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European Gravity Service for Improved Emergency Management

WP5 NRT & Regional Service – Results and Achievements by GFZ and TUG

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Affiliation: TUG

EGSIEM Final Review Meeting

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Outline

- NRT Service - Implementation Phase
  - Improved Daily GRACE Time Series
  - Pre-operational Simulations

- NRT Service - Operational Phase
  - Results of the Operational Test Run
  - Reanalysis

- Summary And Outlook

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NRT Service – Results of the Implementation Phase

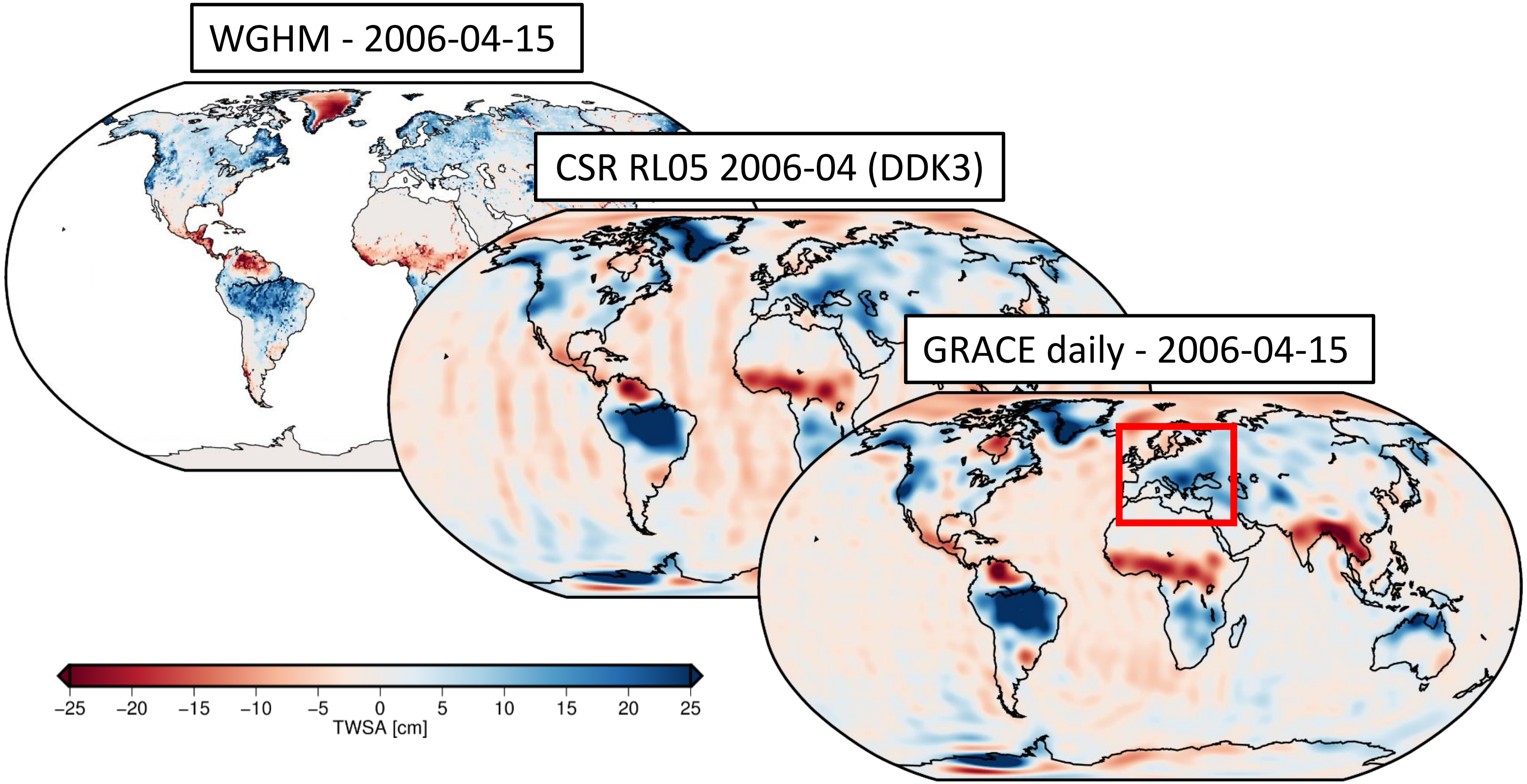
Horizon2020

Implementation Phase - Introduction and Objectives

- Main objective of the NRT Service implementation phase were:
  - the development and improvement of methods to infer high frequency mass variations from GRACE
  - implementation of automation frameworks which allow the production of robust mass variation data in near real-time

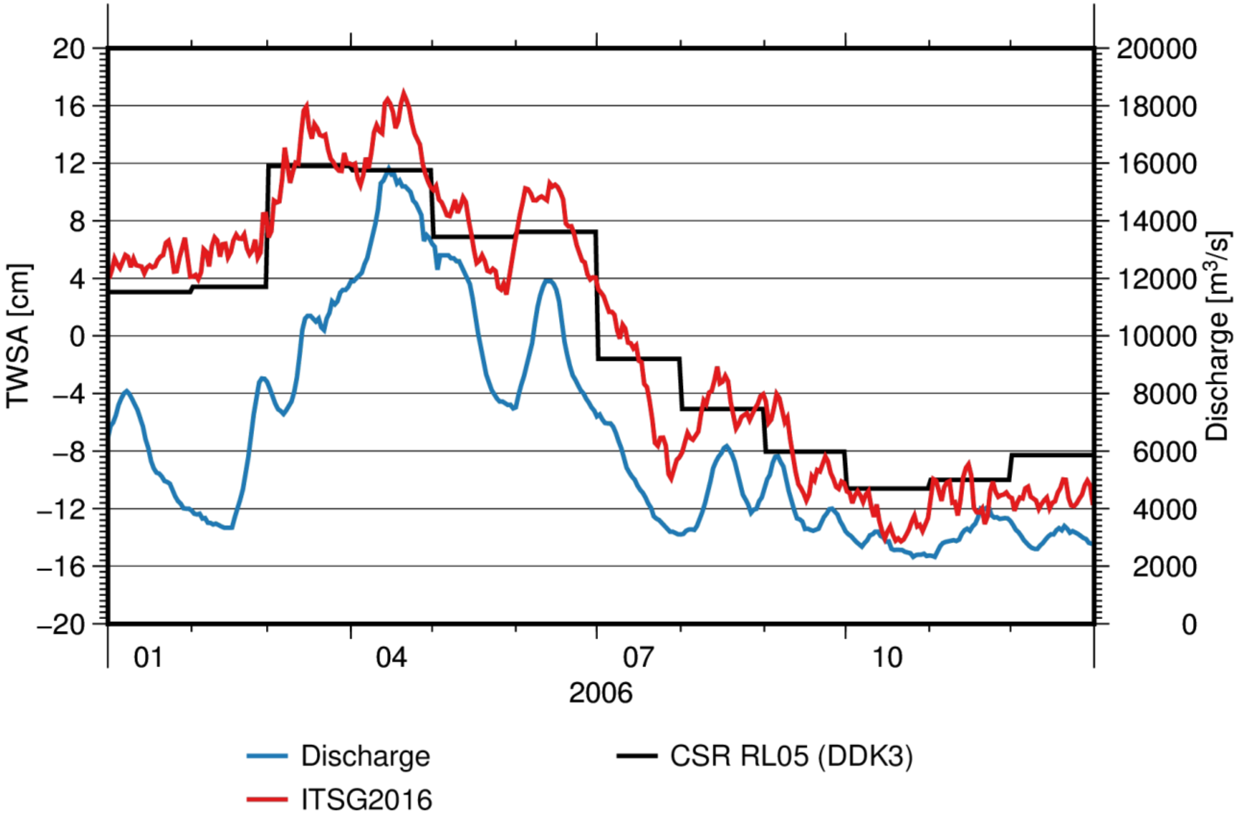
- Additionally, a simulation study was conducted to quantify the impact of the degrading satellite health during the operational service test run

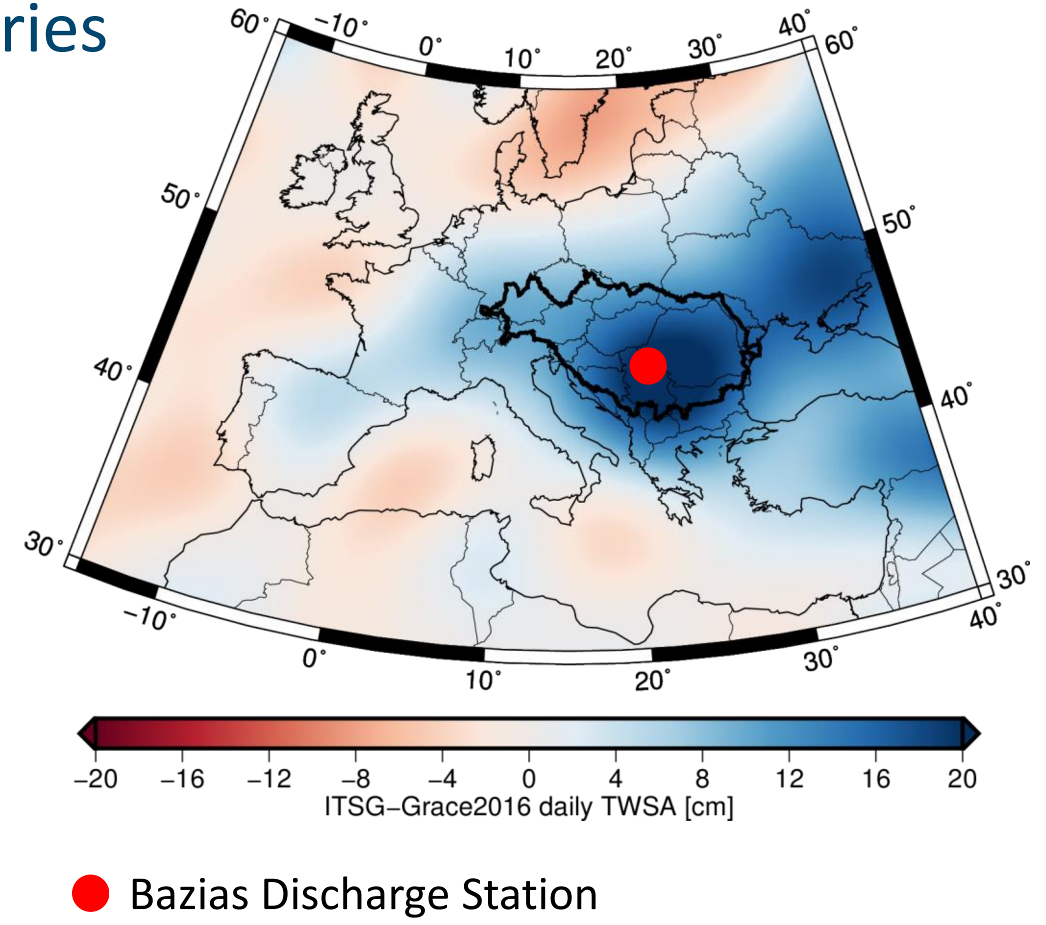
Implementation Phase – Post-processing time series



Implementation Phase – Post-processing time series

- Comparison of GRACE monthly and daily solutions with in-situ data
  - Discharge measurements at Bazias station during the 2006 Danube Flood



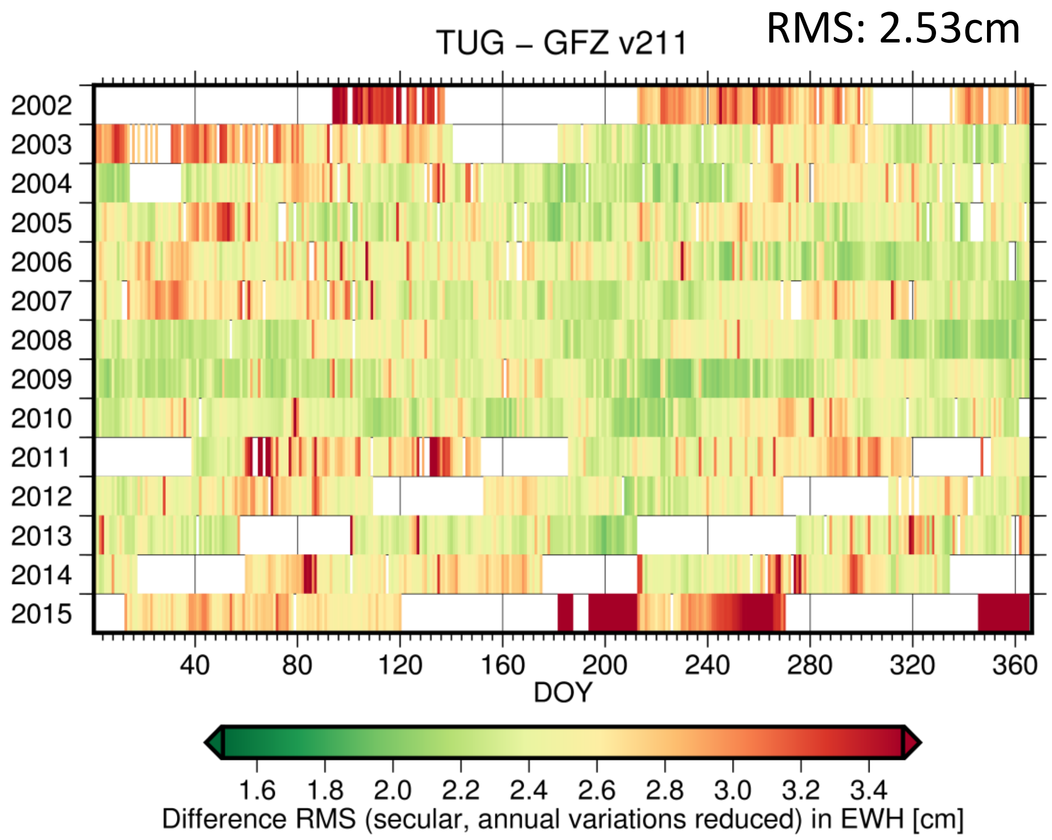


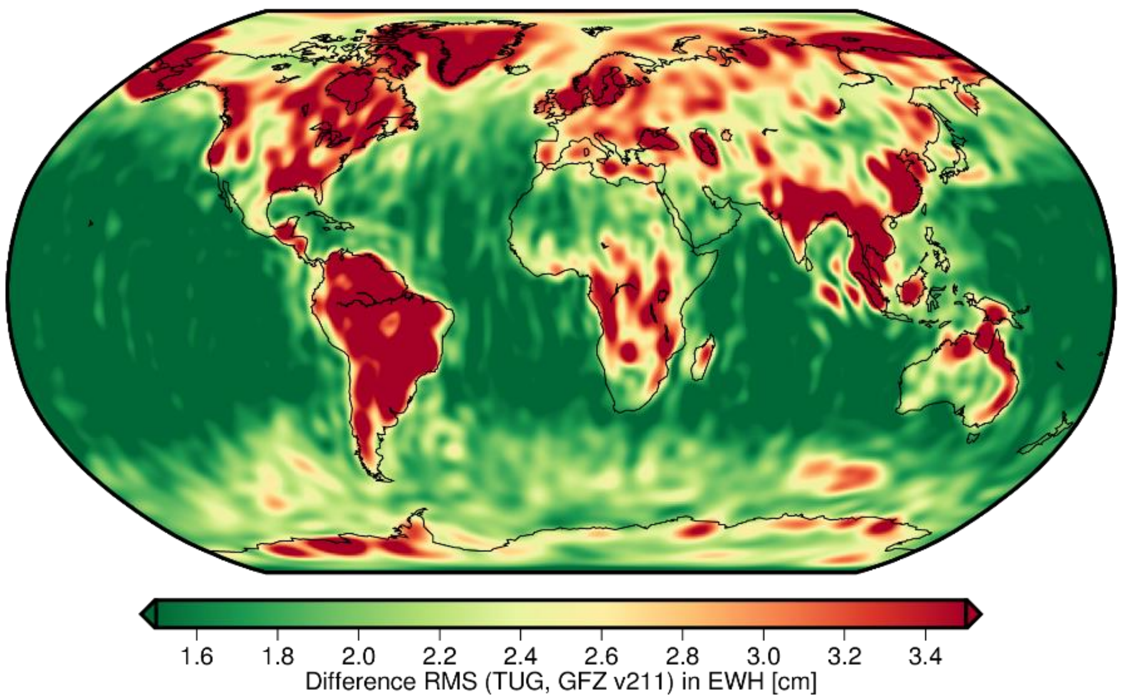
Implementation Phase – Post-processing time series

