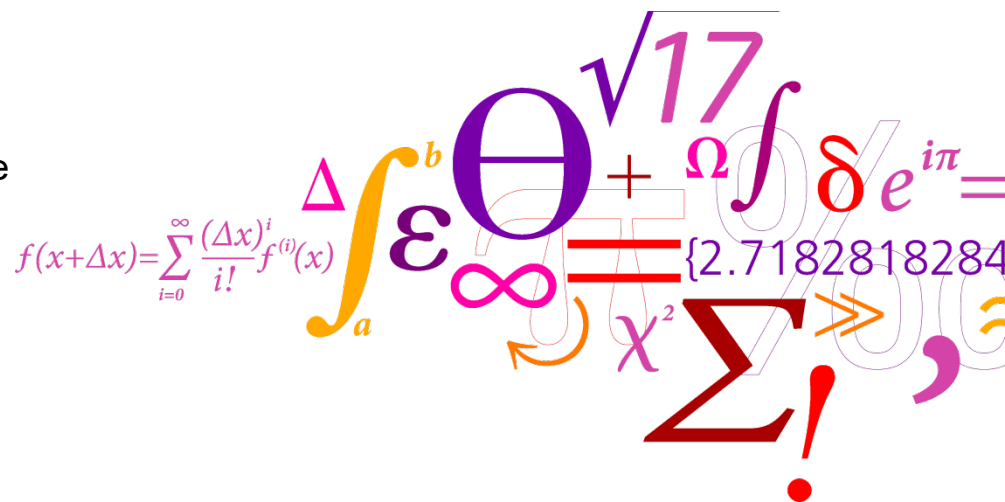


Marine Gravimetry: My Take

by
Gabriel Strykowski, DTU Space

with contribution of

Sebastian Holbech, DTU Space
Tim Enzlberger Jensen, DTU Space
Jonathan F. Kirby, DTU Space
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Joachim Schwabe, BKG Germany
Bjarke Nilsson, DTU Space
Ole B. Andersen, DTU Space



Contents

- NKG gravity DB: “Off-shore” data in NKG area
- Marine Gravimetry Fundamentals
- Data Processing: a Personal Take
- Test of AT1A marine gravimeter onboard a commercial ferry
- Marine gravimetry: Takeaway

NKG gravity DB: “Off-shore” data in NKG area

Measurement techniques

- Measurements on sea ice
- Sea bottom gravimetry
- Old marine gravimetry
- **Modern marine gravimetry (dedicated, automated)**
- Airborne gravimetry
- INS/IMU gravimetry
- **Gravimetry from satellite altimetry**
-

NKG gravity DB: “Off-shore” data in NKG area

Relevant recent regional projects

-
- NKG2015 (lead: Jonas Ågren, LM, Sweden)
- FAMOS (lead: Jonas Ågren, LM, Sweden)
- FAMOS ext. (lead: Joachim Schwabe, BKG, Germany)
- BSCD2000 (lead: Joachim Schwabe, BKG, Germany)
- BalMarGrav (lead: Monika Wilde-Piórko, IGIK, Poland)
- NKG202X (lead: Ove C.D. Omang, KV, Norway)
-

Schwabe et al., 2026

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<https://doi.org/10.1007/s00190-026-02096-z>

ORIGINAL ARTICLE



The development of the unified Baltic Sea Chart Datum 2000 (BSCD2000) height transformation grid: an unprecedented example of height system unification based on state-of-the-art marine geoid modelling

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Abstract

The shallow Baltic Sea is a vital waterway with dense shipping traffic, requiring accurate and reliable nautical charts for safe navigation. Until recently, different realisations of the mean sea level were used in the paper charts of each country, sometimes even between harbours. This created obstacles for the digitalisation of ship navigation, including electronic nautical charts combined with satellite-based positioning. To resolve this, the Baltic Sea Hydrographic Commission decided in 2013 to introduce the Baltic Sea Chart Datum 2000 (BSCD2000) as a common height/depth reference system for the maritime sector in the Baltic Sea. The new reference level for all depth and water level information is strictly the quasigeoid, which is practically identical to the geoid at sea. The BSCD2000 is defined in accordance with the European reference systems: the European Terrestrial Reference System 1989 (ETRS89) for ellipsoidal coordinates and the European Vertical Reference System (EVRS) for physical heights. This enables the practical implementation of the zero level through a seamless height transformation grid with standard uncertainties of approximately 1–2 cm, which is harmonised with national coordinates, heights, and height reference surfaces. To the authors' knowledge, this level of harmonisation is unprecedented in the maritime sector and exemplifies the value of the unification of height systems in geodesy. The paper outlines the foundations of the BSCD2000 and the approach to construct the BSCD2000 height transformation grid. While the computation of the gravimetric marine quasigeoid model is based on well-established methods, special focus is placed on practical harmonisation across national borders and along the coastline. To this end, a novel fitting and blending scheme based on distance maps was developed. Finally, comparison of the new gravimetric marine quasigeoid solution with a preliminary geometric marine geoid model based on SWOT altimetry data and hydrodynamic modelling confirmed good agreement within a few centimetres in most areas of the Baltic Sea.

Keywords Baltic Sea · Chart datum · Geoid modelling · Harmonisation of height systems · Height system unification · Marine navigation

Marine Gravimetry Fundamentals

Fundamental equation of relative gravimetry

$$g = g_{ref} + \alpha [r - r_{ref}]$$

$$g = g_{ref} + \alpha \left[\left(\tilde{r} - c_g \right) - r_{ref} \right]$$

$\tilde{r}$ uncorrected reading
 c_g total correction budget

2D with assumption $H = H_{ref}$ for orthometric heights (RTK in harbor)

$$\Delta g = \Delta g_{ref} + \alpha \left[\left(\tilde{r} - c_g \right) - r_{ref} \right] - \left(\gamma_0 - \gamma_{0,ref} \right)$$

3D with measured ellipsoidal sensor height h and h_{ref} (GNSS)

$$\delta g = \delta g_{ref} + \alpha \left[\left(\tilde{r} - c_g \right) - r_{ref} \right] - \left(\gamma_0 - \gamma_{0,ref} \right) + \frac{\partial \gamma}{\partial h} (h_{ref} - h)$$

Data Processing: a Personal Take

Corrections of marine gravimeter readings $\propto \left[\left(\tilde{r} - c_g \right) - r_{ref} \right]$ corrected reading $r = \tilde{r} - c_g$

“Perfect correction” = “implemented correction” + “unmodelled correction”,

Modelling Requirement: “unmodelled correction” must be insignificant.

Relative verification: insignificant misfit at crossings of survey lines

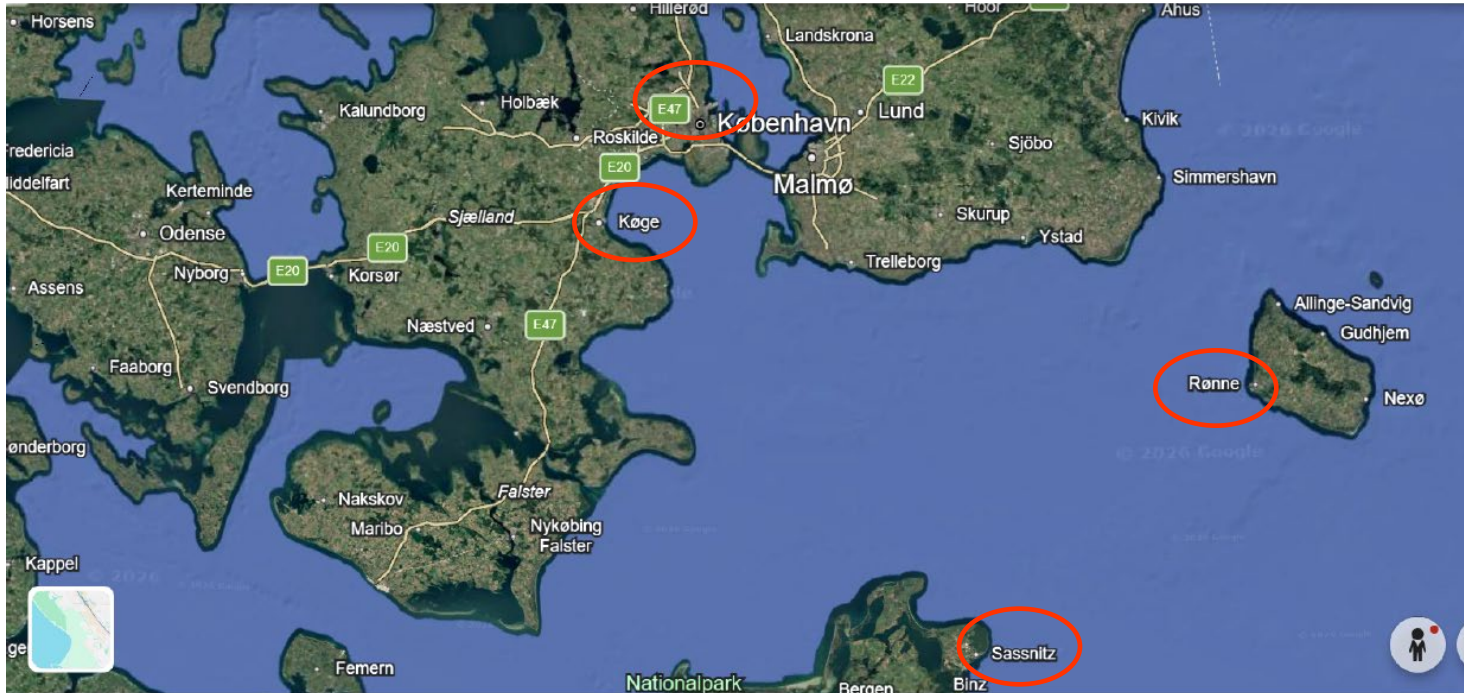
“Standard modelling methods”

- Standard corrections: filtering, Eötvös correction
- Imposed gravimeter drift model based on land measurements in harbors
- Marine areas: (subjective) separation of signal from residual noise for survey lines
- Stand-alone and independent survey by survey modelling (My take: questionable)

My take

- Standard corrections: filtering, Eötvös correction
- Control of **reference level** (and gravimeter drift at sea) using **FA from satellite altimetry**
- **Proximity principle**: results for locations in the vicinity must be the same
- Validation: **Qualitative** comparison with FA from satellite altimetry and consistency with control measurements on-shore

