EGU 2023 G5 – GEODETIC MONITORING OF THE ATMOSPHERE

G5.1 Ionosphere, thermosphere and space weather: monitoring and modeling

ZARM thermospheric neutral density solution from GRACE data: Approach, validation and comparison

Florian Wöske, Benny Rievers

Sharing is encouraged

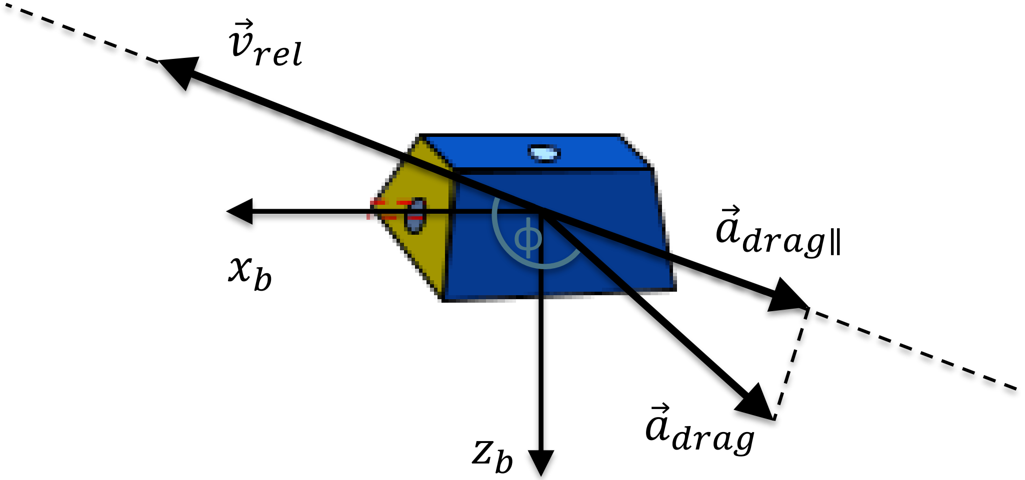
Vienna, 28. April 2023

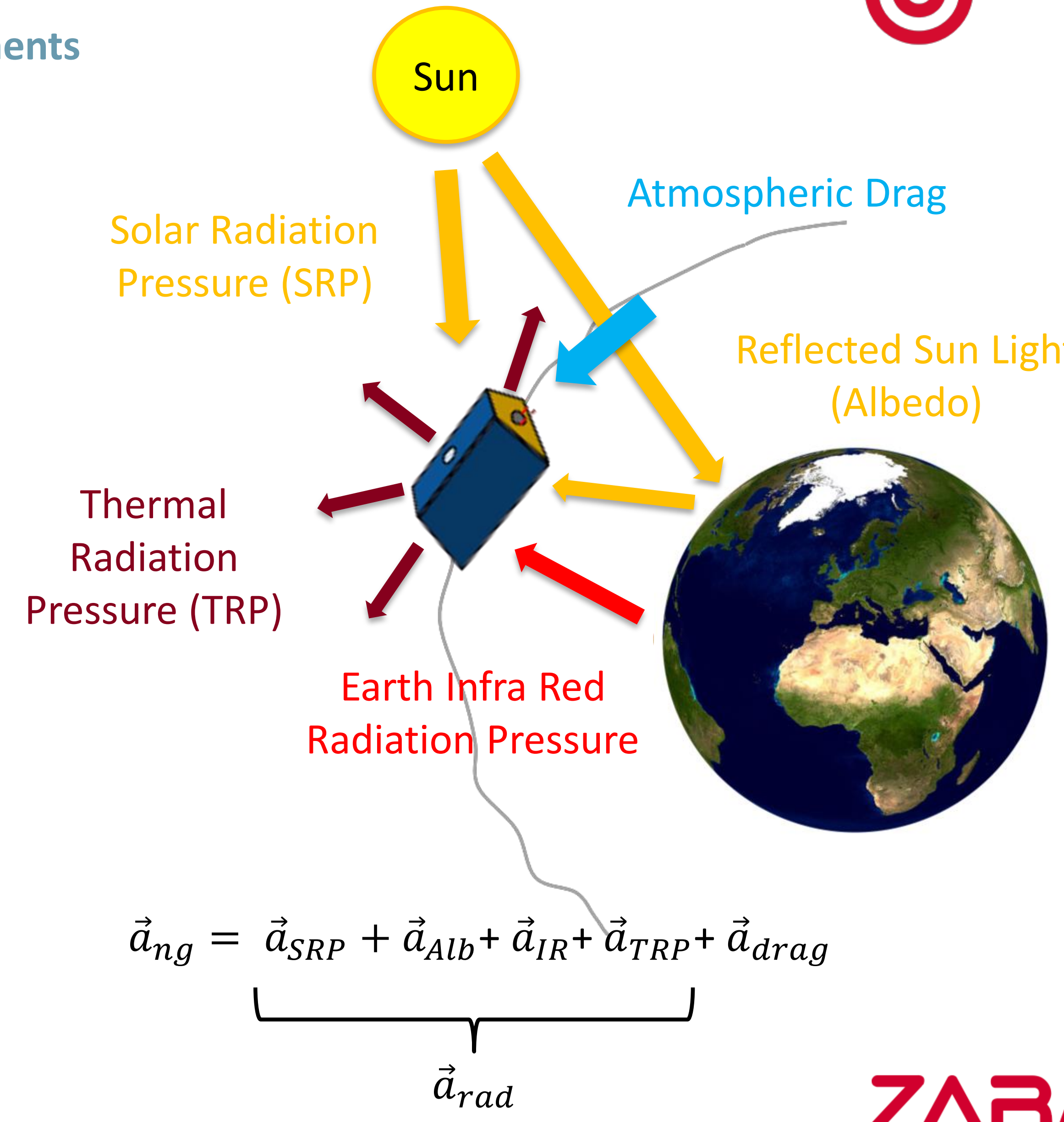
CENTER OF APPLIED SPACE TECHNOLOGY AND MICROGRAVITY
ZARM

General Concept

Density Estimation from Satellite Accelerometer Masurements

- Accelerometer measures sum of all non-gravitational accelerations acting on satellite
- Drag: Accelerometer measurement (ACC) minus simulated radiative accelerations:
- $\vec{a}_{drag} = ACC_{cal} - \vec{a}_{sim,\,rad}$
- Project $\vec{a}_{drag}$ on relative velocity direction
- $\rho = \frac{2\,|\vec{a}_{drag\parallel}|\,m_{sat}}{C_D\,A_{proj}|\,\vec{v}_{inc}|^2}$





University of Bremen

ZARM

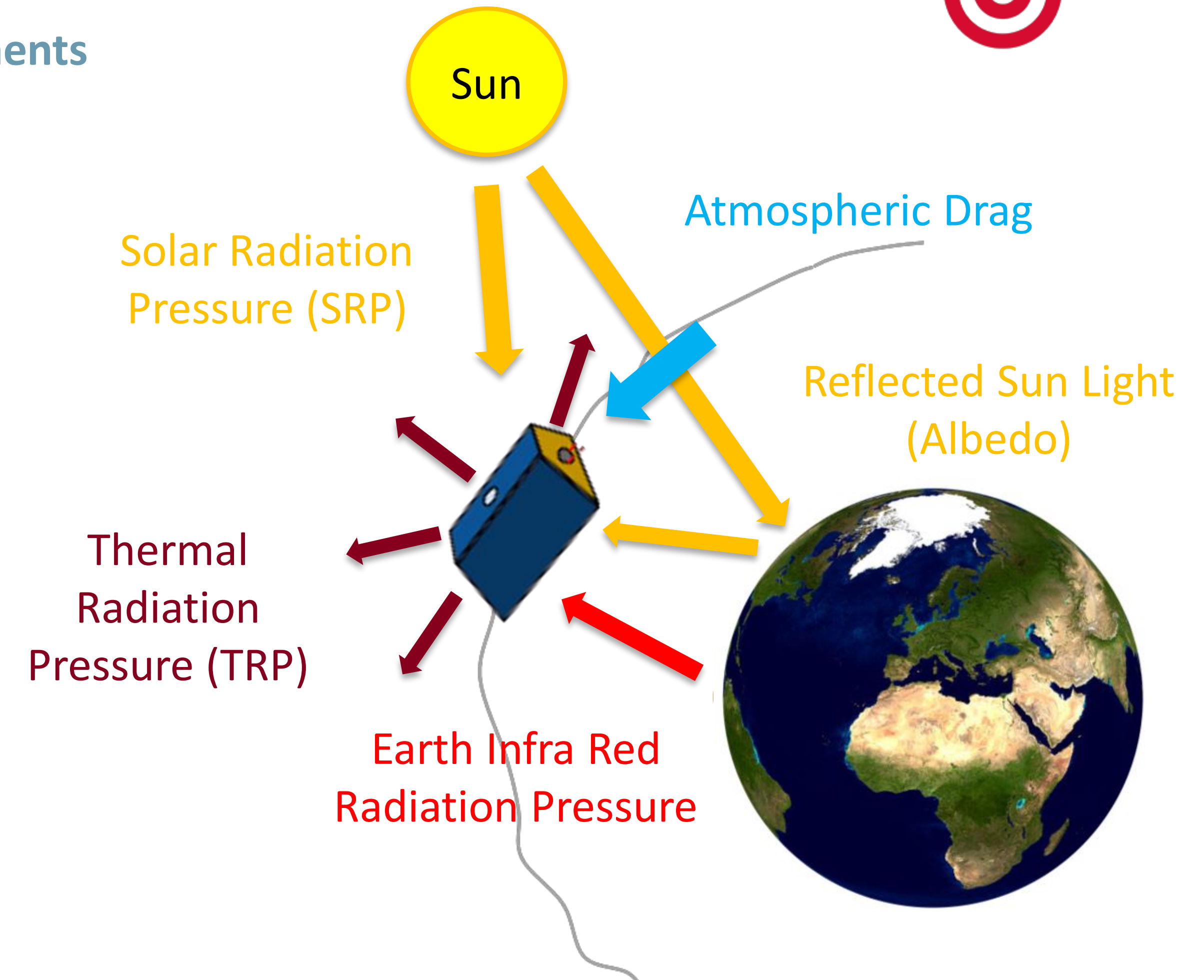
General Concept

Density Estimation from Satellite Accelerometer Masurements

- Three key competences

1. Accelerometer calibration
   by dynamic Precise Orbit Determination (POD)
2. Radiative non-gravitational force modeling
3. Drag coefficient C_D modeling

