Improving Platform Magnetometer Measurements Using Physics-informed Neural Networks

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Swarm 10 Year Anniversary & Science Conference 2024

Motivation

- Calibration of platform magnetometer readings
  - GOCE (2009-2013), GRACE-FO (2018-ongoing)
  - Non-dedicated satellites carrying platform magnetometers
  - Calibrated datasets increase the spatiotemporal coverage
    - MLT, altitude

- Enlarging datasets of magnetic space-based measurements
  - interesting to space physics and geomagnetism

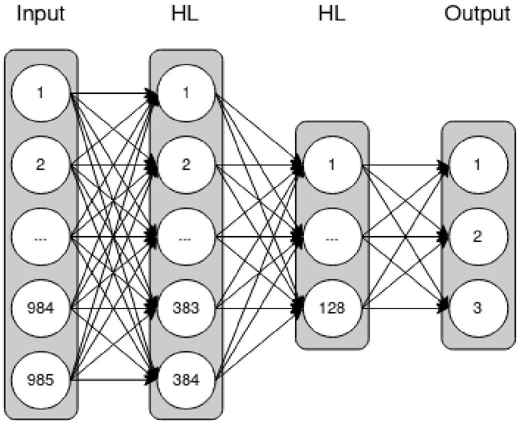
Problem

- Platform magnetometers are only roughly calibrated
  - Part of attitude and orbit control system (AOCS)
  - Typical residuals of 500nT - 1000nT (compared to CHAOS-7)

- Our goal: post-launch / in-situ calibration
  - Adjusting artificial disturbances
  - As much information as possible
  - Enable scientific application of the measurements
    - Below 10nT

First Approach

- Applying Machine Learning with long preprocessing pipeline
  - Feed-forward neural network
  - Architecture found through Hyperparameter Optimization
- Inputs include magnetometer measurements, electric currents, temperatures, magnetorquer activations, thrusters, telemetry data like status variables, flags, and others
- The reference model consists of the CHAOS-7 model
  - Empiric model supported by Swarm mission
- Further details in publications (Styp-Rekowski et al. & Michaelis et al.)



New Developments

- Introduce physics-informed neural networks
- Combine the CHAOS-7 and AMPS model for the reference model

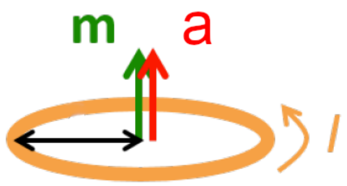
Next Step: Physics-Informed NN

- Make the calibration ’physically more correct’
  - Previously strictly data/statistics driven
- Constraint the NN to follow certain physical laws
  - Electric currents may only be used in their physical meaning
  - Ensure more meaningful results

- Improve modeling and calibration of electric current-induced artificial magnetic fields

Physics-informed NN

- Biot-Savart law for dipoles
  - $\vec{B}(\vec{r},\vec{m}) = \frac{\mu_0}{4\pi}\left(\frac{3\vec{r}(\vec{m}*\vec{r})}{|\vec{r}|^5} - \frac{\vec{m}}{|\vec{r}|^3}\right)$
  - $\vec{m} = IN\vec{a}$ (Dipole moment)

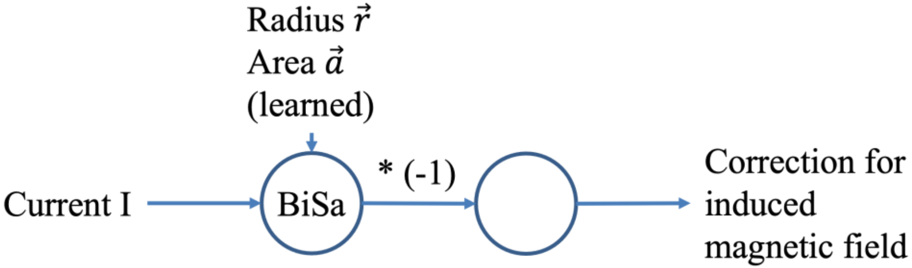


Source: https://users.physics.ox.ac.uk/~harnew/lectures/EM-lecture12-handout-abridged.pdf

