University of Bremen

EGU 2024 G2 - Reference Frames and Geodetic Observing Systems

G2.1 Precise Orbit Determination for Geodesy and Earth Science

Tailored accelerometer calibration by POD for thermospheric density computation with GRACE and GRACE-FO

Sharing is encouraged

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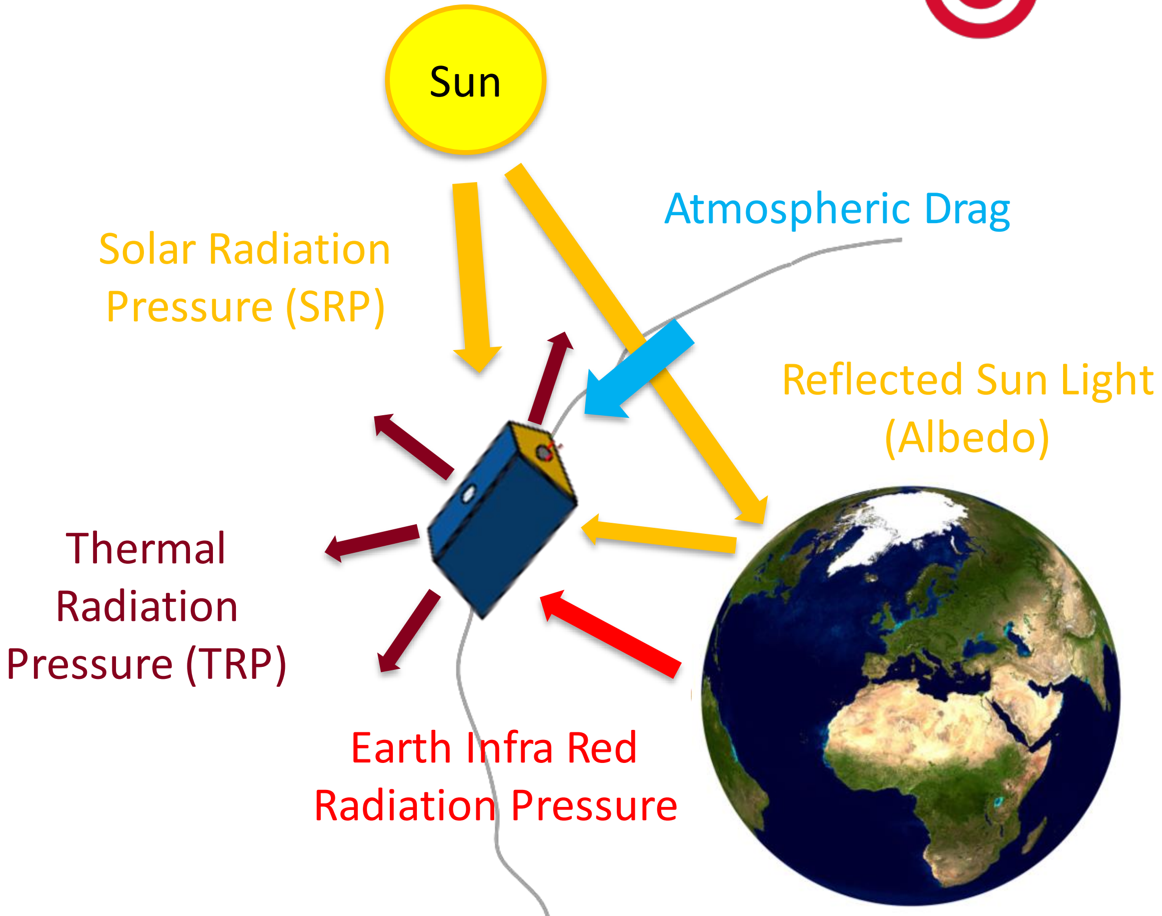
CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY
ZARM

Density Retrieval from Accelerometer Measurements

Introduction

- Accelerometer measures sum of all non-gravitational accelerations acting on satellite
- Drag: Accelerometer measurement (ACC) minus simulated radiative accelerations:
- $\vec{a}_{drag} = ACC - \vec{a}_{mod,\,rad}$
- Atmospheric density ρ follows from:
- $\vec{a}_{drag} = \frac{1}{2}\,\rho\, C_D\, A_{proj} |\,\vec{v}_{inc}| \vec{v}_{inc}$
- 1. Computation of drag coefficient C_D
- 2. Modelling of radiative accelerations
- 3. ACC data need to be calibrated (by POD)

→ Radiative forces can be modeled with much higher accuracy than drag



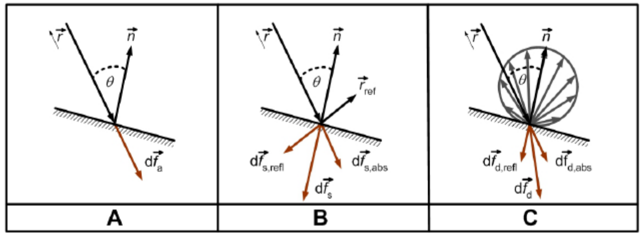
$$\vec{a}_{ng} = \underbrace{\vec{a}_{SRP} + \vec{a}_{Alb} + \vec{a}_{IR} + \vec{a}_{TRP}}_{\vec{a}_{rad}} + \vec{a}_{drag}$$

Radiative Non-Gravitational Force Modeling

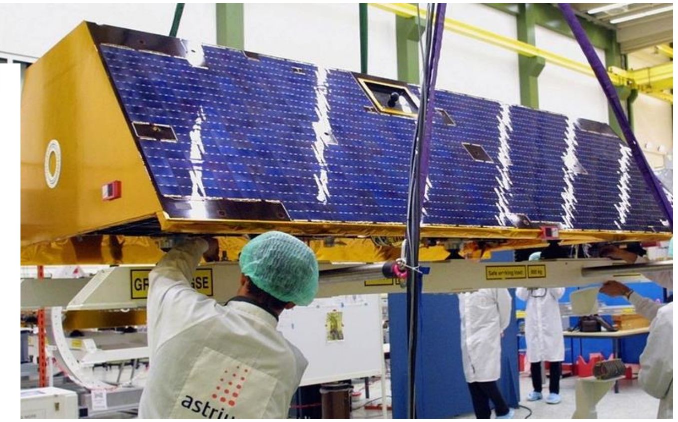
Introduction

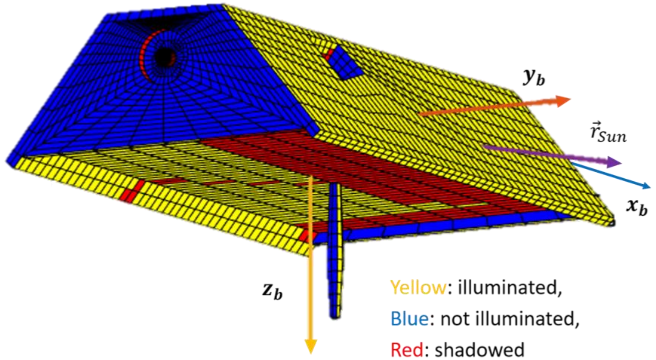
- Computation of each force with FE Model, including shadowing
- Hourly CERES data for Earth‘s reflectivity and infra red radiation on 1°*1° latitude-longitude grid
- Well known geometric conditions, attitude of satellite, and intensity of the Sun
- Optical parameters of satellite surfaces known relatively well from ground testing

Treatment of optical properties:

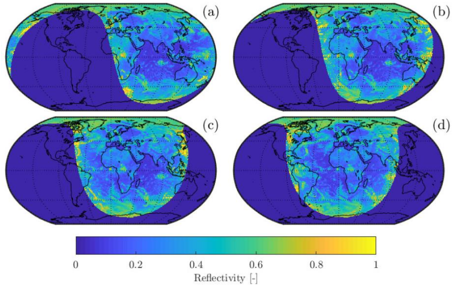


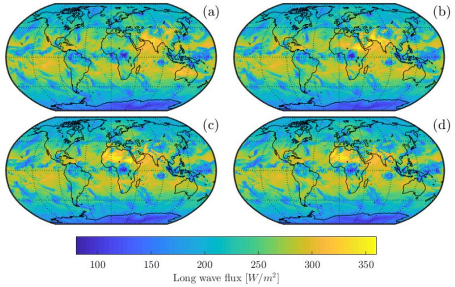
A: Absorption, B: Spec. Reflection, C: Diff. Reflection