- All contribute seperately to total error budget of estimated density with own systematics

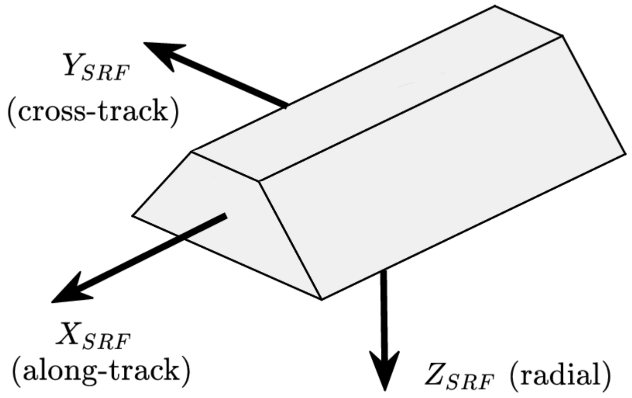


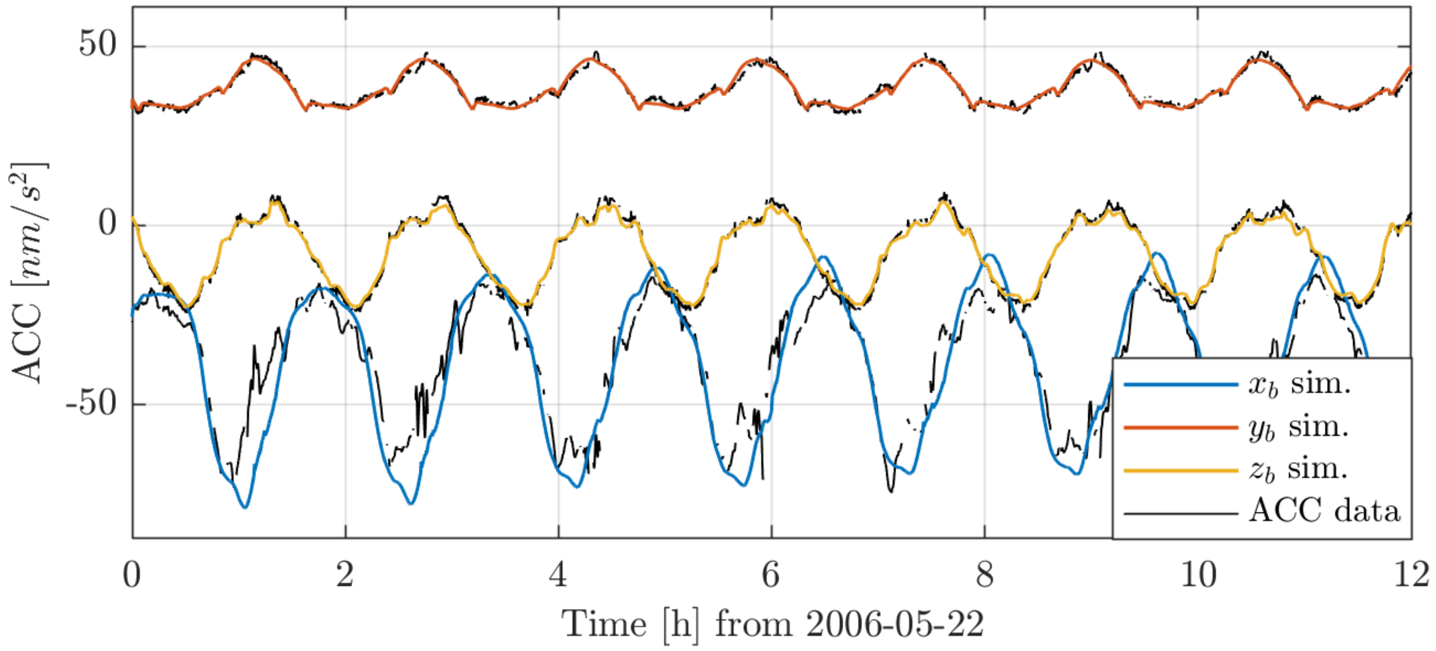
$$\vec{a}_{ng} = \underbrace{\vec{a}_{SRP} + \vec{a}_{Alb} + \vec{a}_{IR} + \vec{a}_{TRP}}_{\vec{a}_{rad}} + \vec{a}_{drag}$$

Non-Gravitational Force Modeling

Comparison with GRACE ACC Data

- X_{SRF} axis closely aligned with orbital velocity direction
- → Y- and Z-axis barely contain any drag acceleration





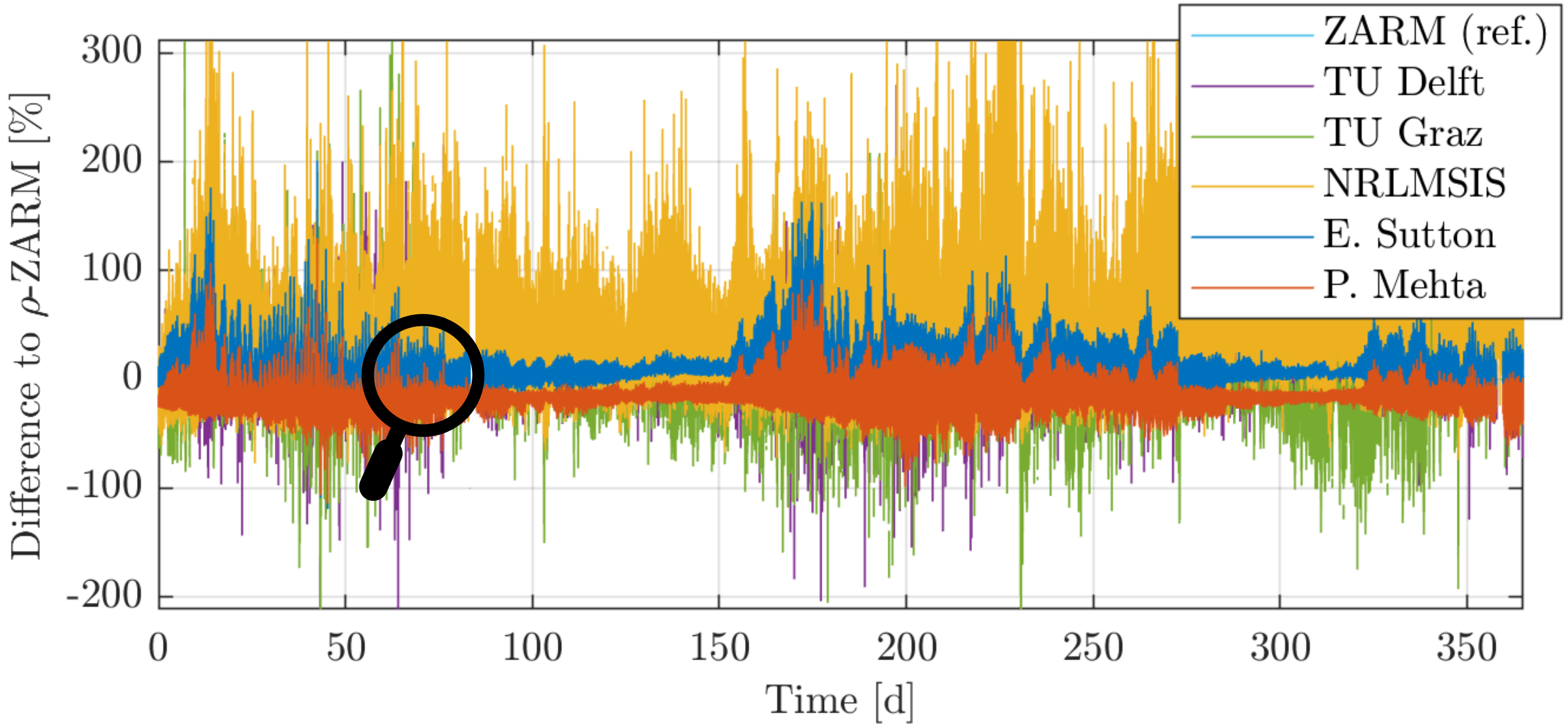
Simulated non-grav. accelerations and calibrated ACC data (daily bias for each axis), GRACE A. Times of attitude thruster firings removed

Estimated Density

Comparison of Results with other Solutions

- Results from different institutions and authors:
- TU Delft
- TU Graz
- Eric Sutton [1] (CU Boulder)
- Piyush Mehta [2] (West Virginia U)
- NRLMSISE