- Parameters $\vec{r}$ and $\vec{a}$ will be learned
  - Position relative to the inducing current at origin
- Produces a 3dimensional output corresponding to the magnetic field induced by the electric current I
- Assumption: The artificial disturbance can be approximated by a dipole

Biot-Savart Neuron

- Biot-Savart (BiSa) Neuron
- Input is an electric current
- Produces 3-dimensional output
  - Representing the induced magnetic field
- Output is subtracted from calibration result to correct for this induced artificial disturbance



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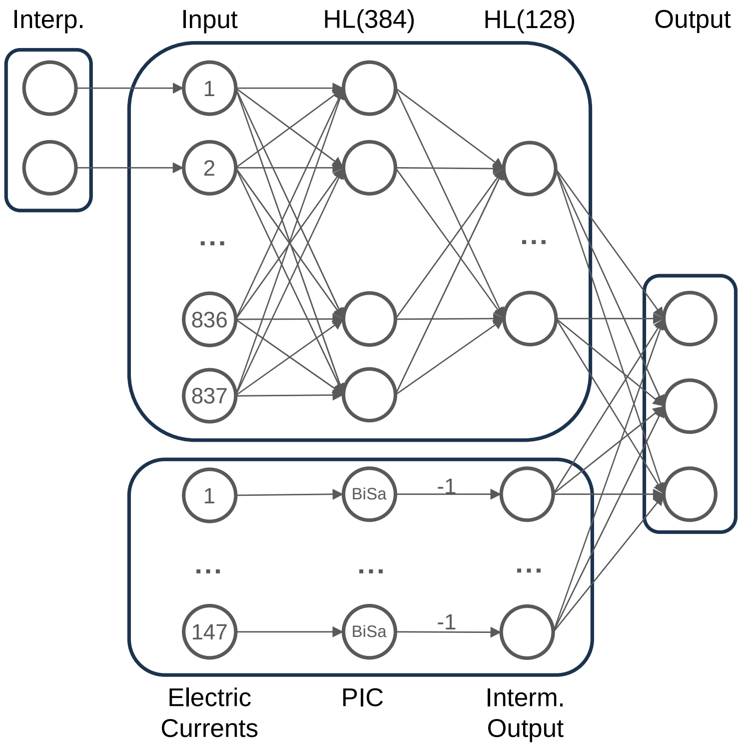
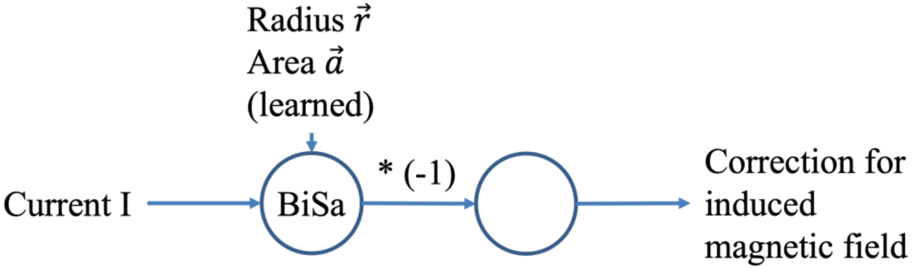
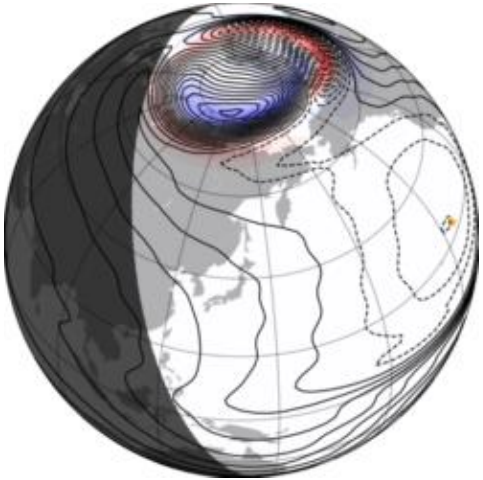