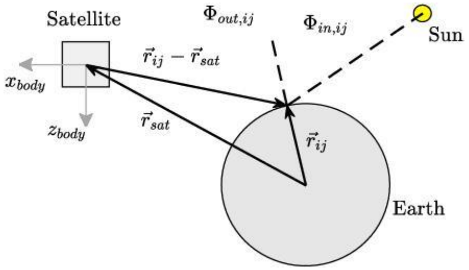


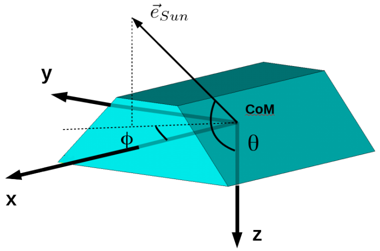


Yellow: illuminated,
Blue: not illuminated,
Red: shadowed





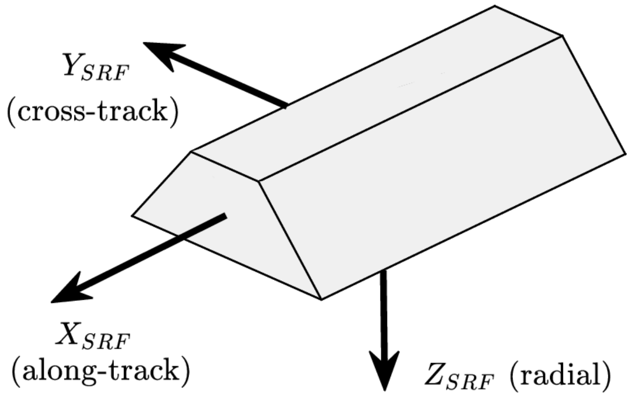


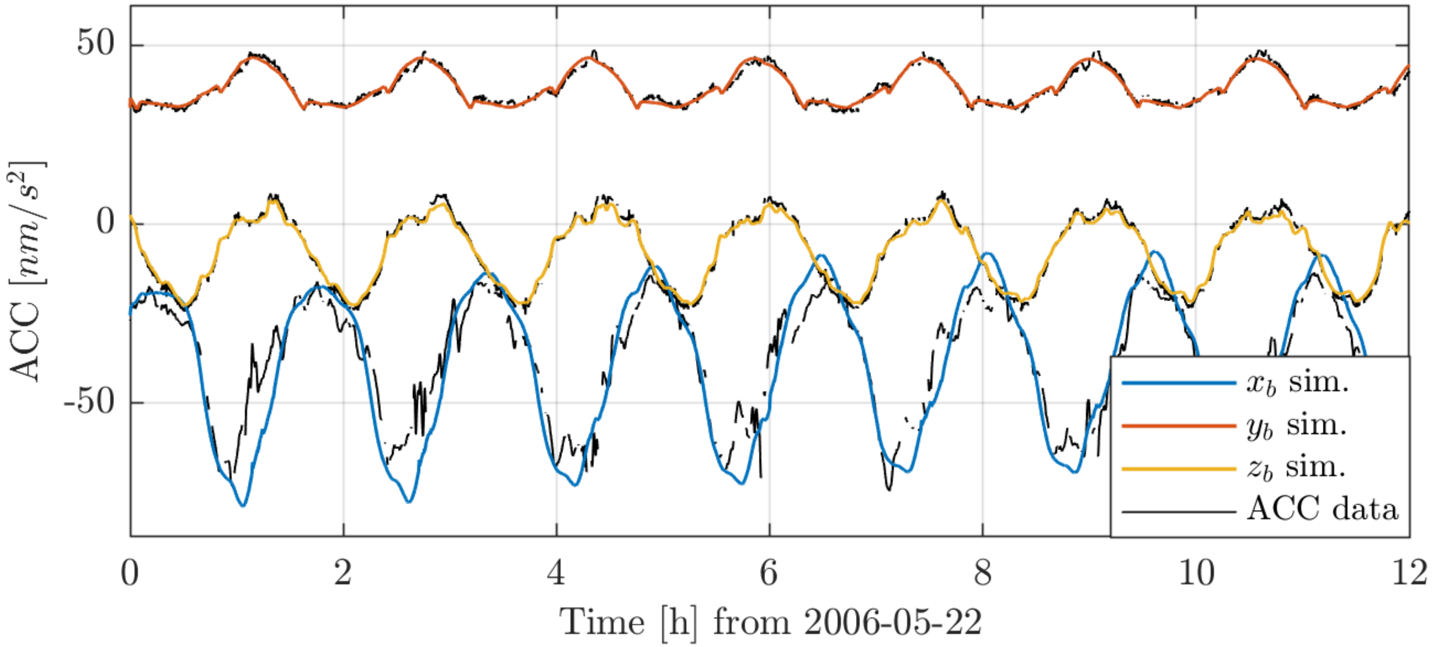


Comparison with GRACE Accelerometer Data

Introduction

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





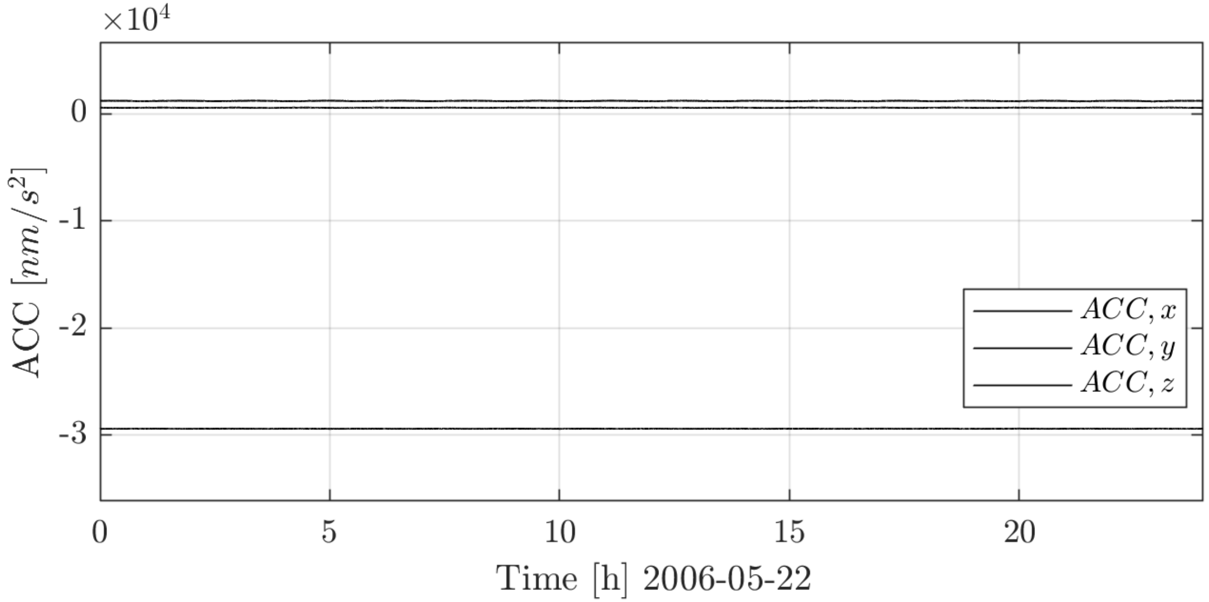
Modeled non-grav. accelerations and calibrated ACC data (daily bias for each axis), GRACE A. Times of attitude thruster firings removed

Accelerometer Calibration

Motivation

- Accelerometer data (ACC) need to be calibrated
- $ACC_{cal} = \vec{s}(t)\ ACC + \vec{b}(t)$
- $\Leftrightarrow ACC_{cal} = \vec{s}(t)\ \left(ACC + \vec{b}(t)/\vec{s}\right)$
  - Scale only affects amplitude
  - Bias is the offset

- Usually accelerometer calibration just side product
  - Orbit determination of all geodetic satellites
  - Gravity Field Recovery (GFR) from GRACE/-FO
- Many estimation parameters, stochastic parameters, parameters for different sensors, high KBR weighting, etc.
- ACC calibration parameters absorb many different effects → no physical accelerometer calibration

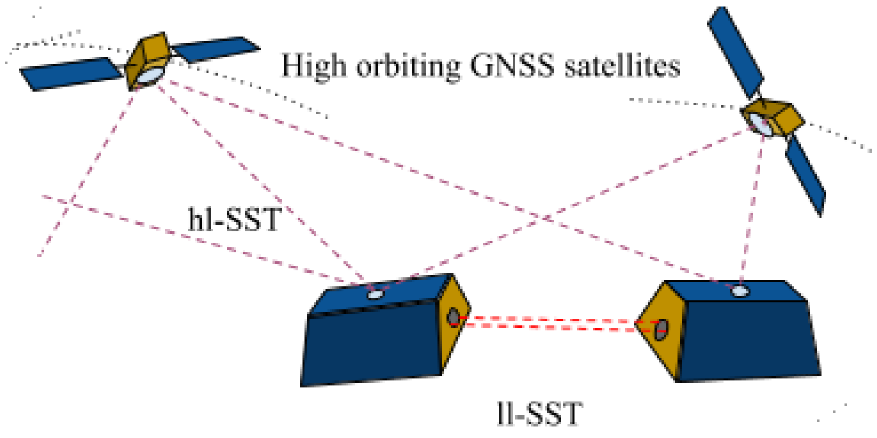


Raw accelerometer data of x-,y-, z-axis ACC L1B, GRACE A

POD Accelerometer Calibration

Overview of Dynamic POD

- Classical dynamic POD with "standard" state-of-the-art force models
- Observation data
  - GNSS position data
    - GNV L1B
    - Kinematic Orbit Solution (KOS) – TU Graz
  - Low-low Satellite-to-Satellite Tracking
    - KBR L1B



Pertubation	Model
Earth gravity	Different: GOCO06s, EIGEN-6s4, ITSG, COST-G/ FSM, GGM05s
Third body	JPL DE430 ephemerides
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

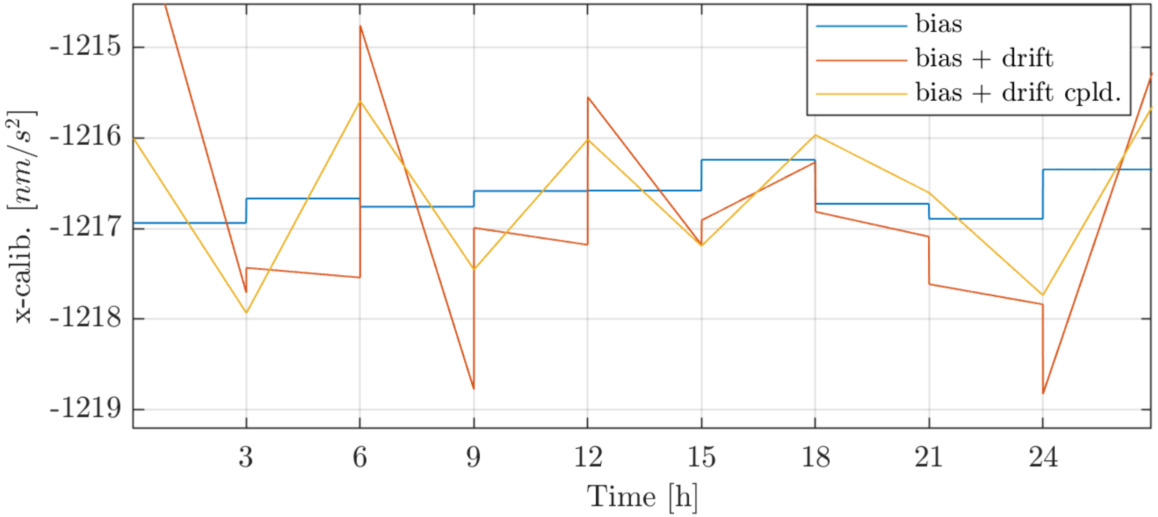
POD Accelerometer Calibration

Parametrization

- Calibration of Accelerometer
- $ACC_{cal} = \vec{s}\,\left(ACC + \vec{b}(t)/\vec{s}\right)$

Scale **Offset**

- Parametrization
  - Which parameter
  - Global and local parameters
  - Arc length for glob. and loc. parameters
  - Couple parameters between arcs



Different offset parametrizations: bias, bias+drift and bias+drift coupled, for one axis

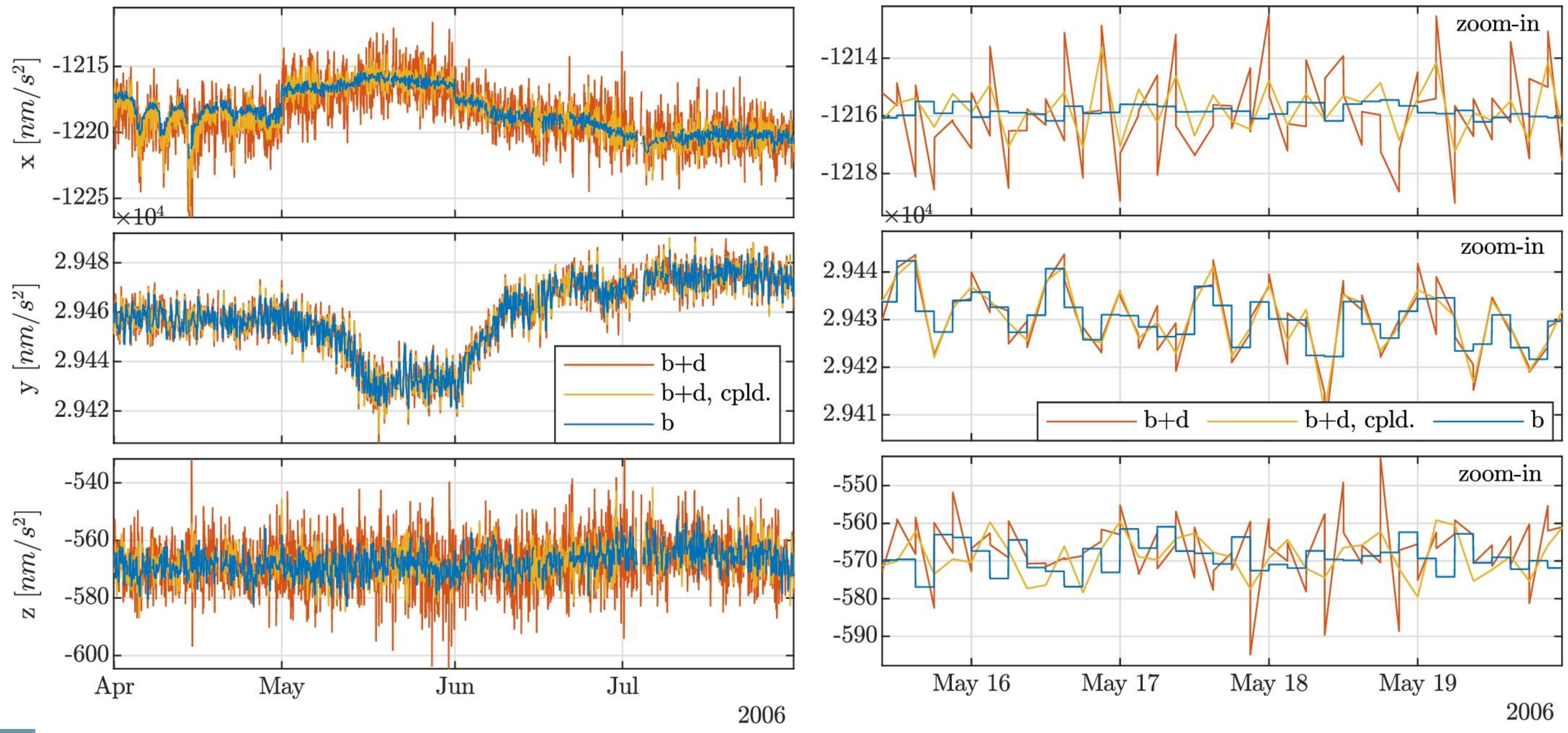
Offset	Scale factor	Arc length scale	Arc length offset
Bias	estimated or constant	3h, 1, 3, 7 days, 1 month	3h
Bias + drift	est., const.	3h … 1m	3h
Bias + drift cpld.	est., const.	1m	3h

POD Accelerometer Calibration

Parametrization - Offset

- $ACC_{cal} = \vec{s}\,\left(ACC + \vec{b}(t)/\vec{s}\right)$
- Additional drift increases offset variability
- Coupling only reduces variability slightly
- Bias only gives smoothest offset
- Lower variability in x-axis than y- and z-axis