- Both GFZ and TUG produced post-processing time series to evaluate their approaches in preparation of the service run
  - GFZ focused on alternative representations of the gravity field in conjunction with a time varying Kalman filter approach
  - TUG focused on the derivation of the spatiotemporal constraints required for the Kalman filter approach
- While both centers rely on the same input data, the approaches are very different and hence should produce sufficiently independent solutions
- Both time series are available from the institutes web sites, as well a public portals such as ICGEM and have been used by the (hydrological) scientific community
- To ensure robust daily gravity time series, we checked that there is:
  - Consistency between both analysis centers (AC)
  - Good agreement with external data – GNSS displacements, ocean bottom pressure

Implementation Phase – Post-processing time series

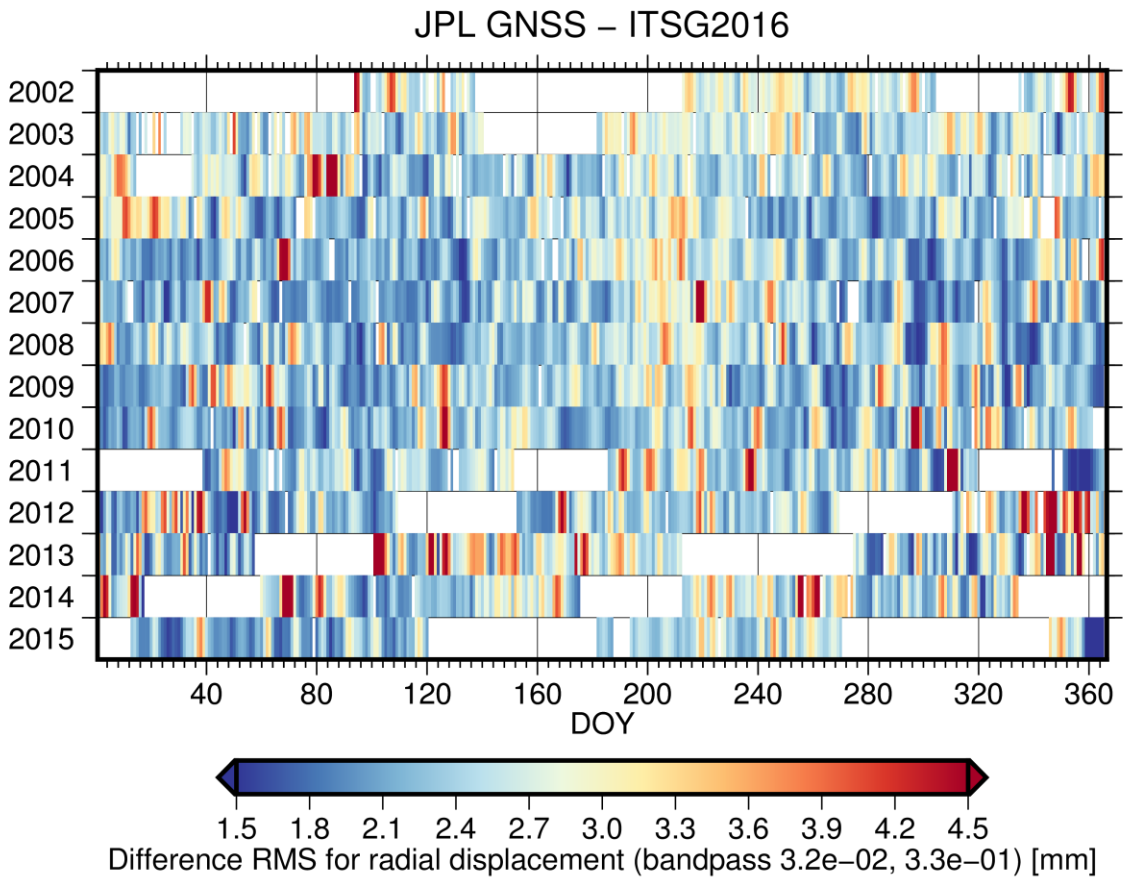
- Intercomparison of historical time series

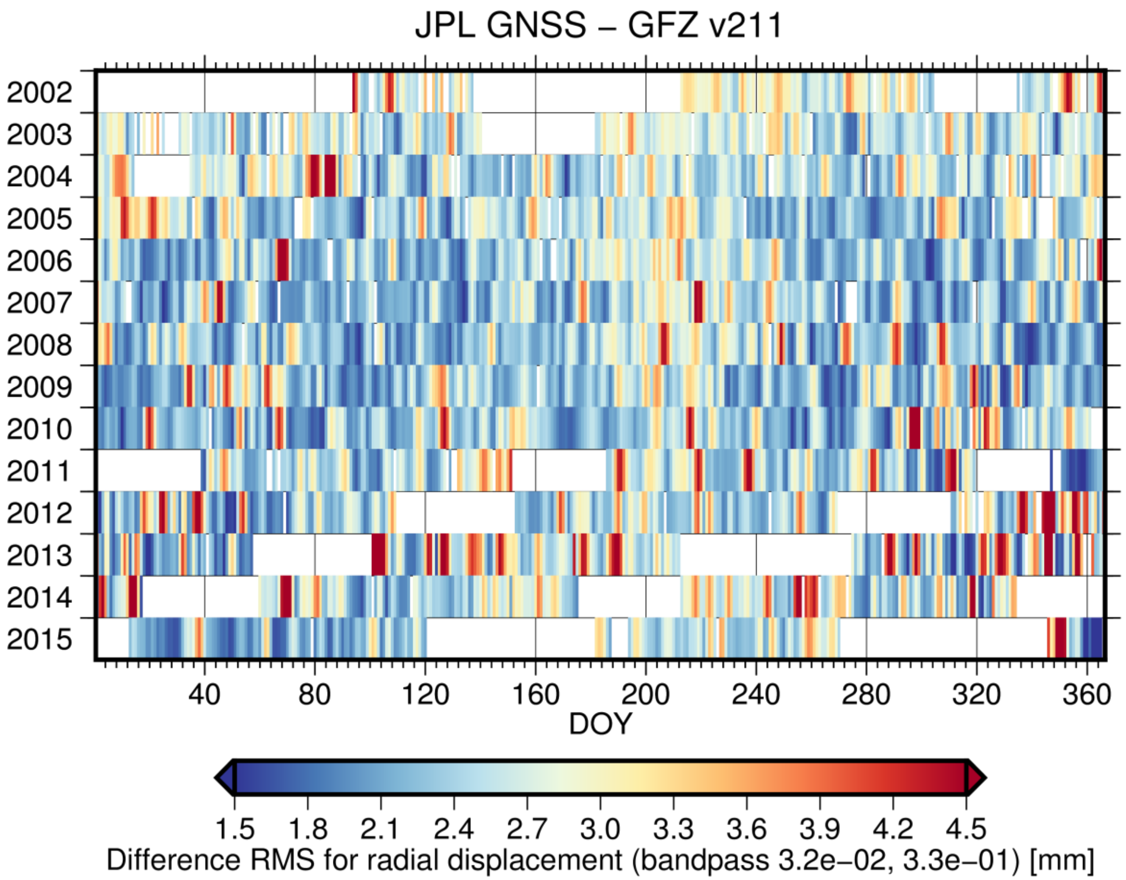




Implementation Phase – Post-processing time series

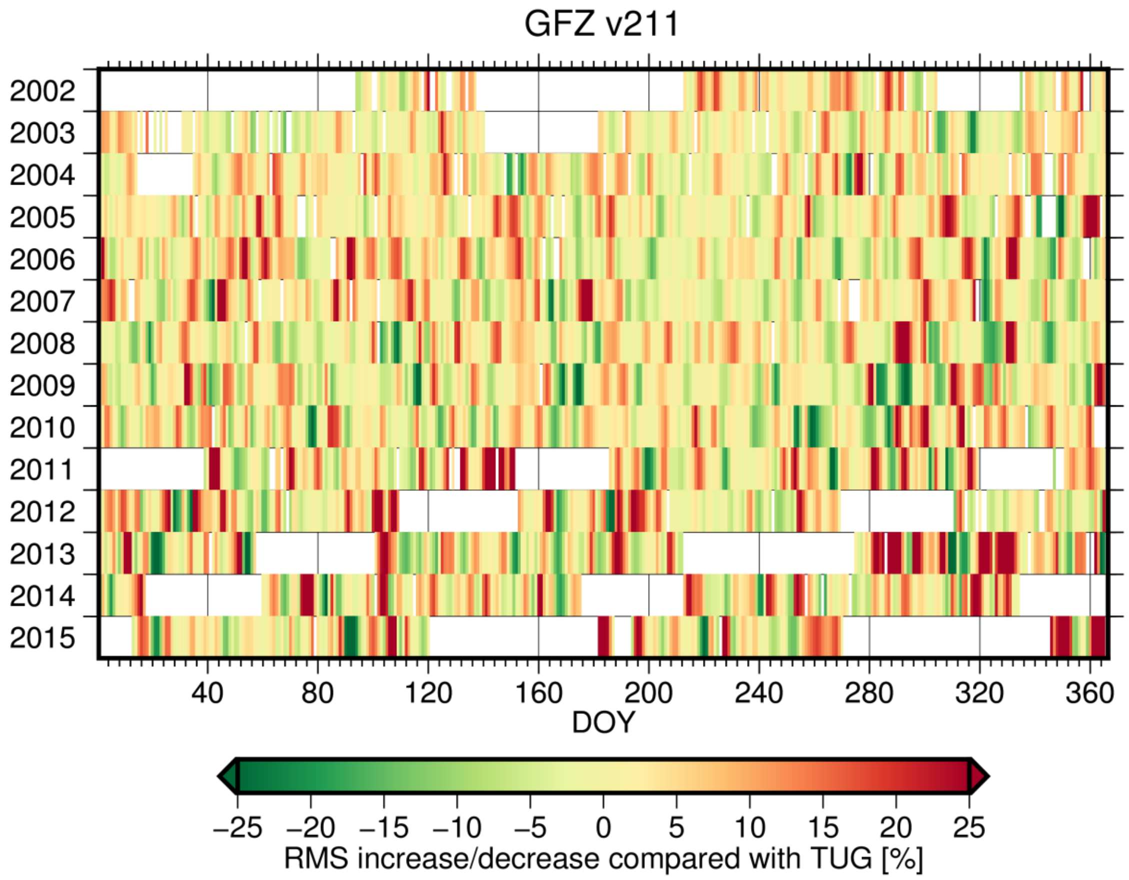
- Comparison with GNSS displacements:





Implementation Phase – Post-processing time series

- Comparison with GNSS displacements:

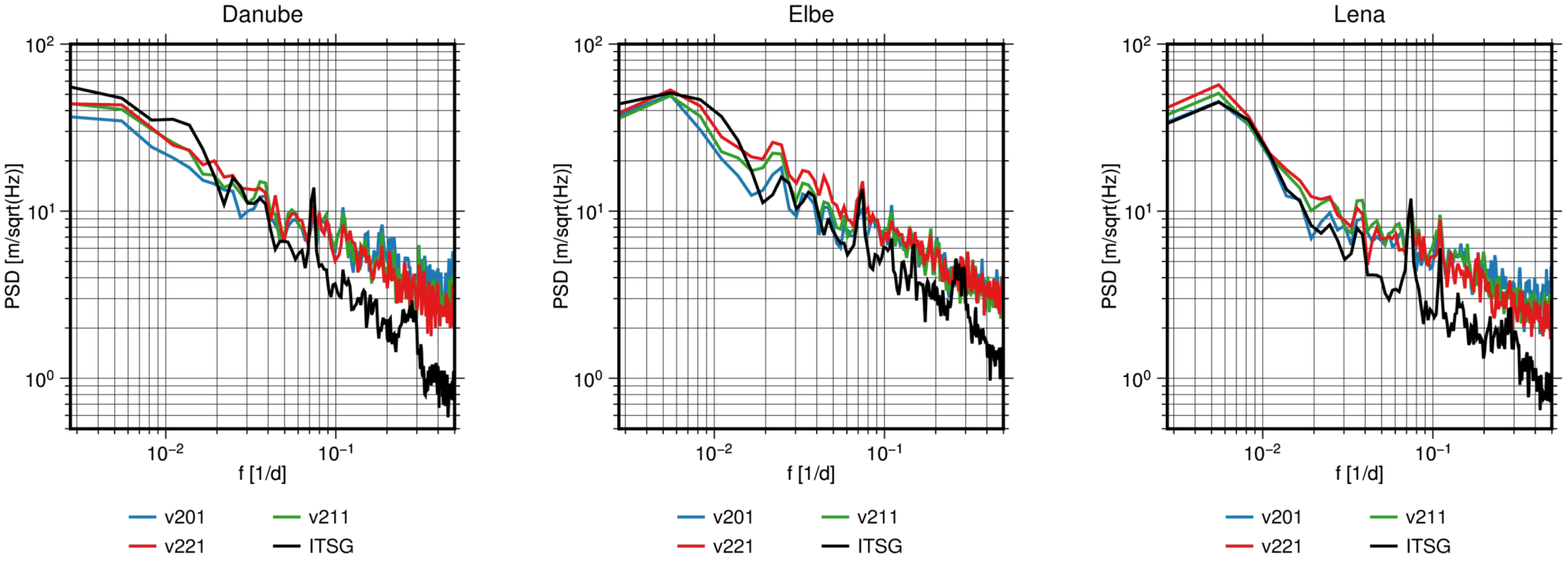


Average increase: 7.5%

Radial Displacement RMS [mm]	Full time span	2004-2010
V211	2.67	2.57
ITSG2016	2.59	2.51

Implementation Phase – Post-processing time series

- Power spectral density for selected basins
  - Annual/secular variations removed
  - GFZ generally has more high frequency content → more signal, more noise



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NRT Service – Pre-operational simulations

Implementation Phase – Pre-operational simulation

- The degrading satellite health – mainly the power supply aboard the spacecraft – required constraints for data collection

- During the operational service run it was expected that
  - Science data collection was only possible in full sunlight
  - No accelerometer data on GRACE-B would be available

- For the GRACE input data this meant that
  - Overall data volume would be reduced to about 60% in combination with systematic data gaps
  - Non-conservative forces on GRACE-B would have to be modelled by an "accelerometer transplant"

- To quantify the impact of these effects, a simulation study based on historic data was conducted
  - The standard L1B data was modified by applying the constraints above

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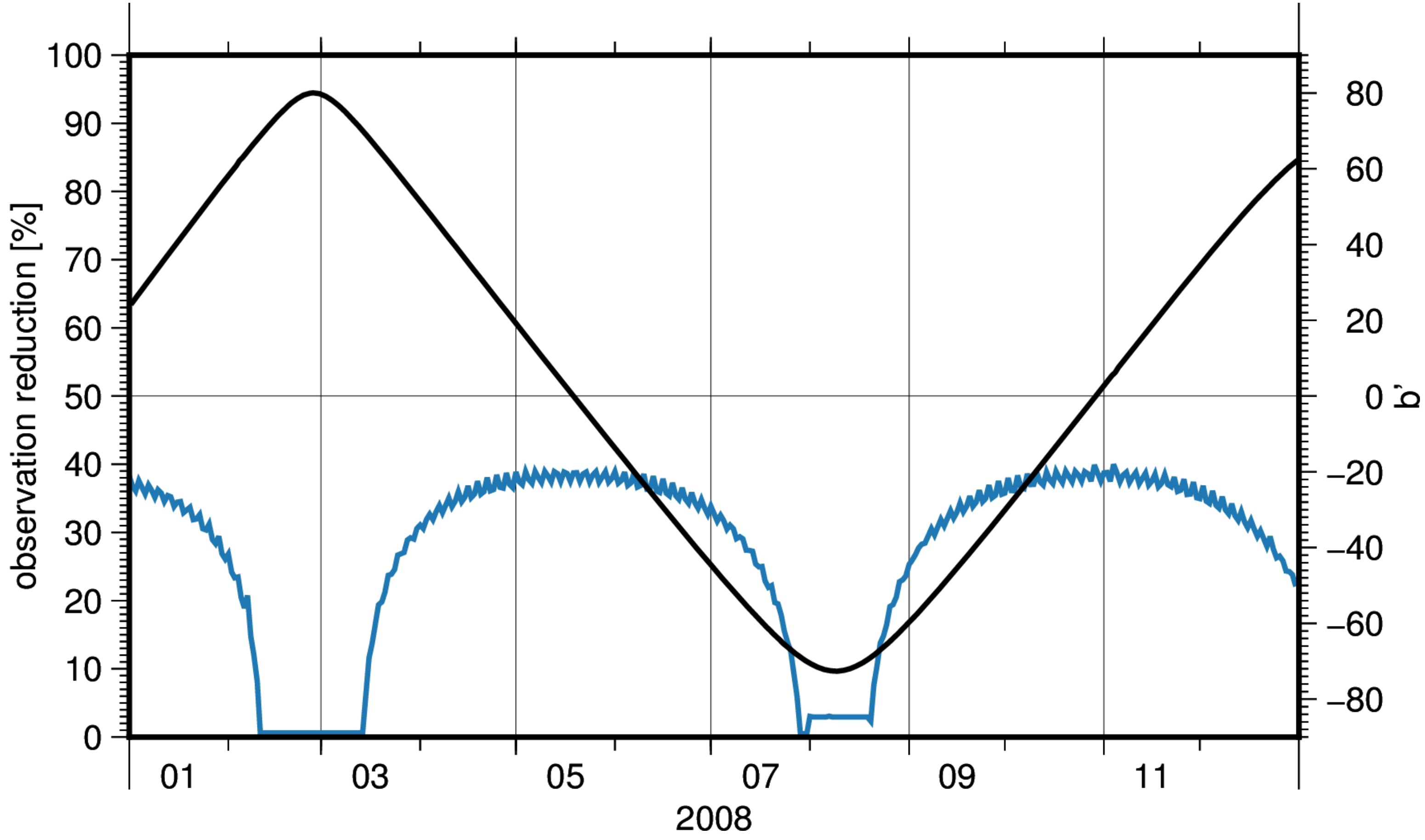
Implementation Phase – Pre-operational simulation