AMPS Model

- Additionally, used a second model in the ground truth
  - Average magnetic field and polar current system (AMPS) (Laundal et al.)
- Combine CHAOS-7 and AMPS models
  - Ground truth now a composition of models

- Large-scale, average structures of FACs
  - Helps to model mean values



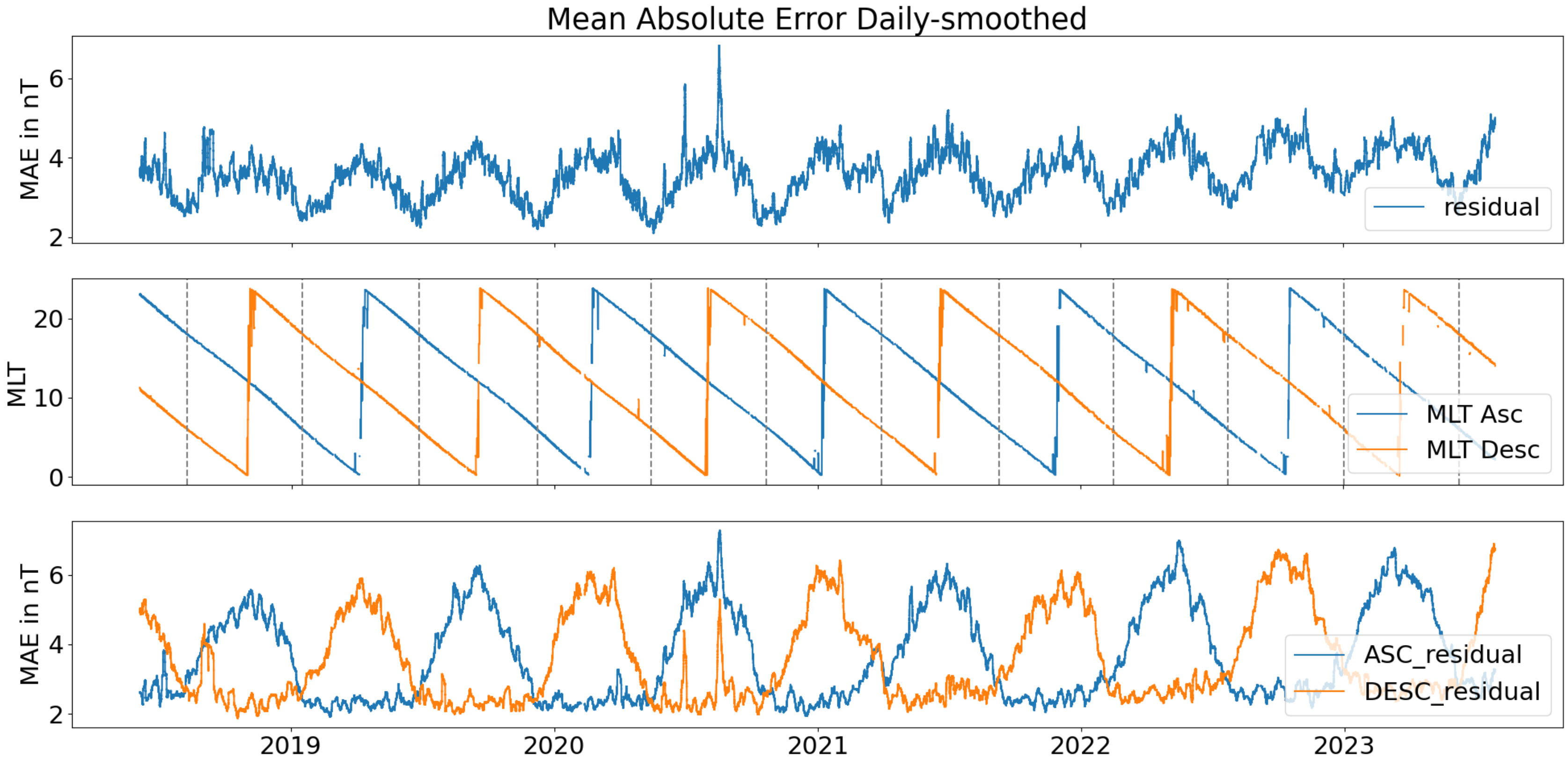
Source: https://klaundal.w.uib.no/files/2017/09/cropped-cropped-130.png