- With 10s sampling we mainly see outliers in the plot over one year → zoom-in



Differences of the estimated density from GRACE A ACC data for the year 2006 w.r.t. to ZARM solution

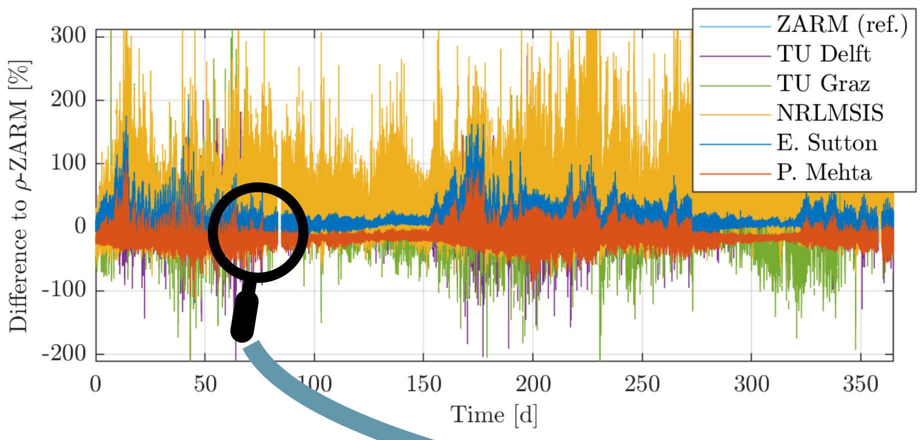
[1] Eric K. Sutton: Normalized Force Coefficients for Satellites with Elongated Shapes, JSR, 2012, https://doi.org/10.2514/1.40940

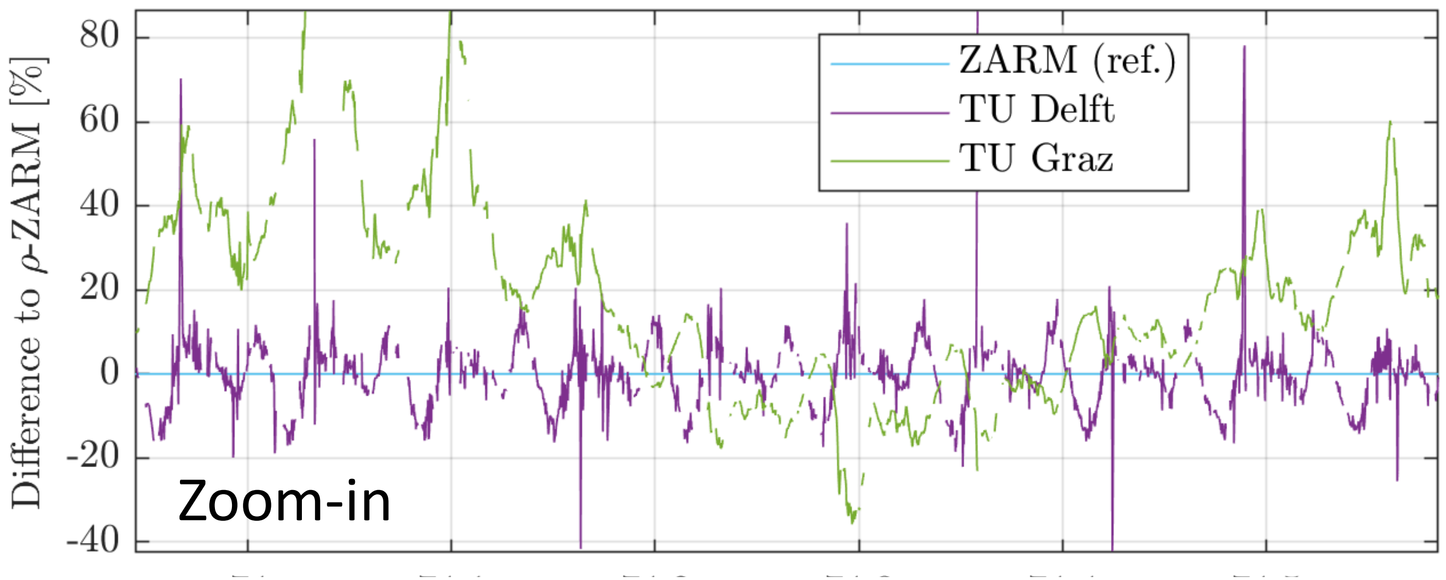
[2] P. M. Mehta et. al.: New density estimates derived using accelerometers on board the CHAMP and GRACE satellites, Space Weather, 2017, https://doi.org/10.1002/2016SW001562

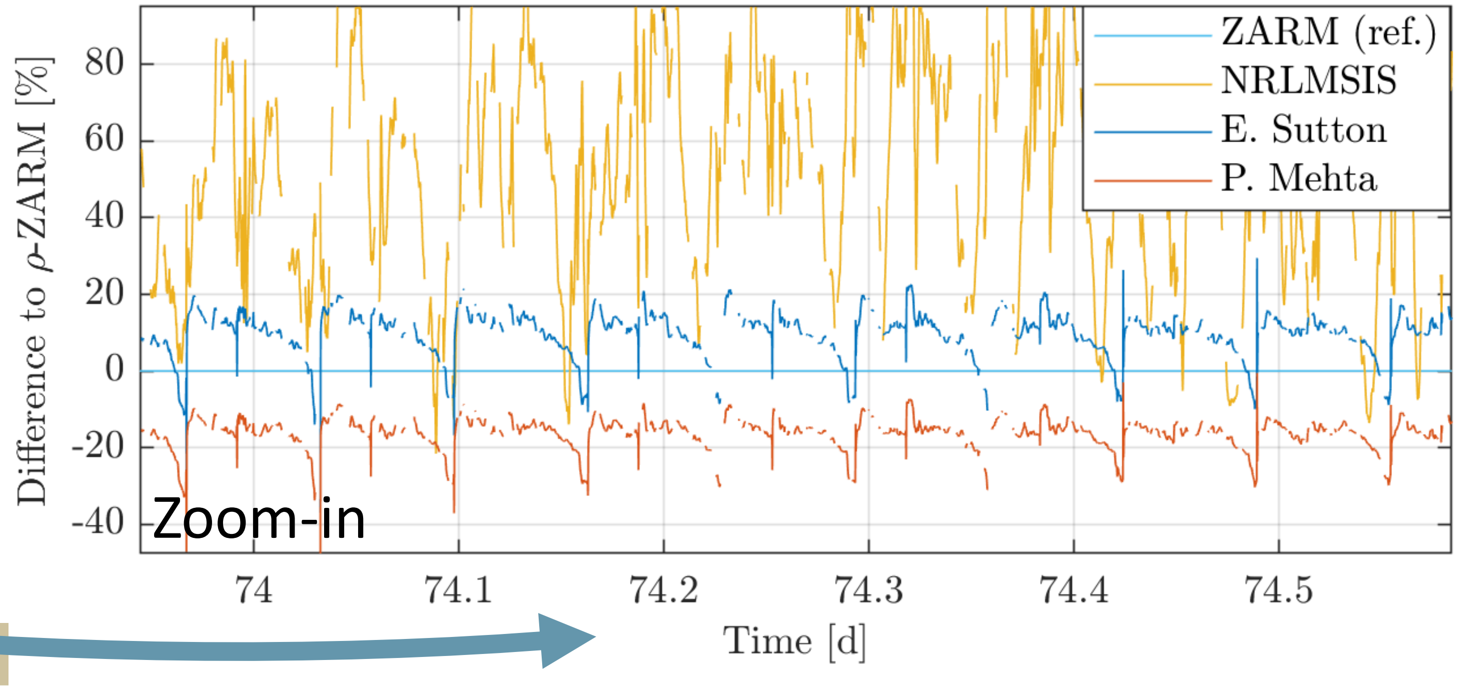
Estimated Density

Comparison of Results with other Solutions

- Results from different institutions and authors:
- TU Delft
- TU Graz
- Eric Sutton [1]
- Piyush Mehta [2]
- NRLMSISE







Acknowledgment

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

Project GRACE Aero, funded under
the contract nr. FKZ 50LZ 2101

Thank You!