Test of AT1A marine gravimeter onboard a commercial ferry



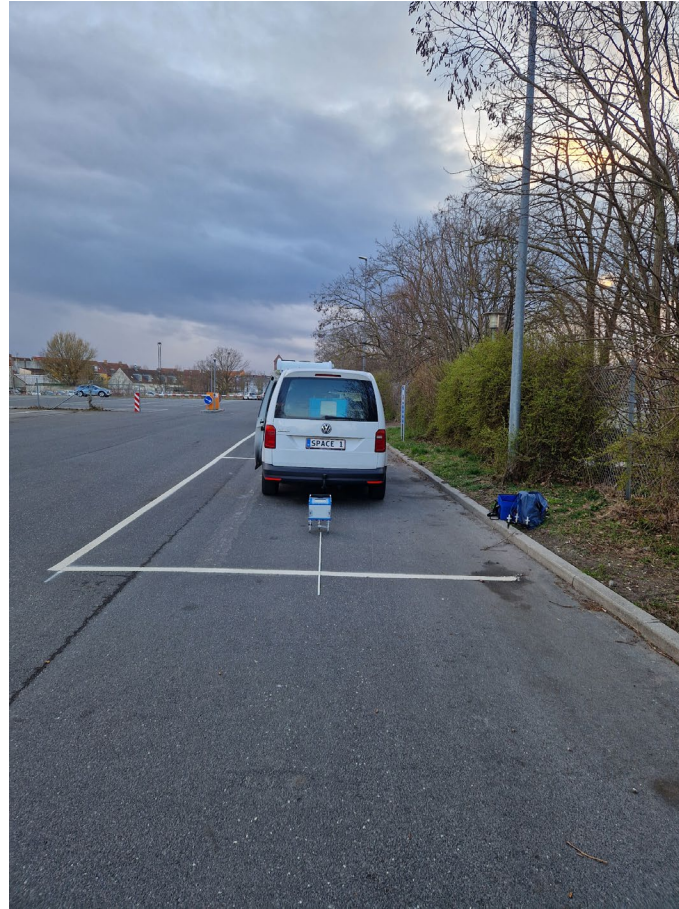
AT1A from Dynamic Gravity Systems (DgS), USA is a (ZLS) airborne/marine gravimeter. A loan from NGA, USA

Test of AT1A marine gravimeter onboard a commercial ferry



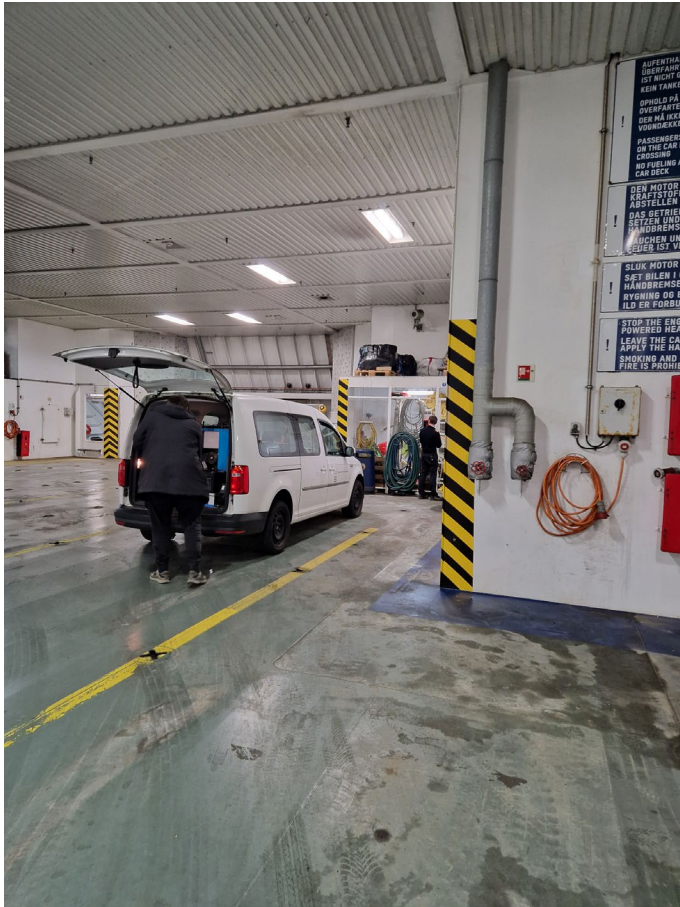
DTU, Kgs. Lyngby, “Gagarin” station

Test of AT1A marine gravimeter onboard a commercial ferry



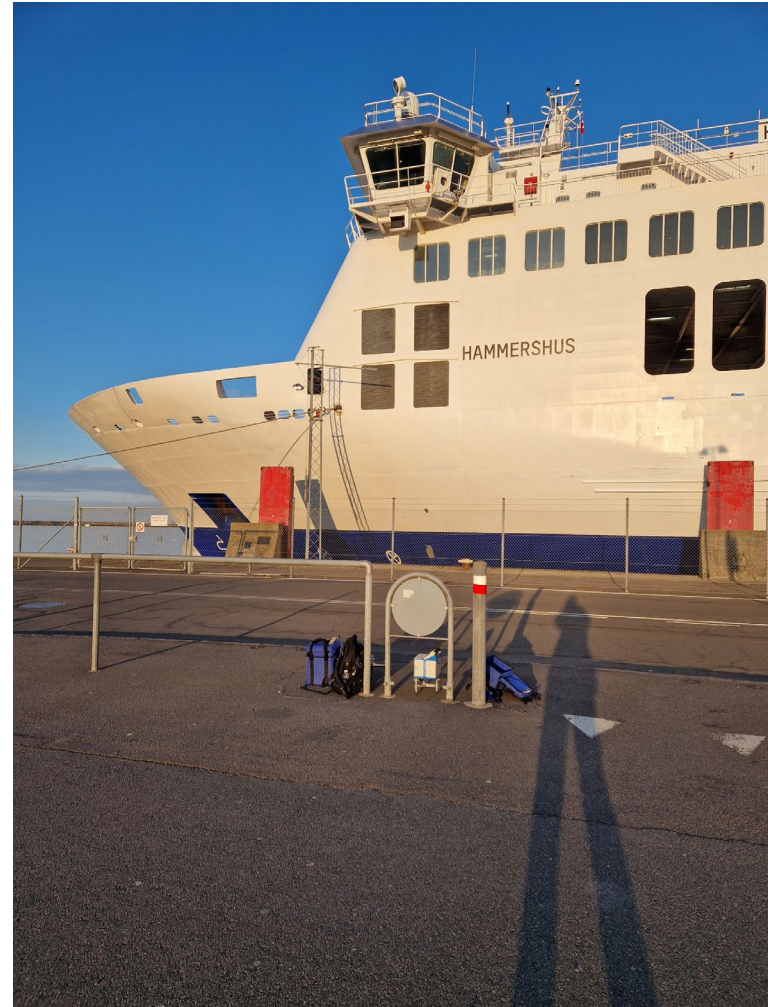
Køge, Trailer/Autocamper Parking

Test of AT1A marine gravimeter onboard a commercial ferry

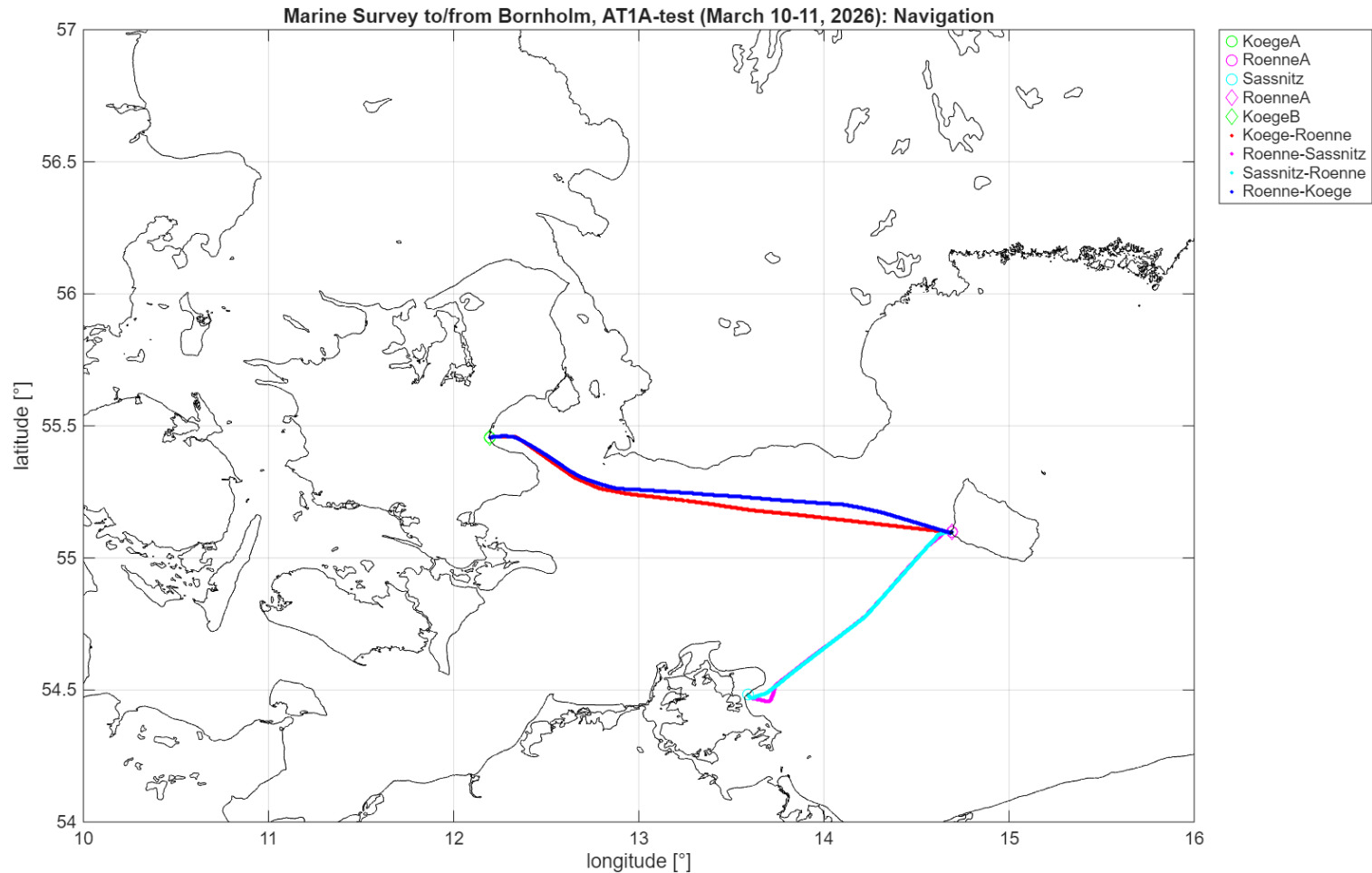


Installation onboard the ferry boat
Left: Space1 near power supply
Right: Our GNSS antenna on top
of the ferry boat