Results

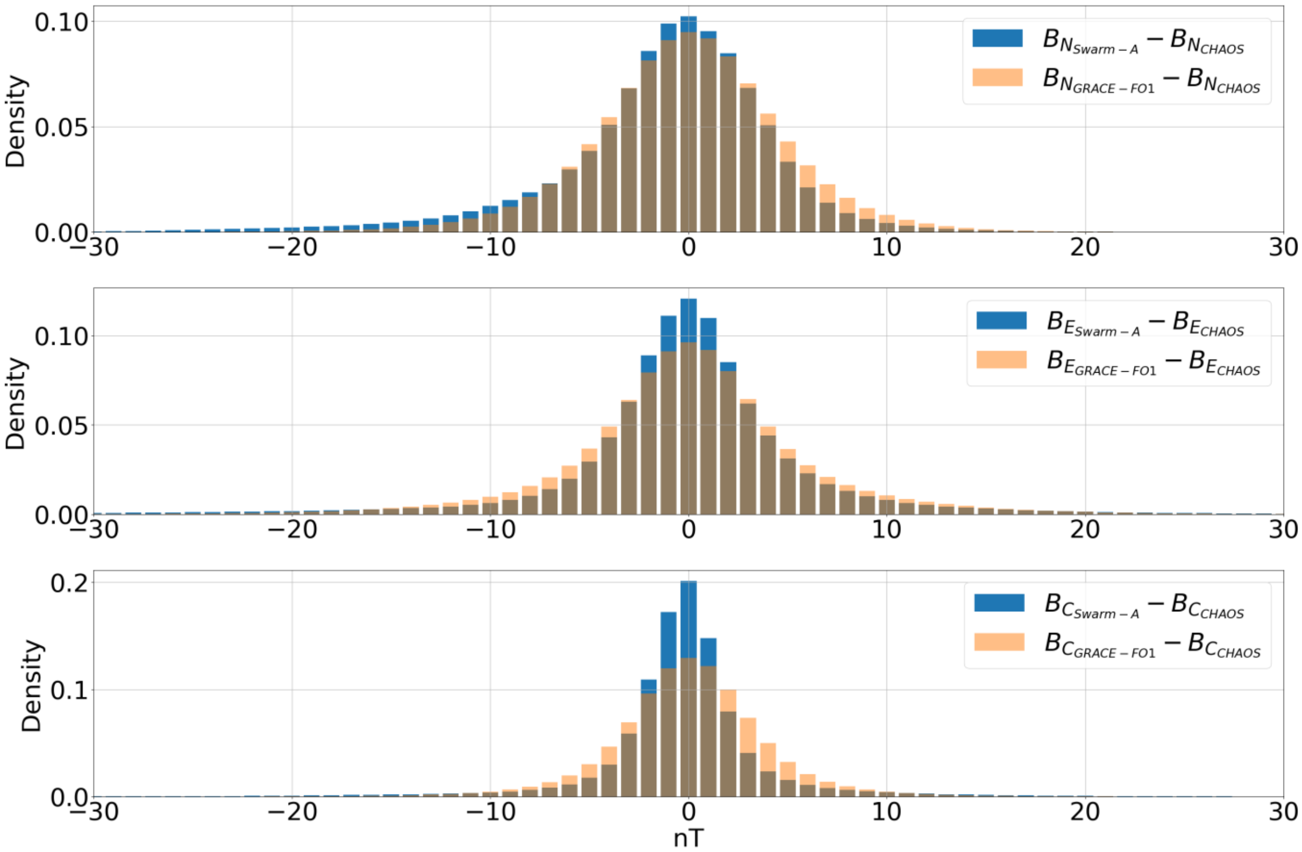
- GOCE: Low residual of 6.6nT for low- and mid-latitudes compared to the reference model

- GRACE-FO: Low residual of 3.7nT for low- and mid-latitudes compared to the reference model