- The number of collected observations depends on the angle between the orbital plane and the sun
  - Low angles: the satellite dives into Earth's shadow
  - High angles: the full orbit is exposed to sunlight



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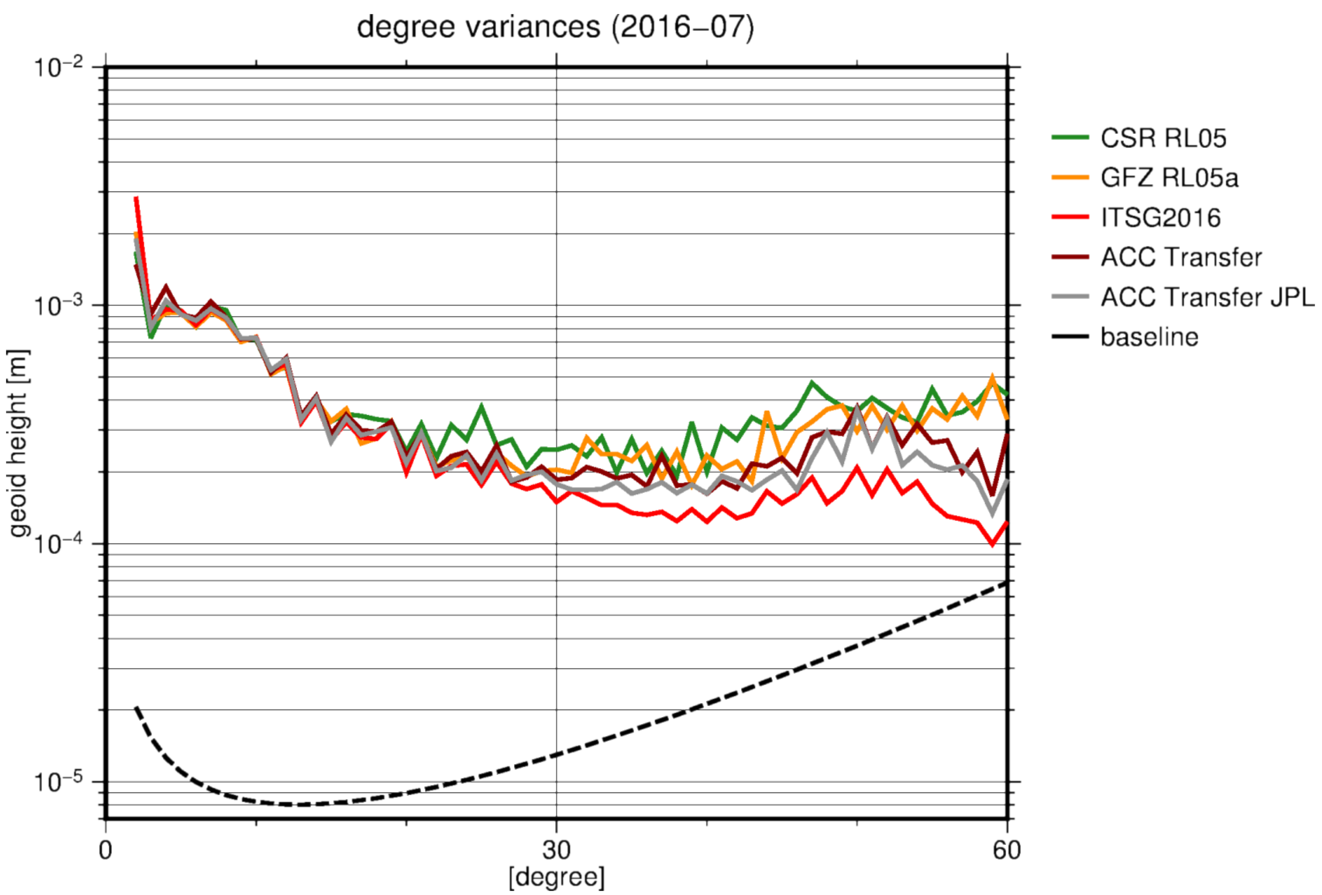
Implementation Phase – Pre-operational simulation

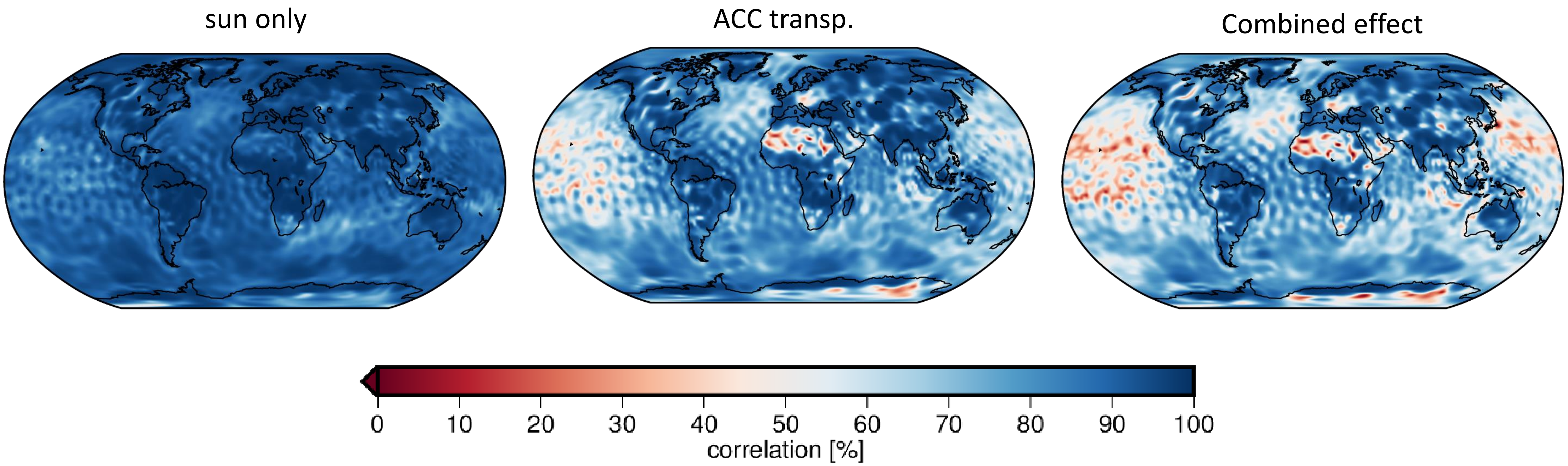
- The “accelerometer transplant” shifts the measured non-conservative forces from GRACE-A to GRACE-B
  - Necessary steps: time shift, rotation, thruster event removal/restoration
  - Less accurate than actual measurements, but still better than models



Implementation Phase – Pre-operational simulation

- Comparison of time series (annual cycle removed) for each of the constraints and the combined effect
  - The less GRACE information is available, the more the solution deviates from the reference

- However: in regions with large signals, a high correlation coefficient is retained



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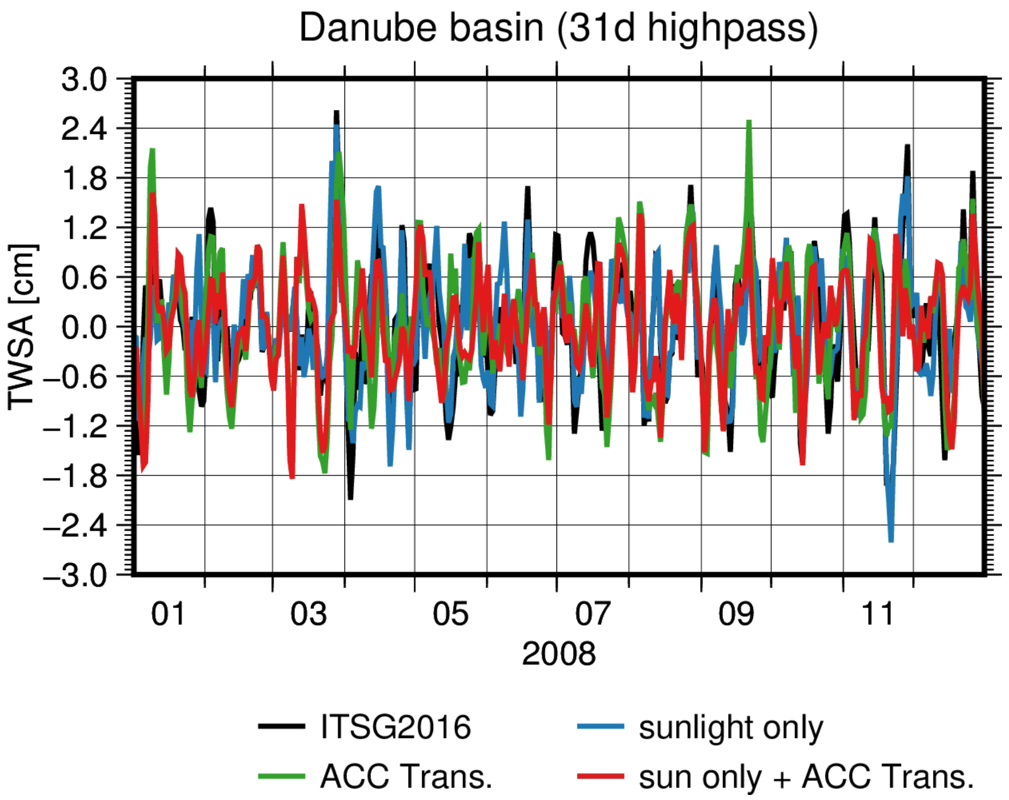

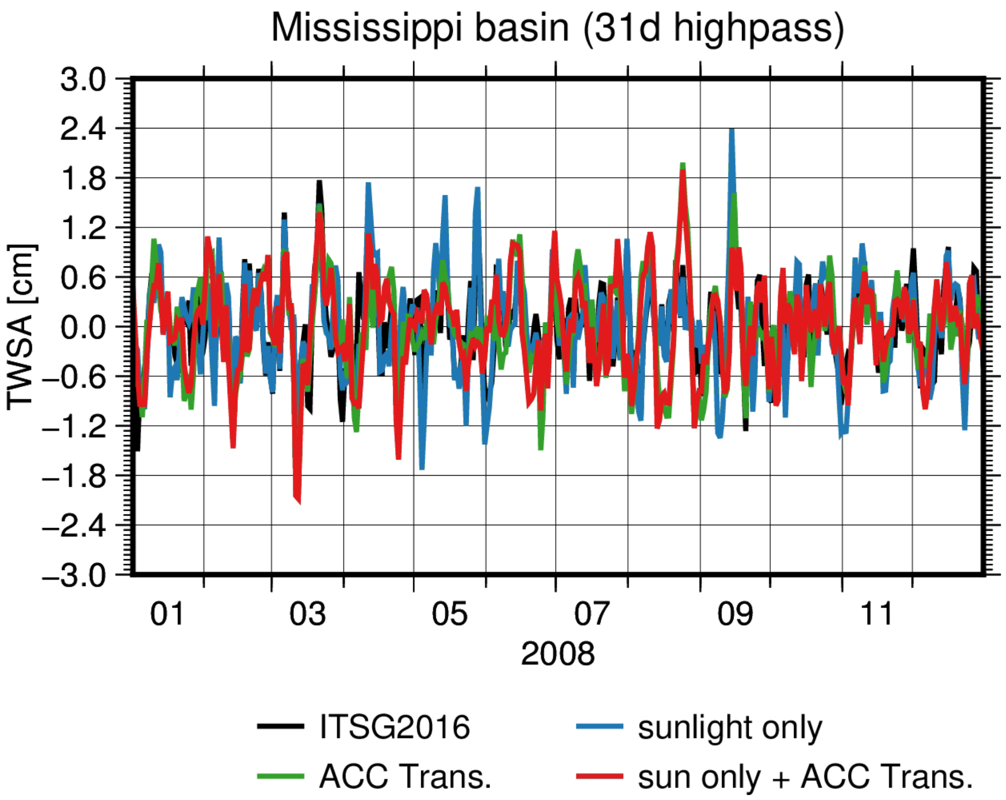

Implementation Phase – Summary

- Both analysis centers improved their processing strategies for high frequency mass variations

- Result of these developments were post-processing time series which have been released to the public:
  - TUG: Daily time series as part of ITSG-Grace2016
  - GFZ: Standalone time series “GFZ v211”

- To quantify the impact of the degrading satellite health simulation studies, which investigated the (then) expected data characteristics, were conducted
  - These studies showed that, while a drop in quality compared to the “good” years was to be expected, hydrological signal should still be captured
  - Unfortunately, during the operational service run a change in satellite attitude made things trickier than expected

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NRT Service – Results of the Operational Phase

Operational Phase – Results of the NRT Test Run

- The operational service test run was planned to run for six months starting on April 1
  - Aim was to produce daily water store grids with a maximum latency of five days as input for the Hydrological Service

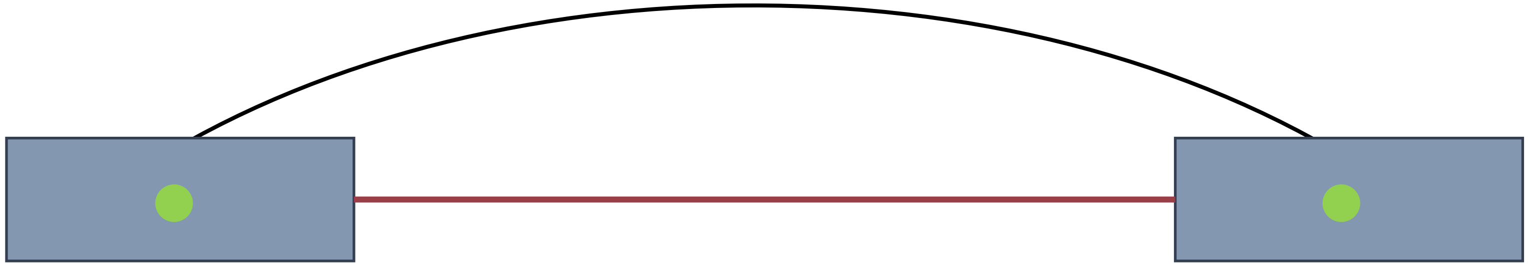
- A battery cell failure on GRACE-B cut the test run short
  - Last measured epoch was June 29 – three months of daily solutions produced

- During the service run latency and availability of the input data was consistent
  - Single day data gaps in GRACE observations during attitude change manoeuvres

- GRACE data quality was also - mostly - consistent
  - Pitch bias removal deteriorated the solutions to some extent
  - Manoeuvre was unannounced, therefore on-the-fly adaptions to the processing chain became necessary

Operational Phase – Results of the NRT Test Run

- The removal of the pitch bias caused an increase in pointing angle of about 0.7 degrees
  - Attitude errors propagate into the ranging measurements more prominently