Offset	Scale factor	Arc len. scale	Arc len. offset
Bias	est., const.	3h … 1m	3h
Bias+drift	est., const.	3h … 1m	3h
Bias+drift cpld.	est., const.	1m	3h



Offset

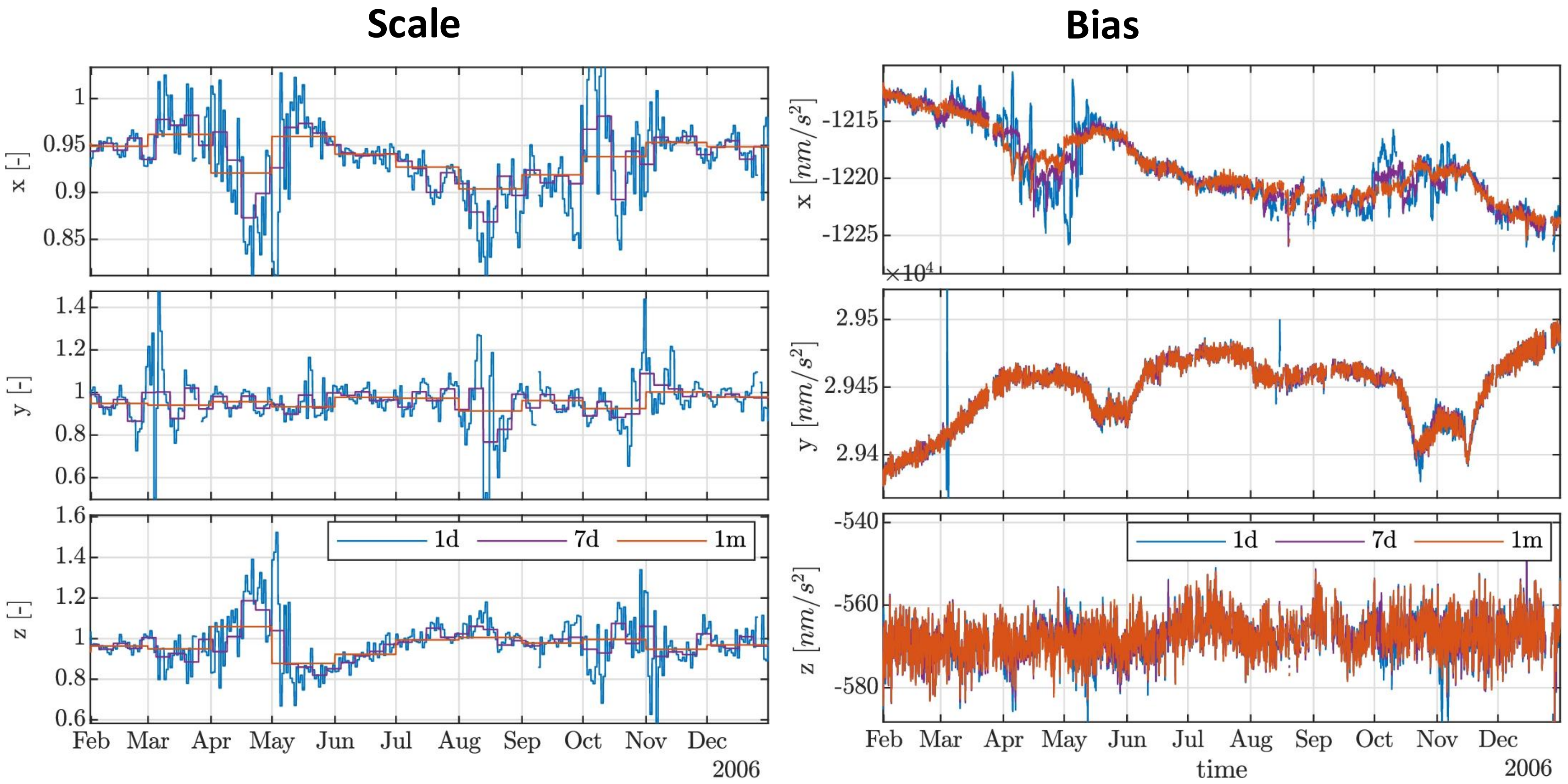
Zoom-in

Calibration with different offset parametrizations: bias, bias+drift and bias+drift coupled, GRACE A

POD Accelerometer Calibration

Parametrization – Scale (arc length)

- $ACC_{cal} = \vec{s}\,\left(ACC + \vec{b}(t)/\vec{s}\right)$
- The shorter the arc length, the higher the scale variability
- Abrupt bias changes reduce with smoother scale
- 1 day results do not seem physical



Offset	Scale factor	Arc len. scale	Arc len. offset
Bias	est., const.	3h … 1m	3h
Bias+drift	est., const.	3h … 1m	3h
Bias+drift cpld.	est., const.	1m	3h

Calibration with different scale parametrization: 1 day, 7 days and 1 month, GRACE A

POD Accelerometer Calibration

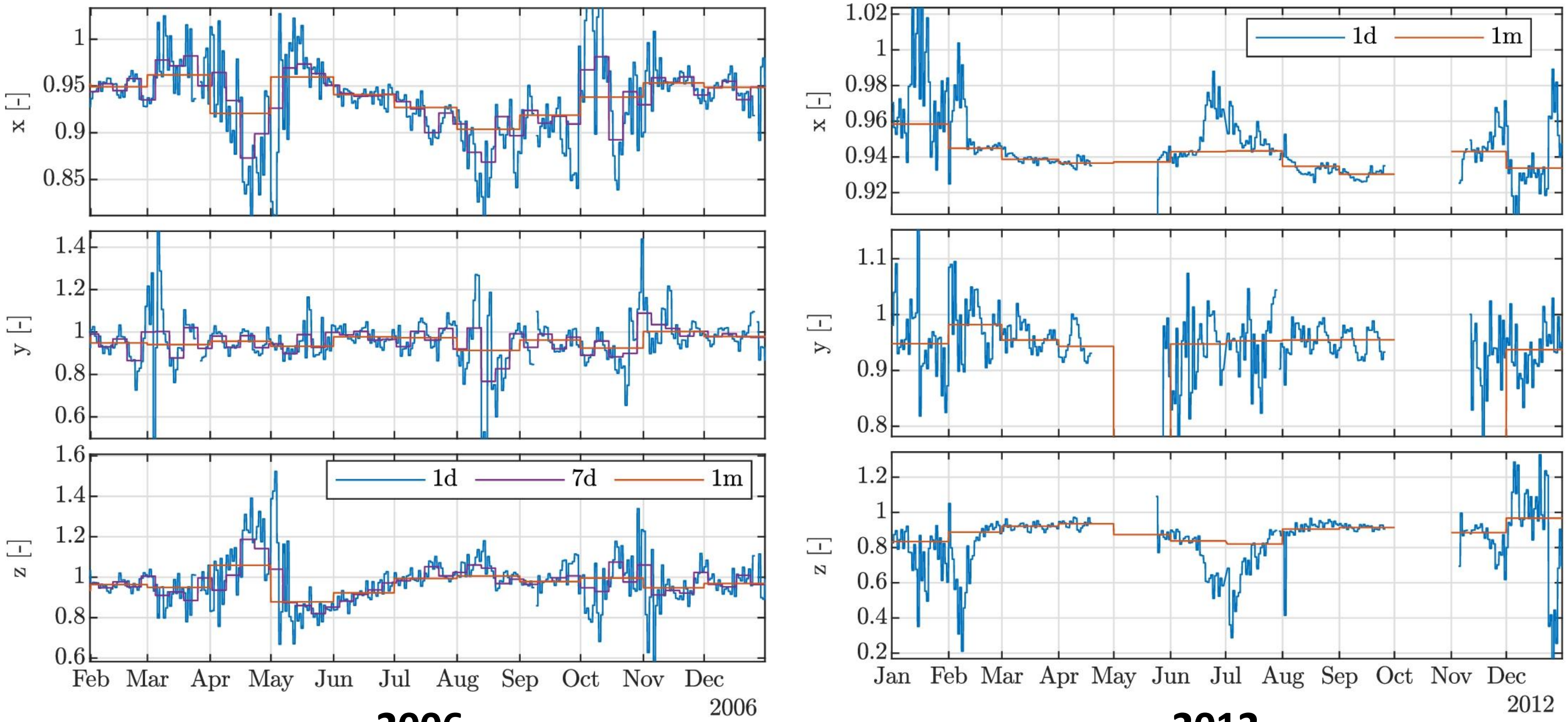
Parametrization – Scale (arc length)

- $ACC_{cal} = \vec{s}\left(ACC + \vec{b}(t)/\vec{s}\right)$

- 2012 higher solar activity -> higher drag in x-axis
- Lower variability in x-axis
- Scale factor sensitive to size of total acceleration, in contrast to offset (bias)

Scale

Scale



2006 **2012**

Scale with different parametrization: 1 day, 7 days and 1 month, GRACE A

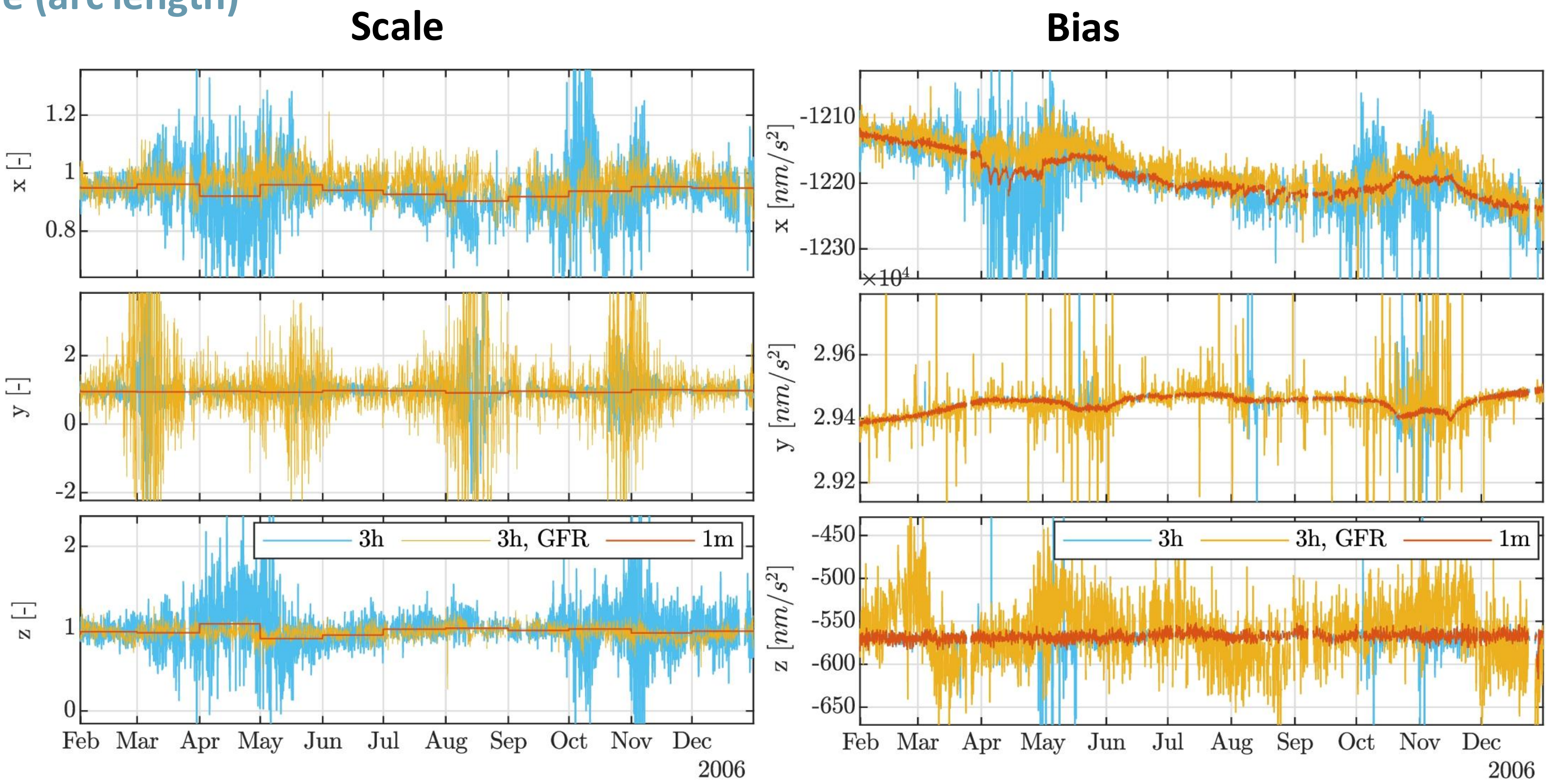
Offset	Scale factor	Arc len. scale	Arc len. offset
Bias	est., const.	3h … 1m	3h
Bias+drift	est., const.	3h … 1m	3h
Bias+drift cpld.	est., const.	1m	3h