Result - GRACE-FO1



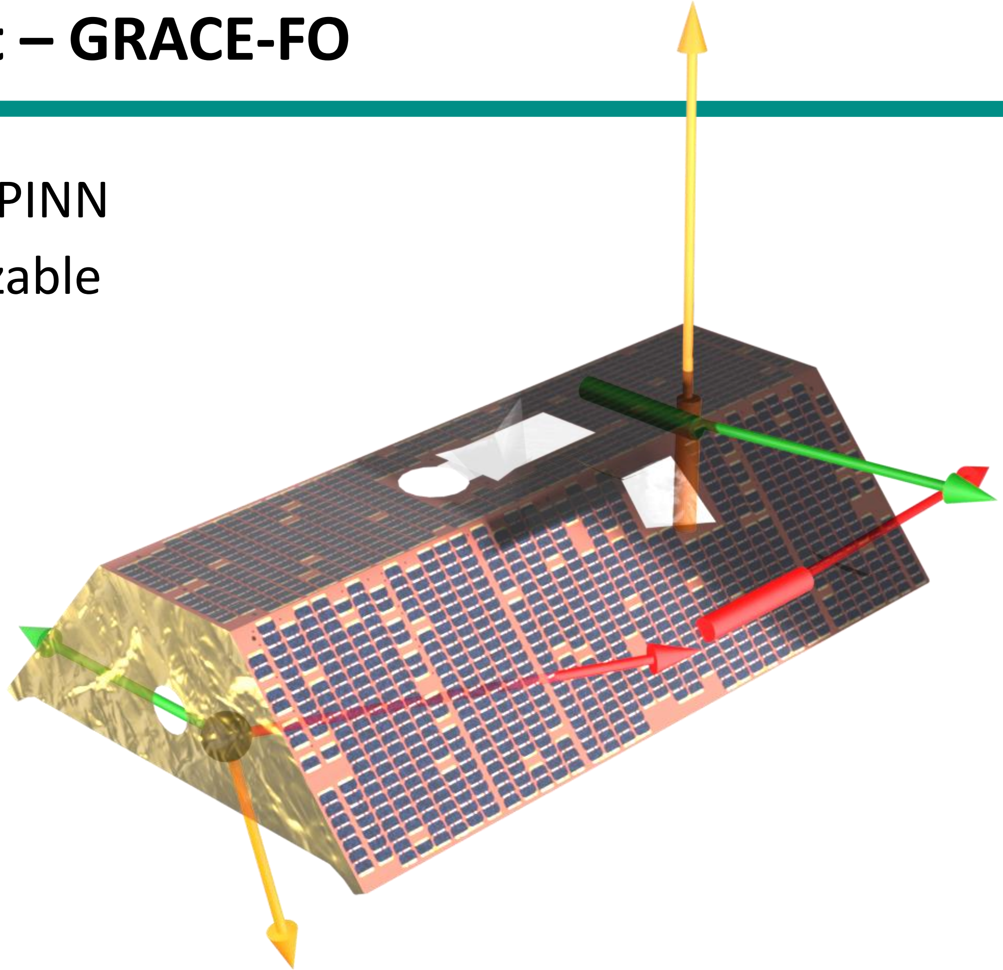
Result - GRACE-FO1 vs. Swarm-A



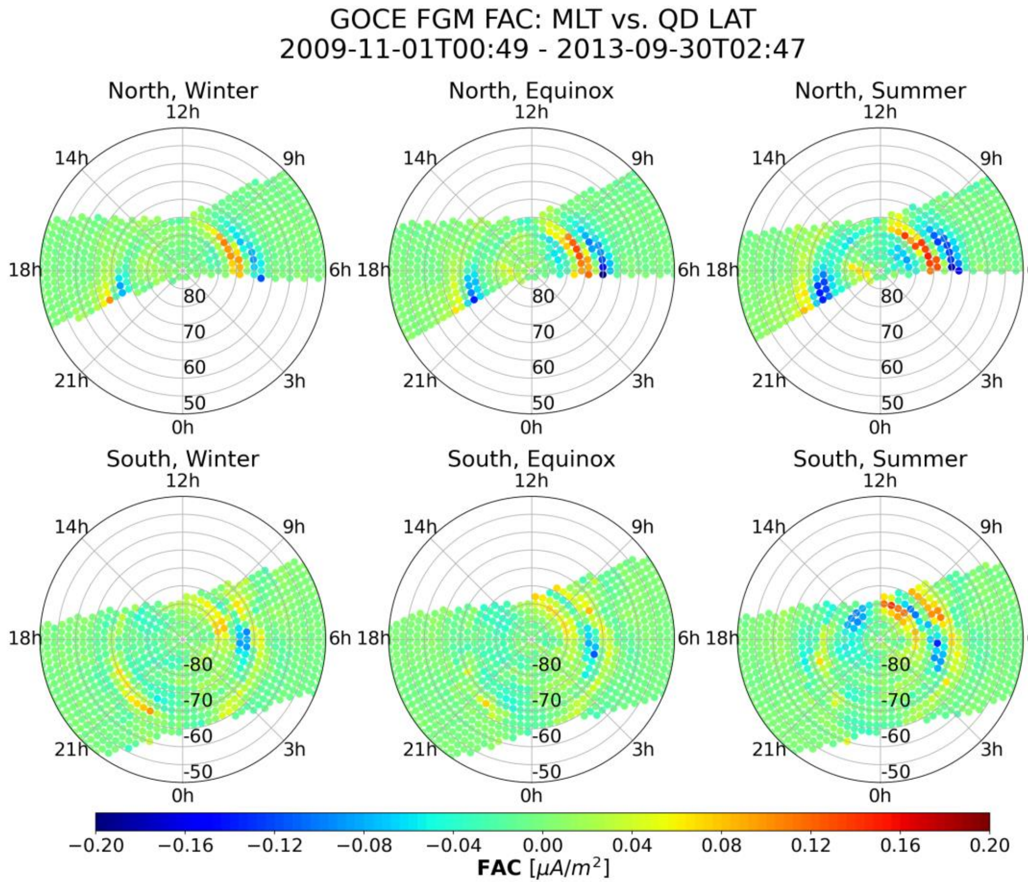
Result – GRACE-FO

- Analyze the 'black box' of the PINN
- Biot-Savart neurons are analyzable
  - Learned parameters $\vec{r}$ and $\vec{a}$