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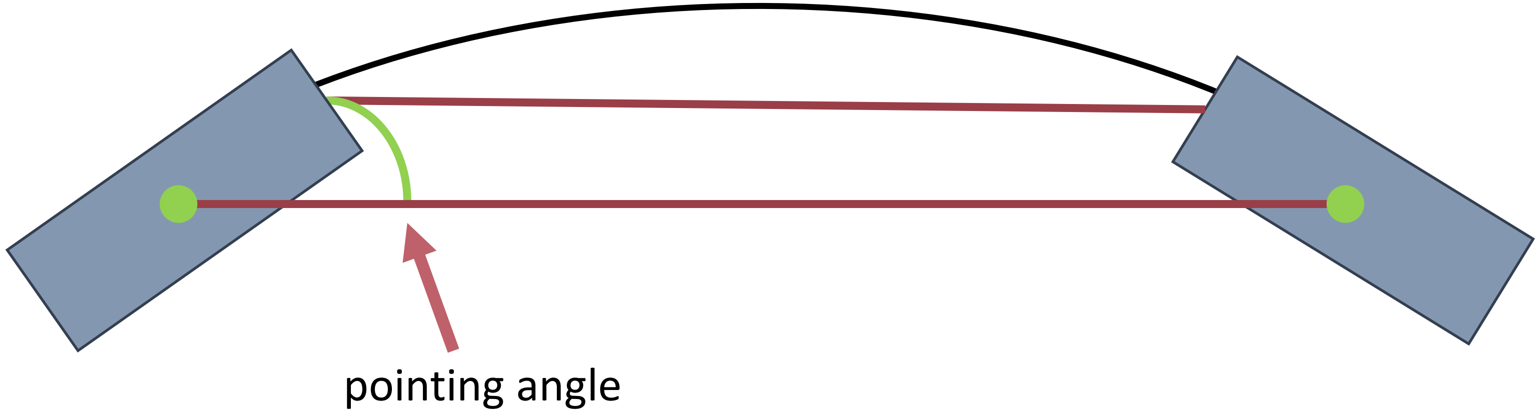

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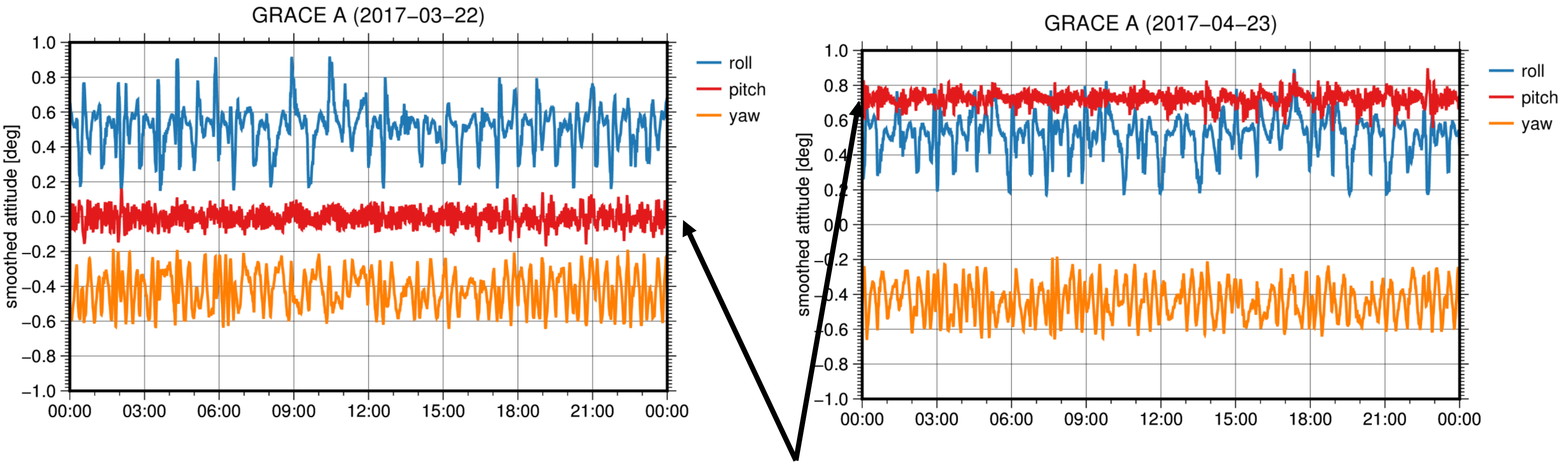

increased pointing angle

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Operational Phase – Results of the NRT Test Run

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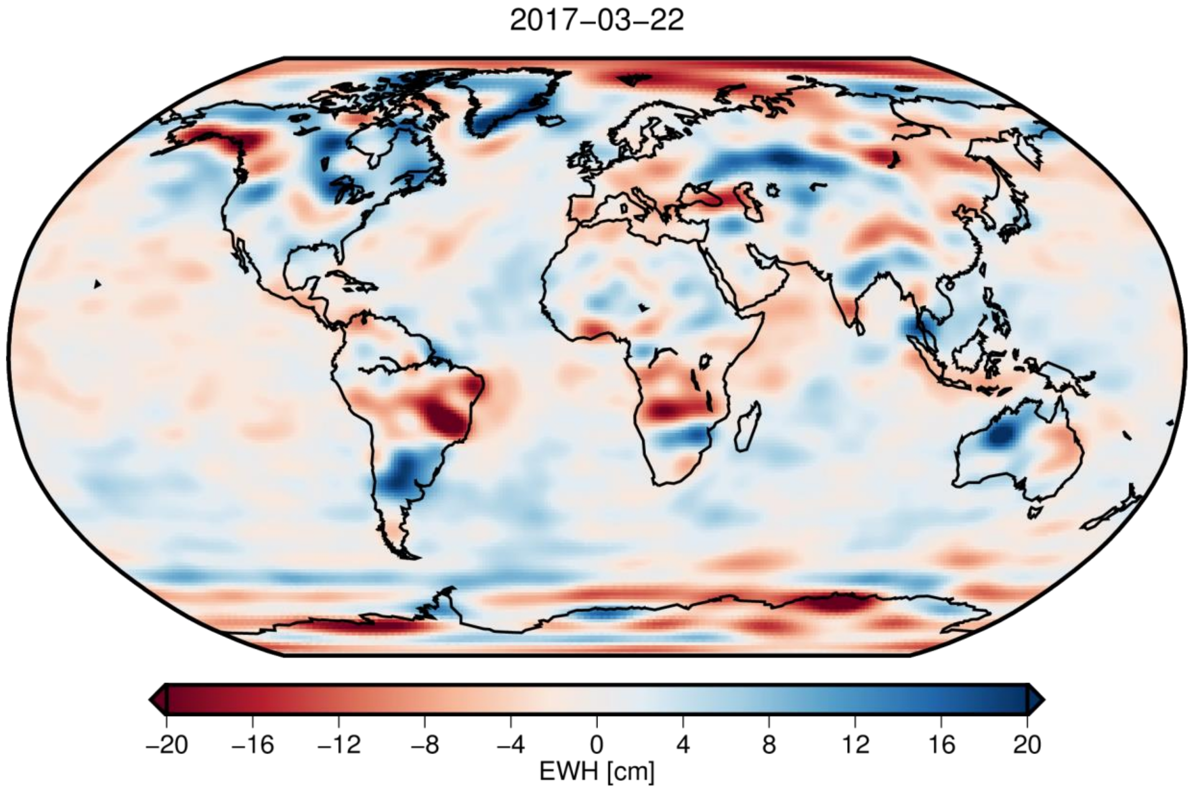
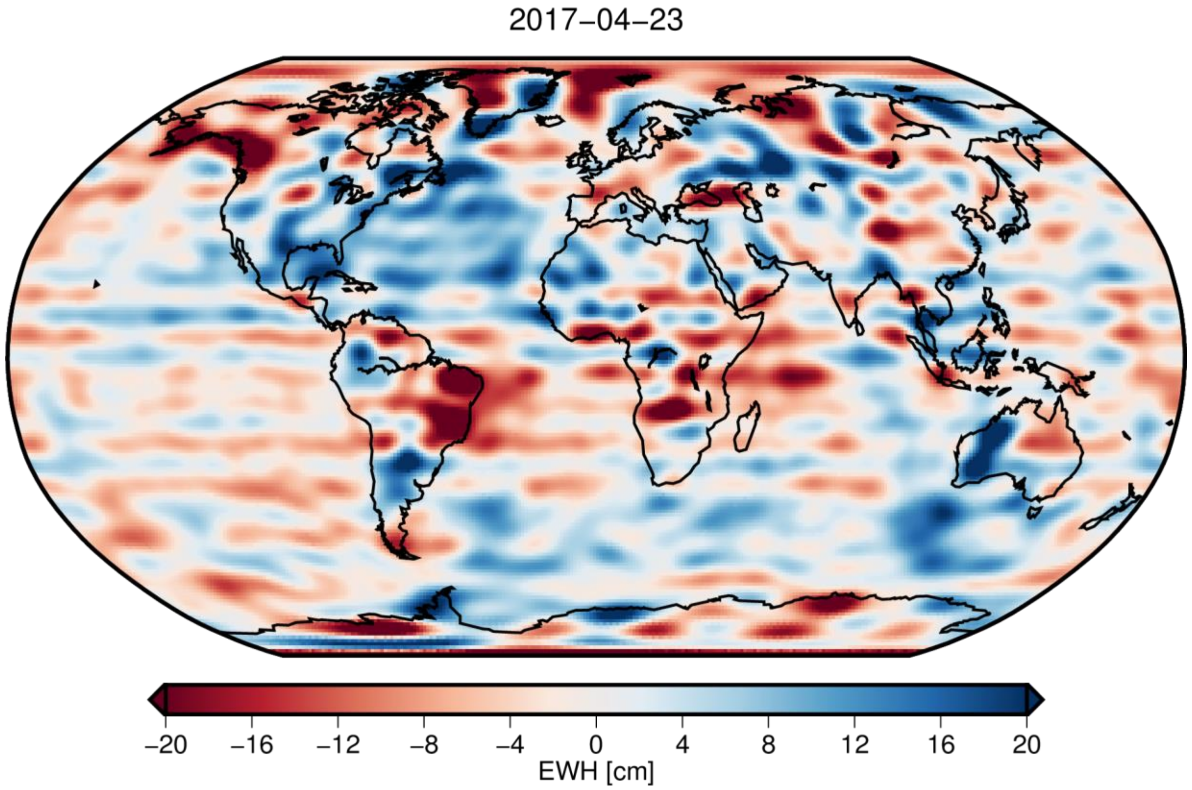
nominal attitude

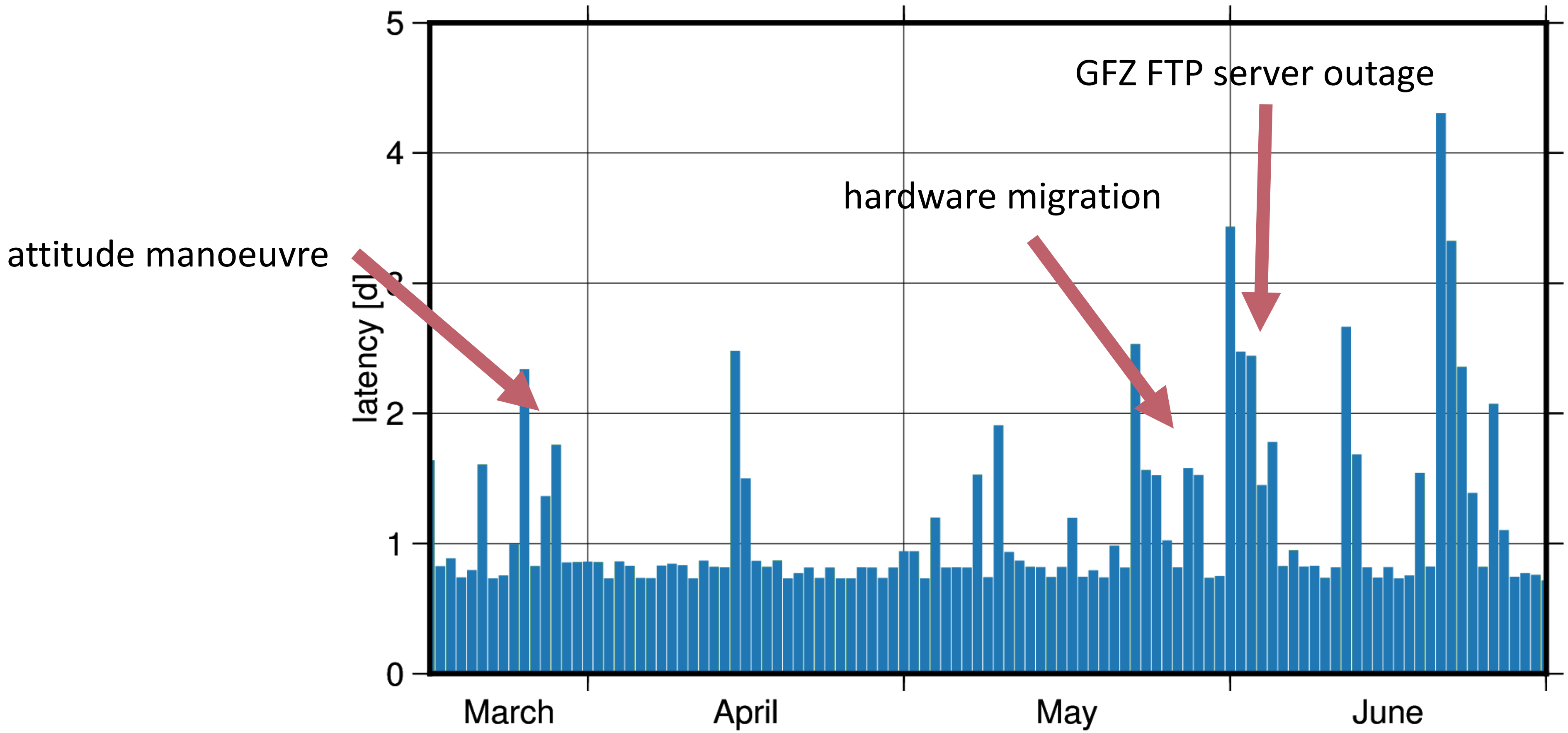


pitch bias removed



Operational Phase – Results of the NRT Test Run

- Latency of the computed water storage anomalies was below one day for most epochs
  - Single spikes in latency mostly caused by infrastructure issues



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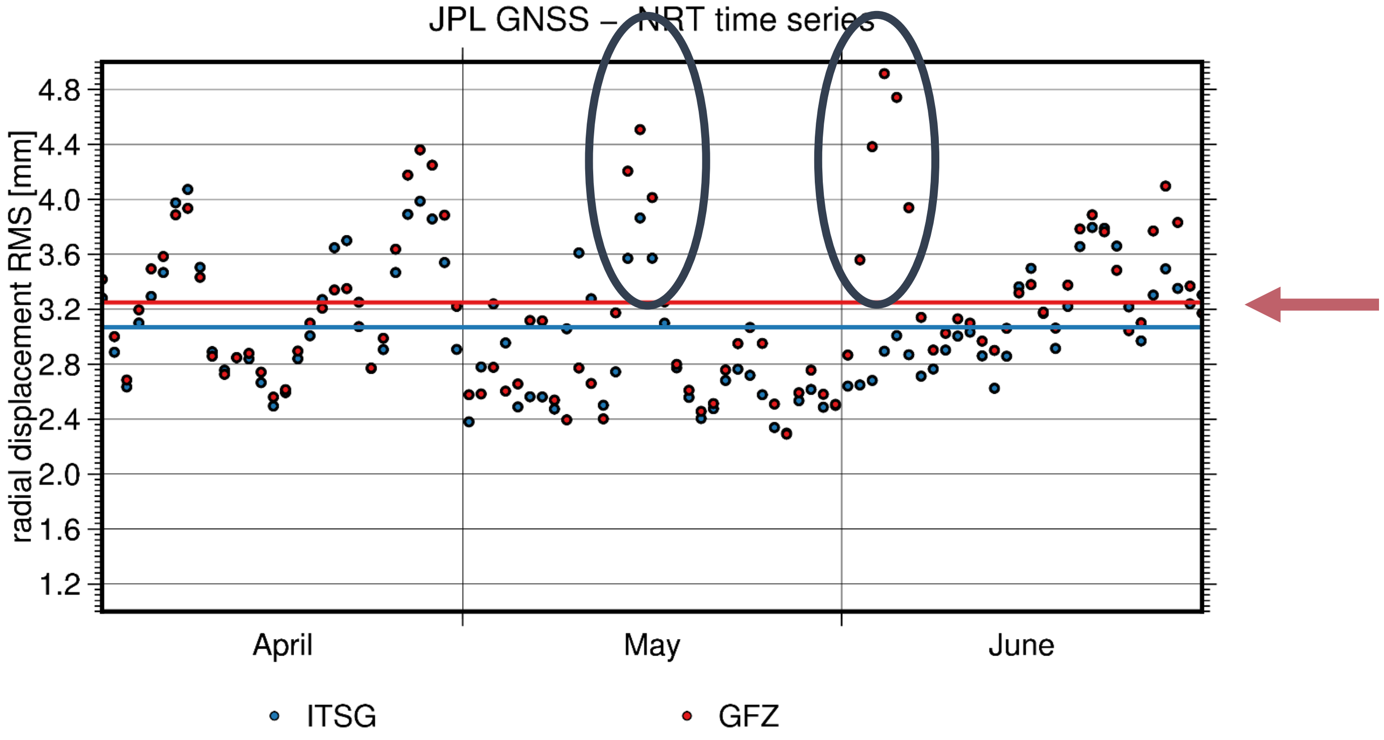
Operational Phase – Results of the NRT Test Run

