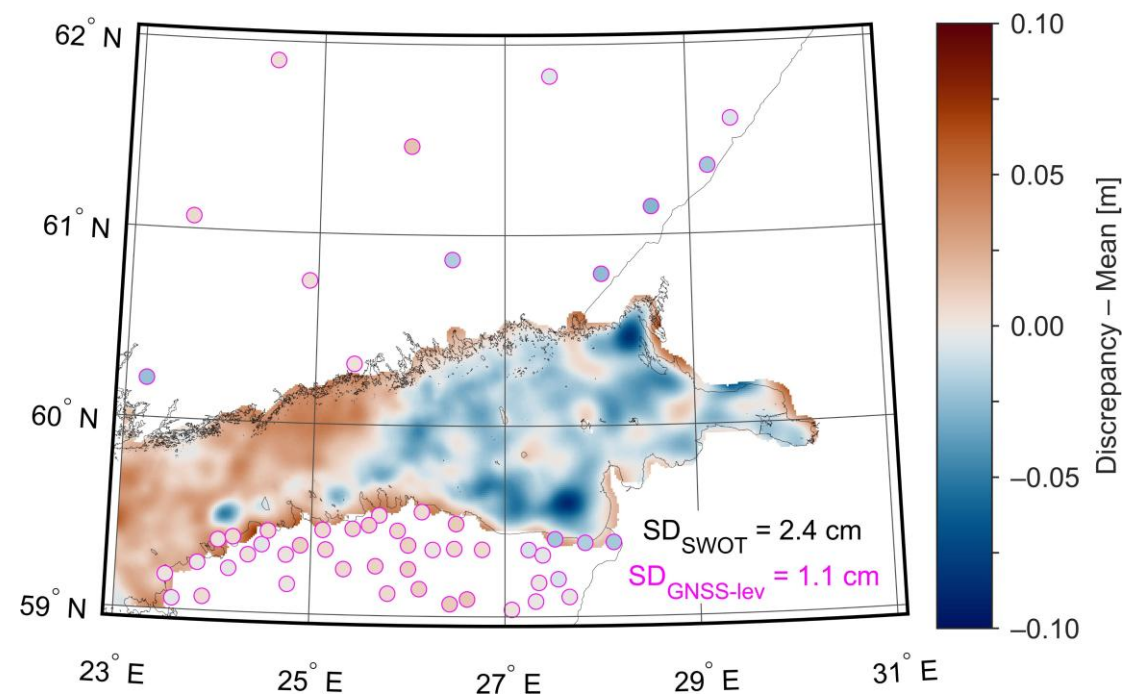


QUASIGEOID MODELLING

XGM2019₂₁₉₀ PATCH

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Test solution (XGM2019₂₁₉₀ patch)
minus the reference solution



CONCLUSIONS AND REMAINING WORK

- SWOT-based geoidal heights can be valuable for evaluating gravimetric modelling solutions offshore, like GNSS-levelling is used on land
- A gravity data patch generated using XGM2019 appears to improve quasigeoid modelling accuracy in the eastern portion of the Gulf of Finland compared to the original patch
- Remaining work:
 - Some tests with spherical/ellipsoidal harmonic transformations
 - Gravimetric quasigeoid modelling using TUM implementation of least-squares collocation
 - Prepare and distribute a report to working group members



THANK YOU FOR YOUR ATTENTION!