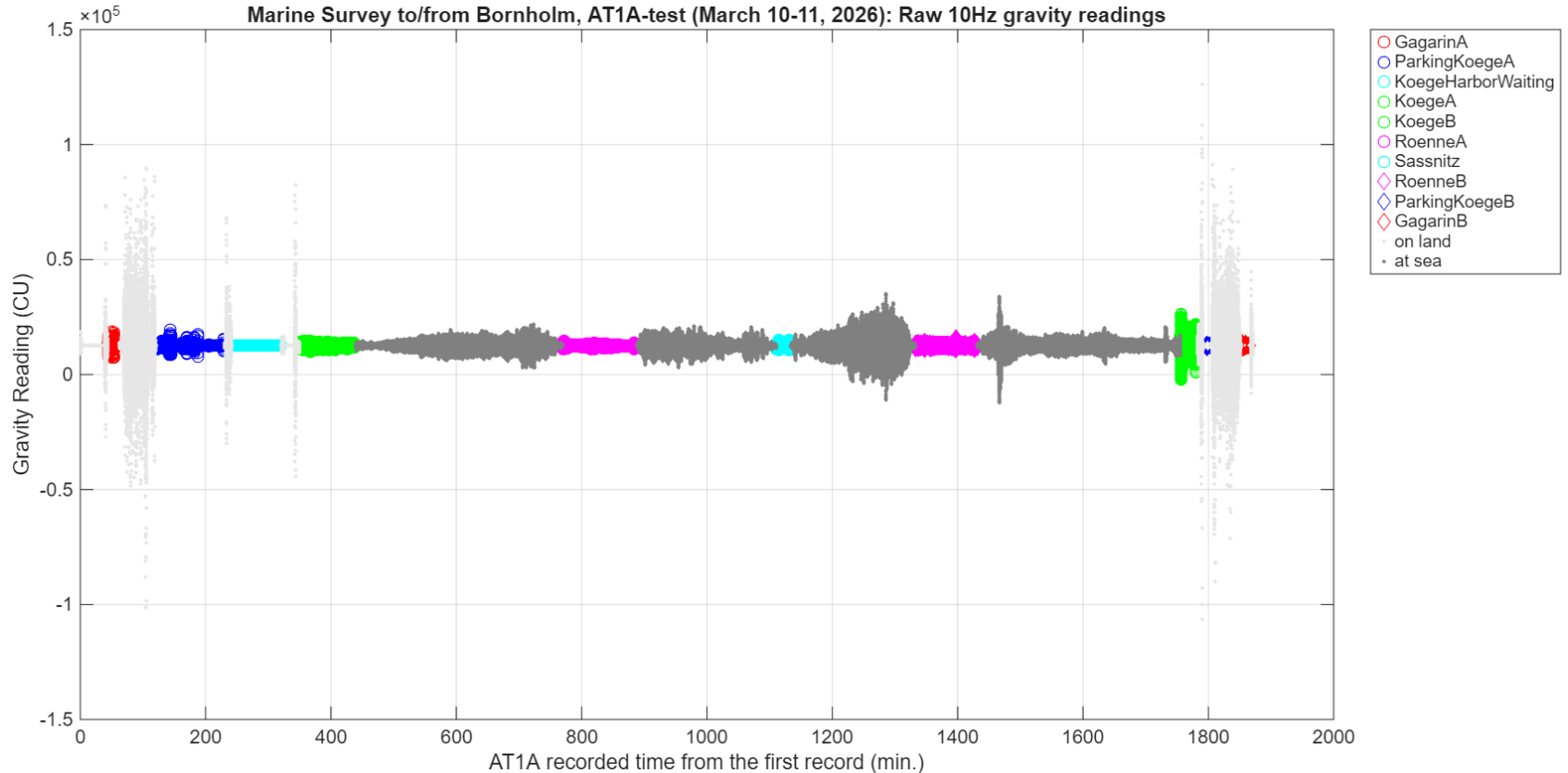
Test of AT1A marine gravimeter onboard a commercial ferry



Test of AT1A marine gravimeter onboard a commercial ferry

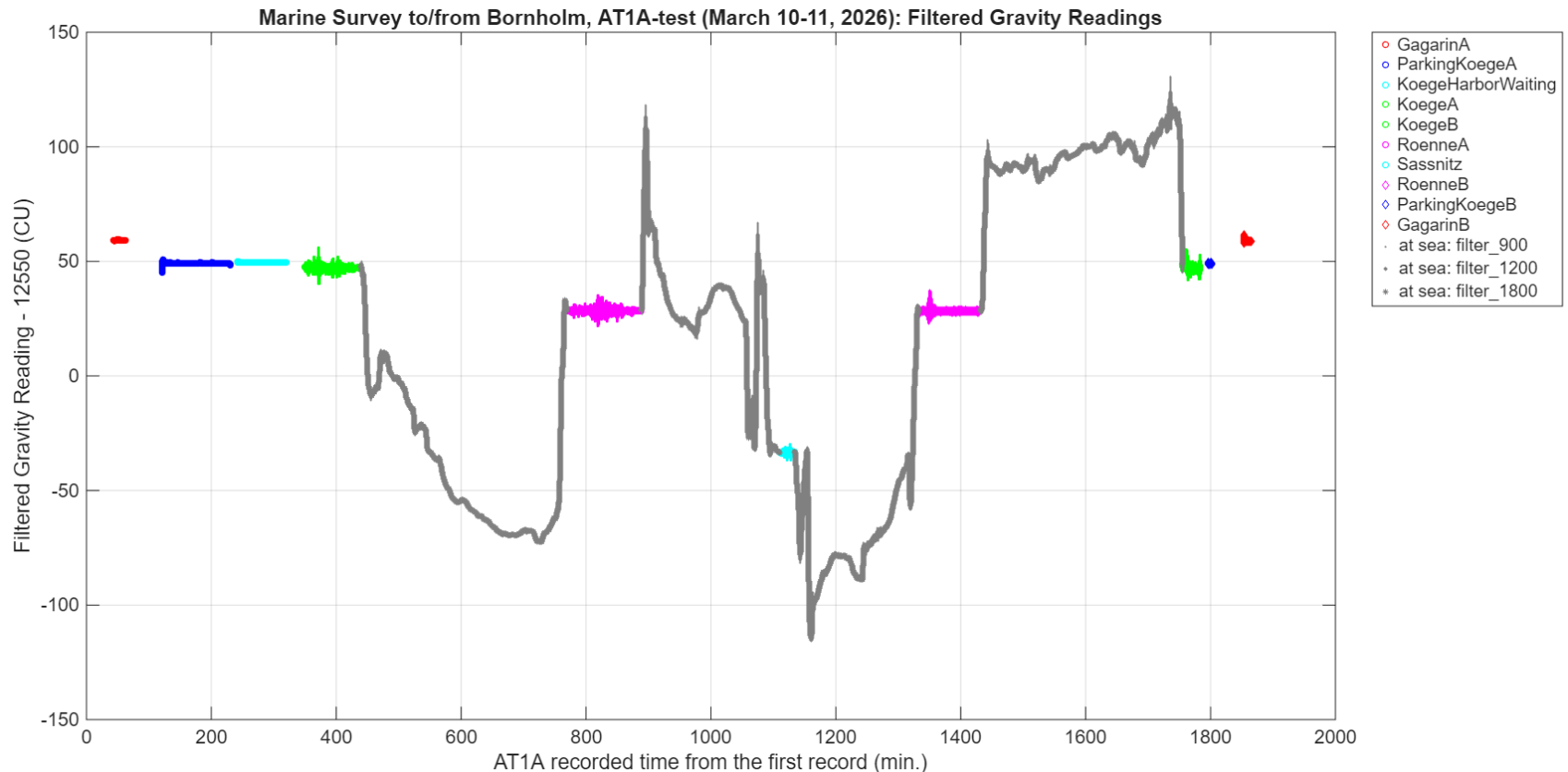


Test of AT1A marine gravimeter onboard a commercial ferry



Raw 10Hz marine gravimeter data

Test of AT1A marine gravimeter onboard a commercial ferry



Filtered gravity data; (arbitrary) bias: -12550 CU

Test of AT1A marine gravimeter onboard a commercial ferry

“Sanity check” combining land and marine information: “rough 3D-model” in harbors.

$$\frac{\partial \gamma}{\partial h} \left(\boxed{H_{ferry}^{KøgeA}} - H_{pier}^{Køge} \right) \approx \alpha \left[r_{ferry}^{KøgeA} - r_{pier}^{Køge} \right] \quad H_{ferry}^{KøgeA} \approx 9.9019m$$

Use the above and models to get consistent:

$$g_{ferry}^{KøgeA}, \quad \zeta^{KøgeA}, \quad \Delta g_{ferry}^{KøgeA}, \quad \delta g_{ferry}^{KøgeA}$$

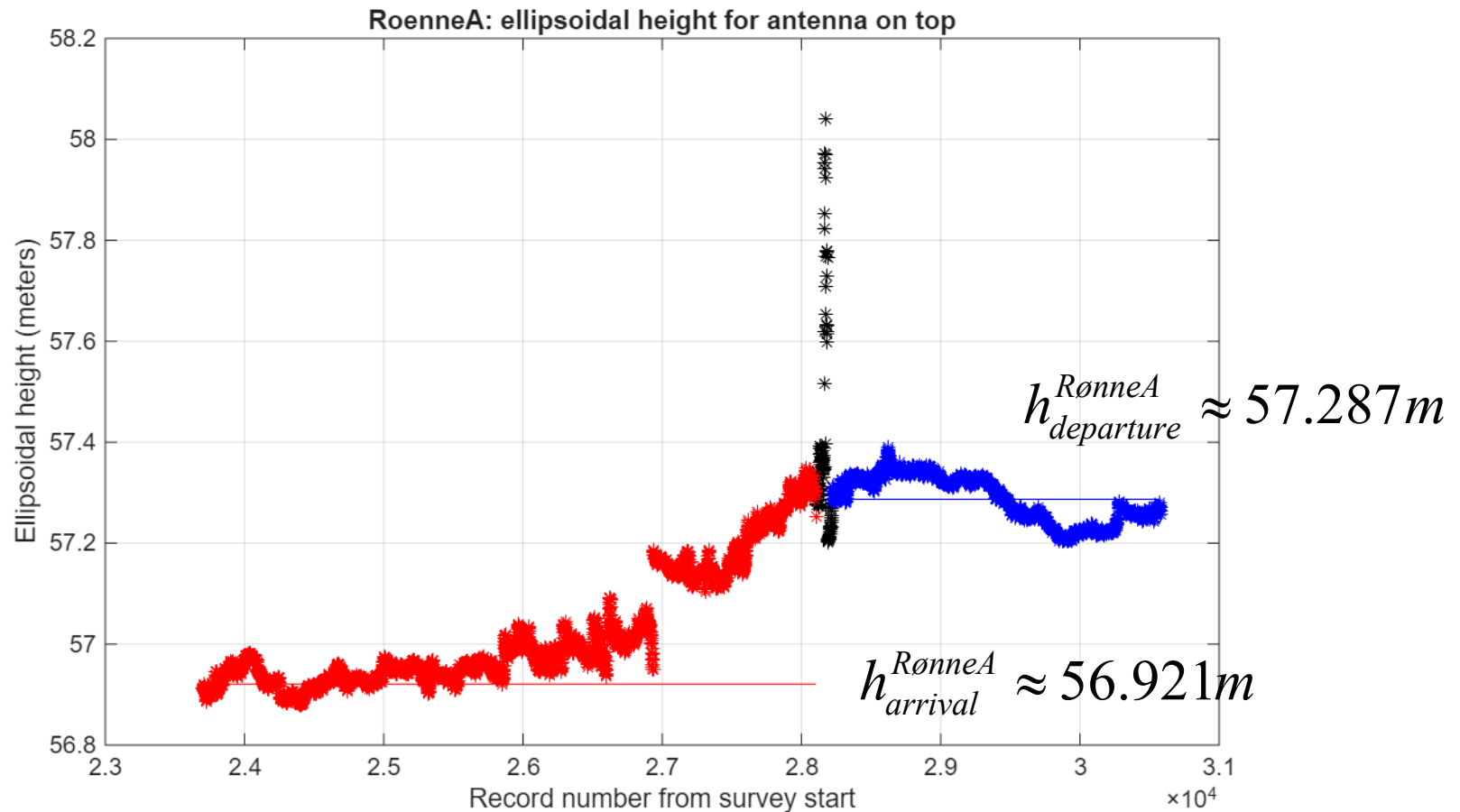
2D transfer of FA from KøgeA to RønneA:

$$\Delta g_{ferry}^{RønneA} \approx \Delta g_{ferry}^{KøgeA} + \alpha \left[r_{ferry}^{RønneA} - r_{ferry}^{KøgeA} \right] + \left(\gamma_0^{RønneA} - \gamma_0^{KøgeA} \right)$$

Is the result consistent with $\Delta g_{pier}^{RønneA}$ from a land tie?