For more information: PICO 3a.10

zarm.uni-bremen.de/

florian.woeske@zarm.uni-bremen.de

University of Bremen

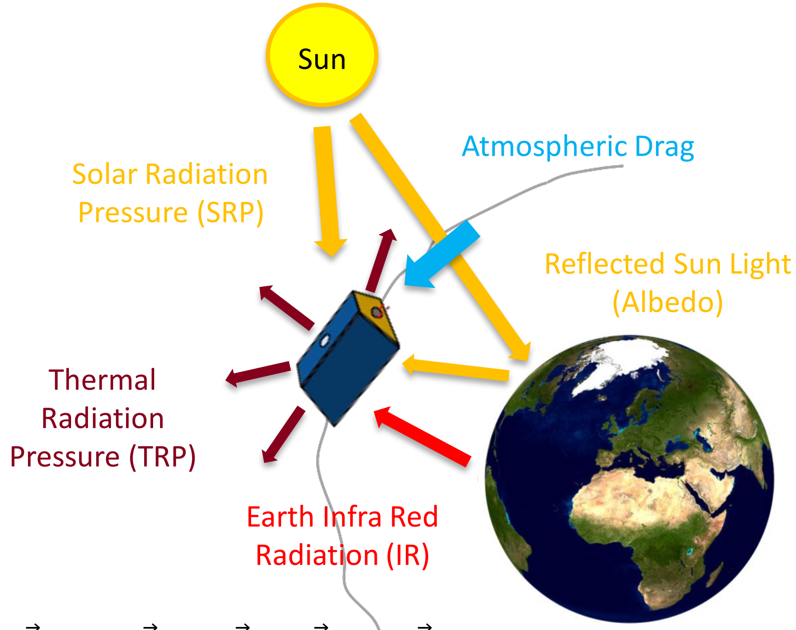
CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY
ZARM

Non-Gravitational Force Modeling

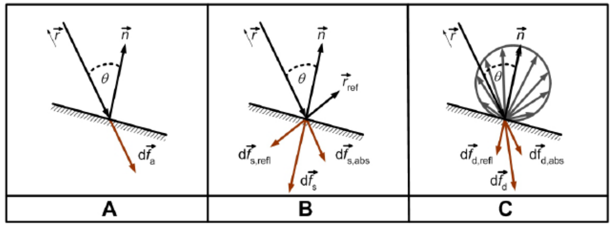
Overview

- **Modeling of all forces based on Finite Element Model (FEM) of satellites**
- Computation of all forces for each element of FEM and subsequent summation
- Shadowing of elements by other elements
- Optical material parameters for each element (for Vis and IR)
- Preprocessing: Computation of normalized coefficients with respect to incident radiation direction (ϕ, θ) (rotation of $\vec{e}_{inc}$ around satellite)
- Then just interpolation with actual radiation direction (ϕ, θ) and multiplication with actual incomming flux q_{in}

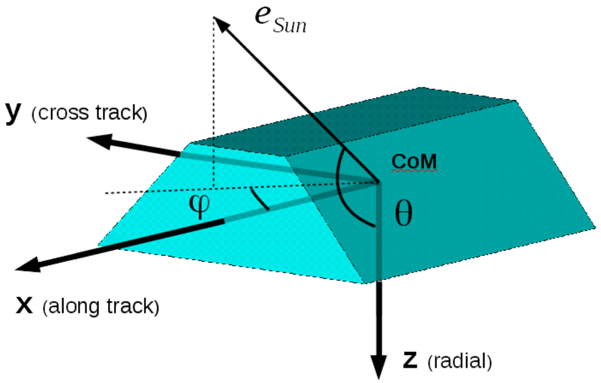
  → Very efficient computation with complex models

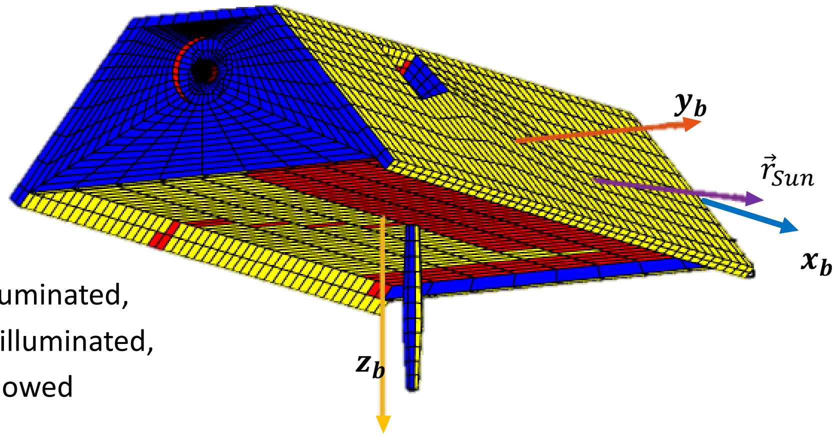


$$\vec{a}_{ng} = \underbrace{\vec{a}_{SRP} + \vec{a}_{Alb} + \vec{a}_{IR} + \vec{a}_{TRP}}_{\vec{a}_{rad}} + \vec{a}_{drag}$$



A: Absorption, B: Spec. Reflection, C: Diff. Reflection





Yellow: illuminated,
Blue: not illuminated,
Red: shadowed

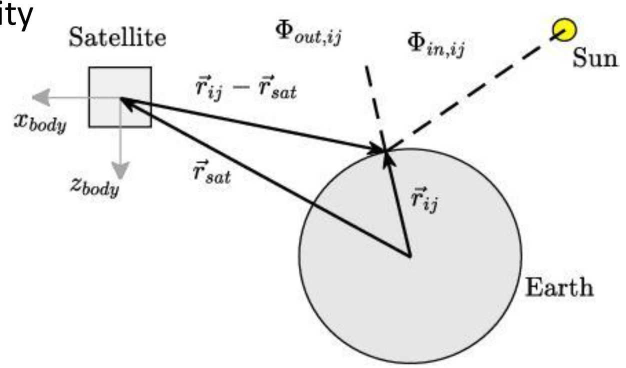
Illumination conditions for one direction $\vec{r}_{Sun}$

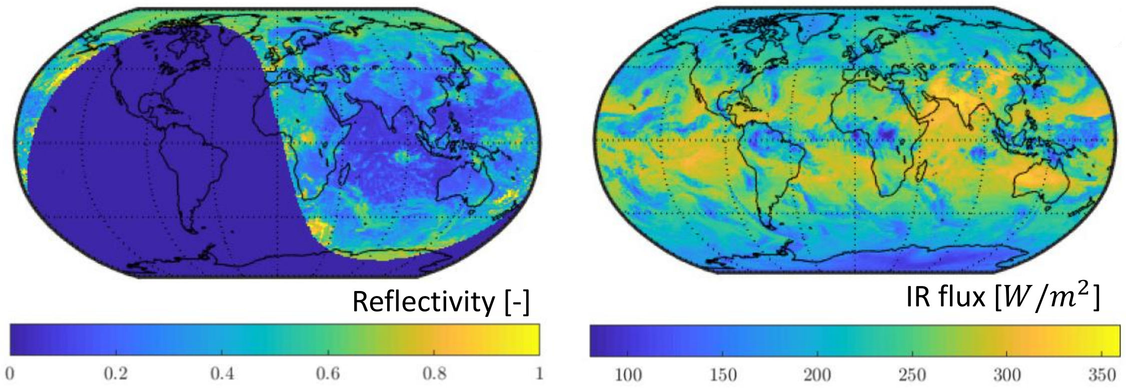
Non-Gravitational Force Modeling

University of Bremen

Albedo and Earth Infra-Red

- Same look-up tables as for SRP (processed for Vis and IR), but not just one incident direction, but from all Area on Earth in the Field of View (FoV) of the satellite.
- 1° x1° gridded, hourly Reflectivity and Longwave Flux data from CERES (SYN1deg TOA)
- Summation of contribution of all FoV cells on Earth
- We assume diffuse radiation from the Earth





CERES radiation data for 2006-05-01, 06:00 -07:00 UTC

Thermal Radiation Pressure (TRP)

- Radiation of satellite itself, due to its surface temperature T (Stefan-Boltzmann law)
- Computation for each element k with temperature T_k

$$\vec{F}_{trp,k} = -\frac{2}{3}\frac{A_k\ \varepsilon_k\ \sigma}{c} T_k^4\ \vec{e}_{N,k}$$

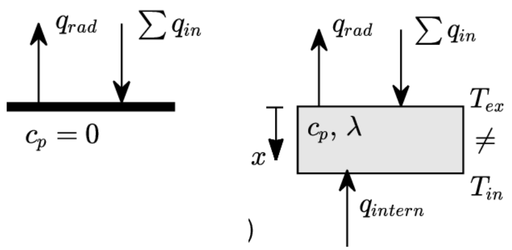
- Different model approaches for temperature calculation
  a) static c) transient + heat conduction

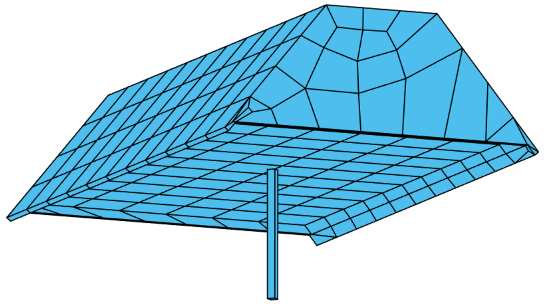
$$\text{a)}\quad T_k = \left(\frac{q_{abs,k}}{\varepsilon_k\ \sigma}\right)^{\frac{1}{4}} \qquad \text{c)}\quad c_{p,k}\ \rho_k \frac{\partial T_k}{\partial t} = \lambda_k \frac{\partial^2 T_k}{\partial x_k^2}$$