POD Accelerometer Calibration

Parametrization, POD and GFR – Scale (arc length)

- $ACC_{cal} = \vec{s}\left(ACC + \vec{b}(t)/\vec{s}\right)$

- Definitely no physical calibration results with 3h scale
- Not enough data for estimation of insensitive parameters
- Scale and bias coupled
- GFR shows different trend
- Sensitivity of GFR and POD interchanged in y- and z-axis



POD and GFR calibration with **3h** scale parametrization, GRACE A.
(Monthly POD scale as reference)

Offset	Scale factor	Arc len. scale	Arc len. offset
Bias	est., const.	3h … 1m	3h
Bias+drift	est., const.	3h … 1m	3h
Bias+drift cpld.	est., const.	1m	3h

POD Accelerometer Calibration

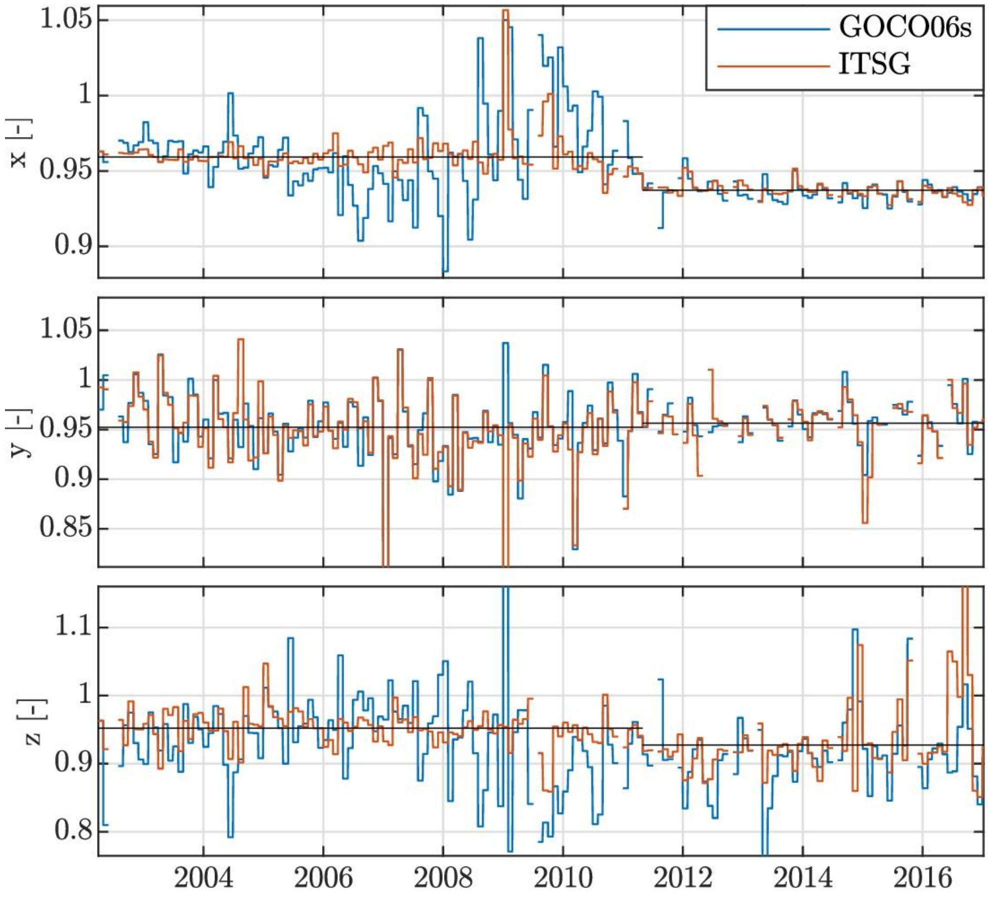
Scale Parametrization, Gravitational Models

- $ACC_{cal} = \vec{s}\,(ACC + \vec{b}(t)/\vec{s})$

- Scale variability correlates with size of total acceleration (x-axis)
- ACC temperature control switch-off in April 2011
- We also estimated const. scale factors for two periods
- Much higher variability with GOCO06s

Pertubation	Model
Earth gravity	Different: GOCO06s, EIGEN-6s4, ITSG, COST-G/ FSM, GGM05s

Offset	Scale factor	Arc len. scale	Arc len. offset
Bias	est., const.	3h … 1m	3h
Bias+drift	est., const.	3h … 1m	3h
Bias+drift cpld.	est., const.	1m	3h



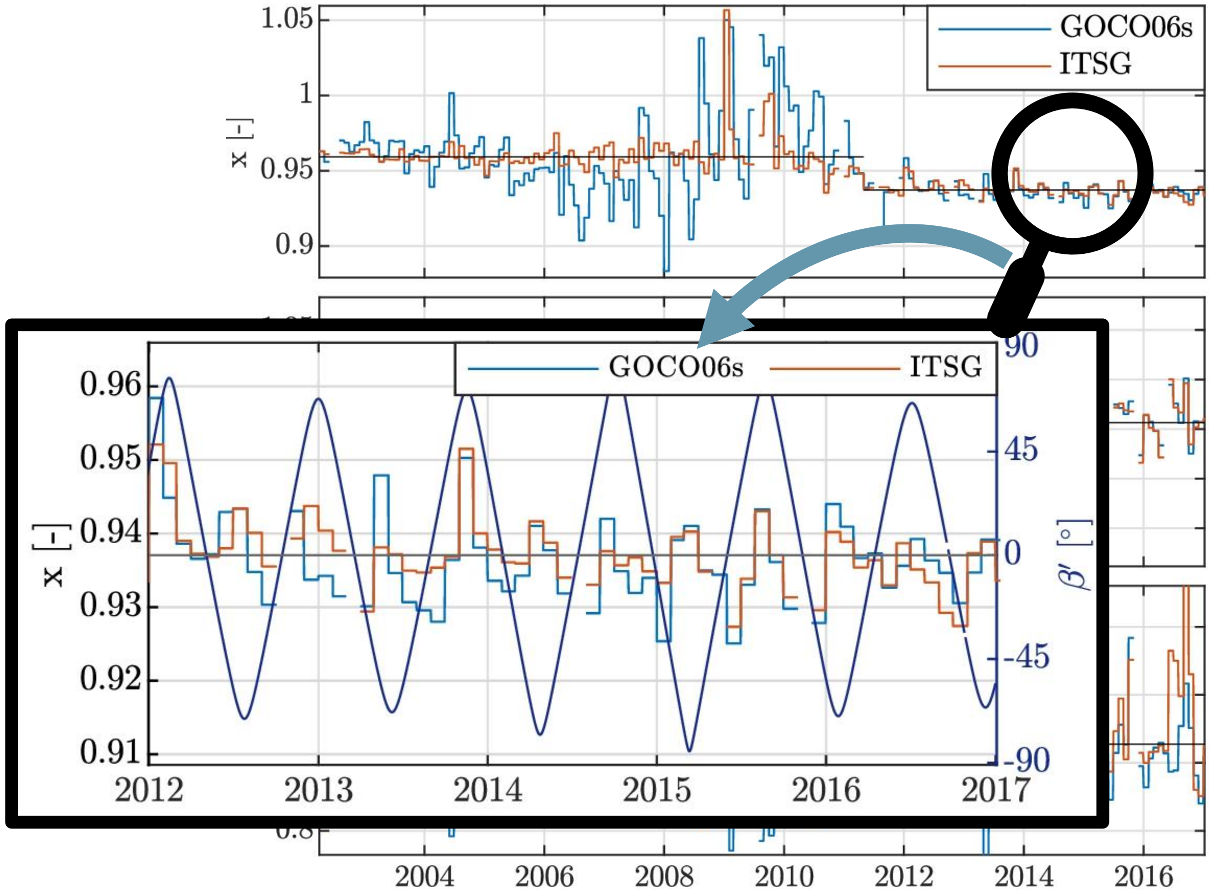
Estimated monthy and const. scale, with GOCO06s and ITSG gravitational models, GRACE A.

POD Accelerometer Calibration

Parametrization – Scale

- $ACC_{cal} = \vec{s}\ (ACC + \vec{b}(t)/\vec{s})$

- Oscillation with β’ angle which correlates with sensor temperature
- Visible due to distinctly higher total accelerations



Estimated monthy scale, with GOCO06s and ITSG gravitational models, and const. scale (two periods), GRACE A.

Offset	Scale factor	Arc len. scale	Arc len. offset
Bias	est., const.	3h … 1m	3h
Bias+drift	est., const.	3h … 1m	3h
Bias+drift cpld.	est., const.	1m	3h

POD Accelerometer Calibration

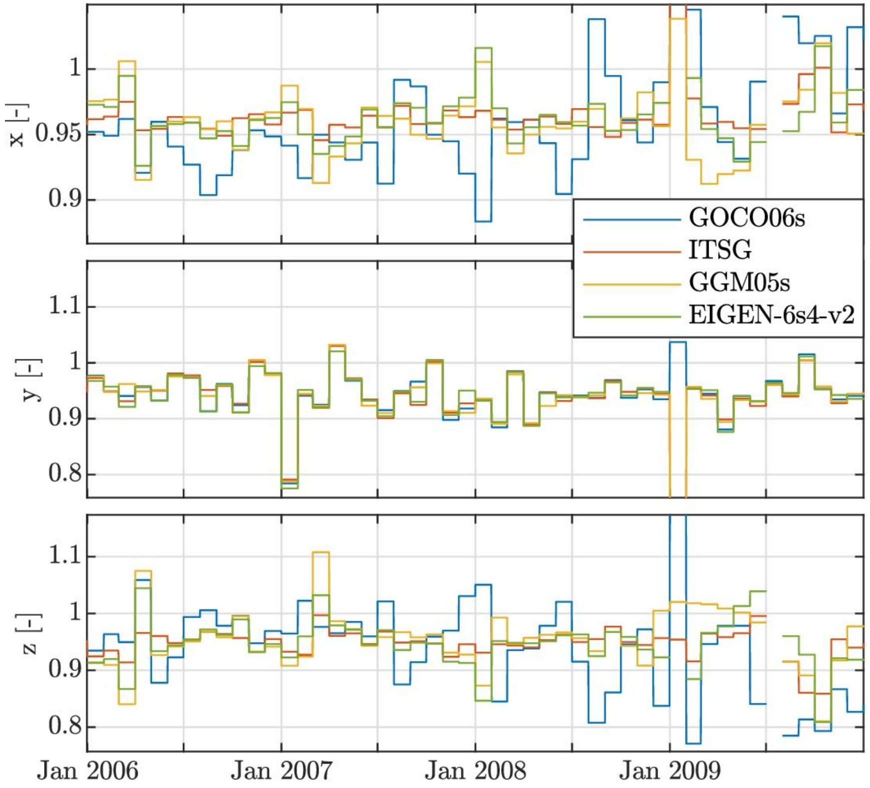
Gravitational Models GRACE

- Different type of models
- GOCO06s time dependent
- EIGEN-6s4 time dependent
- ITSG monthly
- GGM05s mean, 2003-2013

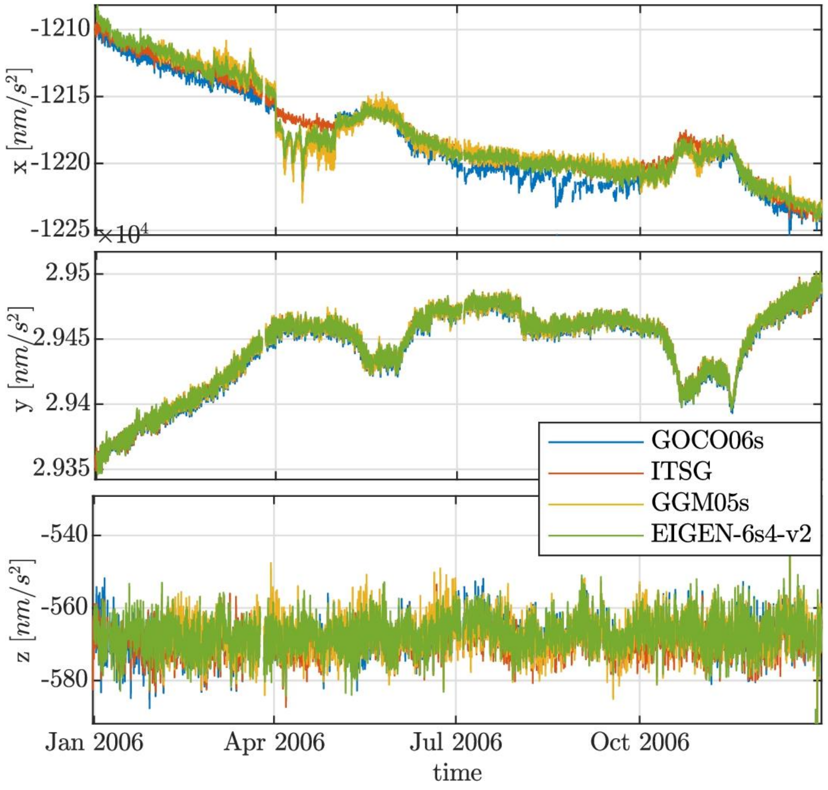
- Much bigger scale variability for GOCO06s
- ITSG giving smoothest results for scale and bias

  (very similar to monthly COST-G models)

Scale



Bias



Calibration with monthly scale for different gravitational models GOCO06s, ITSG, GGM05s and EIGEN-6s4, **GRACE A**.