Answer: Yes!

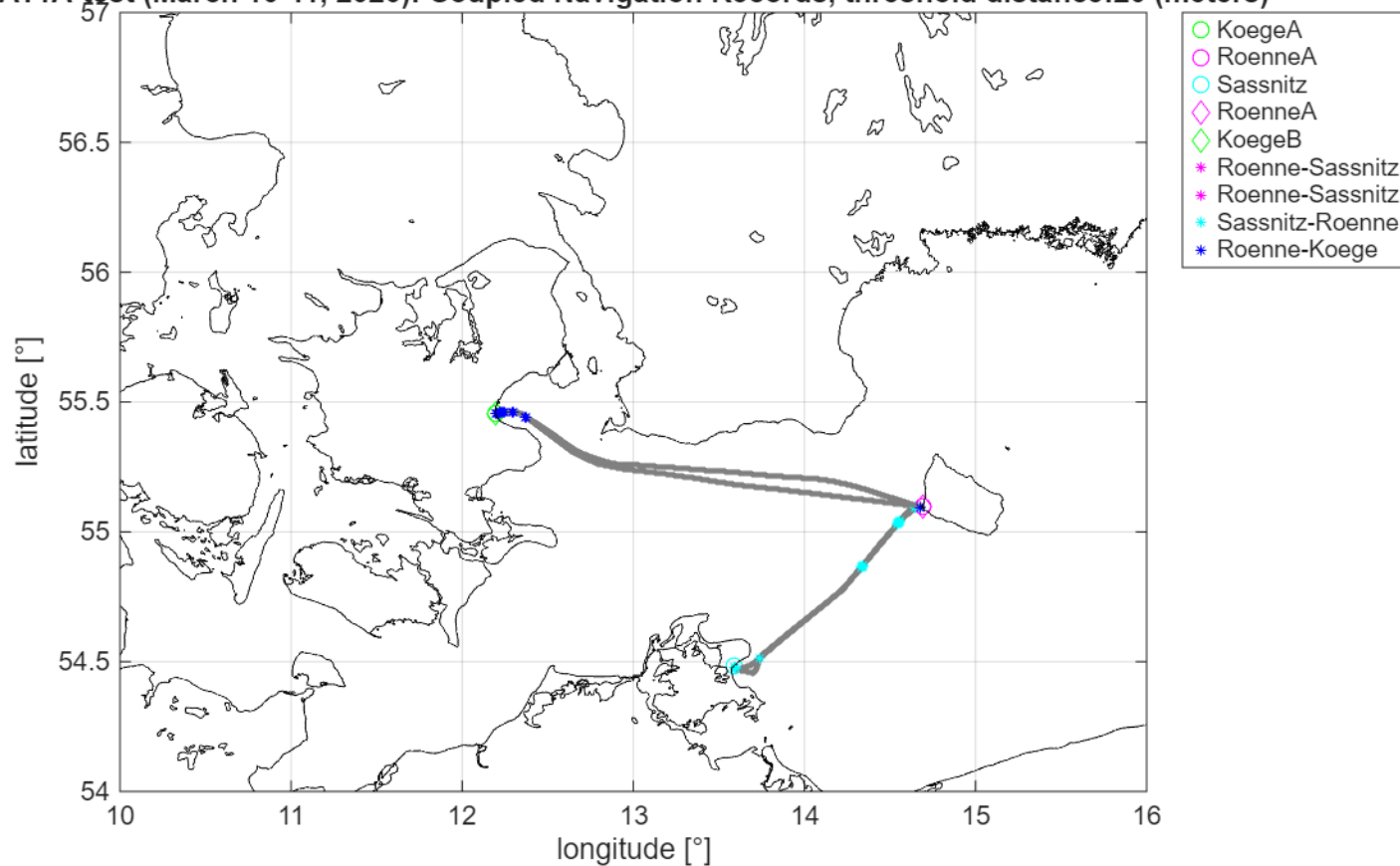
Test of AT1A marine gravimeter onboard a commercial ferry



RønneA, antenna position changed (red->blue)

Test of AT1A marine gravimeter onboard a commercial ferry

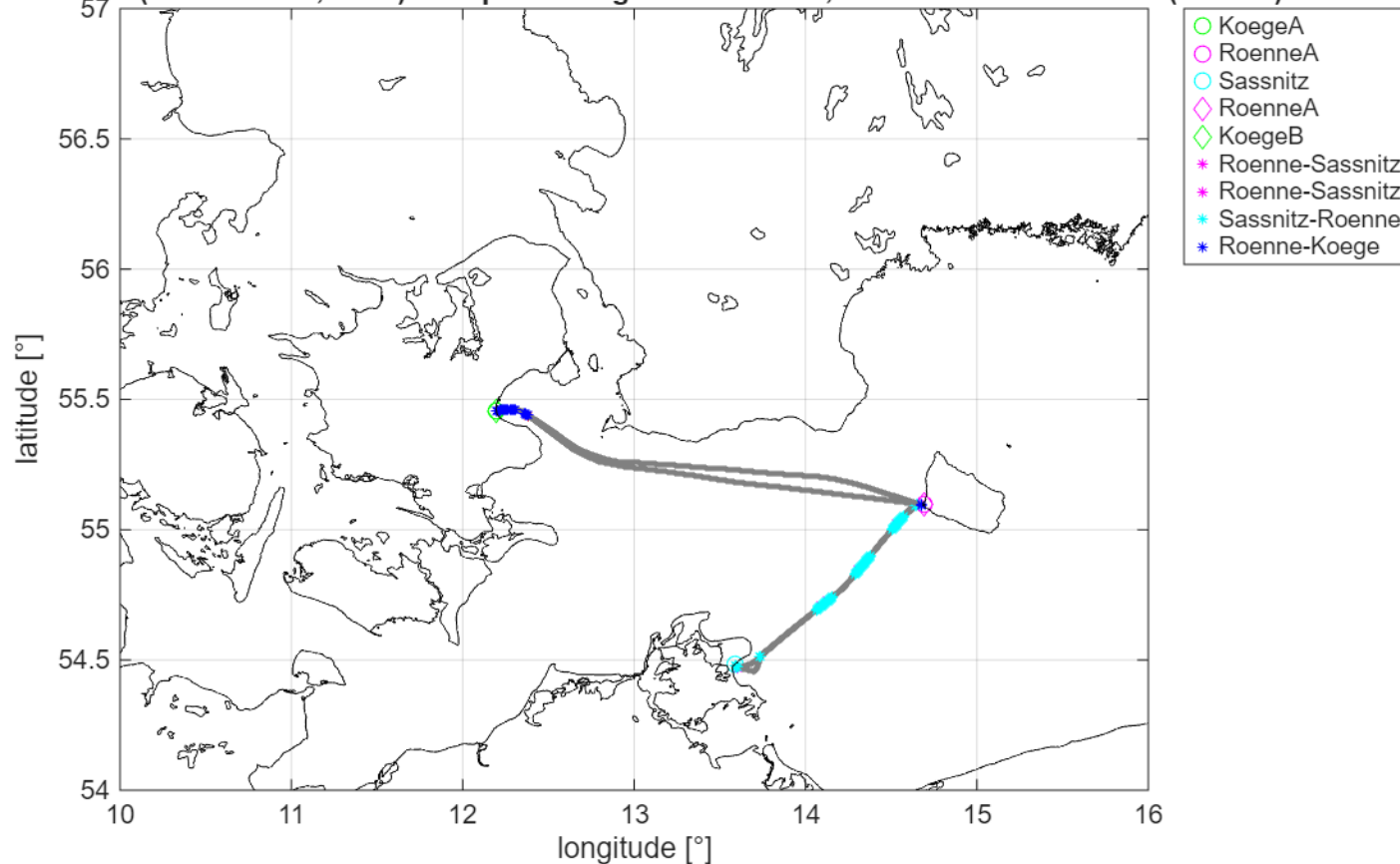
AT1A-test (March 10-11, 2026): Coupled Navigation Records, threshold distance:20 (meters)