- Magnetorquers
  - Influence on PlatMag
  - Dipole Moment

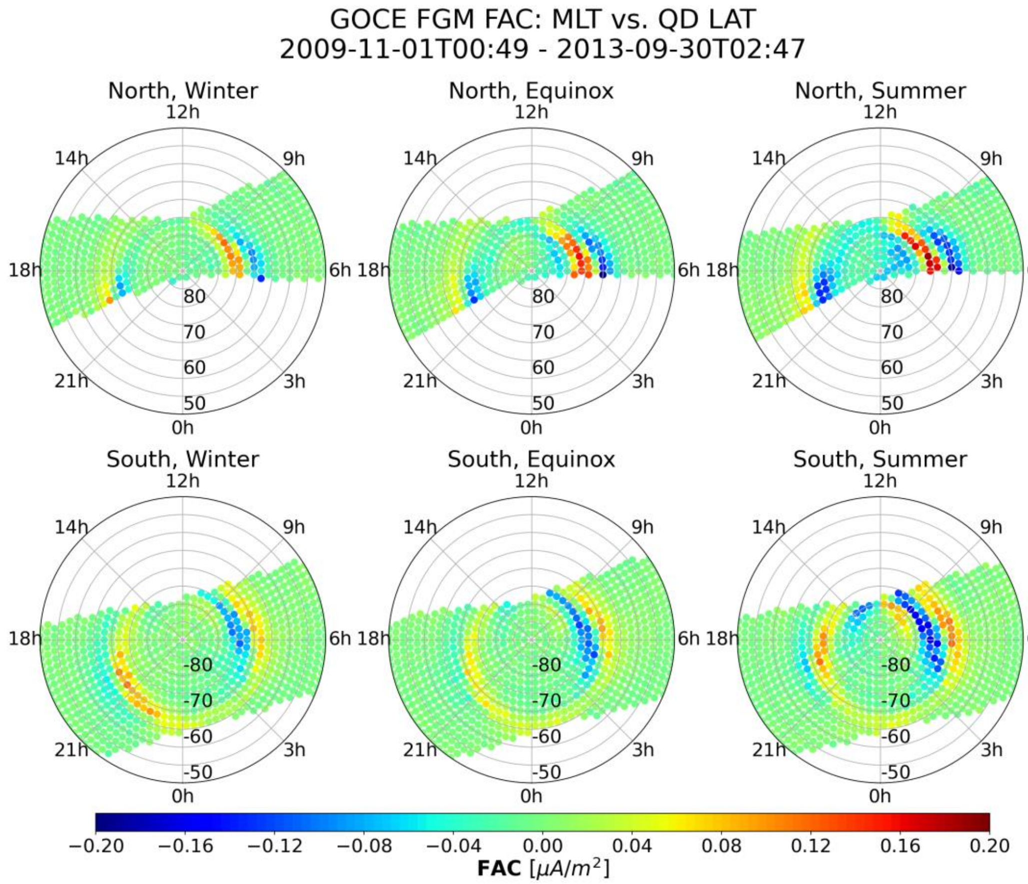


Result - GOCE



GOCE FGM FAC: MLT vs. QD LAT
2009-11-01T00:49 - 2013-09-30T02:47
North, Winter
North, Equinox
North, Summer
South, Winter
South, Equinox
South, Summer
12h
14h
9h
18h
6h
21h
3h
0h
80
70
60
50
-80
-70
-60
-50
−0.20
−0.16
−0.12
−0.08
−0.04
0.00
0.04
0.08
0.12
0.16
0.20
FAC [μA/m²]

Result - GOCE



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FAC [μA/m2]

Conclusion

- More evaluation to assess the data quality
- **Automatic calibration of platform magnetometers**