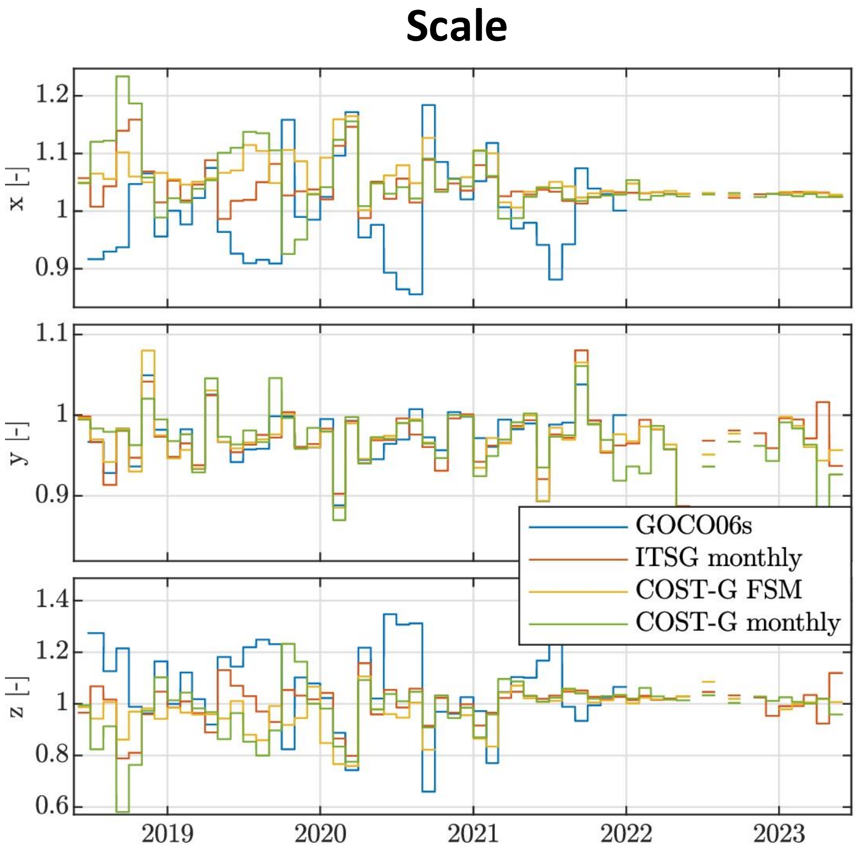
Pertubation	Model
Earth gravity	Different: GOCO06s, EIGEN-6s4, ITSG, COST-G/ FSM, GGM05s

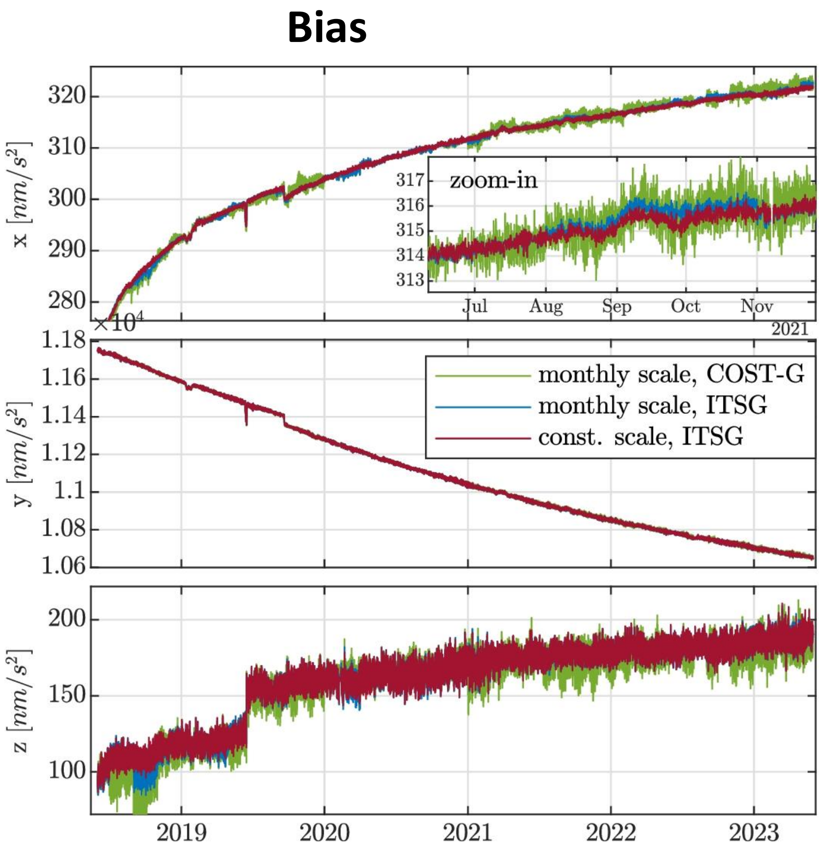
POD Accelerometer Calibration

Gravitational Models GRACE-FO

- Different type of models
- GOCO06s time dependent
- COST-G FSM time dependent
- ITSG monthly
- COST-G monthly

- Also here GOCO06s distinctly different
- Monthly COST-G bias slightly more noisy





Pertubation	Model
Earth gravity	Different: GOCO06s, EIGEN-6s4, ITSG, COST-G/ FSM, GGM05s

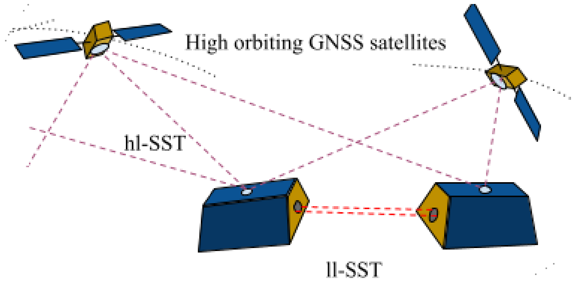
Calibration with monthly scale for different gravitational models GOCO06s, ITSG, COST-G FSM and COST-G monthly, **GRACE-FO C**.

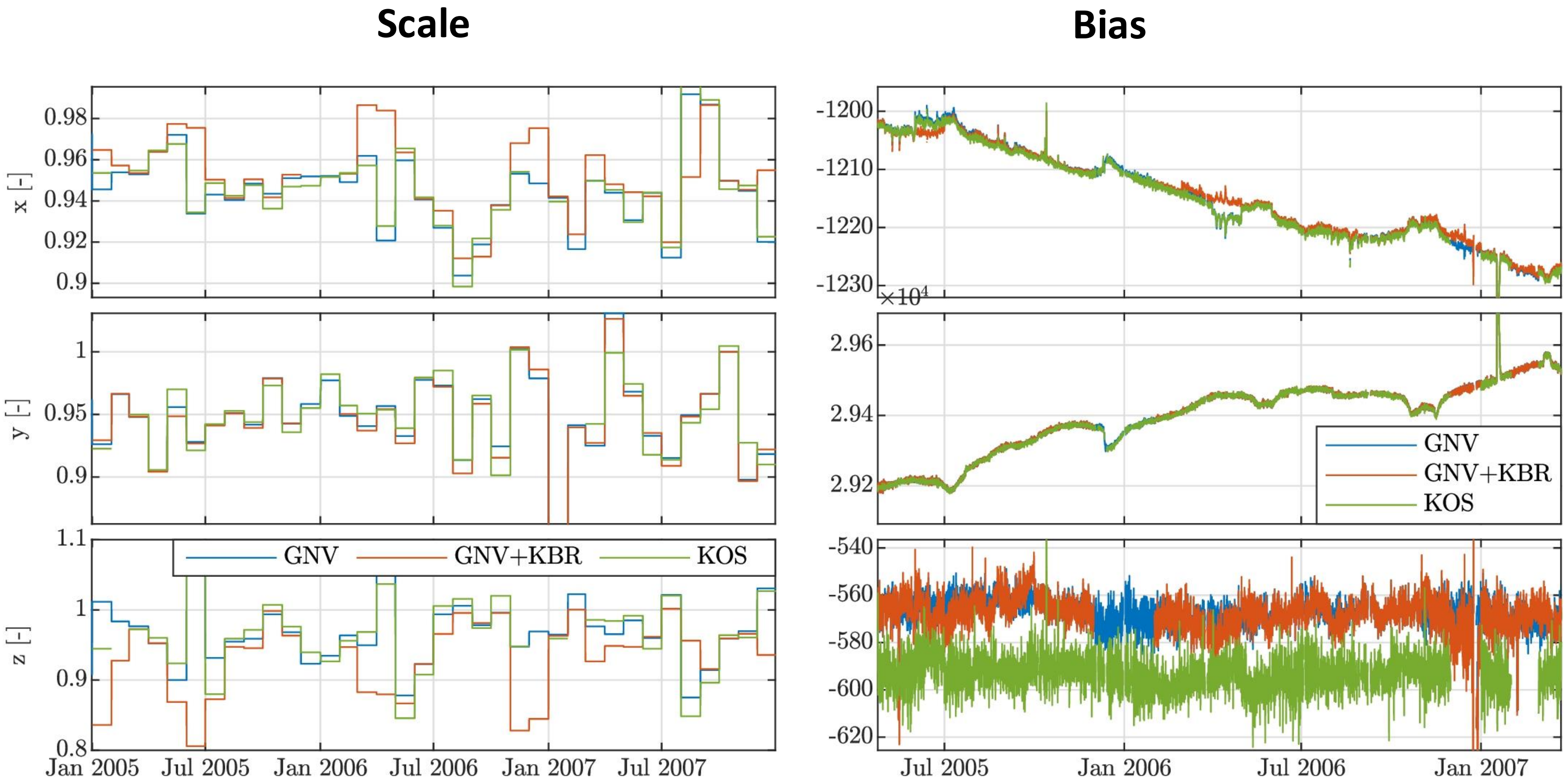
POD Accelerometer Calibration

Different Observation Data

- Official reduced-dynamic orbit solution GNV L1B
- Kinematic Orbits KOS (from TU Graz)
- K-Band inter satellite ranging KBR L1B range rate (+GNV)