- $q_{in,k}$: Absorbed power for each element from previous sources: SRP, Alb, IR
- q_{intern}: Internal heat production (~200W) mainly radiated through nadir radiator

a) static

c) Transient + conduction



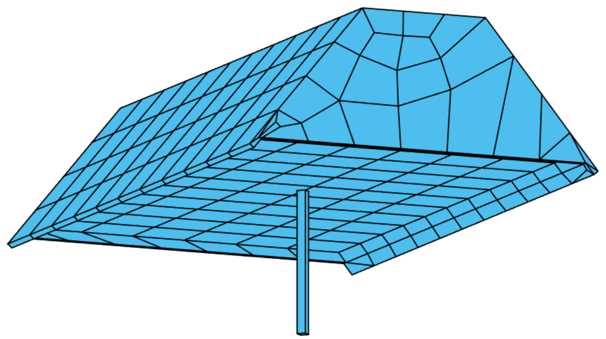


ZARM

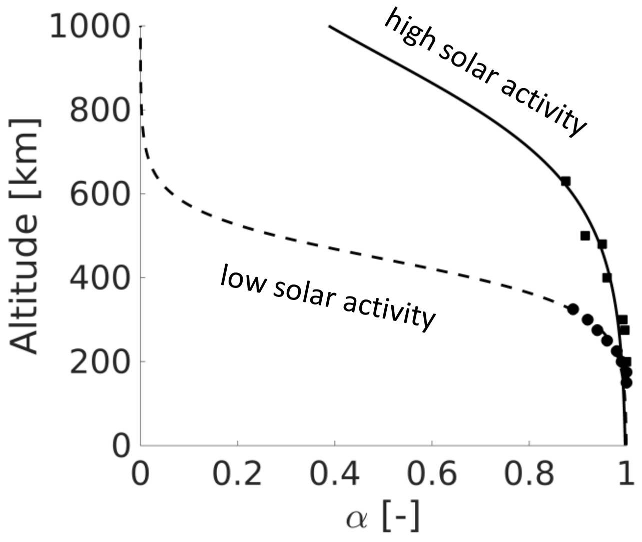
Non-Gravitational Force Modeling

Drag coefficient

- Computation based on Sentman/Doornbos [1,2] model with energy accommodation coefficient α_E (variable or const.)
- Computation with FEM of satellite
- Atmospheric composition and temperature from NRLMSISE model
- Temperature of satellite surfaces from TRP modelling case c)
- Variable α_E based on data from Moe & Moe with Langmuir isotherm for high and low Solar activity (high uncertainty). Very few old data available
- High dependency of C_D on α_E
- Computation of aerodynamic coefficients also for perpendicular directions, but for density determination we just use the relative velocity direction C_D



Same FEM as for temperature calculation from TRP used for Cd, as well



Energy accommodation coefficient α_E: Langmuir isotherm fit for high and low solar activity

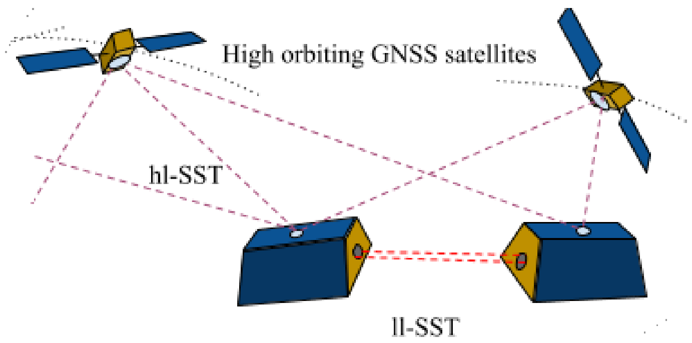
[1] Sentman, L.H. (1961). Free Molecule Flow Theory and its Application to the Determination of Aerodynamic Forces.

[2] Doornbos,E. (2010). Thermospheric Density and Wind Determination from Satellite Dynamics, PhD thesis

ACC Calibration by Dynamic POD

Overview

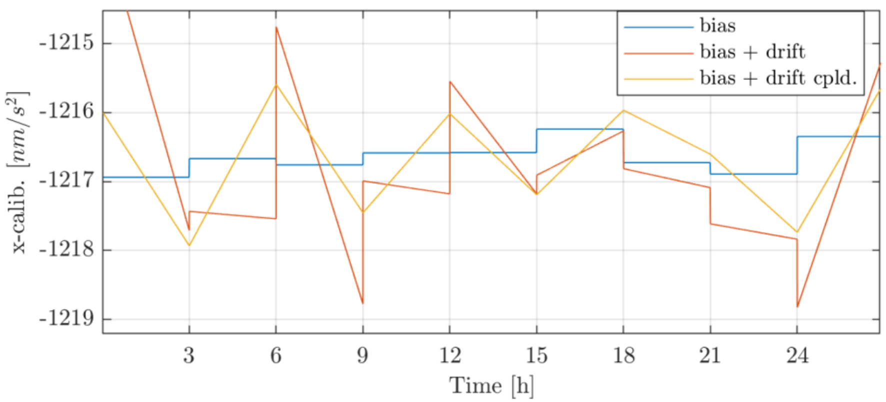
- Classical dynamic POD with "standard" state-of-the-art force models
- Observation data
  - GNSS position data
  - Low-low Satellite-to-Satellite Tracking



- **Calibration Equation:**
- $\vec{a}_{ng} = \vec{s} * ACC_{meas} + \vec{b} + \vec{d} * t$
- $\Leftrightarrow \vec{a}_{ng} = \vec{s} * \left(ACC_{meas} + \vec{b}./\vec{s} + \vec{d} * t./\vec{s}\right)$
- Parametrization
  - Which parameter
  - Global and local parameters
  - Arc length for glob. and loc. parameters
  - Couple parameters between arcs

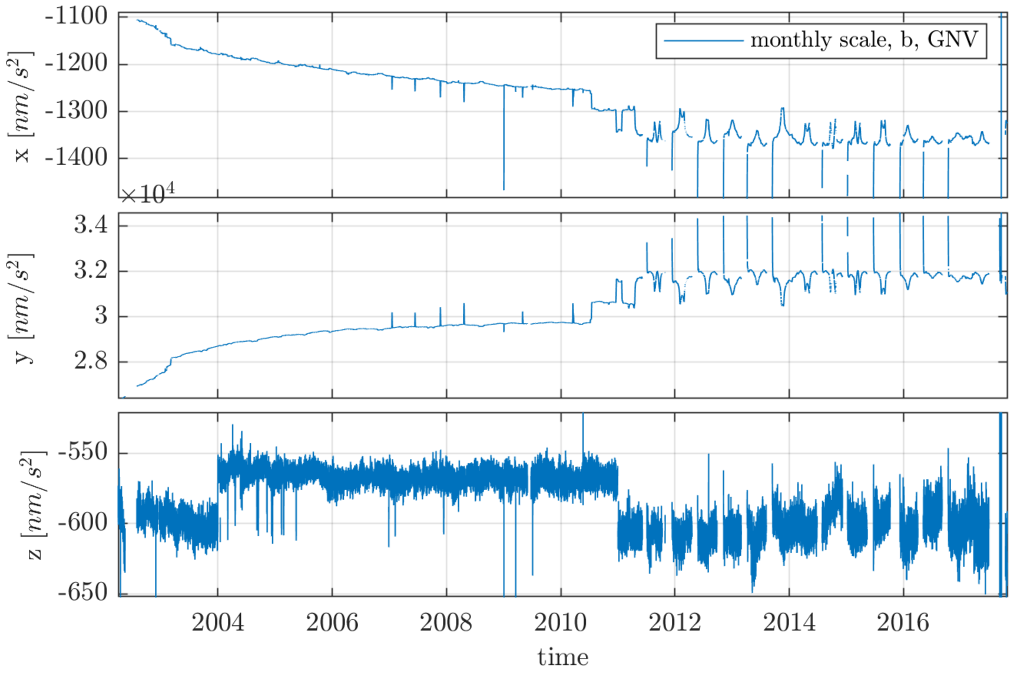
Pertubation	Model
Earth gravity	GOCO06s
Third body	JPL DE430 ephemeris
Solid Earth tides	IERS 2010
Ocean tides	FES14b
Pole pides	IERS 2010
Ocean pole tides	IERS 2010
Atmospheric tides	N1 Biancale & Bode
Dealiasing	AOD1B RL06
Relativistic corrections	IERS 2010
Earth rotation	IERS 2010, EOP 14C04_2000A

Dynamic models used in POD orbit determination

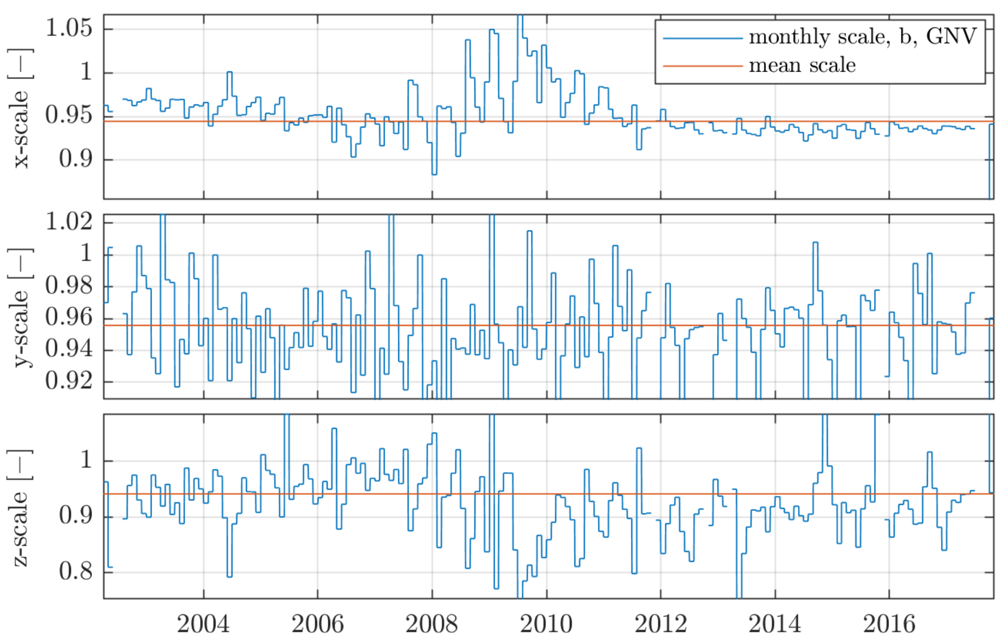


Exemplary calibration with different parametrizations: bias, bias+drift and bias+drift coupled, for one axis