coupled records: distance threshold 20 m

Test of AT1A marine gravimeter onboard a commercial ferry

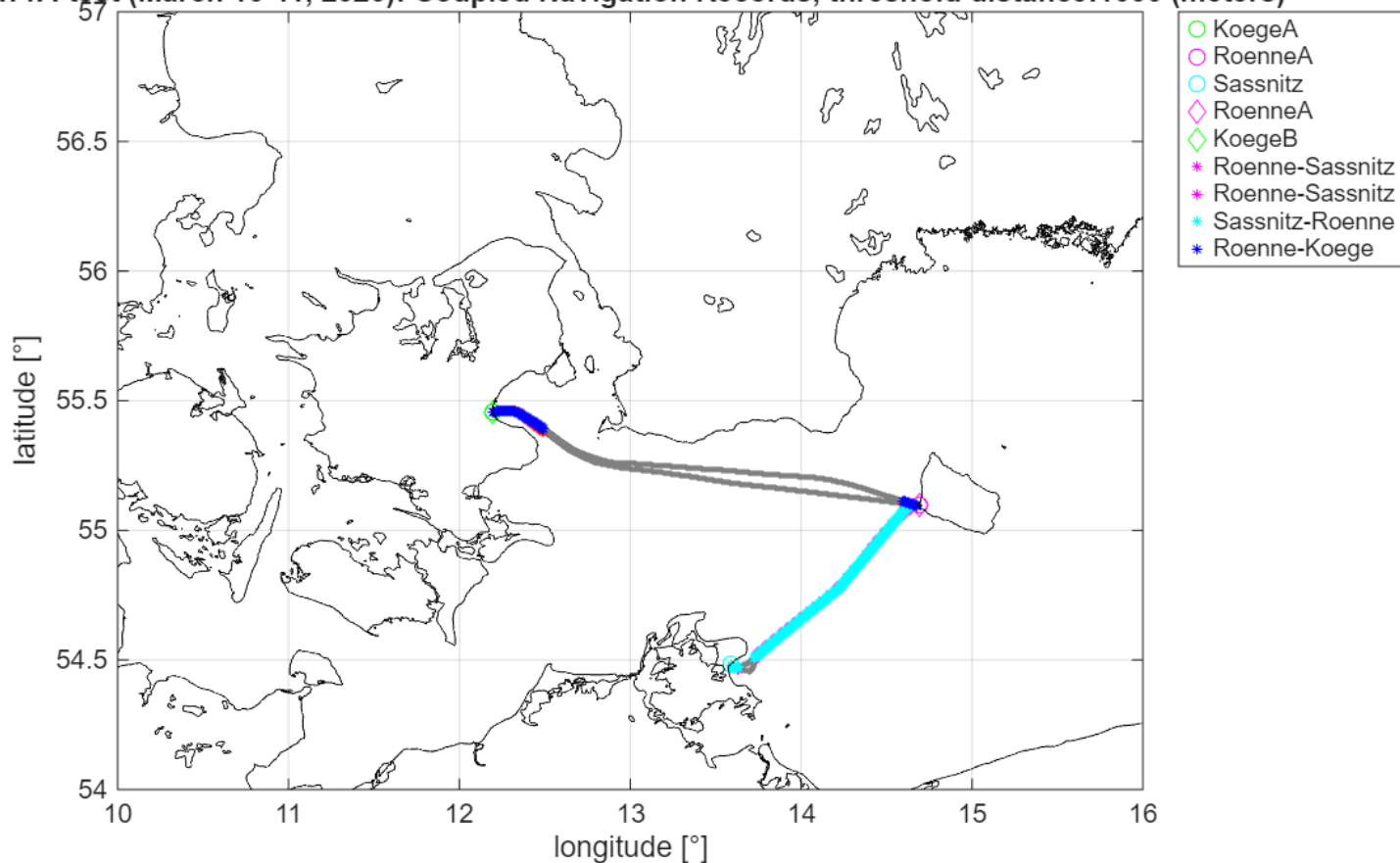
AT1A-test (March 10-11, 2026): Coupled Navigation Records, threshold distance:100 (meters)



coupled records: distance threshold 100 m

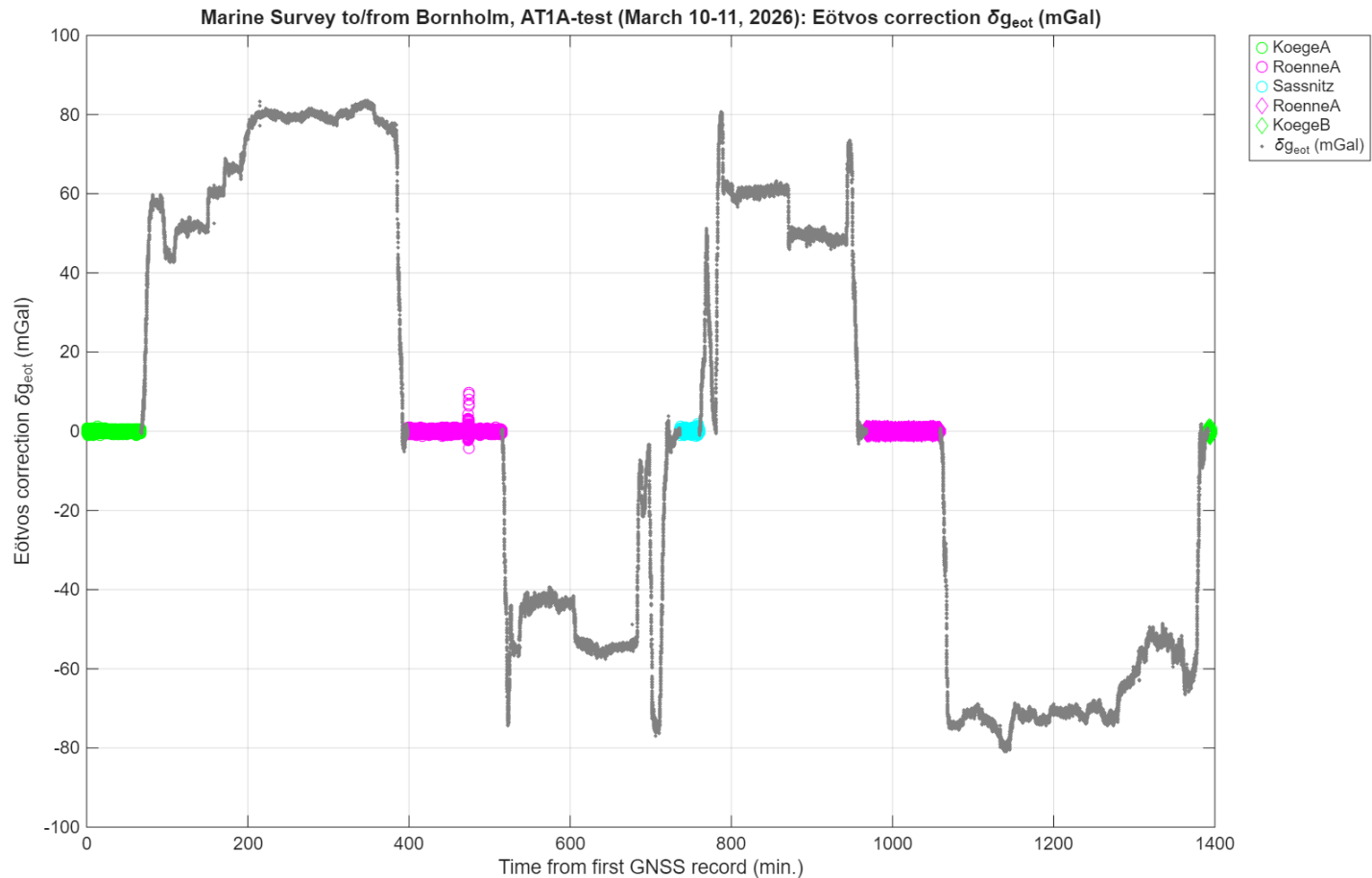
Test of AT1A marine gravimeter onboard a commercial ferry

AT1A-test (March 10-11, 2026): Coupled Navigation Records, threshold distance:1000 (meters)



coupled records: distance threshold 1000 m

Test of AT1A marine gravimeter onboard a commercial ferry



Eötvös correction from GNSS navigation data

Test of AT1A marine gravimeter onboard a commercial ferry

The possibly “controversial part”

Start with 2D pFA equation:

$$\Delta g = \Delta g_{ref} + \alpha \left[\left(\tilde{r} - c_g \right) - r_{ref} \right] - \left(\gamma_0 - \gamma_{0,ref} \right)$$

Rework it slightly:

$$\Delta g = \left(\Delta g_{ref} - \alpha \cdot r_{ref} \right) + \alpha \left(\tilde{r} - c_g \right) - \left(\gamma_0 - \gamma_{0,ref} \right)$$

To get a “bias”:

$$\Delta g = b + \alpha \left(\tilde{r} - c_g \right) - \left(\gamma_0 - \gamma_{0,ref} \right), \quad b = \Delta g_{ref} - \alpha \cdot r_{ref}$$

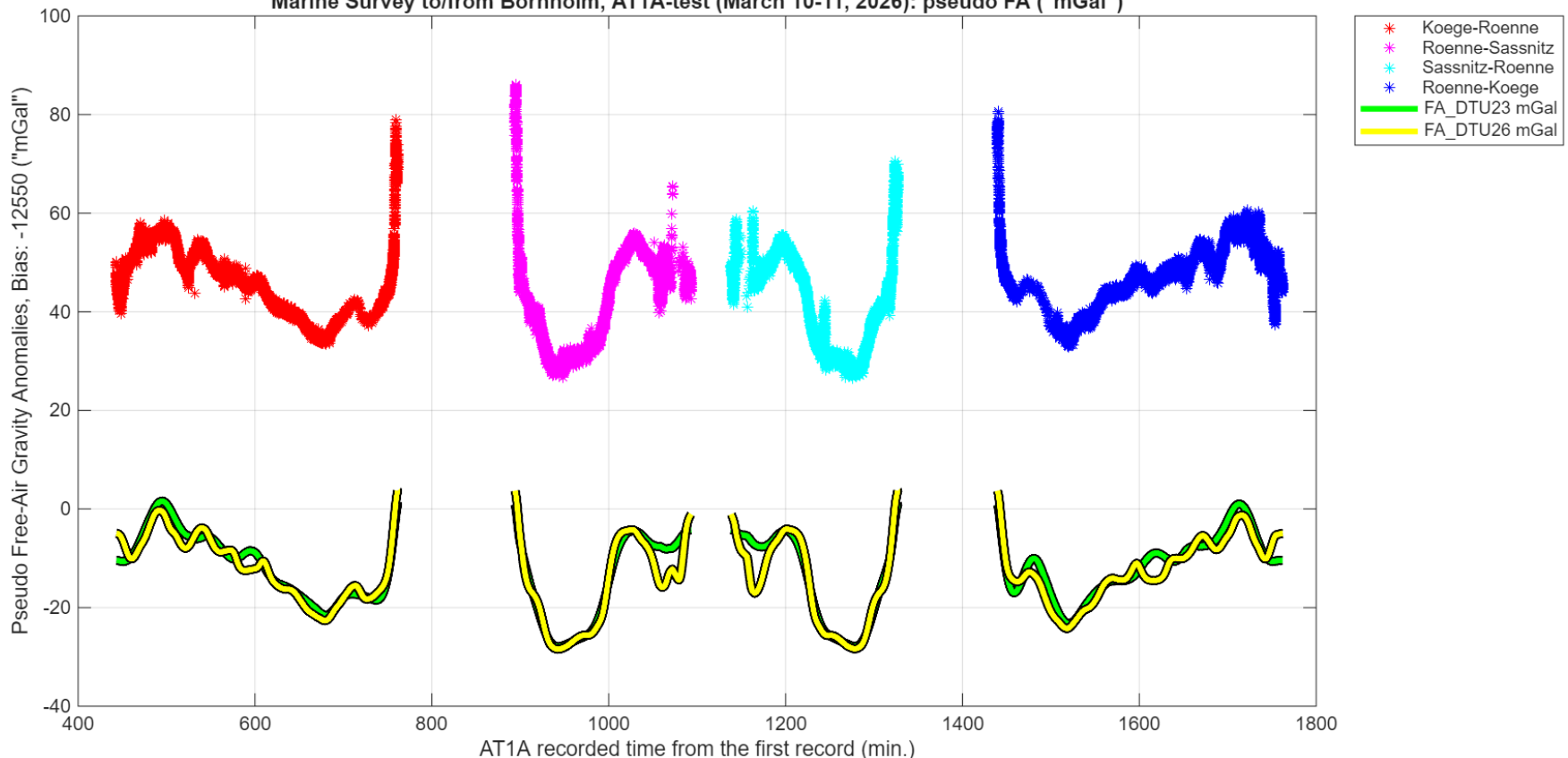
$$\alpha = 1, \quad \gamma_{0,ref} = \gamma_{0,legA} \left(t_{start} \right)$$