- GNV and KOS very similar BUT for z-bias
- With KBR higher scale variability





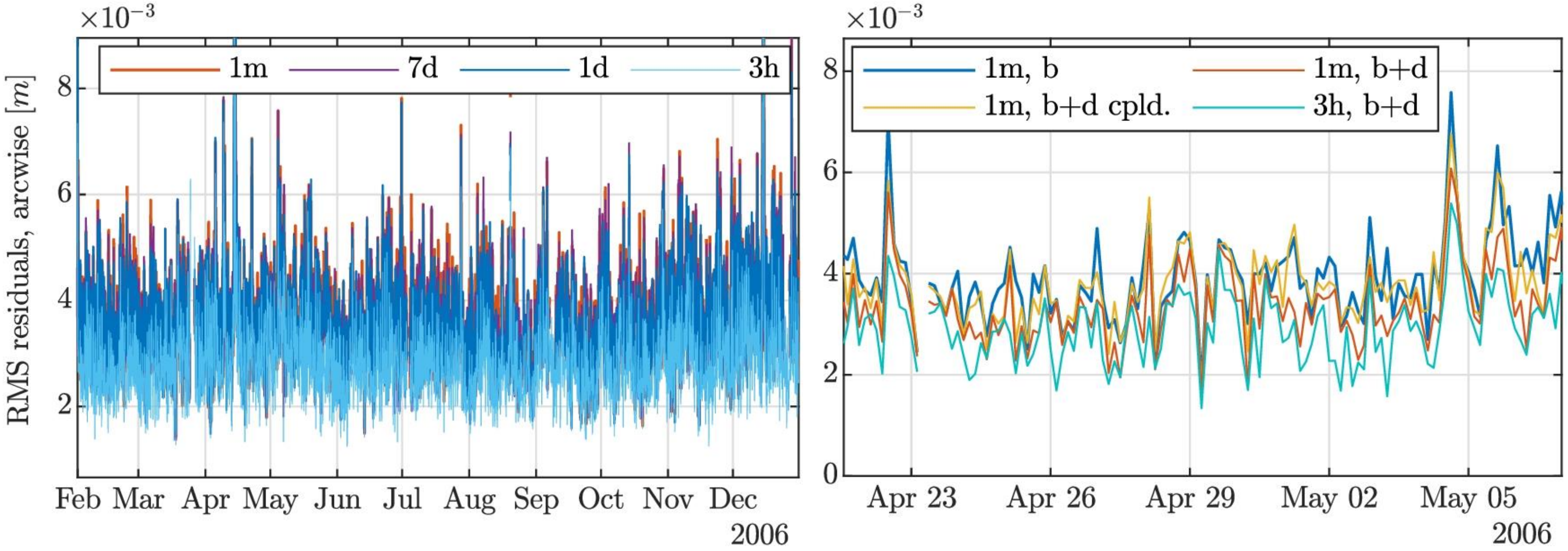
Calibration with monthly scale with different observation data GNV, GNV+KBR and KOS, GRACE A.

Validation of Calibration

Post-fit POD Residuals

- Residuals are lower the more parameters are estimated
- This is the case for all shown parametrizations
- 3h and 1d scale showed very unphysical calibration results
- → Residuals are not able to validate ACC calibration

Arc-wise RMS of position residuals



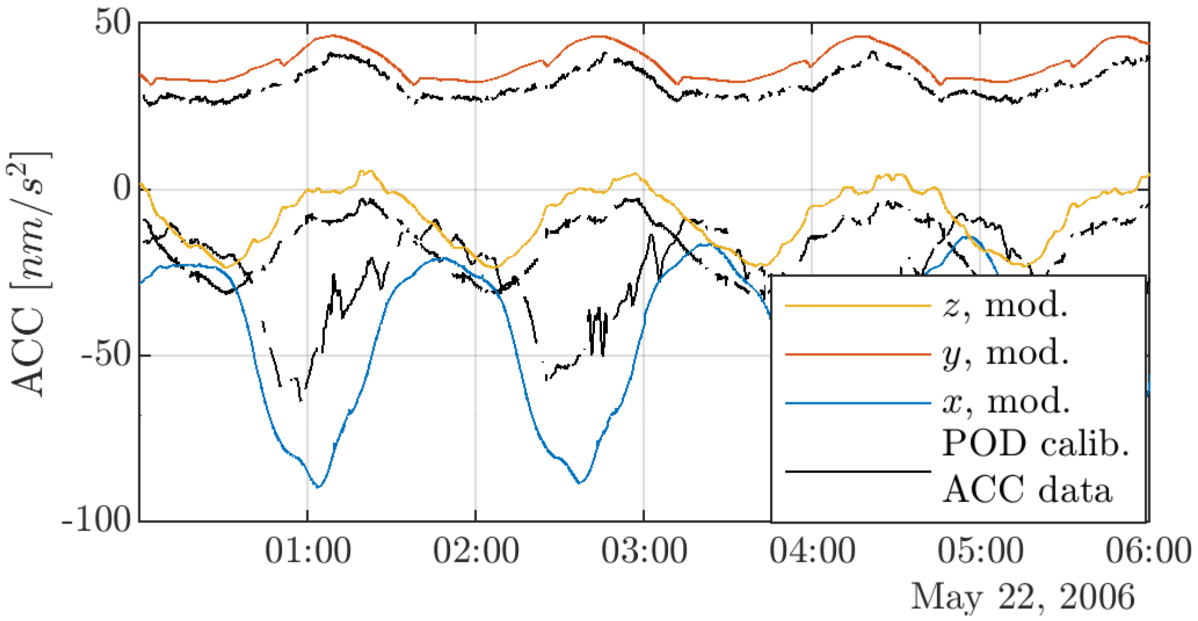
Different scale parametrization:
3 hours, 1 day, 7 days and 1 month

Different offset parametrization:
bias, bias + drift, bias + drift cpld. and bias + drift. 3h

Validation of Calibration

With Modeled Accelerations

- Very accurate radiative non-gravitational force models
- X-axis closely aligned with orbital velocity direction
- → When solar activity is low basically no drag in y-, z-axis
- Comparison of x-axis not meaningful



Modeled accelerations in x-, y-, z-axis and POD calibrated ACC data

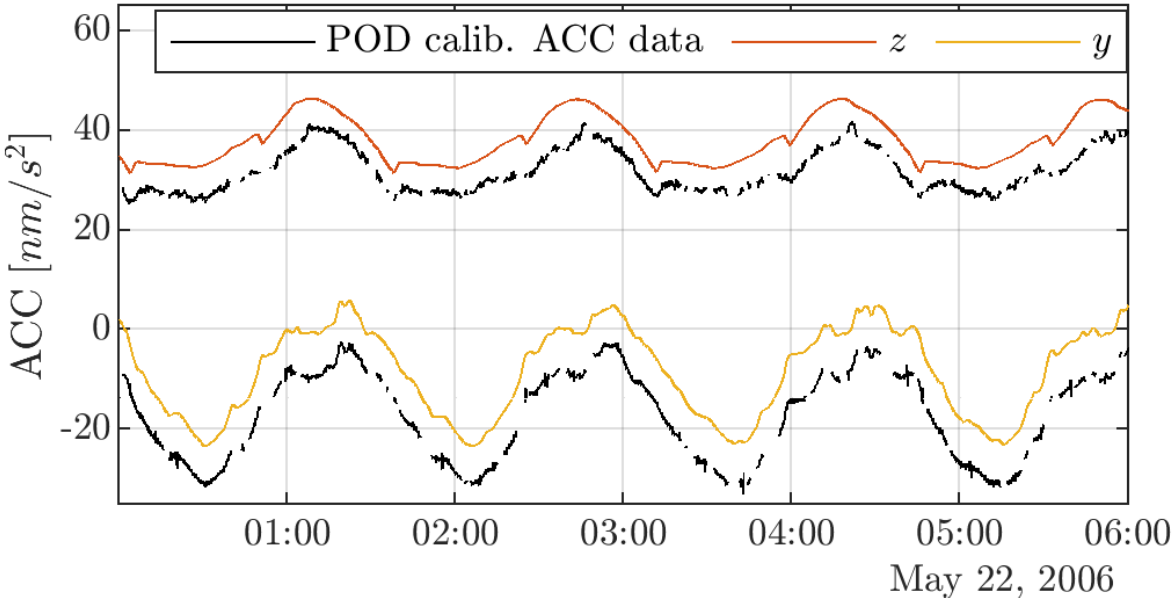
Validation of Calibration

With Modeled Accelerations

- Very accurate radiative non-gravitational force models
- X-axis closely aligned with orbital velocity direction
- → When solar activity is low basically no drag in y-, z-axis
- Comparison of x-axis not meaningful

- Sensitivity of POD in x-direction much higher than in y- and z-direction

  → No direct conclusions from y, z results on x possible!
- But ACC should behave the same in all axes



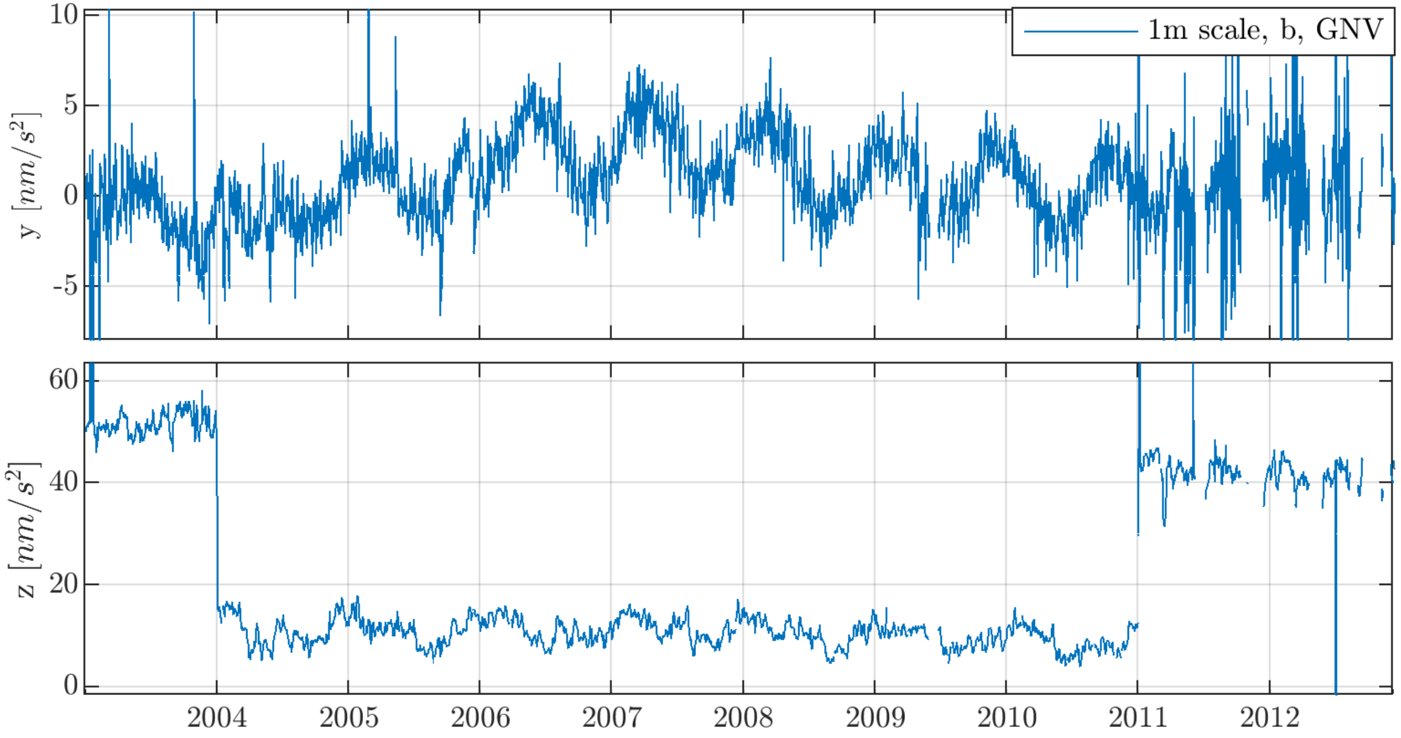
Modeled accelerations in y-, z-axis and POD calibrated ACC data