- Quality of the produced gravity field solutions was - mostly – consistent
  - TUGs approach handled the new data situation better than GFZ

- Overall better agreement with external data from TUG
  - GFZ time series contains outliers in the later stages of the test run



GFZ: 3.3 mm
TUG: 2.9 mm

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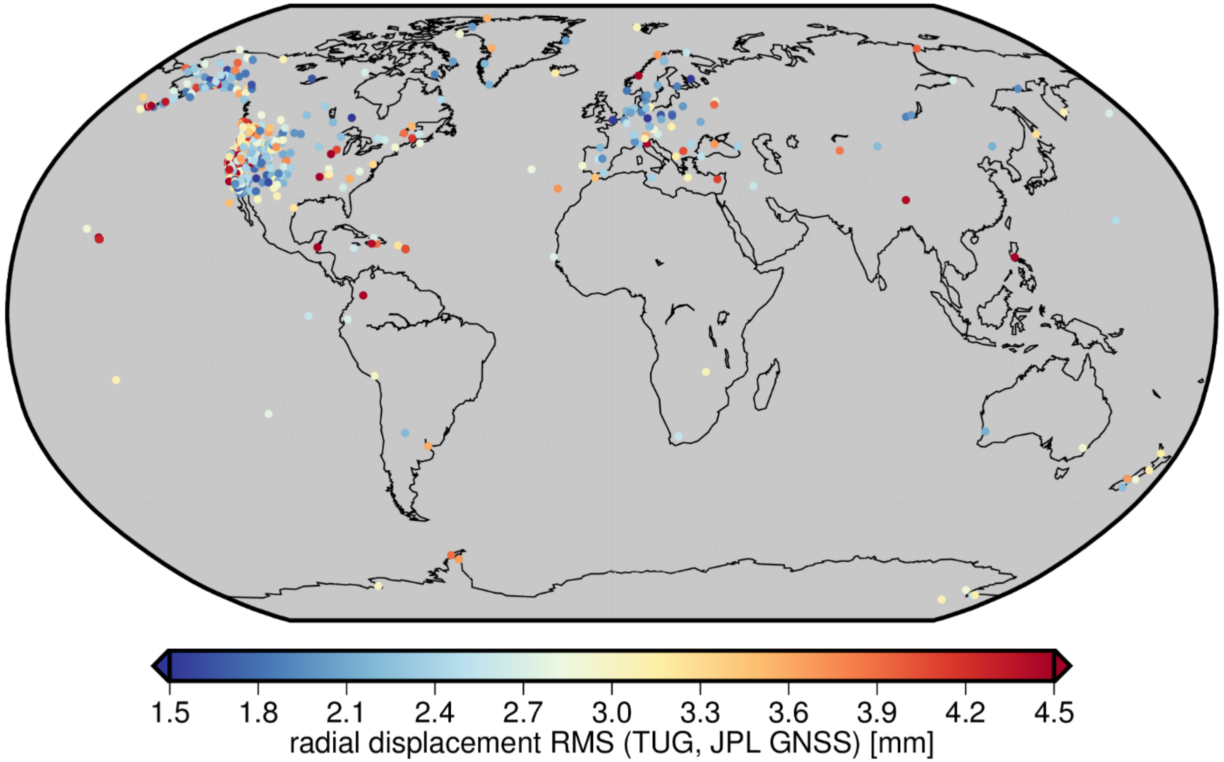
TUG: 2.9 mm



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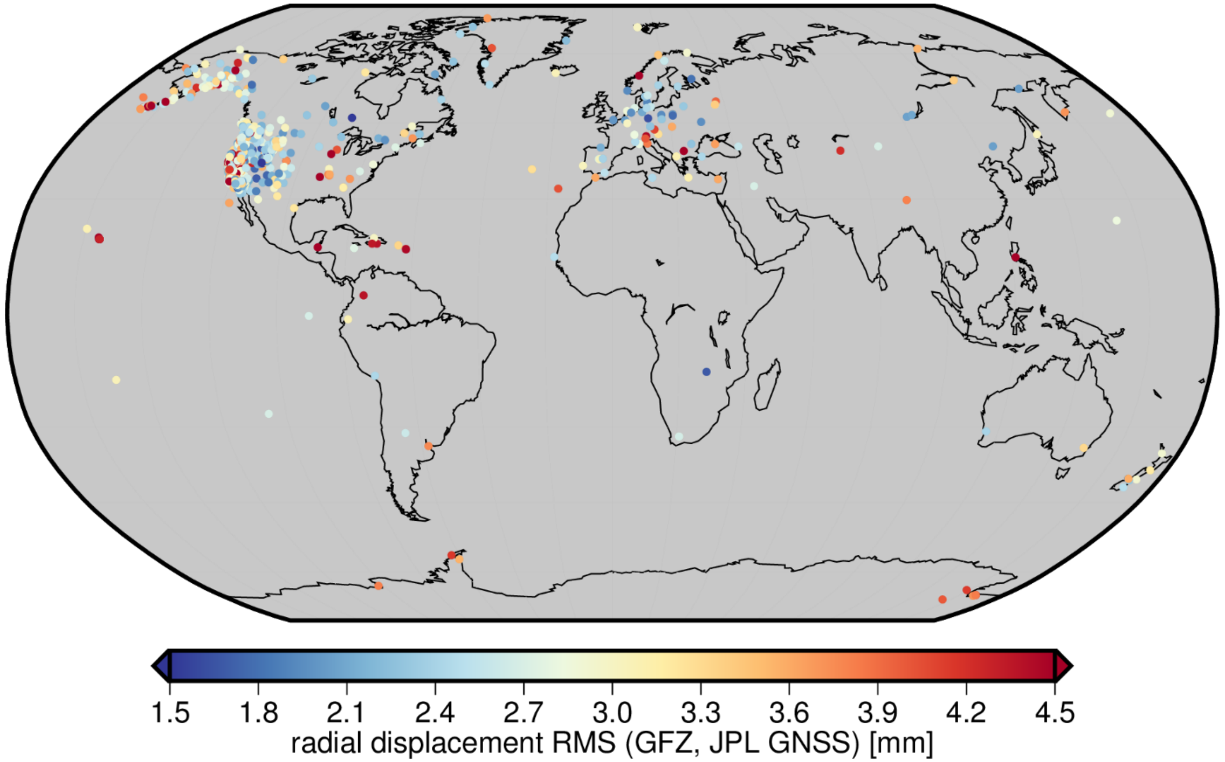

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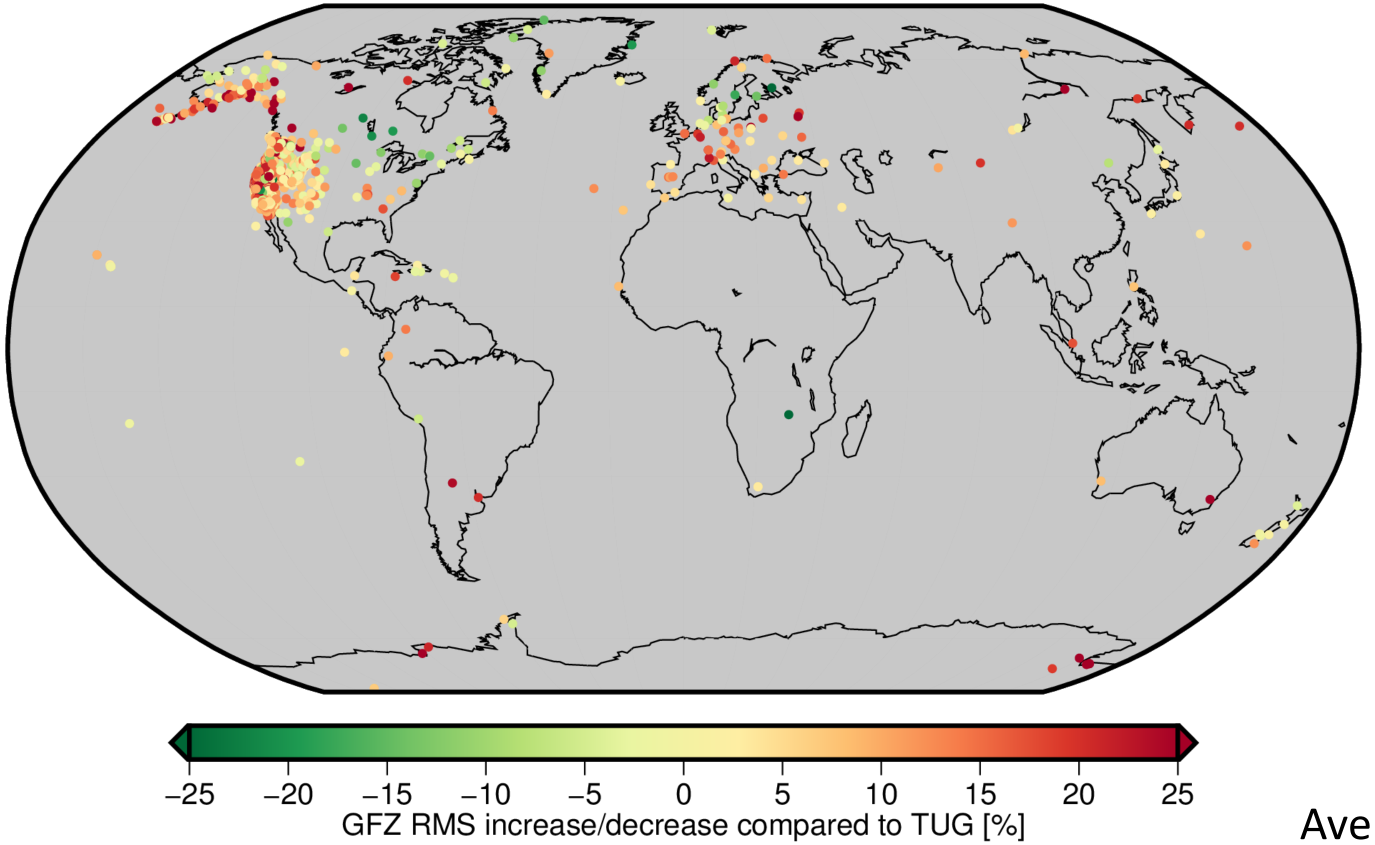

Average increase: 11.7%

Operational Phase - Reanalysis

- ITSG-Grace2016 processing applied to quick-look input data

- Main differences:
  - improved and extended outlier detection
  - Non-causal: we know when data characteristics change and can tailor covariance function estimation accordingly
  - Use of GRACE-B accelerometer data from 2017-05-02 to 2017-05-22 (operational NRT solutions only depended on transplant data)

- Comparison of three time series:
  - "Operational": the automatically processed L1B quick-look data during the service run
  - "Reanalysis": ITSG-Grace2016 processing applied to quick-look data
  - CSR-RL05: the standard monthly gravity field solutions based on final L1B data
  - CSR-21d moving: 21 day sliding window solutions provided by Himanshu Save

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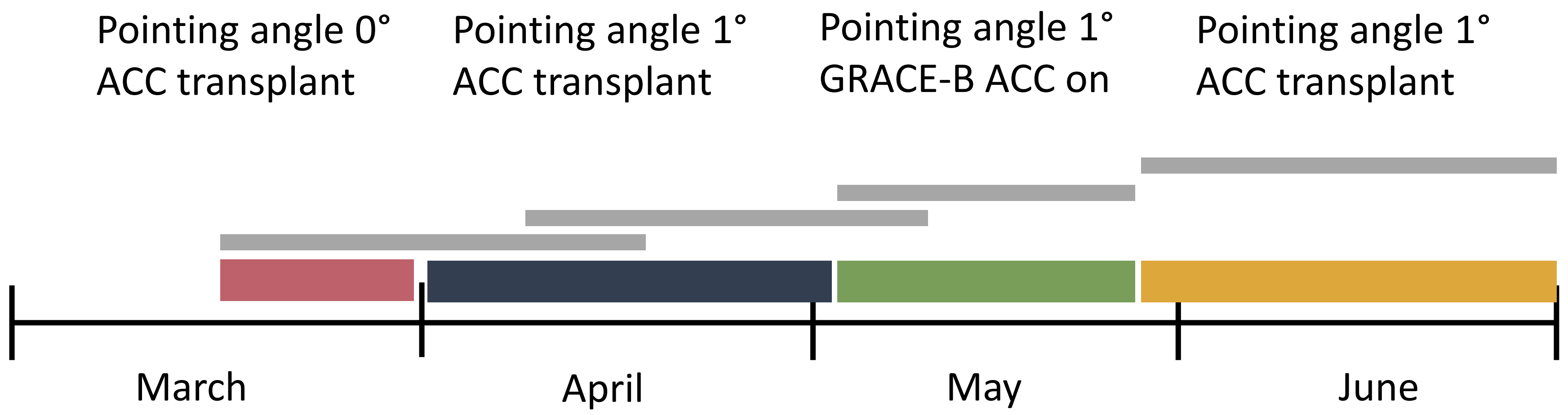
Operational Phase - Reanalysis

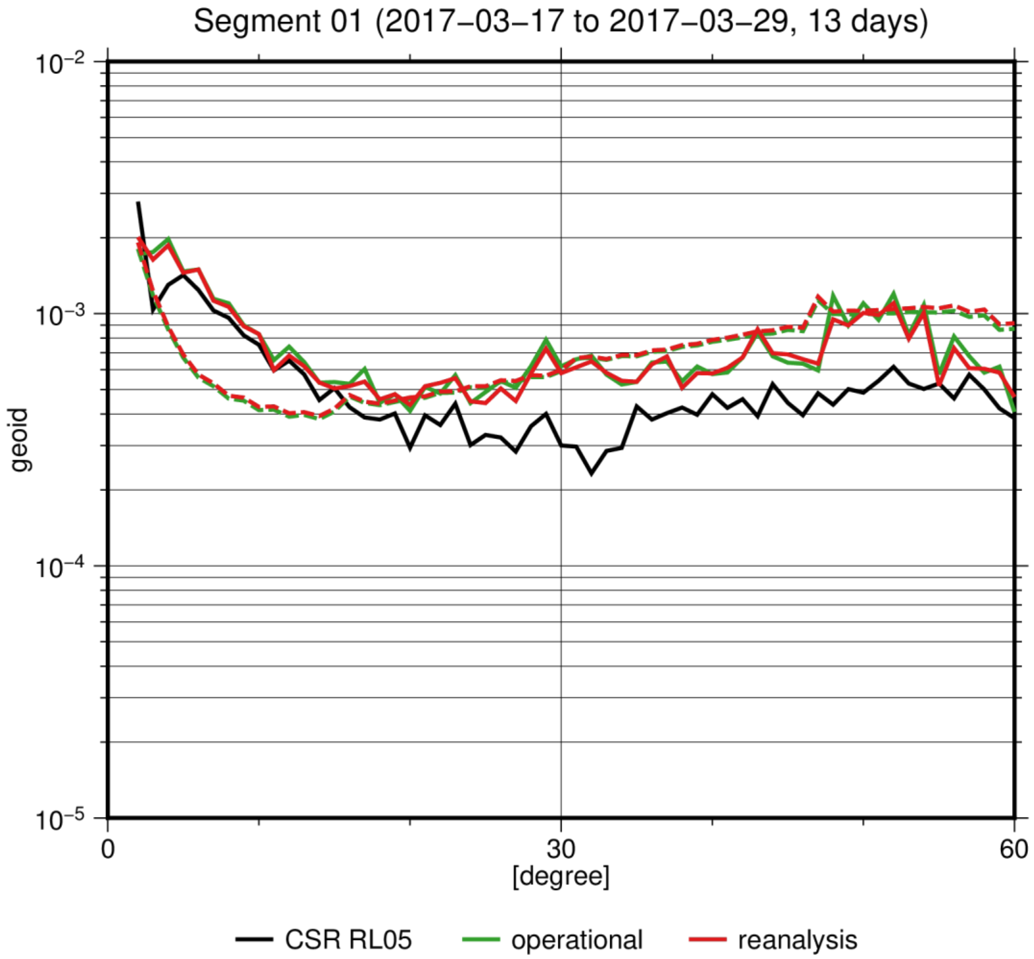
- The NRT service run (2017-03-17 to 2017-06-30) was divided into four segments based on data characteristics