  - Introduced the PINN
    - GOCE: residual of 6.6nT, GRACE-FO: residual of 3.7nT
  - In-situ determination of dipole positions of the satellite system
  - Included large-scale FAC into the reference model
- Preprint published and revision handed in (Styp-Rekowski et al., 2024)

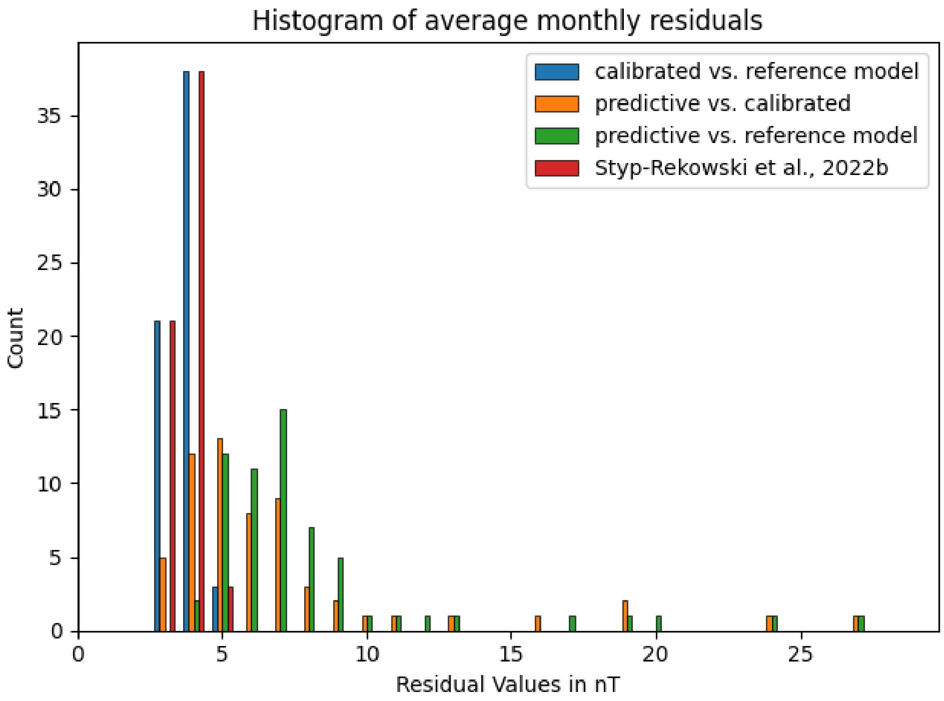
- **Current datasets are available in a Swarm-like format**
  - VirES Client
  - https://isdc.gfz-potsdam.de/platform-magnetometer/
  - GOCE: https://doi.org/10.5880/GFZ.2.3.2022.002
  - GRACE-FO: https://doi.org/10.5880/GFZ.2.3.2023.001