RMS residuals in y, z: 6.16, 8.19 nm/s^2

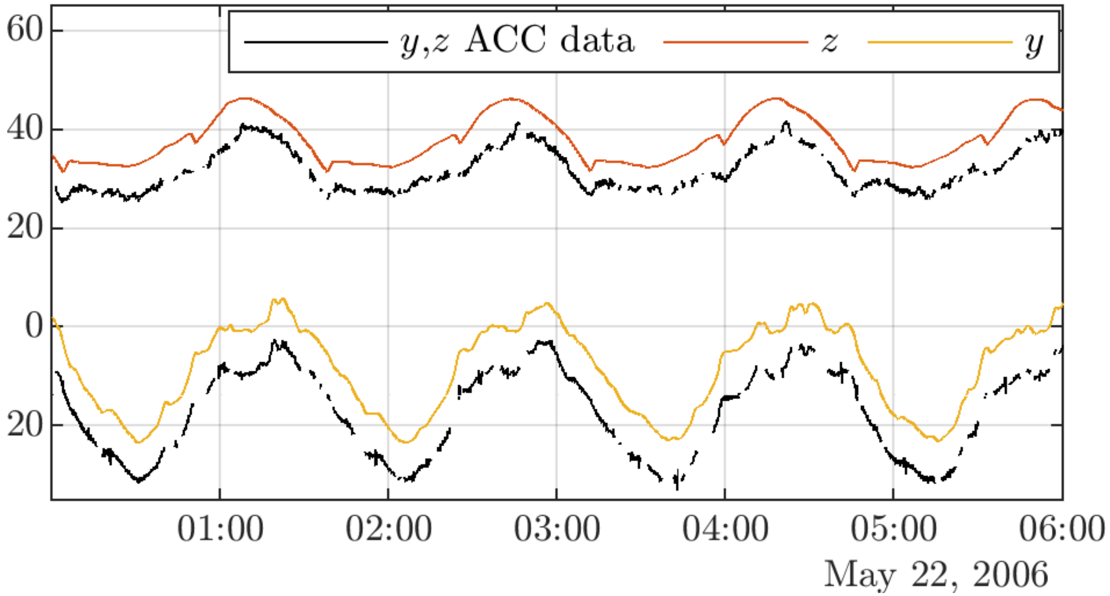
Validation of Calibration

With Modeled Accelerations

- Very accurate radiative non-gravitational force models
- Comparison of x-axis not meaningful



Offset difference POD calibration and modeled acc. (daily bias)



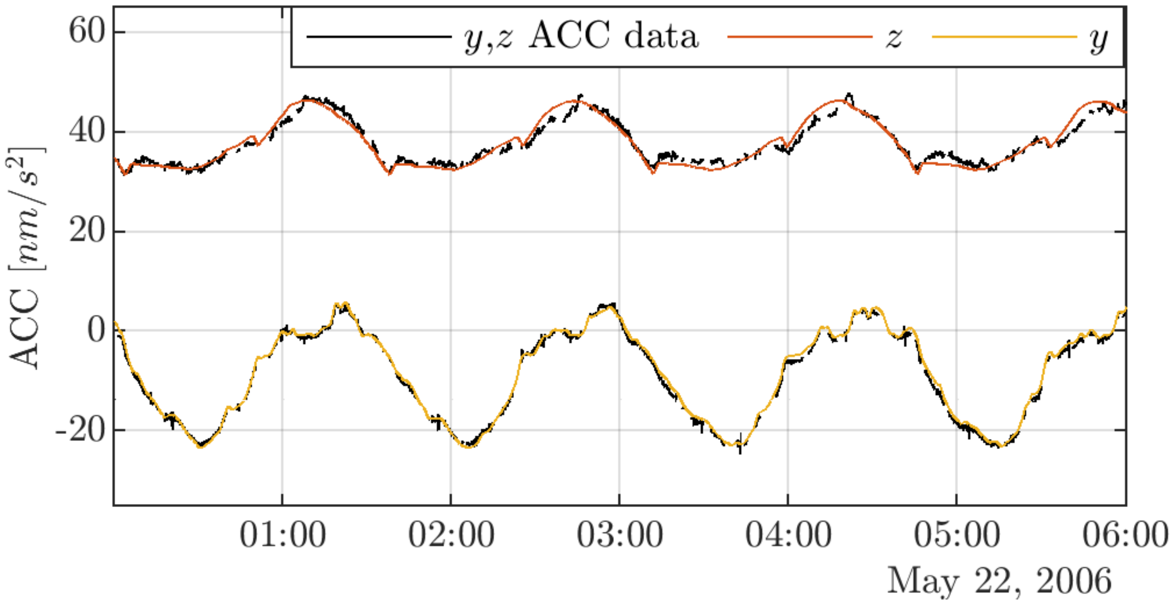
Modeled accelerations in y-, z-axis and POD calibrated ACC data

Validation of Calibration

With Modeled Accelerations

- Very accurate radiative non-gravitational force models
- Comparison of x-axis not meaningful
- When solar activity is low basically no drag in y-, z-axis

- Very big offsets up to 60%
- → Unrealistic that models have such large offset while matching the trend very well
- Difference is mainly an error of POD
- → Estimation of an additional daily bias w.r.t. modeled data for y- and z-axis
- Residuals to validate differernt POD calibration options



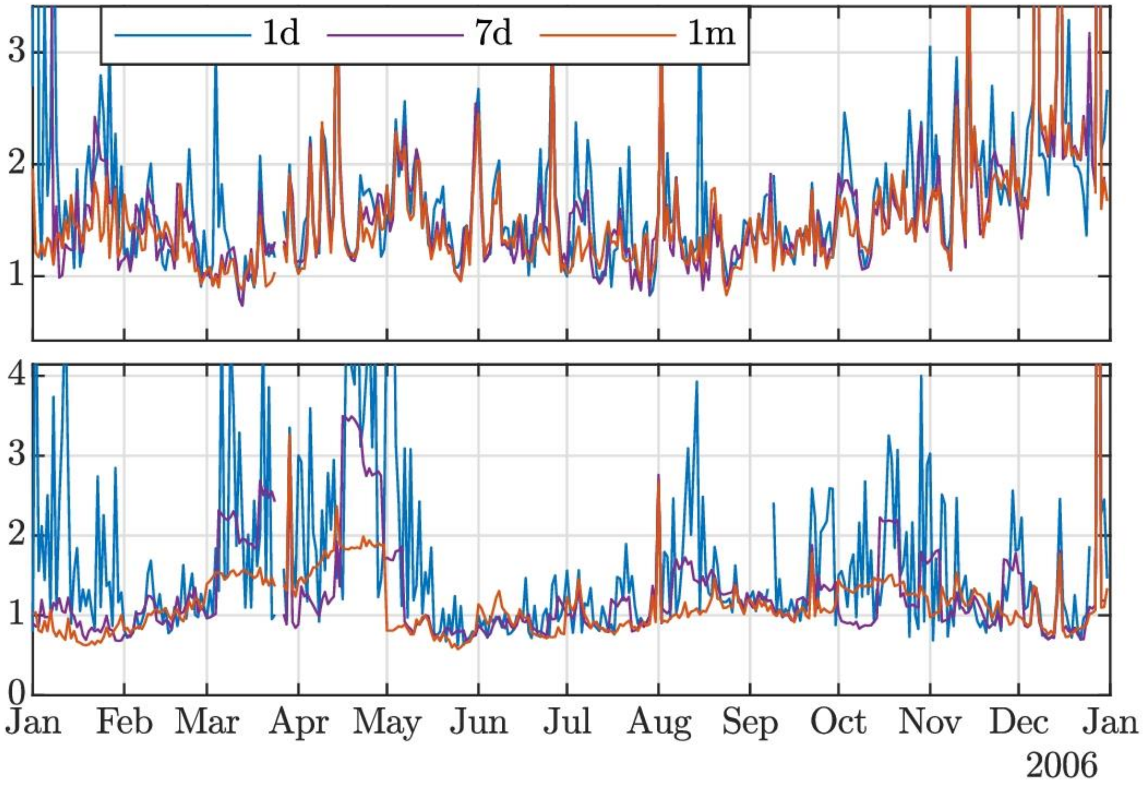
Modeled accelerations in y-, z-axis and POD calibrated ACC data

RMS residuals in y, z: 1.06, 0.70 nm/s^2

Validation of Calibration

With Modeled Accelerations

- Residuals between POD calibration and modeled accelerations
- Scale factor
  - monthly
  - 7 days
  - 1 days

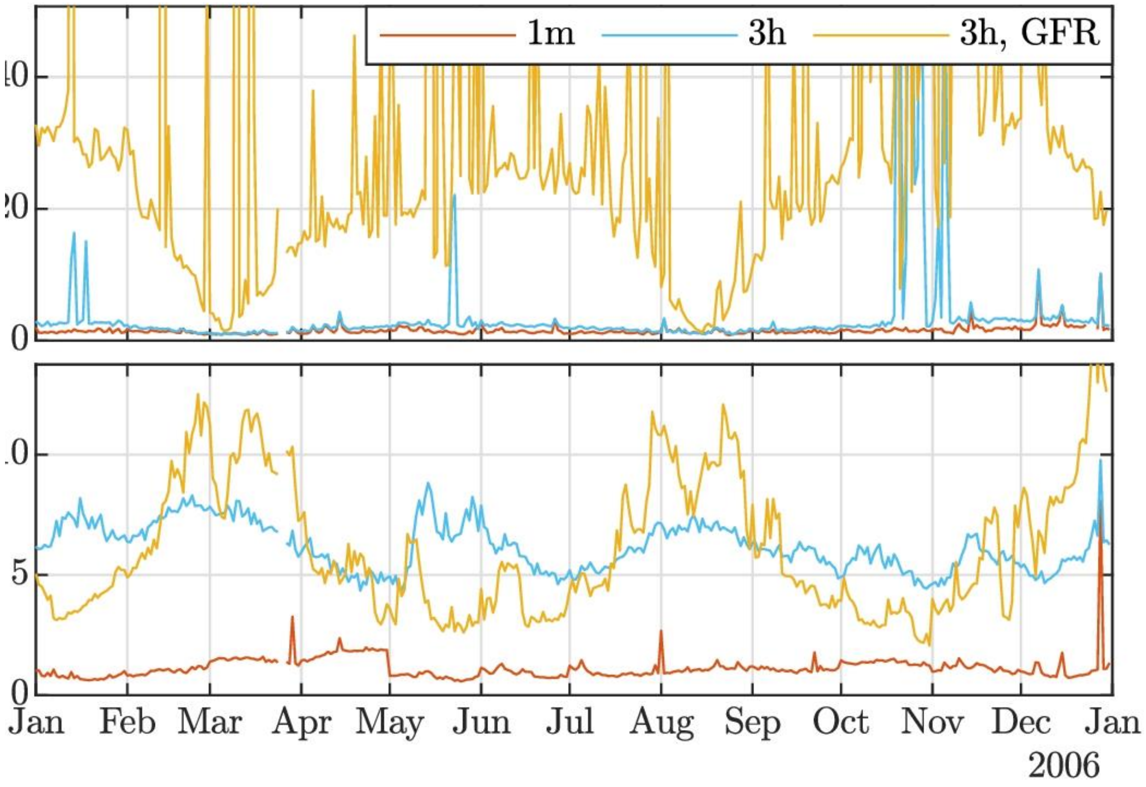


Daily RMS residuals of POD calibration and modeled accelerations (est. daily bias)

Validation of Calibration

With Modeled Accelerations

- Residuals between POD calibration and modeled accelerations
- Scale factor
  - monthly
  - 7 days
  - 1 days
  - 3 hours
  - 3 hours GFR