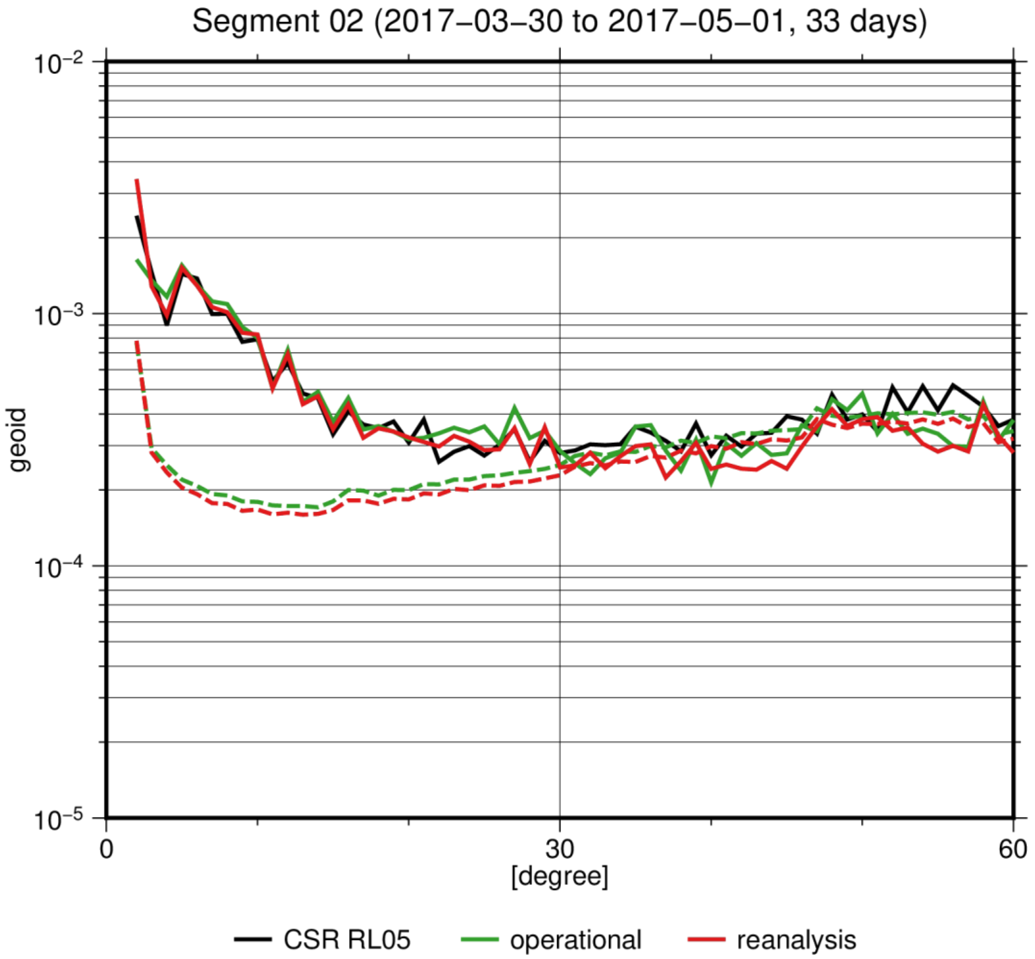


- CSR released four solutions which cover this time span
  - 2017-03-17 to 2017-04-15
  - 2017-04-10 to 2017-05-08
  - 2017-05-02 to 2017-05-22
  - 2017-05-23 to 2017-06-29

Operational Phase - Reanalysis

- Comparison of (quasi-) monthly solutions, CSR solutions were chosen based on number of overlapping days





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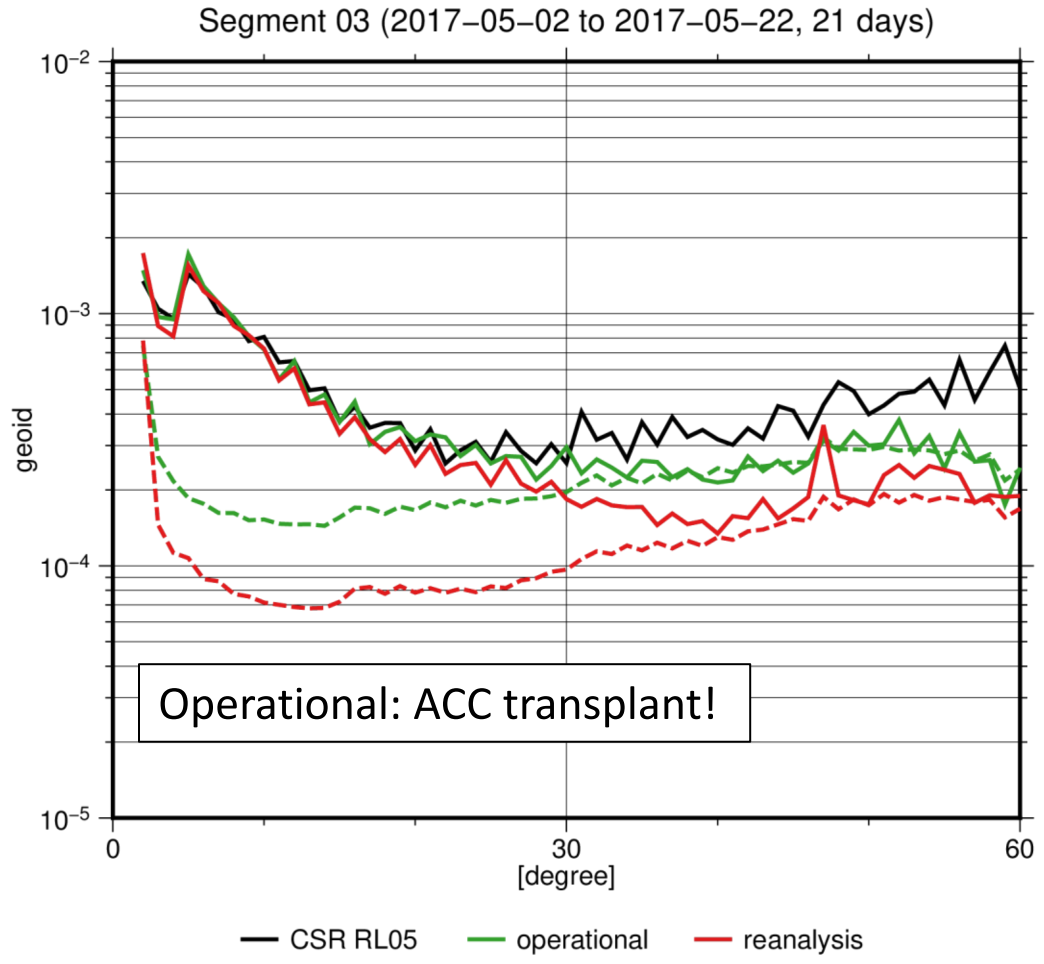

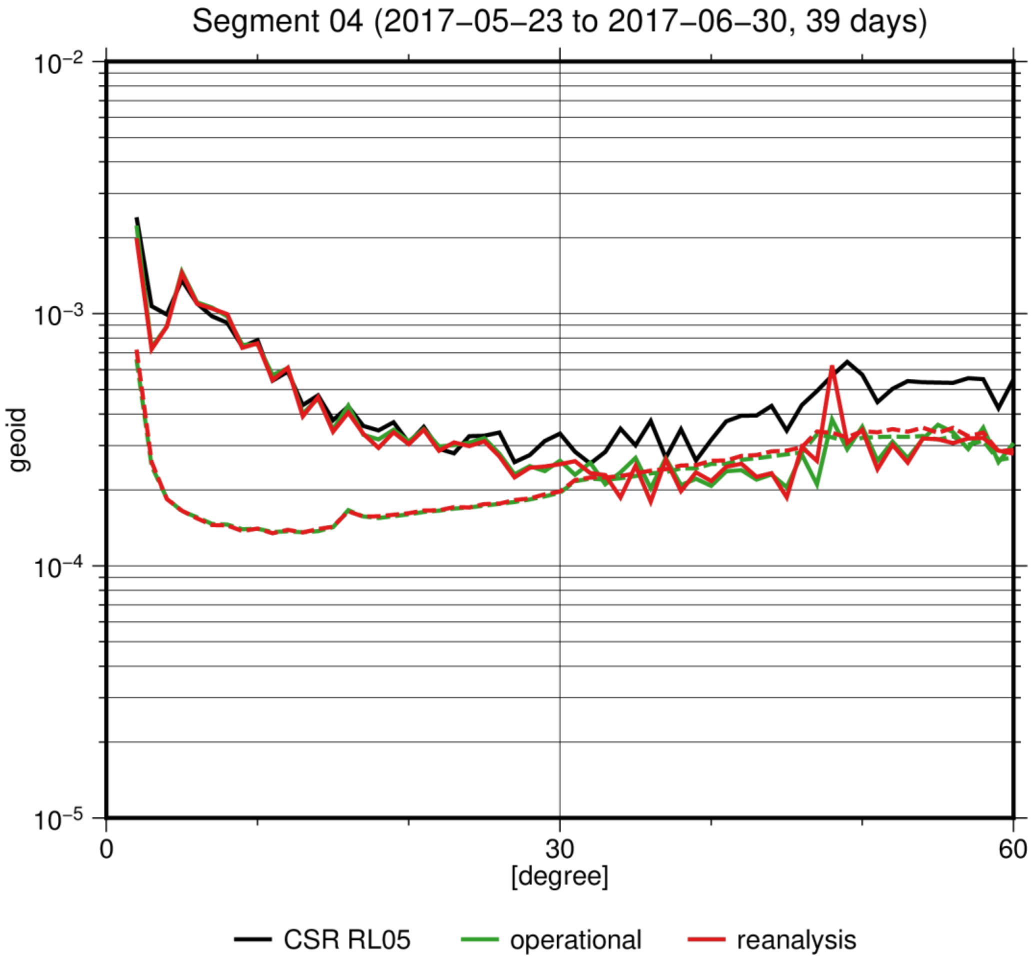

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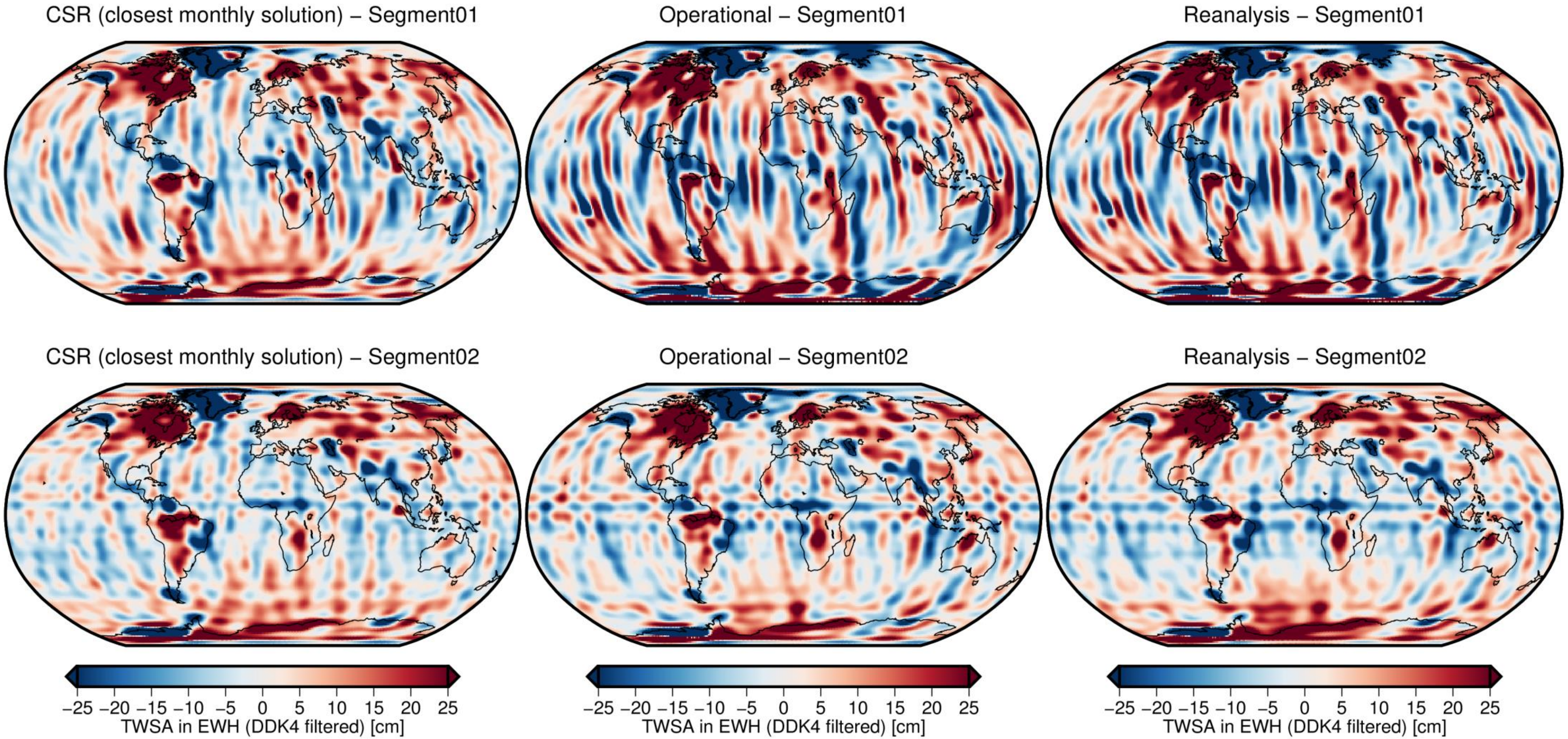

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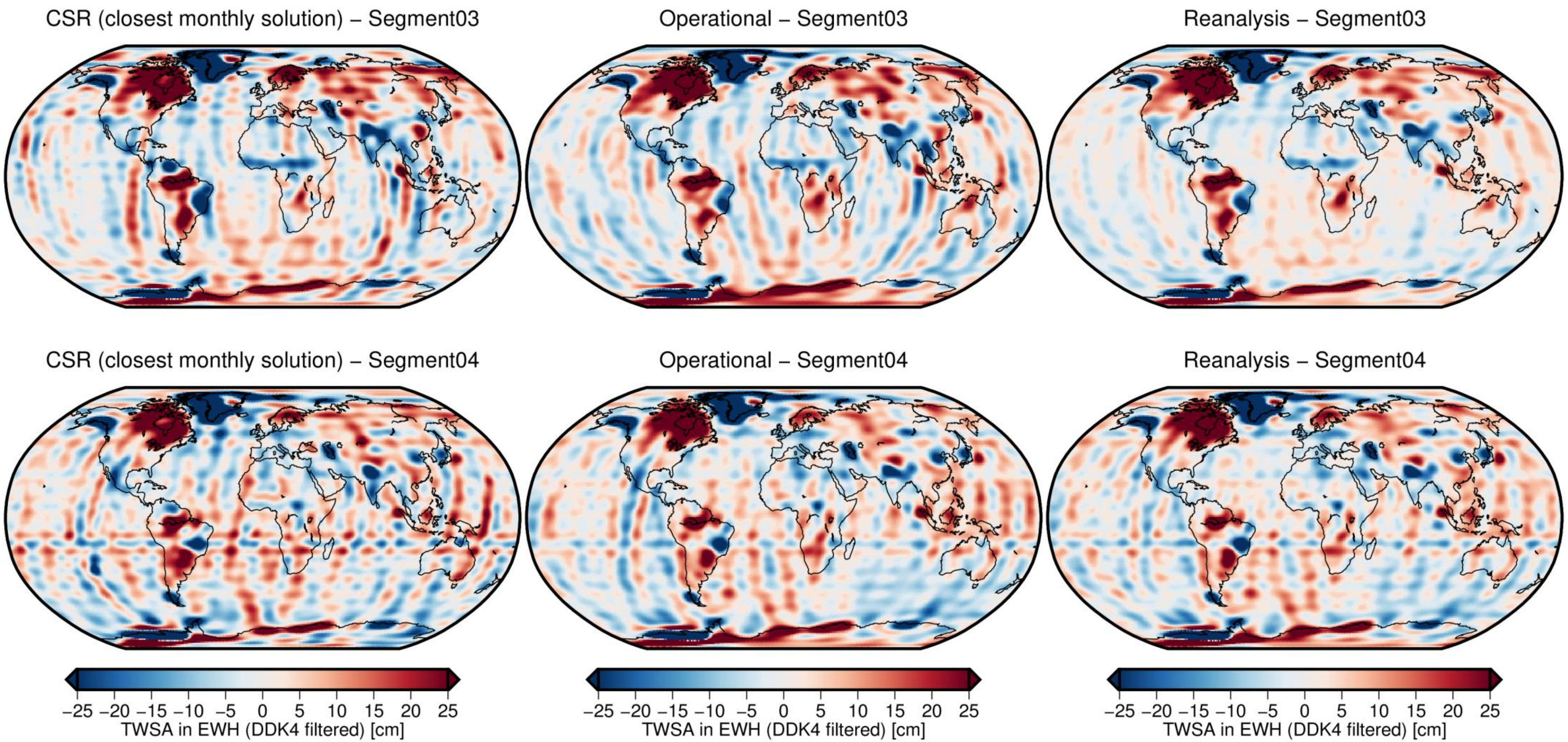
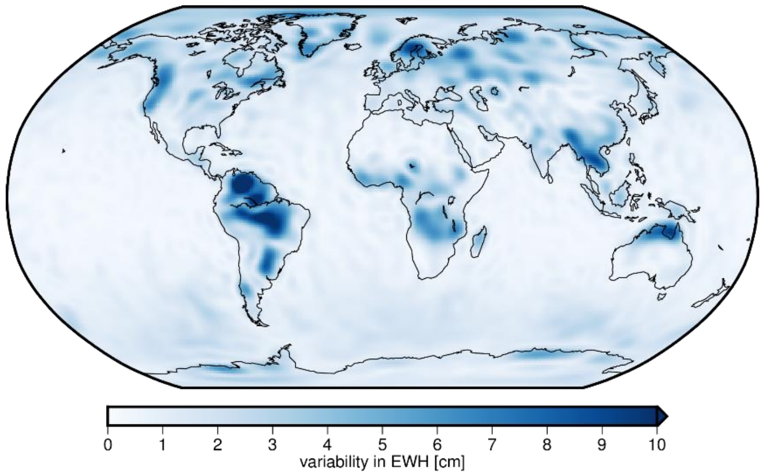