ACC Calibration by Dynamic POD



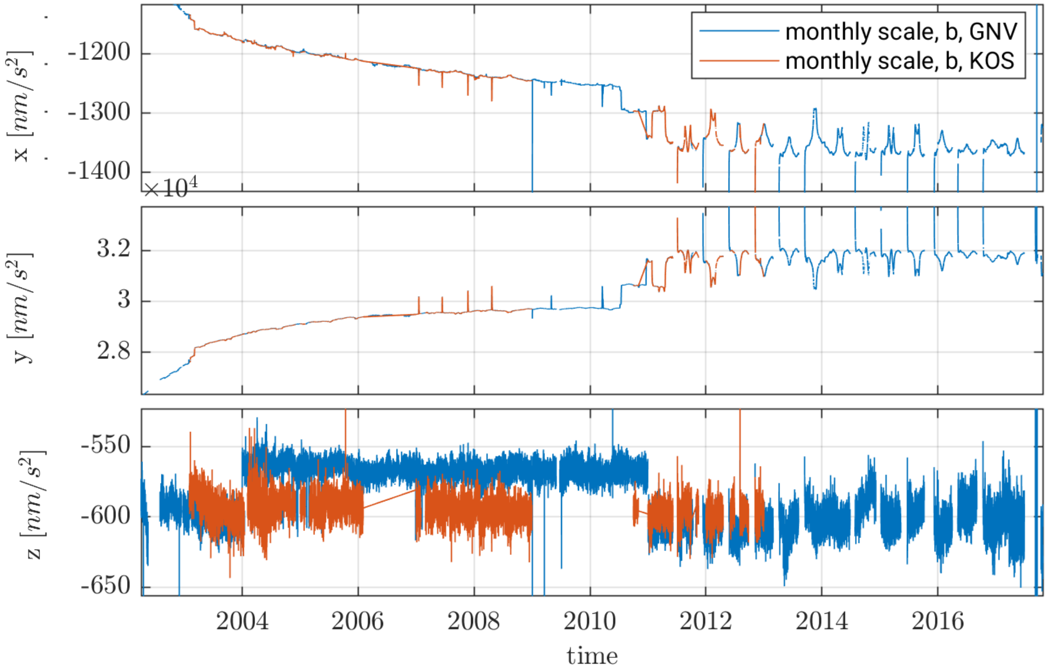
Estimated 3 hourly bias values for GRACE A, with GNV data



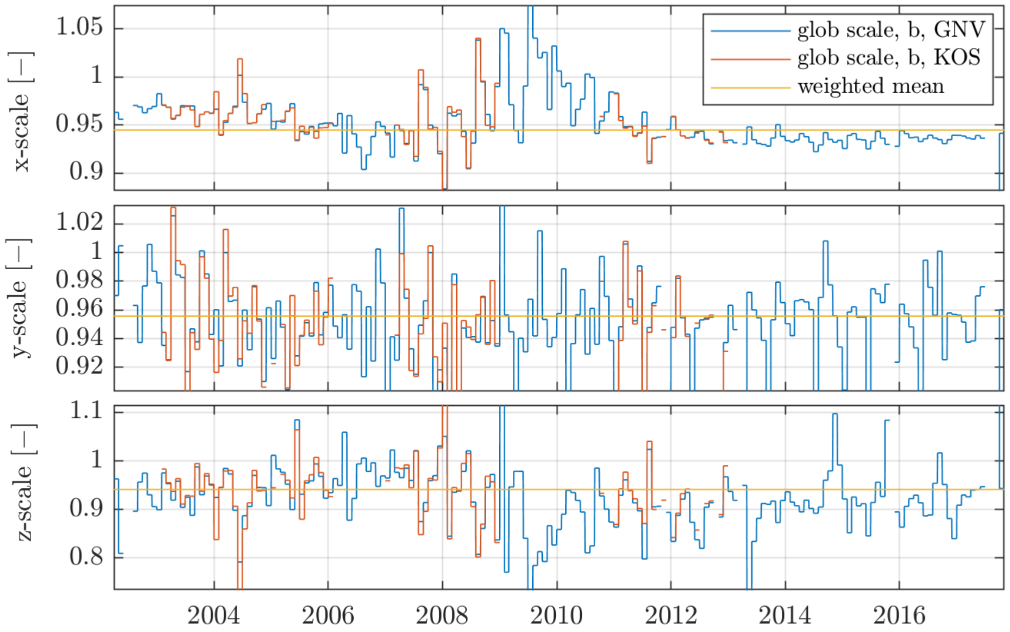
Estimated monthly scale factors for GRACE A, and weighted mean scale over the whole mission

- Scale estimation on shorter time scales gives unrealistic values (3h, 1d, 7d), validation complicated because residuals tend to decrease when estimating more parameters.
- The same holds for additional bias estimation, which results in a higher variability of the estimated offset.
- Accelerometer calibration results with KBR data seem to be less reliable compared to just GNSS orbit data
- The least sensitive z-axis shows a quite high variability, for the other axes it is much smaller. Nevertheless, we filter the estimated bias in all axes (with different filter parameters), before using it for ACC calibration.

ACC Calibration by Dynamic POD



Estimated 3 hourly bias values for GRACE A, with GNV and KOS data, respectively.

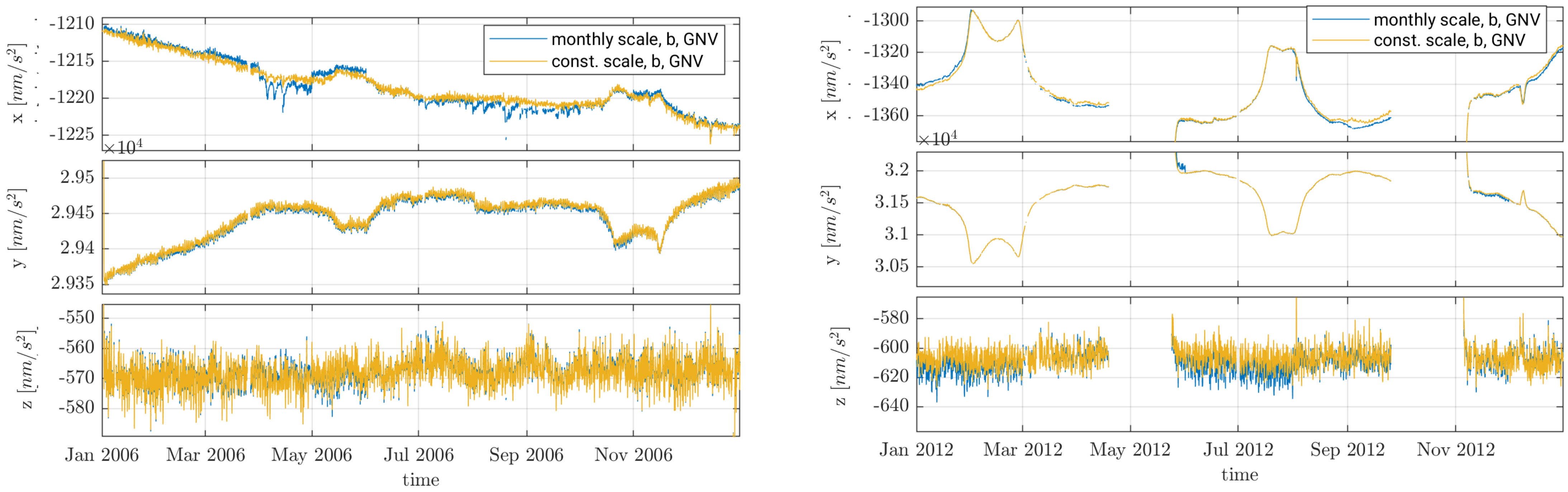


Estimated monthly scale factors for GRACE A, with GNV and KOS as observation data, respectively and weighted mean scale over the whole mission

- Besides the officially processed and available GNVL1B orbit product (GNV) (reduced-dynamic orbit determination) we also used kinematic orbit data from TU Graz [1] with variane-covariance information for every data point (KOS).
- The bias is very similar for all investigated time periods in the x- and y-axes. Nevertheless, the z-axis shows distinct differences.
- The monthly estimated scale factor is very similar as well in all investigated time periods.