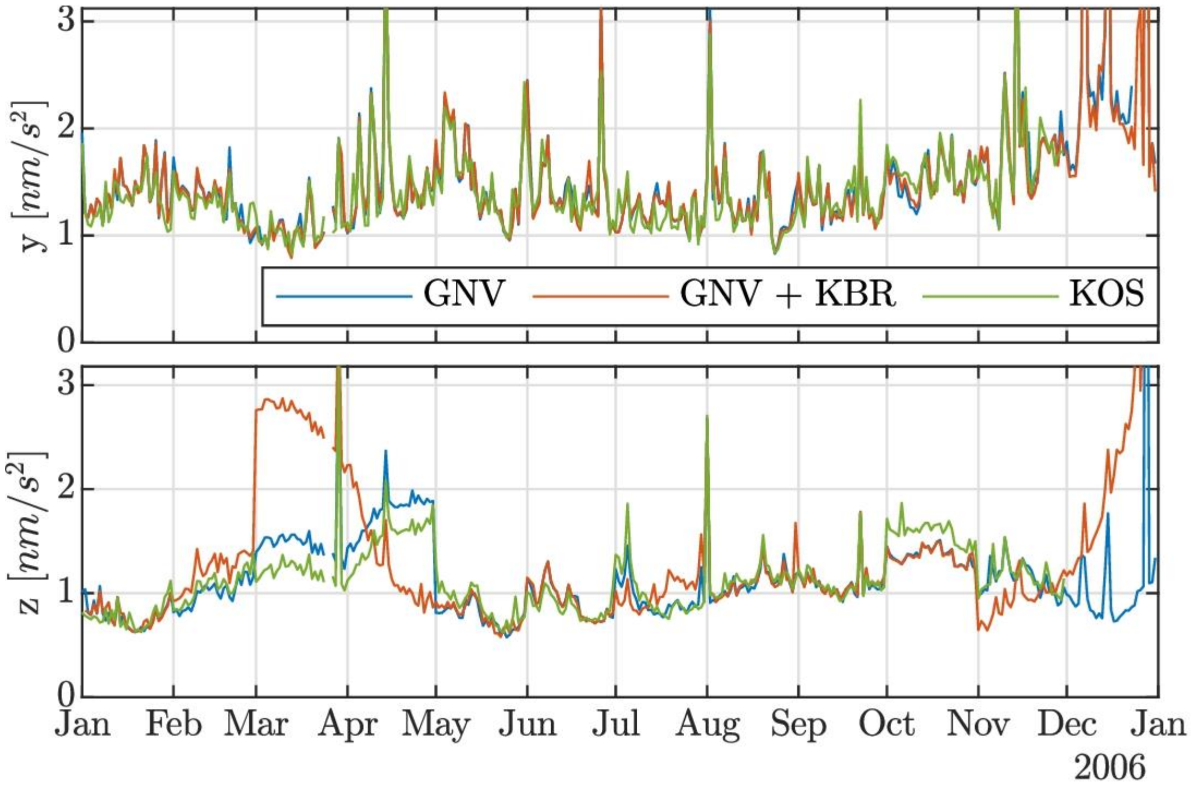


Daily RMS residuals of POD calibration and modeled accelerations (est. daily bias)

Validation of Calibration

With Modeled Accelerations

- Residuals between POD calibration and modeled accelerations
- Scale factor
  - monthly
  - 7 days
  - 1 days
  - 3 hours
  - 3 hours GFR
- Observation data
  - GNV
  - GNV + KBR
  - KOS

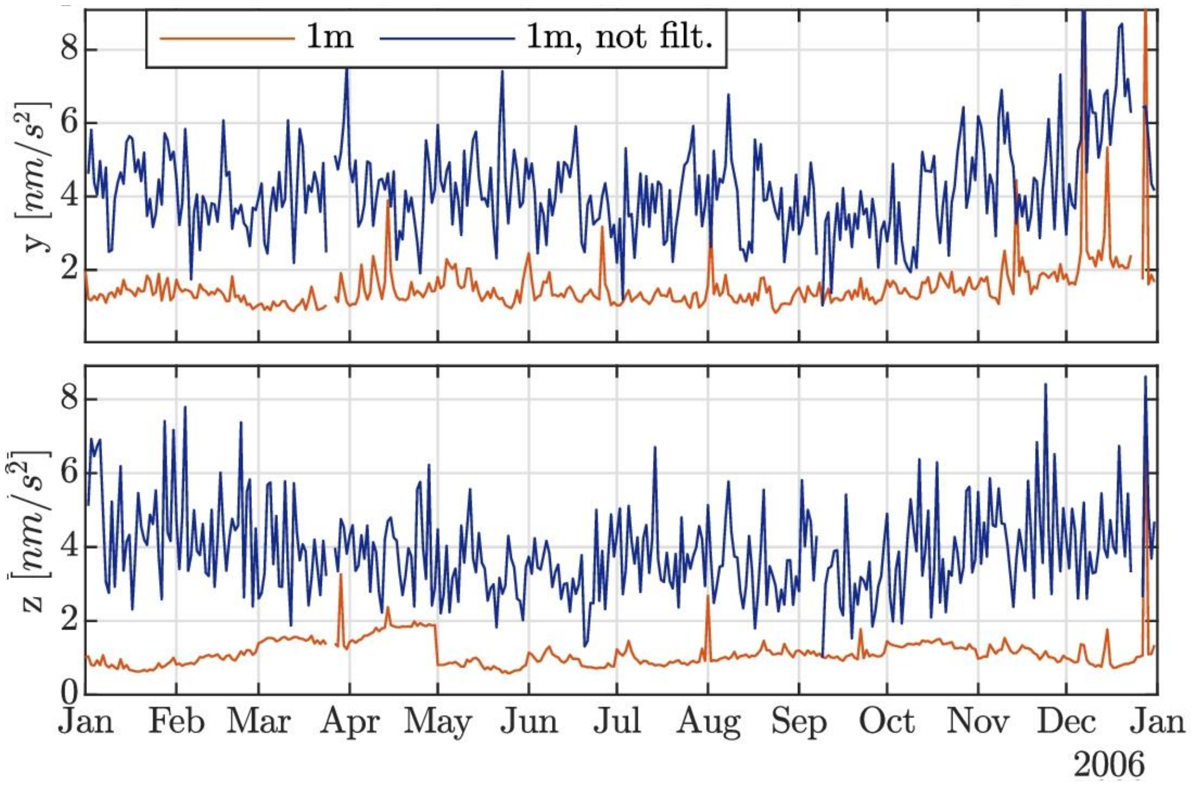


Daily RMS residuals of POD calibration and modeled accelerations (est. daily bias)

Validation of Calibration

With Modeled Accelerations

- Residuals between POD calibration and modeled accelerations
- Scale factor
  - monthly
  - 7 days
  - 1 days
  - 3 hours
  - 3 hours GFR
- Observation data
  - GNV
  - GNV + KBR
  - KOS
- Post-processing
  - bias **not** filtered



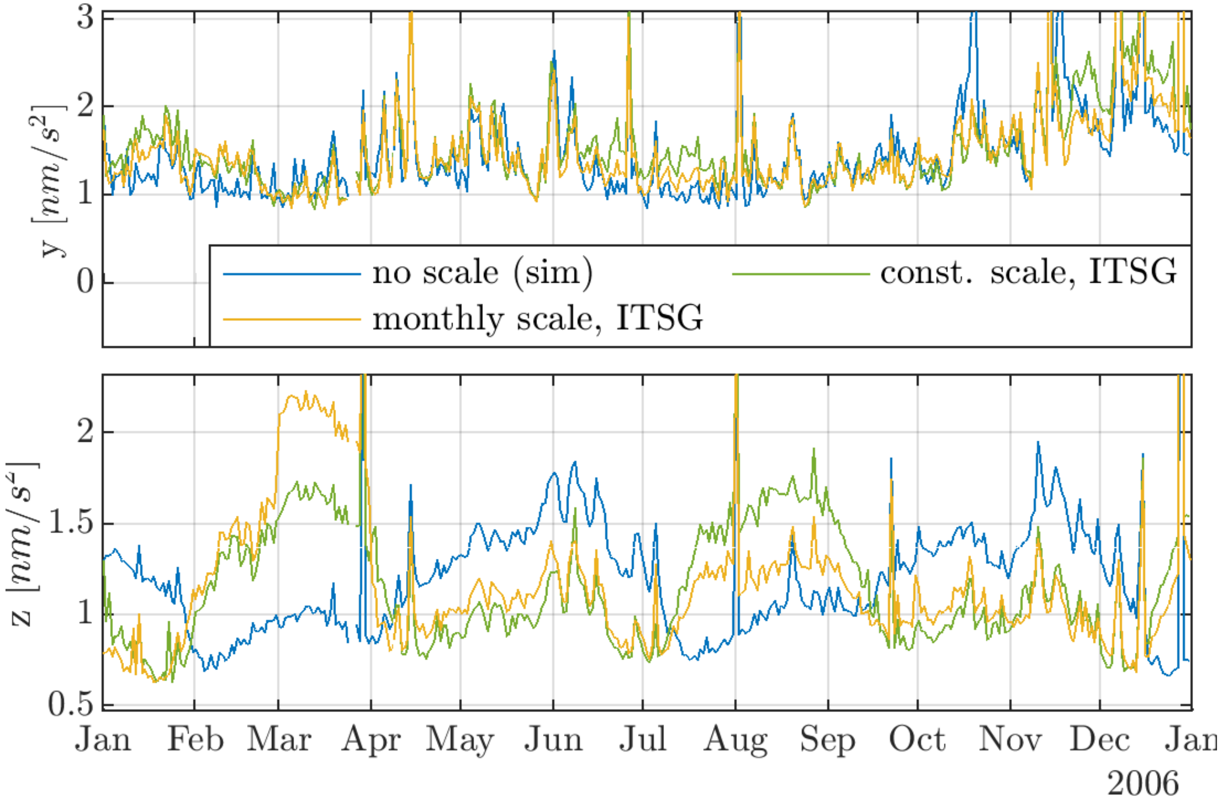
Daily RMS residuals of POD calibration and modeled accelerations (est. daily bias)

Validation of Calibration

With Modeled Accelerations

- Residuals between POD calibration and modeled accelerations
- Most promising accelerometer calibrartions
    - No scale
    - Const. scale, ITSG
    - Monthly scale ITSG

- Opposing trends
- Residuals are in range of anticipated modeling errors → validation not possible
- Final results: Monthly and const. scale, 3h, bias, ITSG gravity, GNV observations, low-pass filter of bias



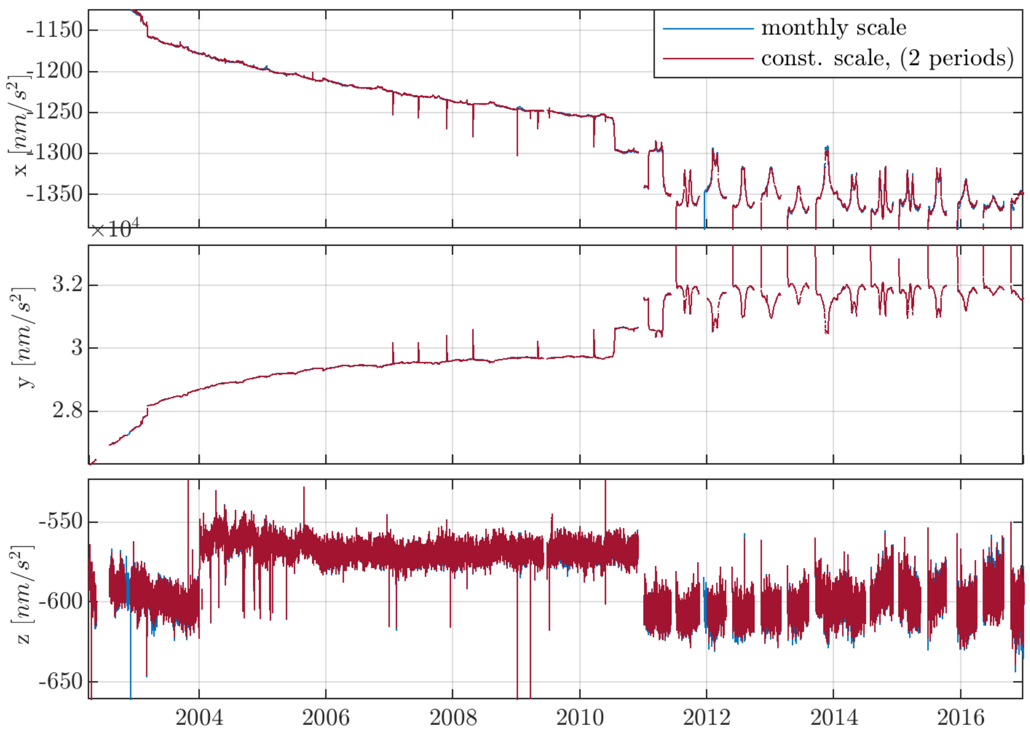
Daily RMS residuals of POD calibration and modeled accelerations (est. daily bias)

Validation of Calibration

Final Calibration

Scale

Bias



- Weighted const. scale for 2 periods or monthly scale
- 3h bias, low-pass filtered
- GNV observations, monthly ITSG models

Summary

- POD accelerometer calibration for GRACE A, B and GRACE-FO C
- Estimated density, all single modeled non-gravitational accelerations and auxiliary data are available for whole missions
- https://zarm.uni-bremen.de/zarm_daten/

- Different sensitivity in of POD in different axes
- POD is not sensitive enough in y- and z-direction for a physical ACC calibration
- Re-calibration of y- and z-axis with modeled data by daily bias
- POD position residuals are not suitable to validate calibration results
- Validation of results complicated

- Additional material uploaded
- Paper submitted to ASR