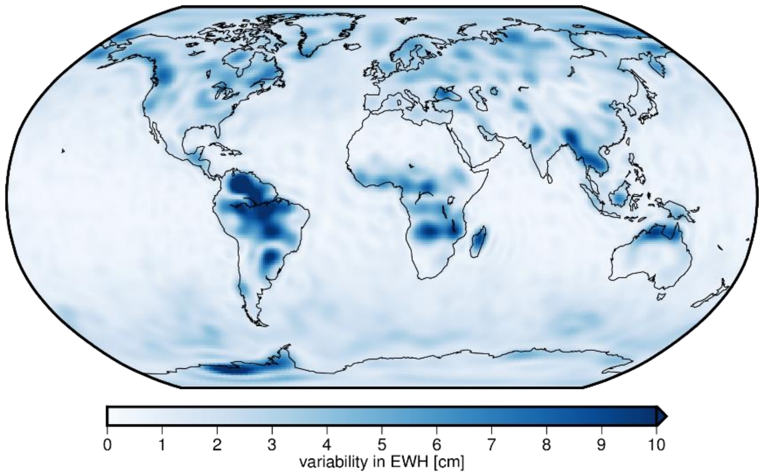
Operational Phase - Reanalysis

- Kalman filtered solutions from 2017-03-17 to 2017-06-30
  - Reanalysis: both forward an backward filtering is possible

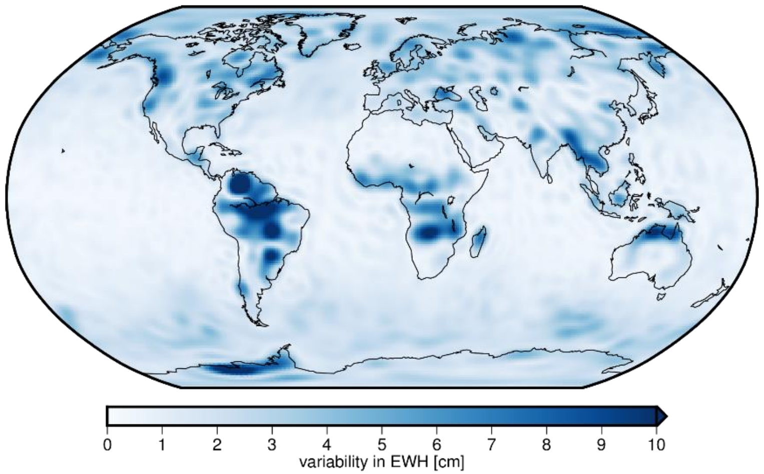
operational



reanalysis (forward)



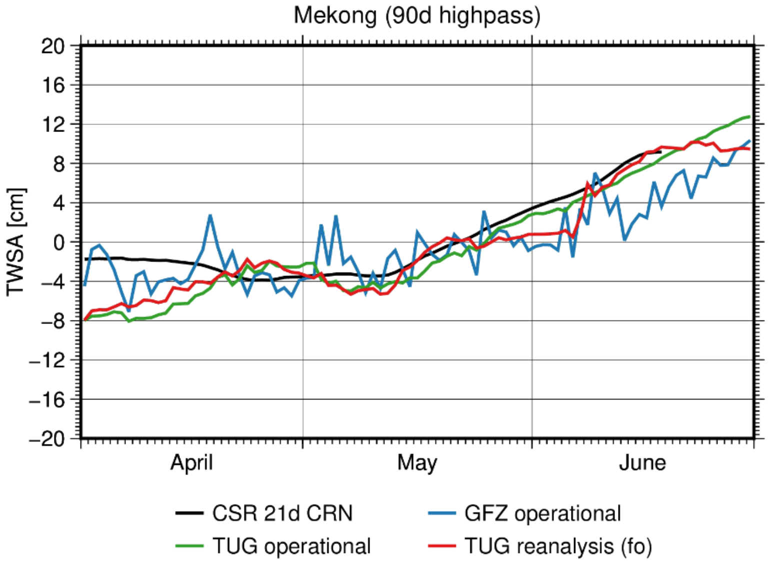
reanalysis (f/b)

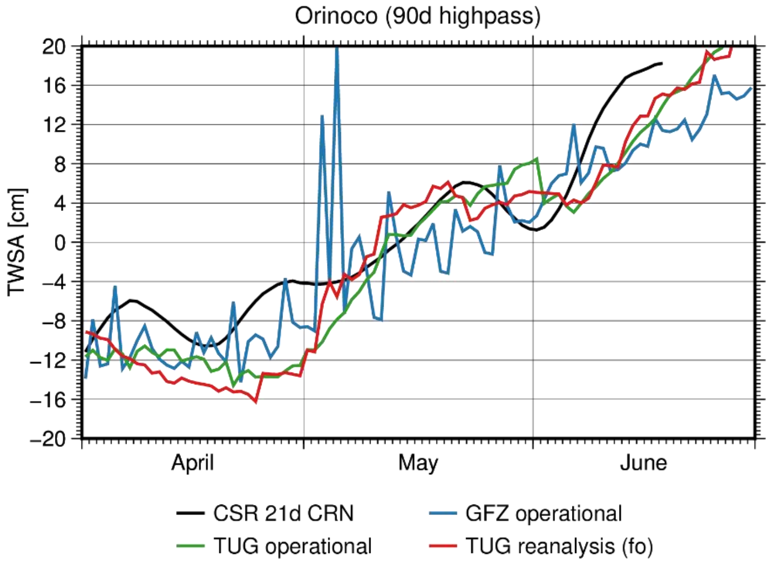


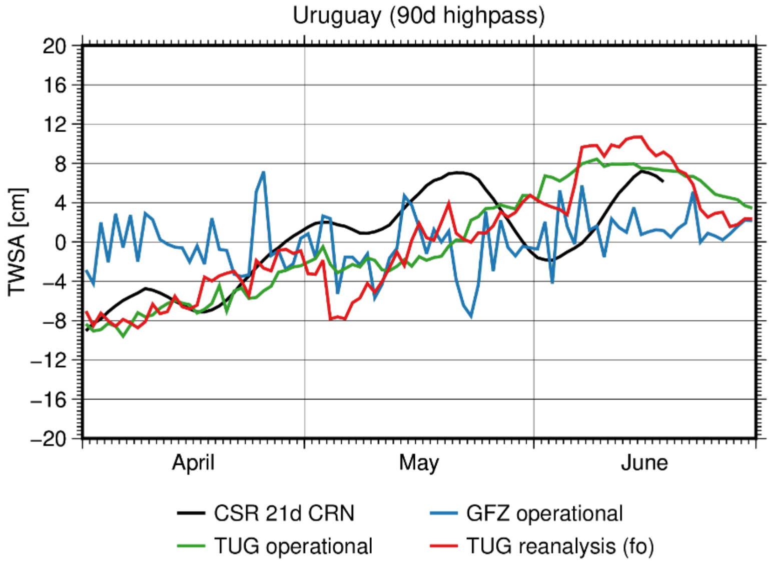
- Operational solutions have less variability (2.1cm EHW) than reanalysis (2.5cm EHW)
  - GRACE has less weight due to suboptimal noise estimation → less contribution to Kalman state

Operational Phase - Reanalysis

- Kalman filtered solutions from 2017-03-17 to 2017-06-30







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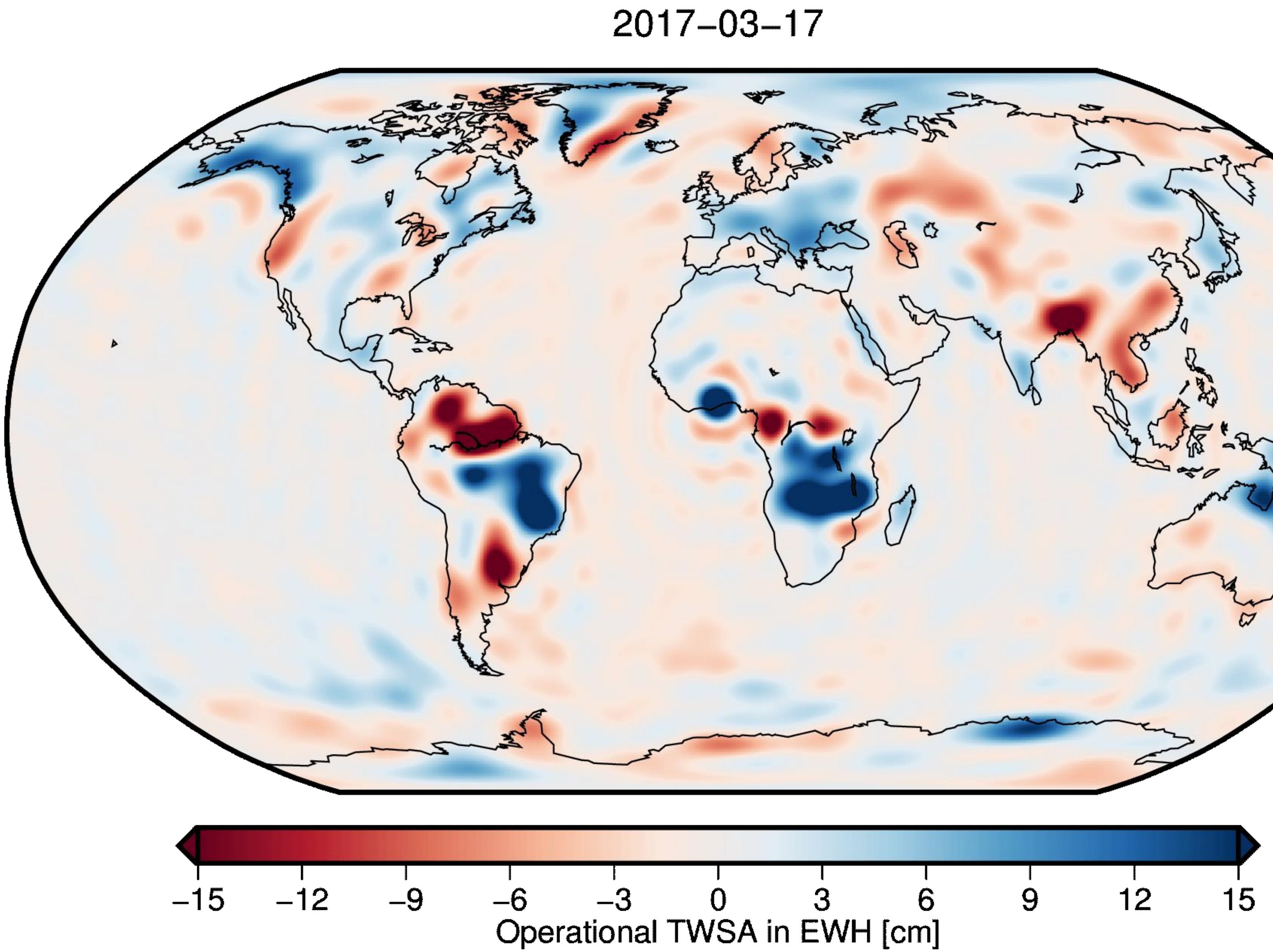
Operational Phase – NRT Solutions



Operational Phase - Summary

- Pre-operational simulation showed that post-processing data quality is transferrable to near real-time applications
  - However, challenging data characteristics during the service run resulted in lower than expected quality
  - Reanalysis and intercomparison confirmed that the developed approach still produced competitive gravity products

- The implemented automation framework was capable of managing the daily processing steps without external action
  - Latency during the operational test run was well below the projected five days
  - Software framework is generic enough to be used for future satellite missions

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Summary And Outlook

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Summary And Outlook

- We were able to show that mass variations can be inferred from satellite data in near real-time
  - Satellite health during the operational test run resulted in challenging data characteristics
  - Quality levels estimated during pre-operational simulations could not be fully reached
  - Reanalysis and external validation showed that the gravity products were nonetheless competitive

- Housekeeping:
  - Finalizing the WP5 chapter for the final project report
  - Publications: Gruber et al. 2018 (submitted), Kvas et al. 2018 (close to be submitted)

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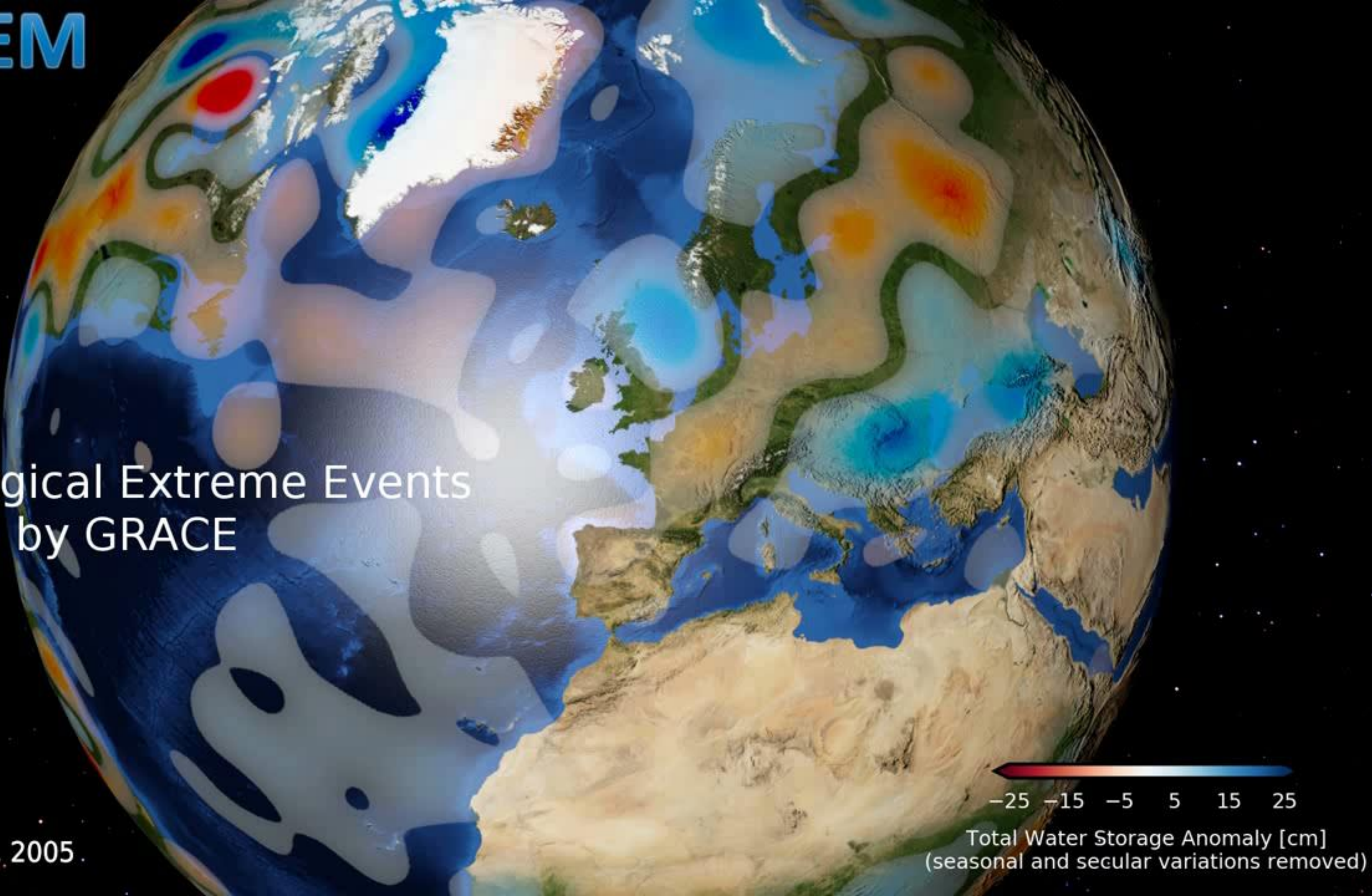
Hydrological Extreme Events as Seen by GRACE