[1] Suesser-Rechberger, B., Krauss, S., Strasser, S. et al. (2022). Improved precise kinematic LEO orbits based on the raw observation approach. Advances in Space Research, 69(10), 3559–3570. doi:https://doi.org/10.1016/j.asr.2022.03.014

ACC Calibration by Dynamic POD



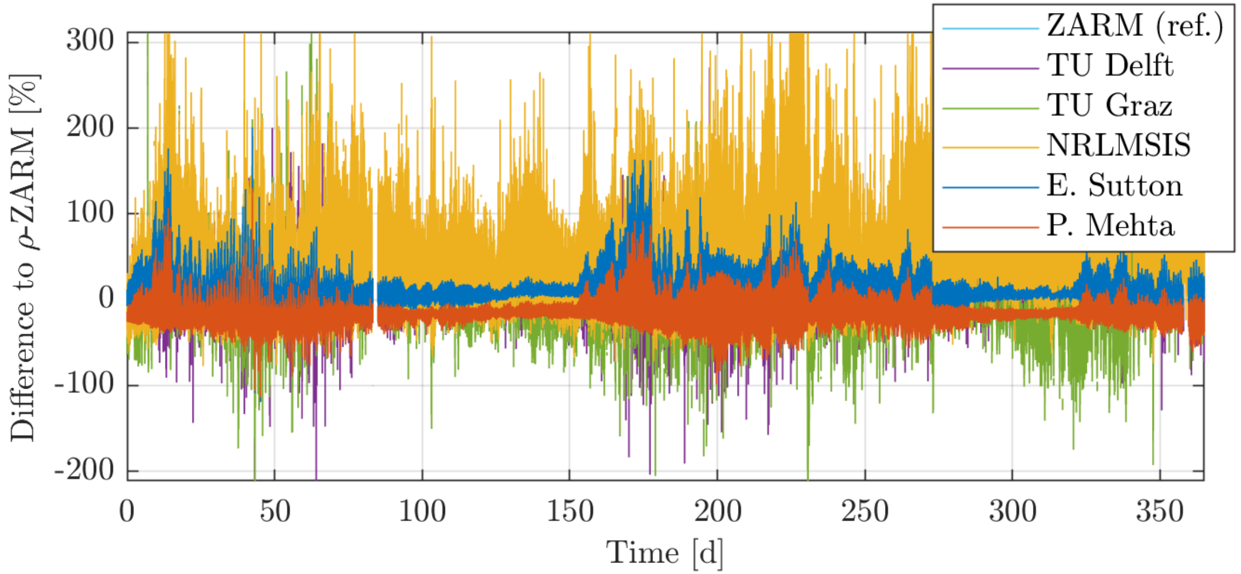
Estimated 3 hourly bias values for GRACE A, GNV, with monthly scale factors and const. scale values, 2006 and 2012

- The POD ACC calibration is repeated with the constant scale factors.
- The differences are not big, but at some periods, especially in the x-axis, some smaller differences are detectable. Because the differnces are mainly in x-axis, it is very hard to validate if the constant scale solution is the more realistic. Nevertheless it is more smooth, which seems more realistic.

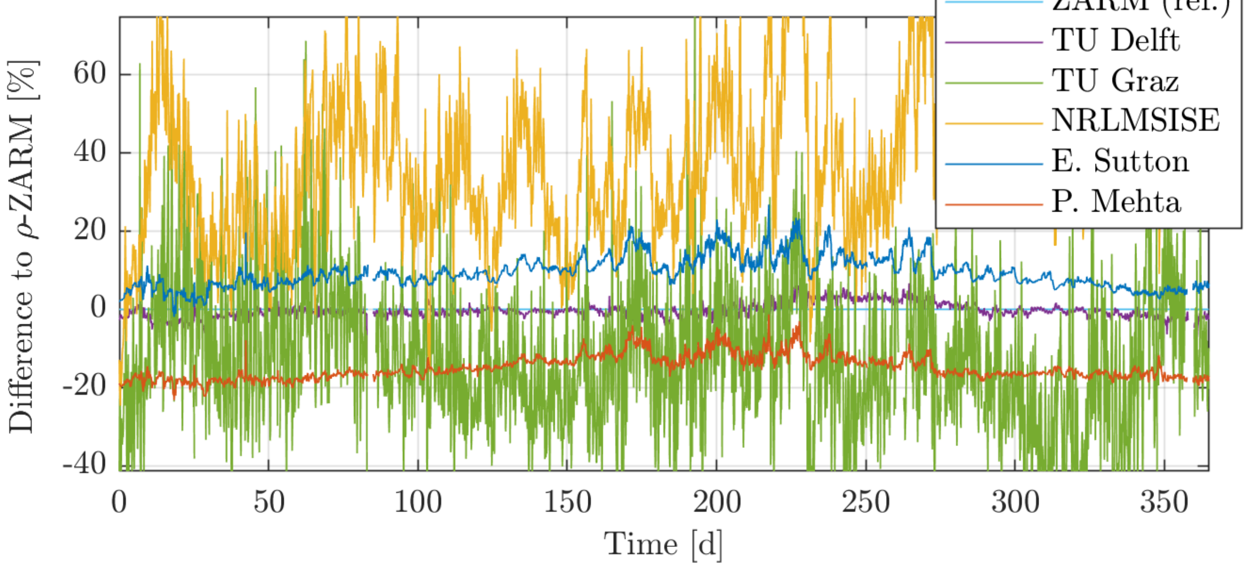
Estimated Density

Comparison of Results with other Solutions

- Results from different institutions and authors:
- TU Delft, TU Graz, Eric Sutton [1] (CU Boulder), Piyush Mehta [2] (West Virginia U), NRLMSISE



3h mean



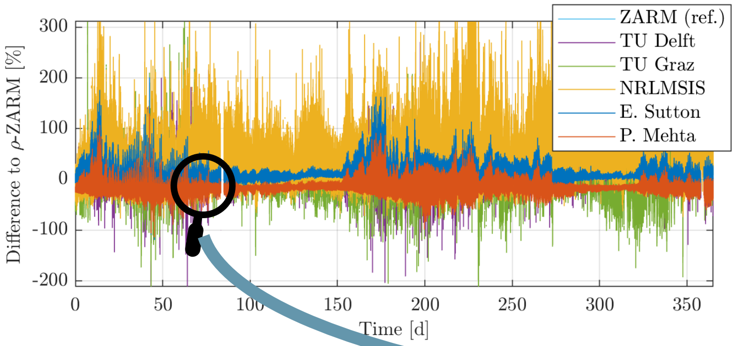
Differences of the estimated density from GRACE A ACC data for the year 2006 w.r.t. to ZARM solution (480 km polar orbit)

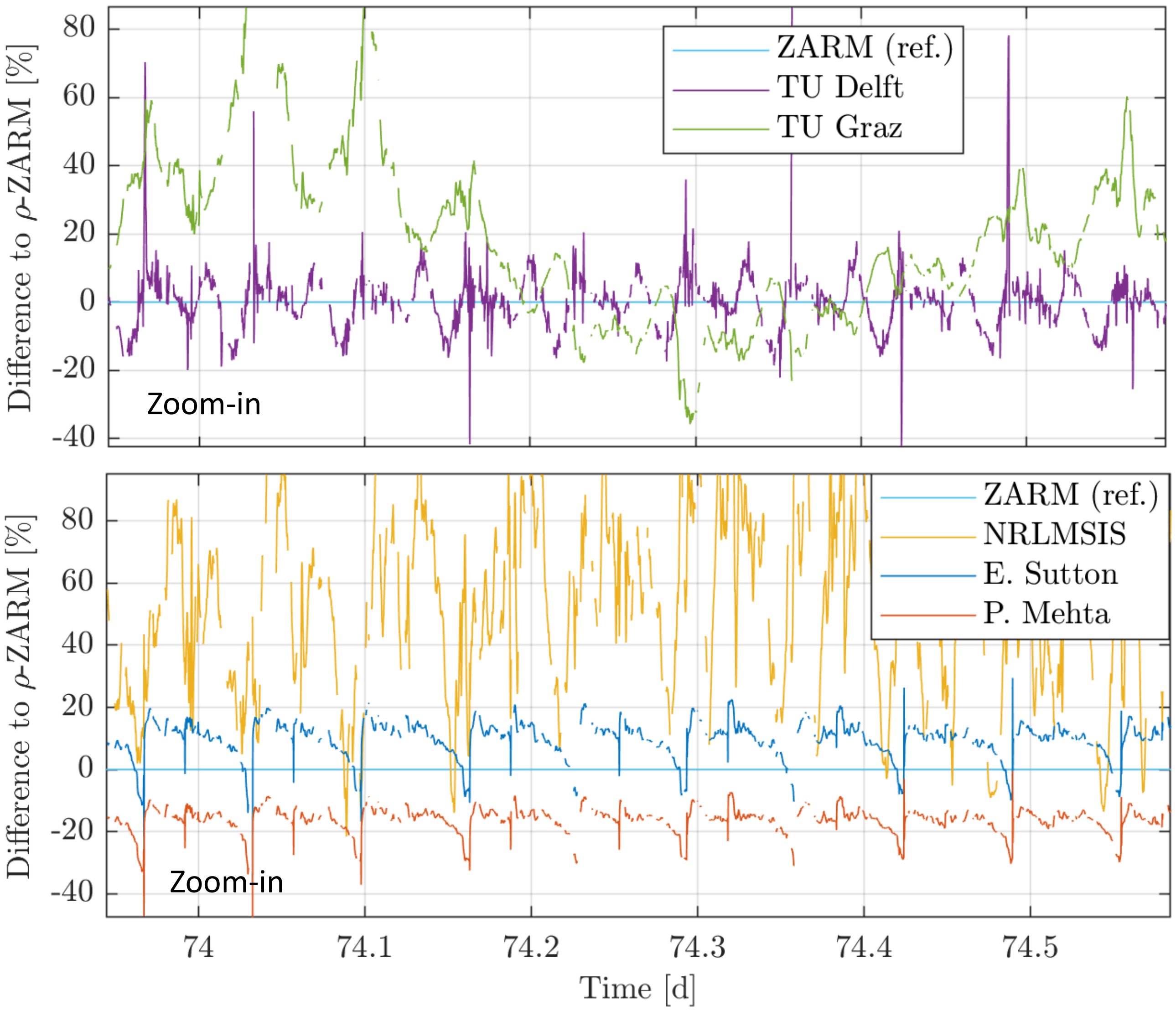
- In the first figure, with 20s data sampling, outliers and peaks dominate the plot, thus the 3h mean (over ~ two orbits) gives a little more smoothed picture over the year
- Still, it shows very big differences from the widely used NRLMSISE model and the different density solutions