Test of AT1A marine gravimeter onboard a commercial ferry

$$b \approx -12550(CU)$$

correction c_g : “filtering”+Eötvös

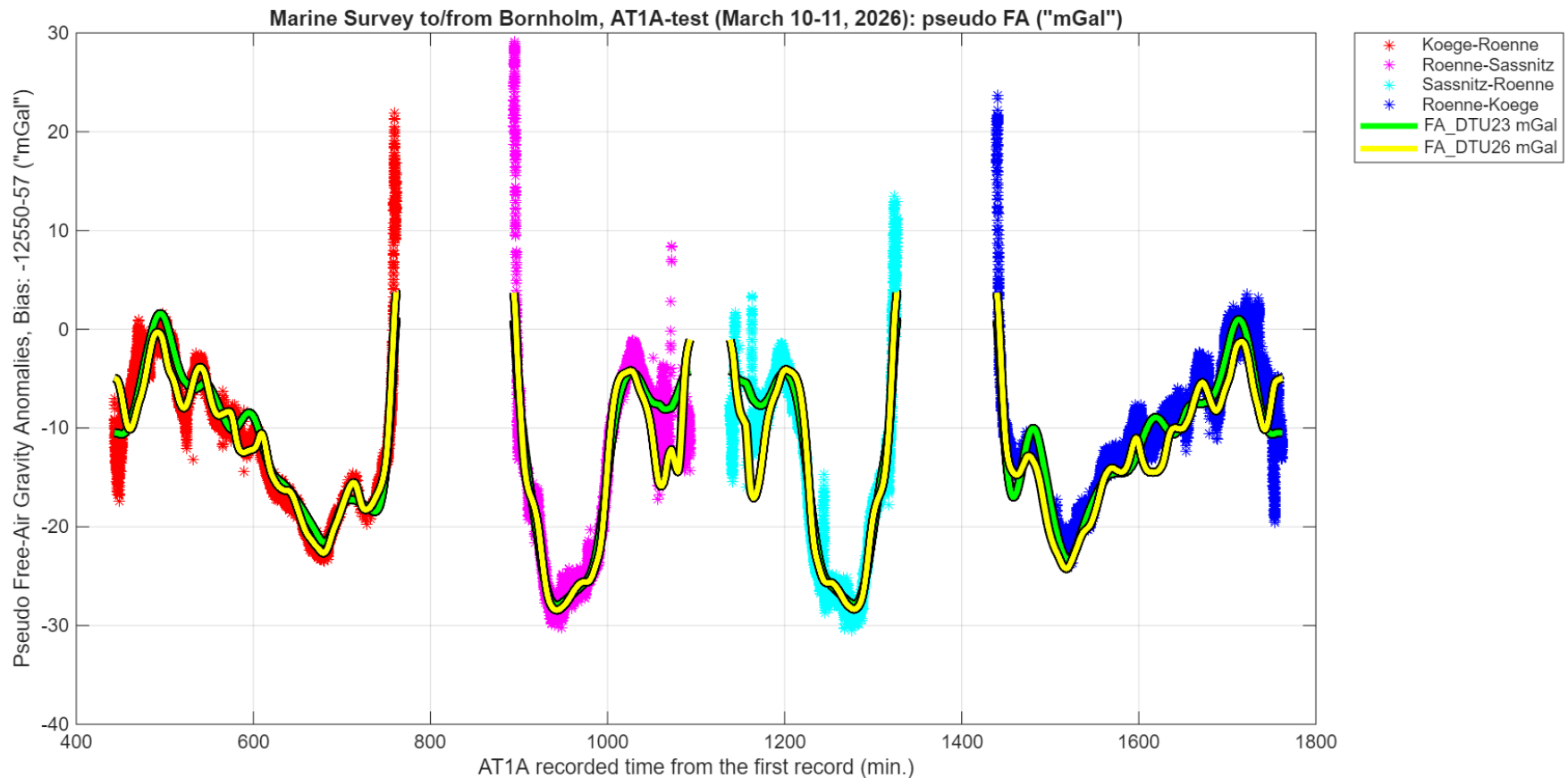
Marine Survey to/from Bornholm, AT1A-test (March 10-11, 2026): pseudo FA (“mGal”)



$$\Delta g = b + \alpha(\tilde{r} - c_g) - (\gamma_0 - \gamma_{0,ref})$$

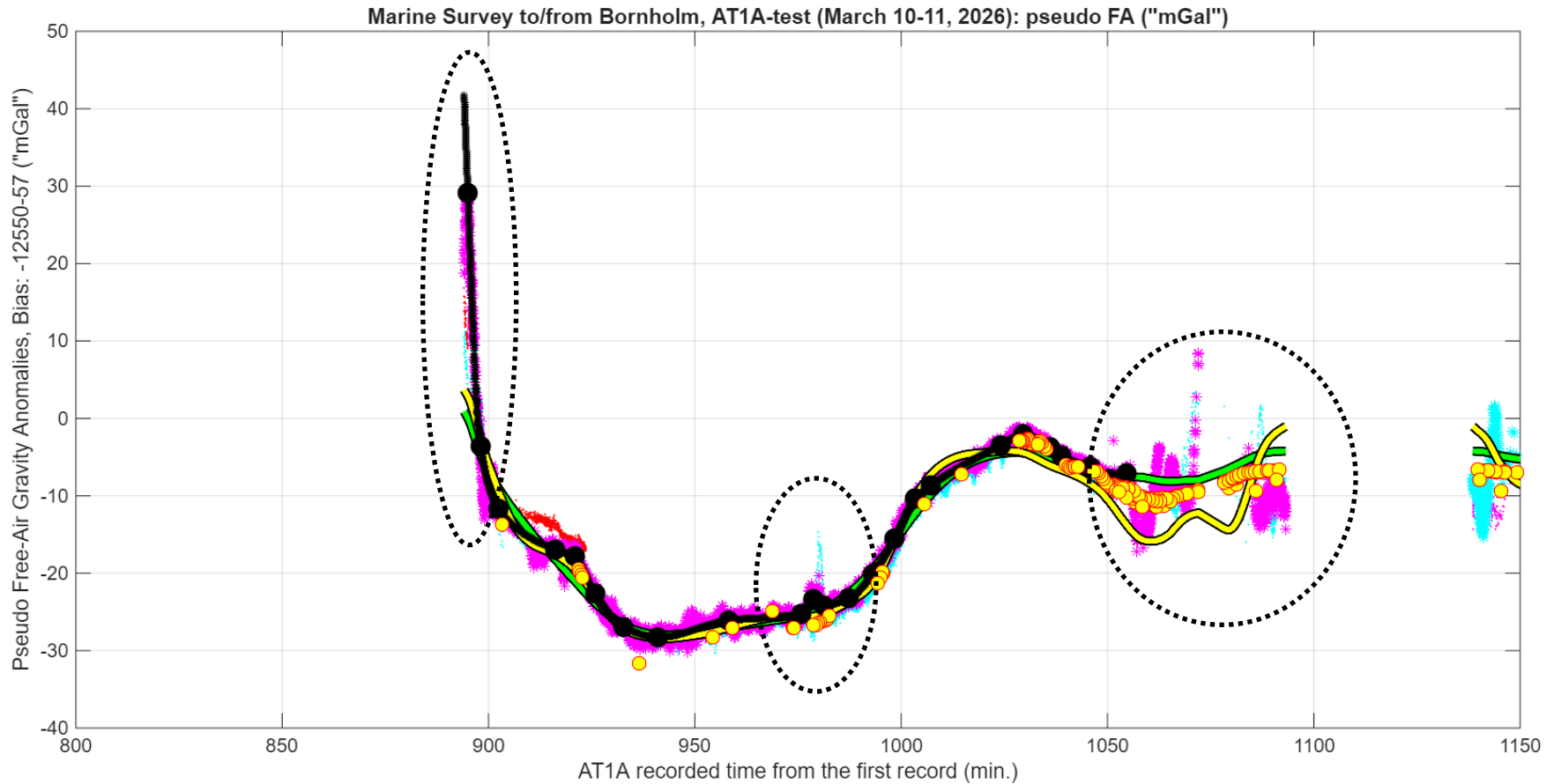
Test of AT1A marine gravimeter onboard a commercial ferry

$b \approx -12550 - 57 = -12607 (CU)$
correction c_g : “filtering”+Eötvös



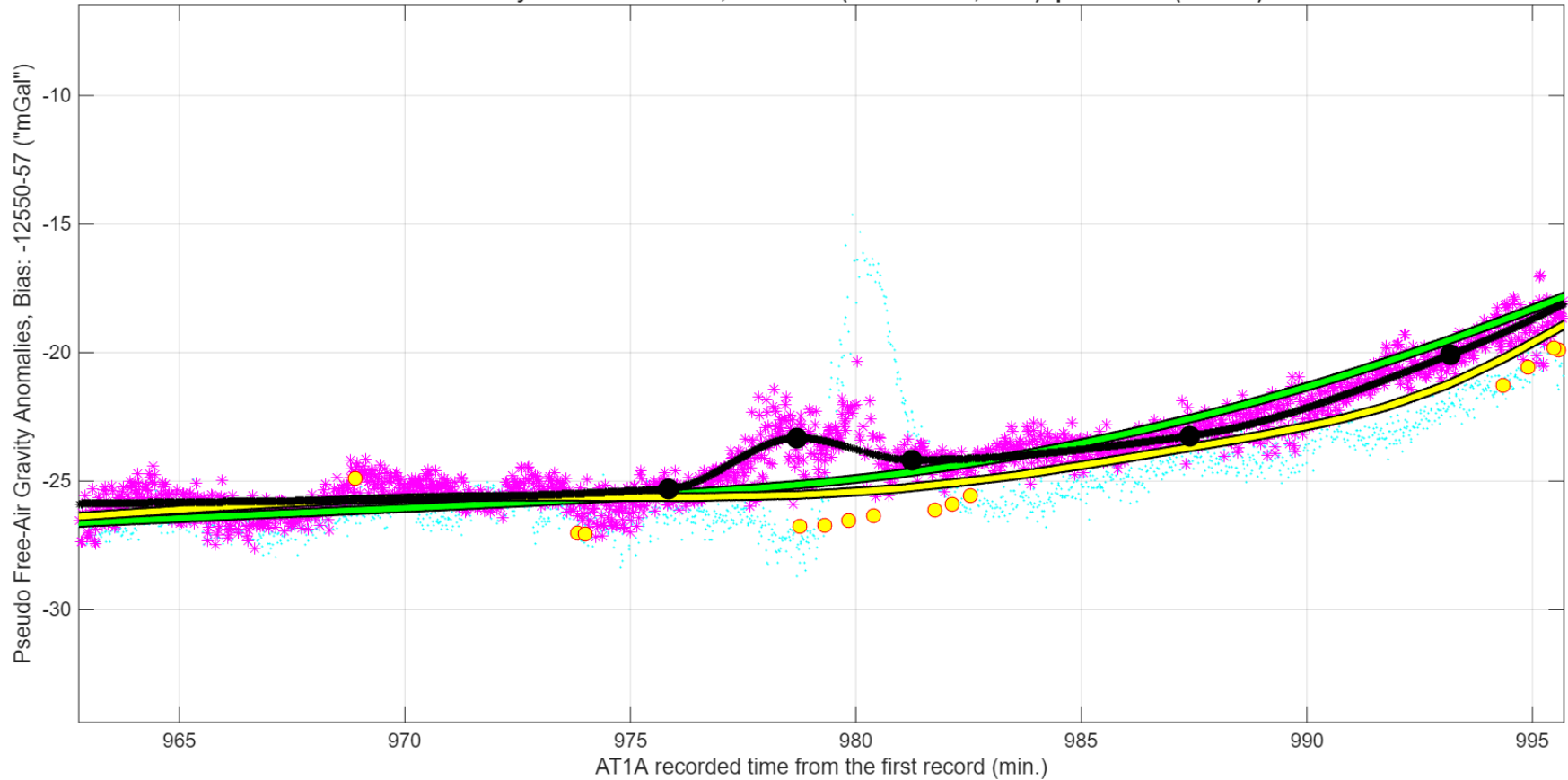
$$\Delta g = b + \alpha \left(\tilde{r} - c_g \right) - \left(\gamma_0 - \gamma_{0,ref} \right)$$