References

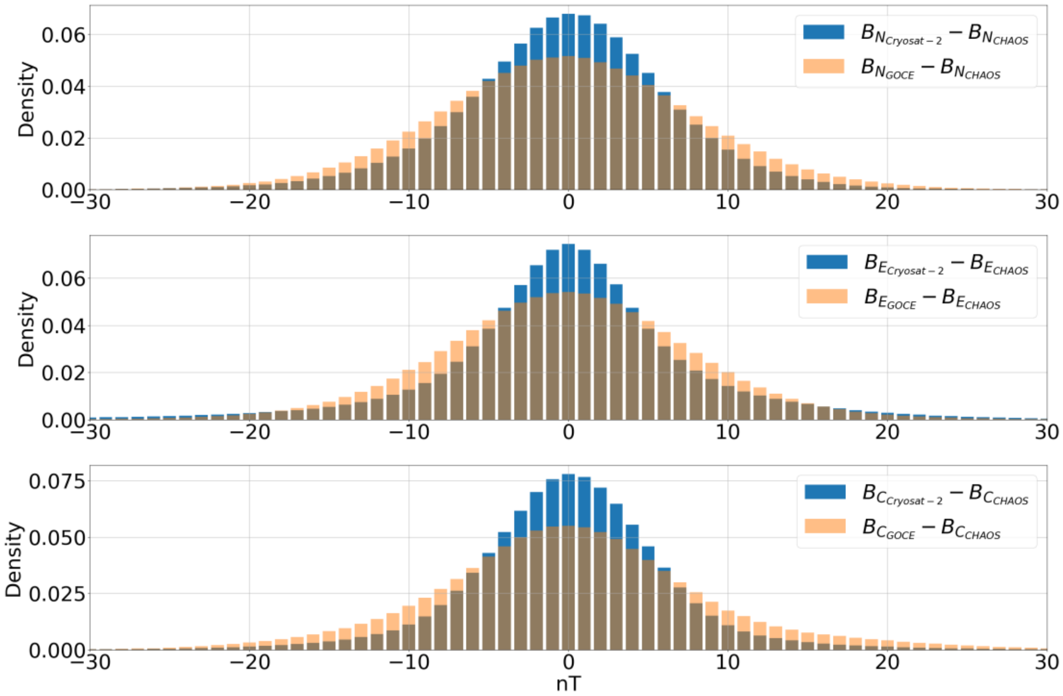
- K. Styp-Rekowski, I. Michaelis, C. Stolle, J. Baerenzung, M. Korte, and O. Kao (2022). Machine learning-based calibration of the GOCE satellite platform magnetometers. Earth Planets Space 74, 138 (2022). https://doi.org/10.1186/s40623-022-01695-2
- I. Michaelis, K. Styp-Rekowski, J. Rauberg, C. Stolle, and M. Korte. Geomagnetic data from the GOCE satellite mission. Earth Planets Space 74, 135 (2022). https://doi.org/10.1186/s40623-022-01691-6
- Laundal, K. M., Finlay, C. C., Olsen, N. & Reistad, J. P. (2018), Solar wind and seasonal influence on ionospheric currents from Swarm and CHAMP measurements, Journal of Geophysical Research - Space Physics. https://doi.org/10.1029/2018JA025387
- Kevin Styp-Rekowski, Ingo Michaelis, Monika Korte, et al. Physics-informed Neural Networks for the Improvement of Platform Magnetometer Measurements. Authorea.

Backup

Previous Month Calibration (towards FAST data)



GOCE vs. CryoSat-2



Conjunctions: GRACE-FO1 with Swarm-A (over 5 years)