[1] Eric K. Sutton: Normalized Force Coefficients for Satellites with Elongated Shapes, JSR, 2012, https://doi.org/10.2514/1.40940
[2] P. M. Mehta et. al.: New density estimates derived using accelerometers on board the CHAMP and GRACE satellites, Space Weather, 2017, https://doi.org/10.1002/2016SW001562

Estimated Density

Comparison of Results with other Solutions

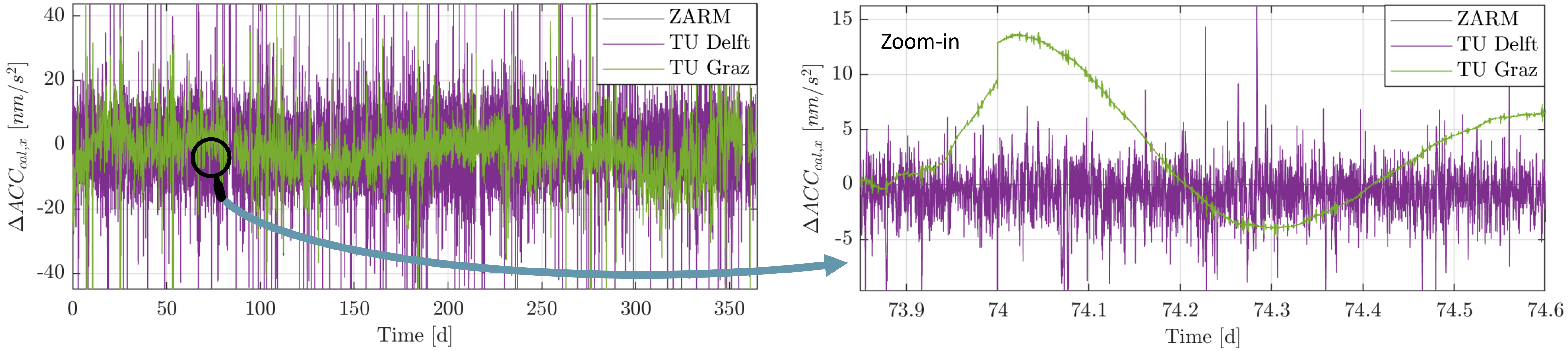




Differences of the estimated density from GRACE A ACC data for the year 2006 w.r.t. to ZARM solution (480 km polar orbit)

- Differences with various frequencies: from shorter periods (sub orbital) to longer (~ daily)
- → Differnces in ACC calibration (POD)
- → Differnces in non-gravitational force and C_D modeling
- → Differences in data processing
- Sutton and Mehta share same ACC calibration and non-grav. force modeling

Reasons for Differences
Accelerometer Calibration by POD

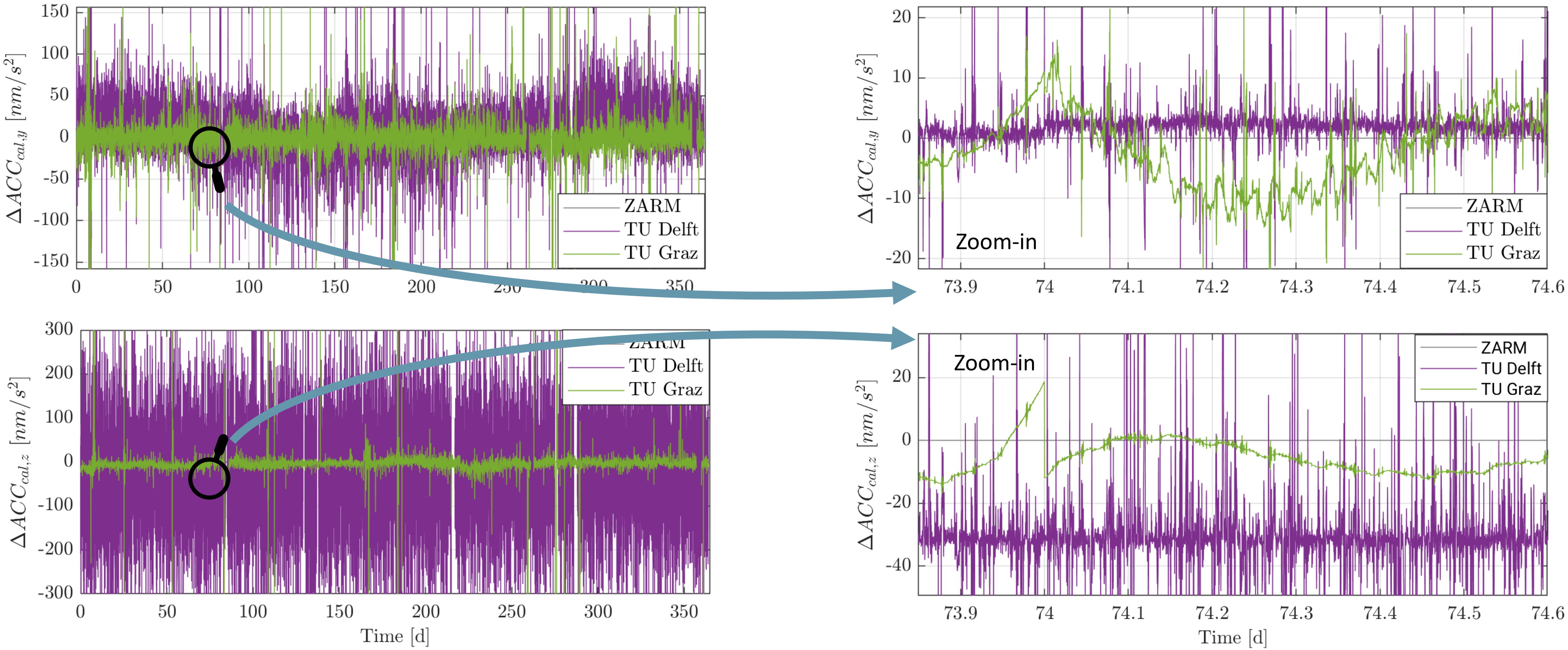


Differences of calibrated x-ACC data from GRACE A, 2006, w.r.t. to ZARM solution (x-axis is decisive for density estimation)

- Distinct differences in calibration due to parametrization of POD or Gravity Field Recoery (GFR) (TUG).
- High short scale „noise“ probably due to ACC data processing (TUD)

Reasons for Differences

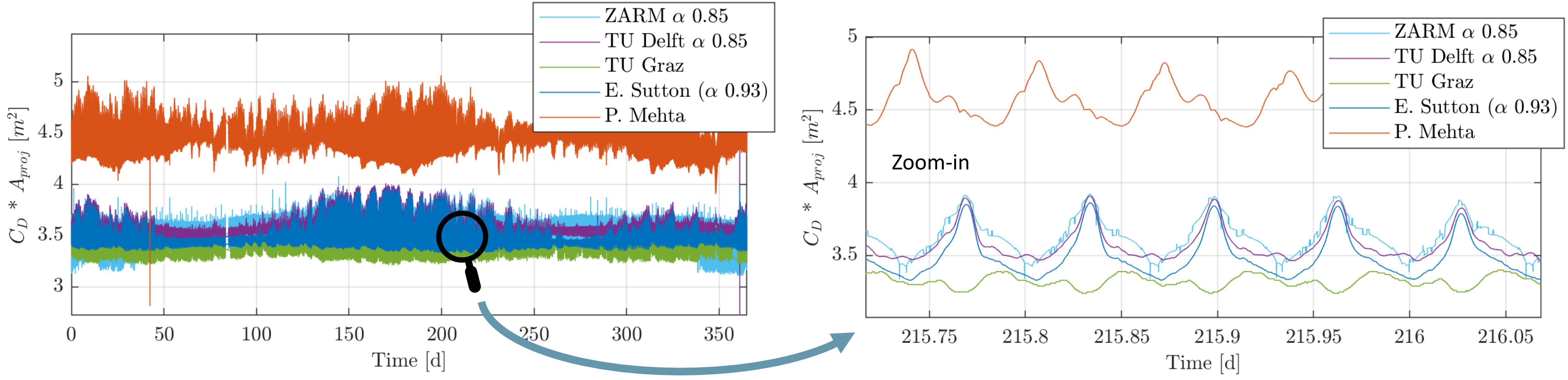
Accelerometer Calibration by POD



Differences of calibrated y- and z-ACC data from GRACE A, 2006, w.r.t. to ZARM solution (x-axis is decisive for density estimation)

Reasons for Differences

Drag Coefficient C_D



Modeled drag coefficient C_D times reference area A_{ref} for GRACE A, 2006

- ZARM, TUD, Sutton use implementations of the DRIA model, thus results are most similar
- Mehta uses a quasi-specular Cercignani-Lampis-Lord (CLL) model with a variable energy accommodation coefficient
- Our (ZARM) model has a slight problem with the Finite Element Model (FEM) resulting in small distinct jumps in C_D when elements drop in or fall out of the calculation.

Acknowledgment

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

Project GRACE Aero, funded under
the contract nr. FKZ 50LZ 2101

Contact:

zarm.uni-bremen.de/

florian.woeske@zarm.uni-bremen.de

University
of Bremen

CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY

ZARM