Test of AT1A marine gravimeter onboard a commercial ferry



Test of AT1A marine gravimeter onboard a commercial ferry

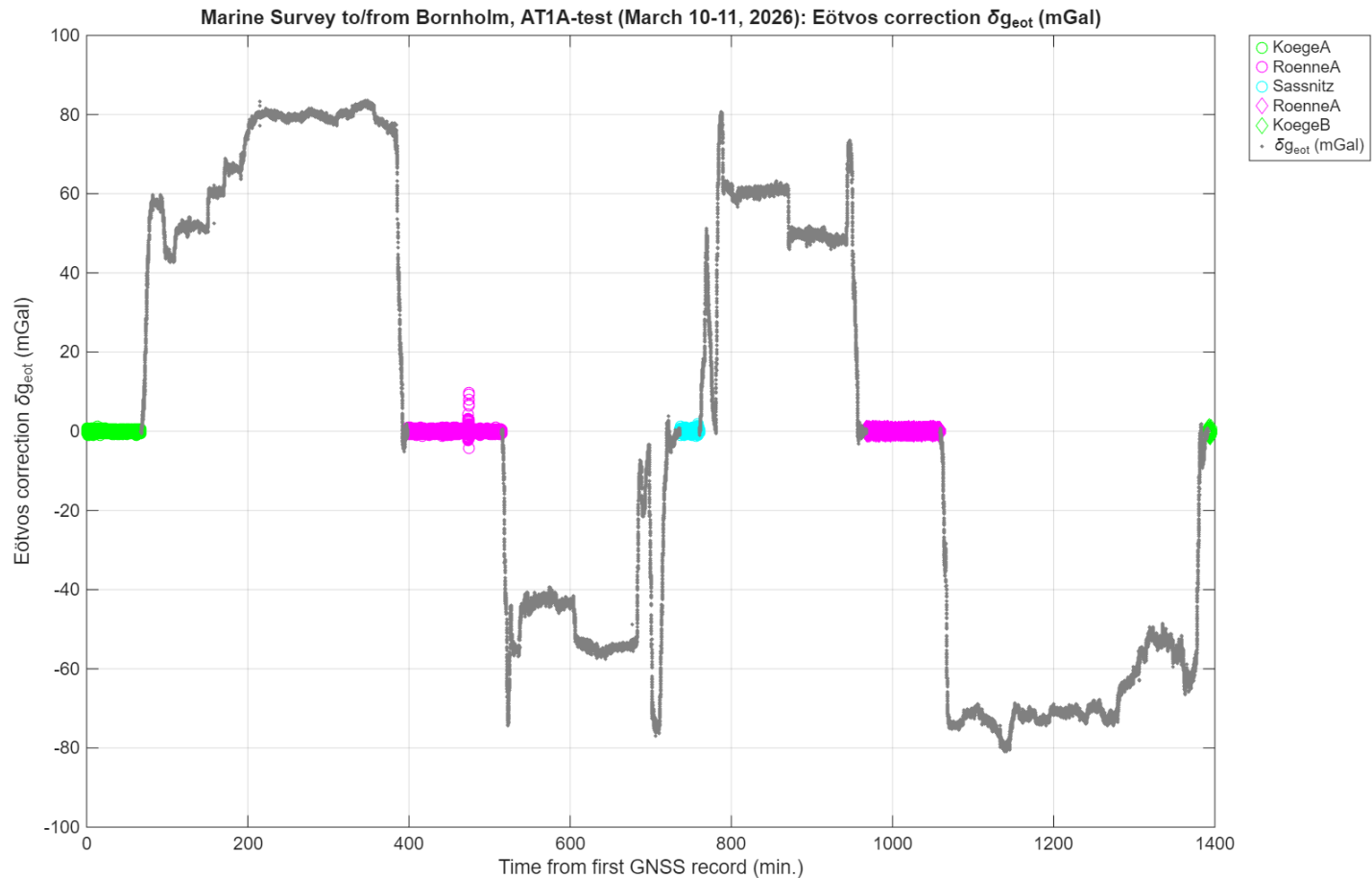
Marine Survey to/from Bornholm, AT1A-test (March 10-11, 2026): pseudo FA ("mGal")



Johan and Dagmar model interpretation detail LegB:

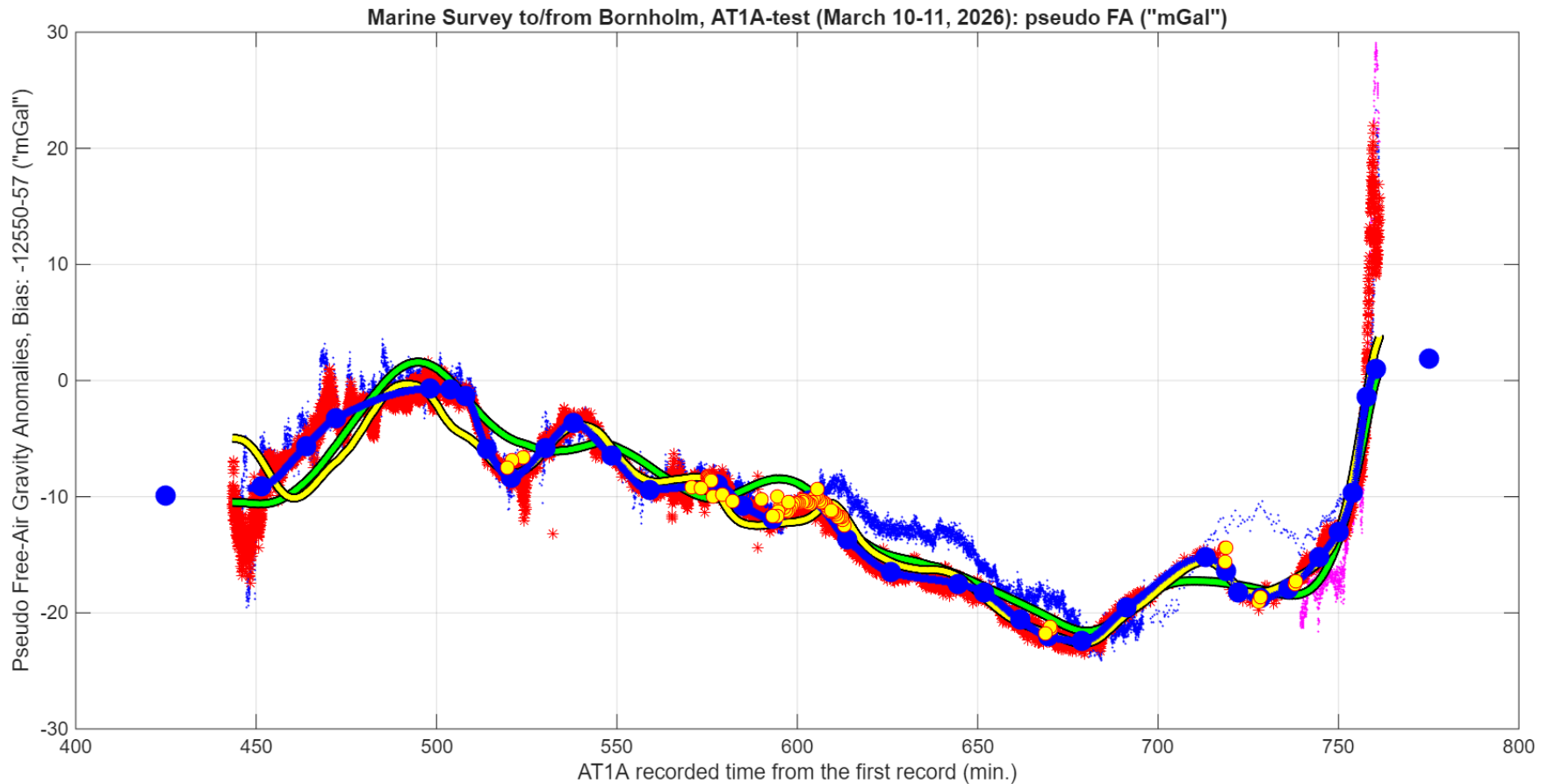
RønneA-SassnitzA

Test of AT1A marine gravimeter onboard a commercial ferry

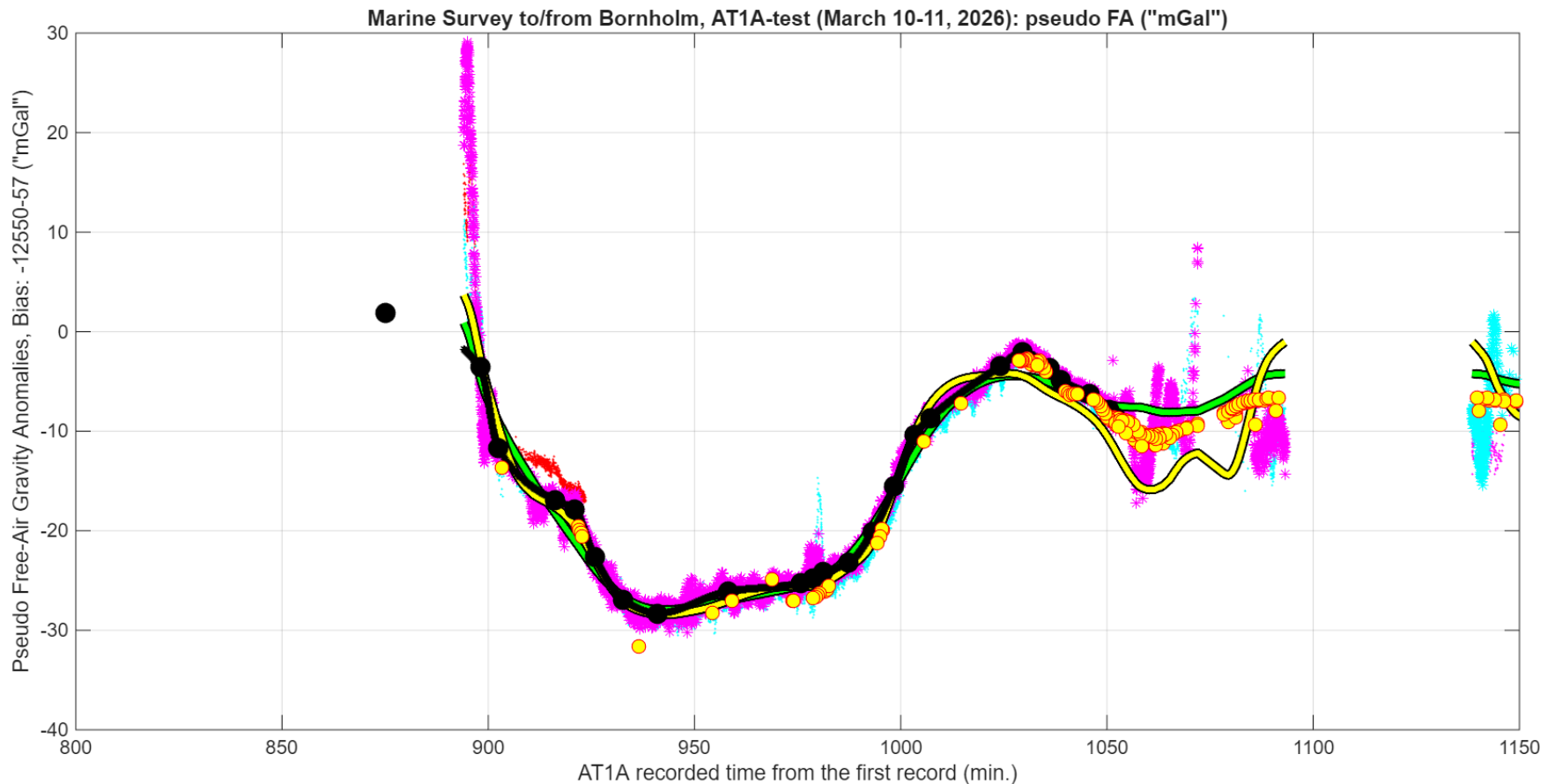


Eötvös correction from GNSS navigation data

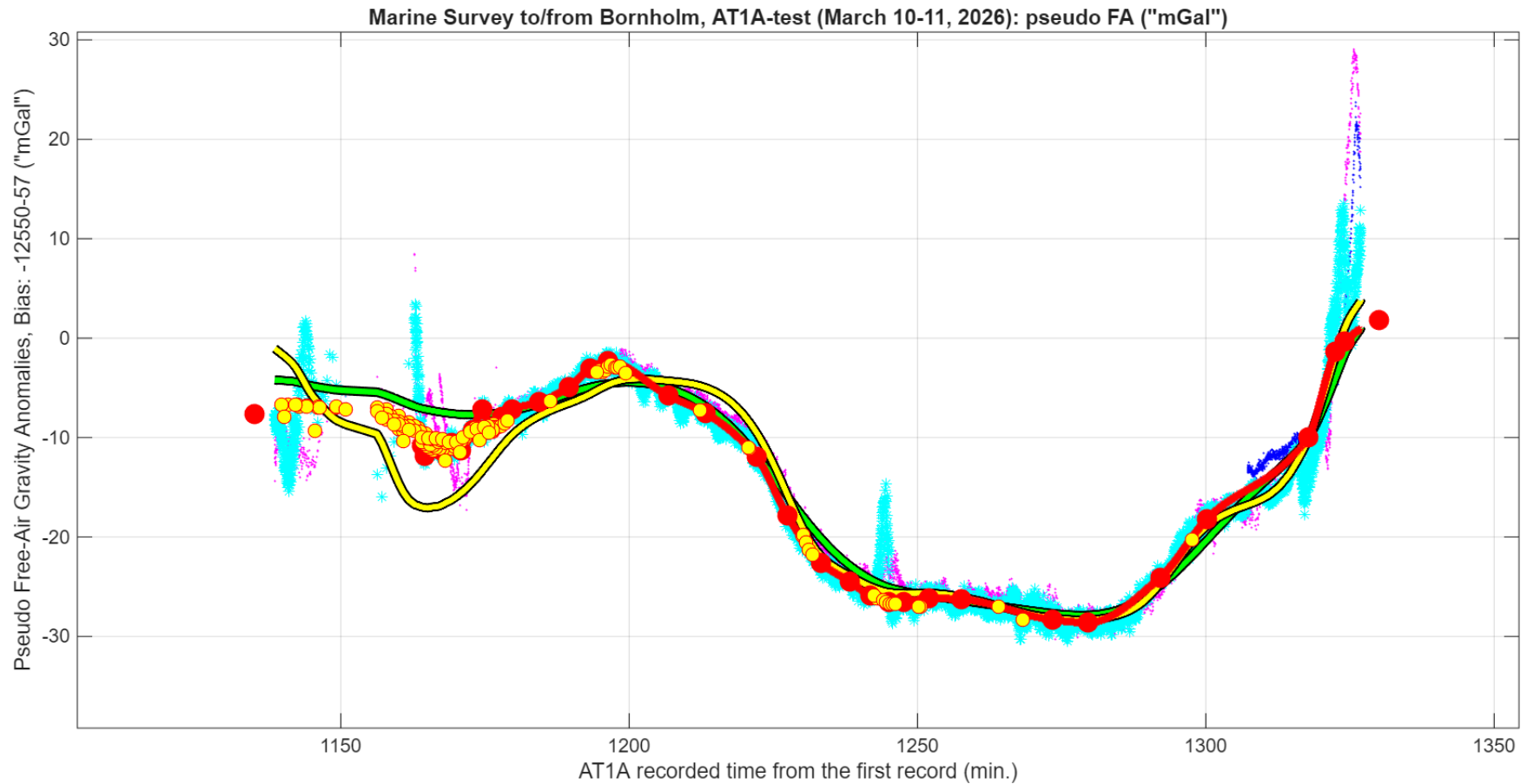
Test of AT1A marine gravimeter onboard a commercial ferry



Test of AT1A marine gravimeter onboard a commercial ferry

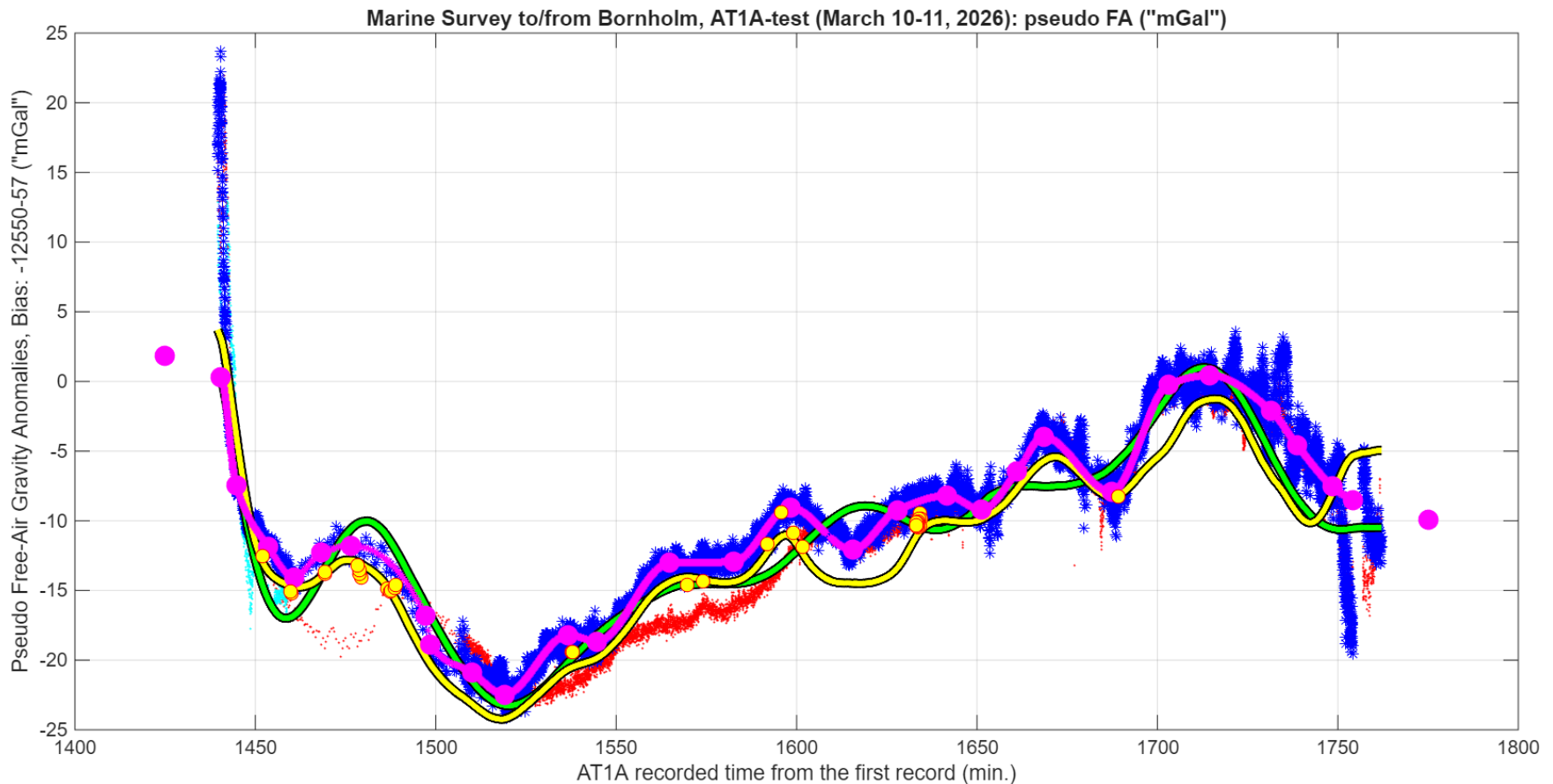


Test of AT1A marine gravimeter onboard a commercial ferry



Johan and Dagmar model LegC: SassnitzA-RønneB

Test of AT1A marine gravimeter onboard a commercial ferry



Gabriel model LegD: RønneB-KøgeB



Marine gravimetry: Takeaway

- We show that even weakly controlled opportunity marine gravity surveys can yield high-quality results.
- In modelling we focus on marine areas and to a lesser degree on control measurements on land.
- Free-air gravity anomalies (FA) from altimetry, such as DTU23 and DTU26, are used to establish “the constant level” of the results by “matching the signals”.
- The general trend of survey results look much like the one for DTU FA models but seem to contain more details. The details are confirmed on parallel lines (proximity principle) and by 3D marine surveys.

Marine gravimetry: Takeaway (continue)

- Advice to modellers: Keep the original gravity and navigation data for possible “revisiting”!
- FA models from satellite altimetry are good, but we see more details in marine gravimetry – if processed correctly.

Thank you!