November 01, 2005

Backup – Regional Solutions

Regional Solutions – Results at TUG

- Regional solutions implemented as radially symmetric spherical splines (RBFs) according to (Eicker, 2008)

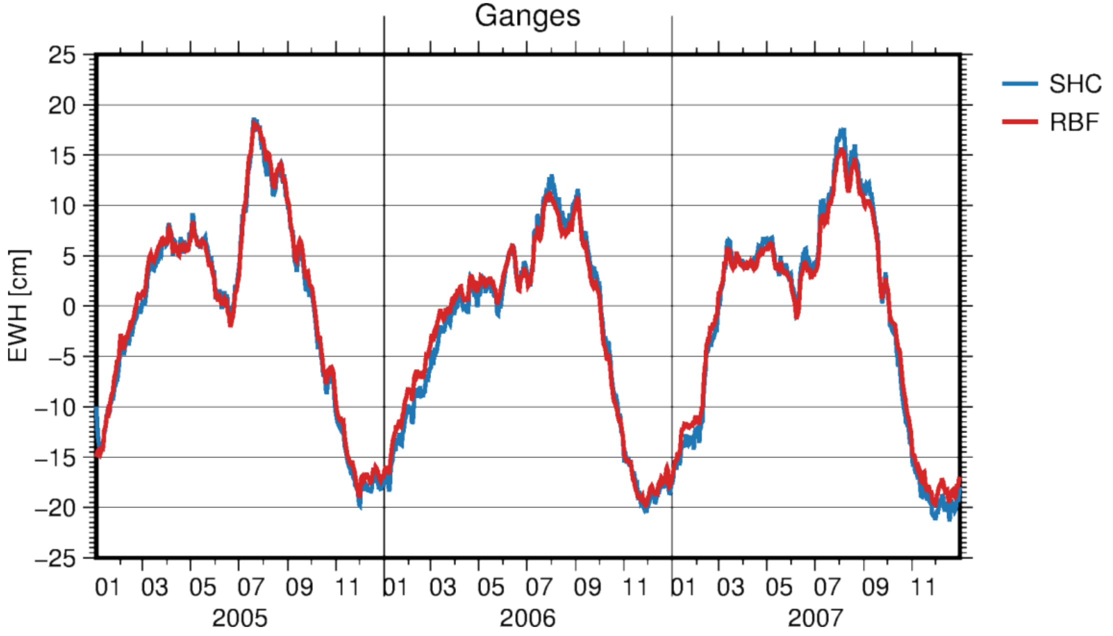
- Three experiments were conducted
  - Daily RBF solutions from a Kalman filter framework (E1)
  - Five day moving average solutions with tailored basis functions (E2)
  - Five day moving average solutions with tailored regularization (E3)

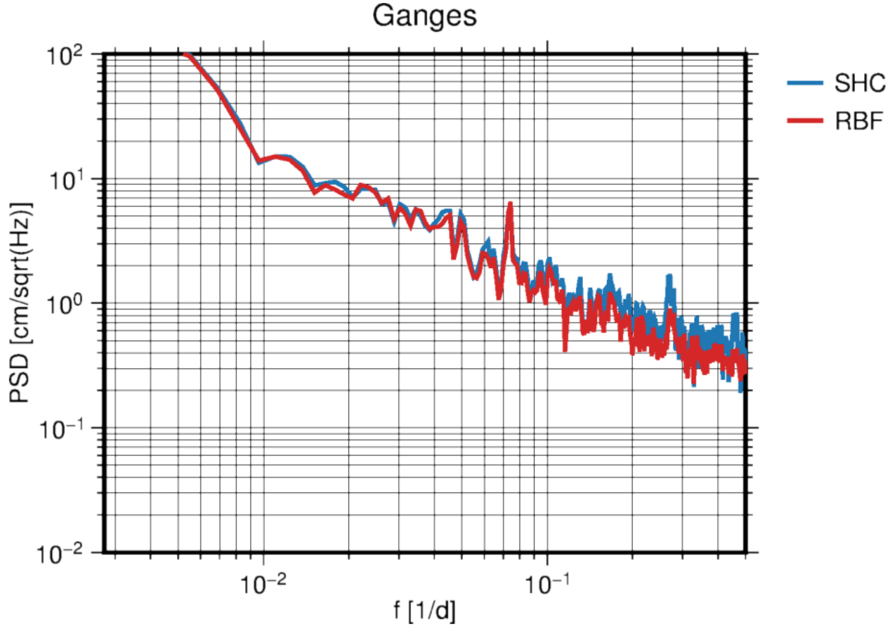
- Spatial representation makes life easier in a few circumstances
  - Regularization matrices are usually very sparse or diagonal
  - Easy separation of spatial domains

Regional Solutions – E1: Kalman filter with different representation

- Daily normal equations with gravity field represented by RBFs
  - Kernel shape: isotropic part of empirical autocovariance matrix, globally uniform
  - RBFs are distributed on a Reuter grid with a nodal point count of 1442 (approximately d/o 40)
  - Kalman filter process model derived from high resolution grids by least squares adjustment

- Comparison with standard spherical harmonic solution (SHC)



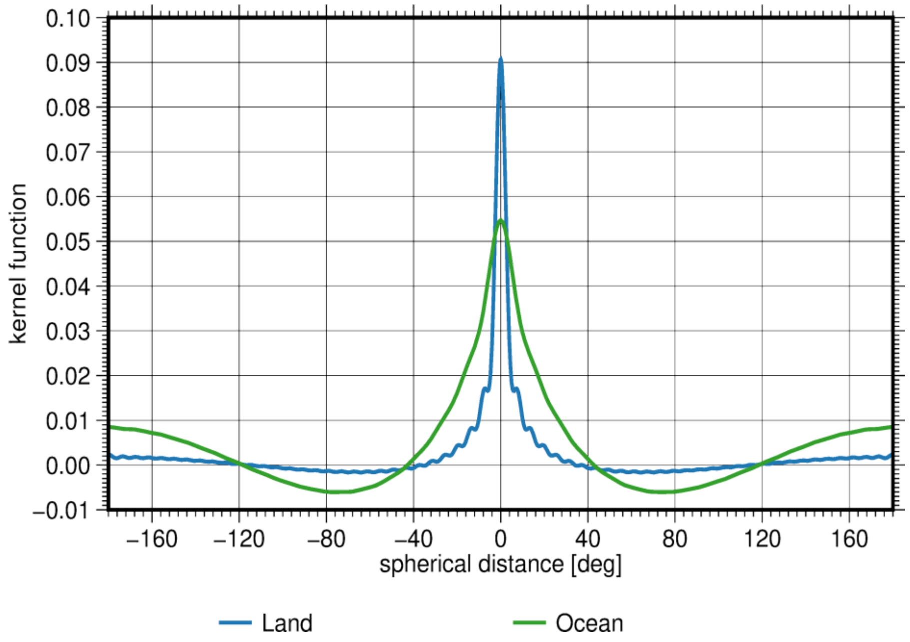


Regional Solutions – E2: tailored kernel shapes

- Tailored RBF kernel shapes
  - Expected signal is quite different between ocean and land, which can be modelled through the basis functions
  - Ocean: lower overall amplitudes and smoother signal, Land: Higher spatial variability

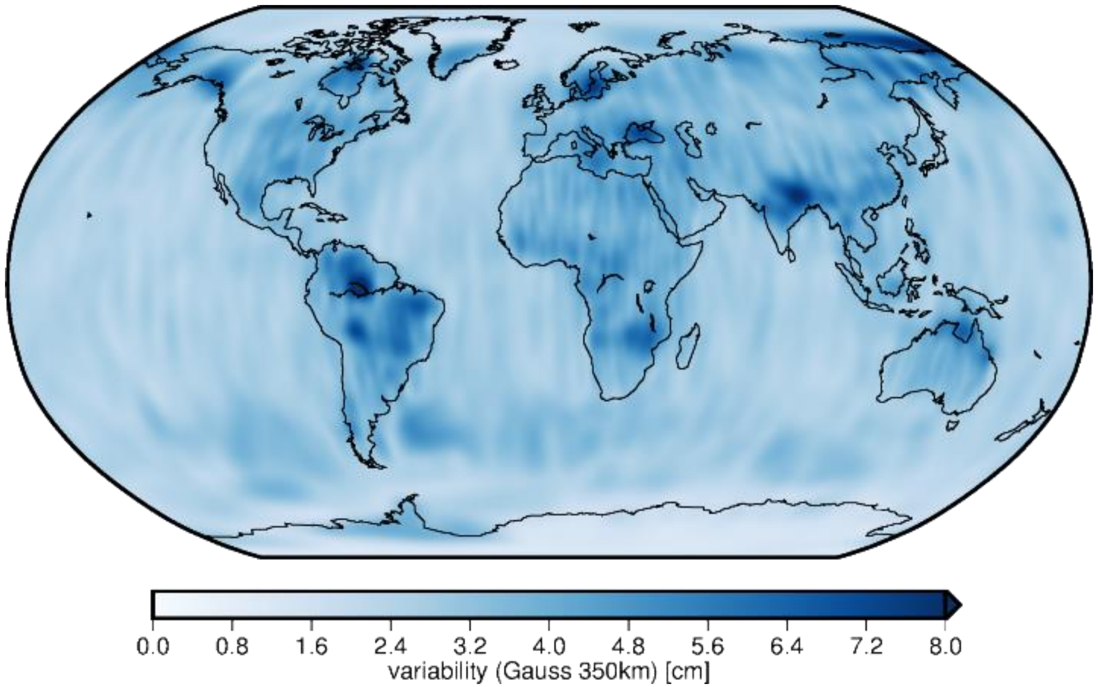
- Shape of kernel functions are derived by fitting Kaula type functions to AOD1B GAD for ocean and WGHM for land
  - Cut off for ocean: degree 30
  - Cut off for land: degree 60

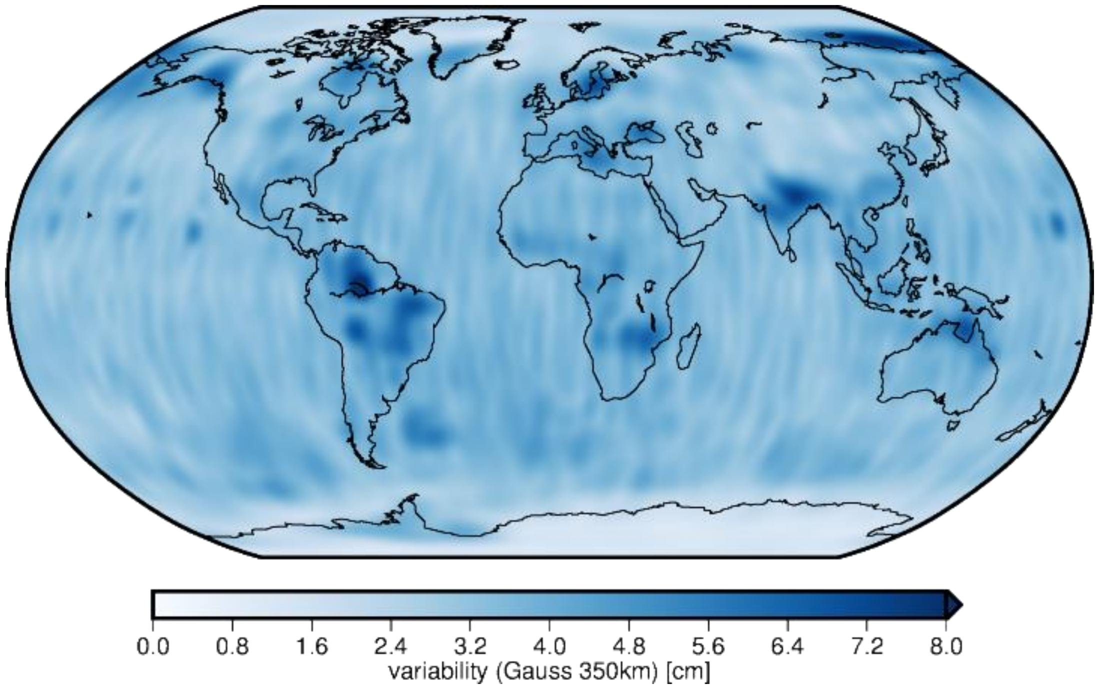
- Different grid densities for land and ocean result in a parameter count of approximately 1800



Regional Solutions – E2: tailored kernel shapes

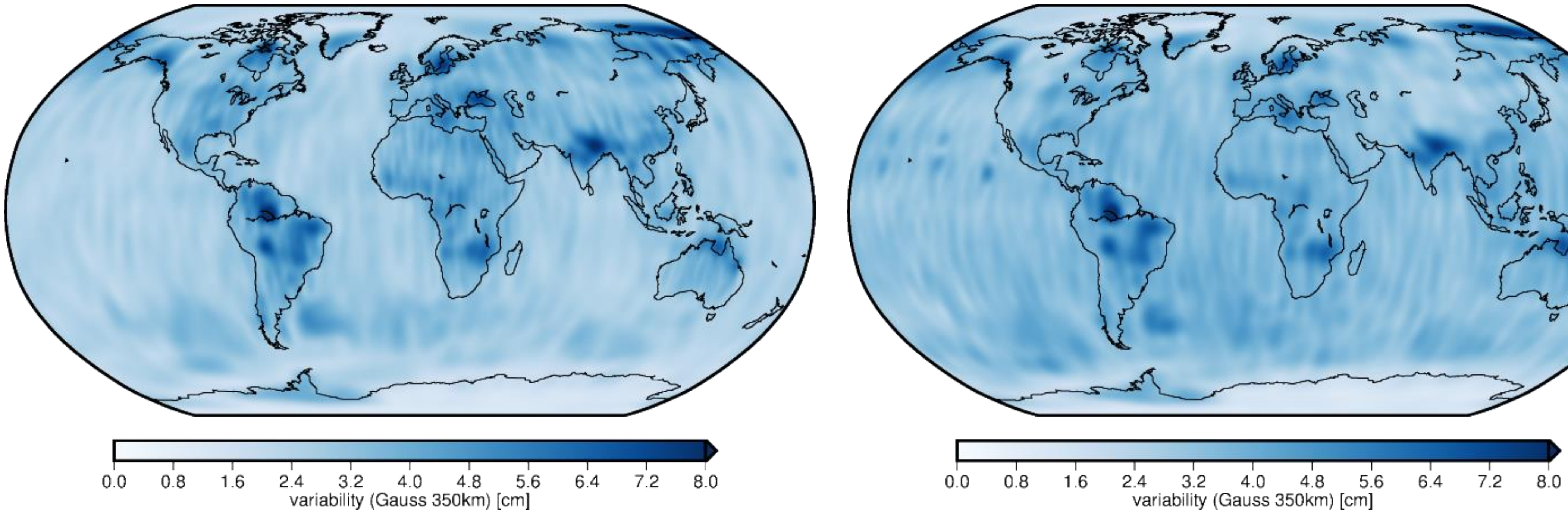
- Comparison of solution with spherical harmonic representation up to degree and order 40
  - Both are five day moving average solutions
  - Gauss filter of 350km is applied to the result





Regional Solutions – E2: tailored kernel shapes

- Higher noise over the ocean in SHC solution → kernel shape acts a low pass filter
- Contrary behavior on land → kernel shape does allow for higher variability



Regional Solutions – E3: regionally adapted regularization

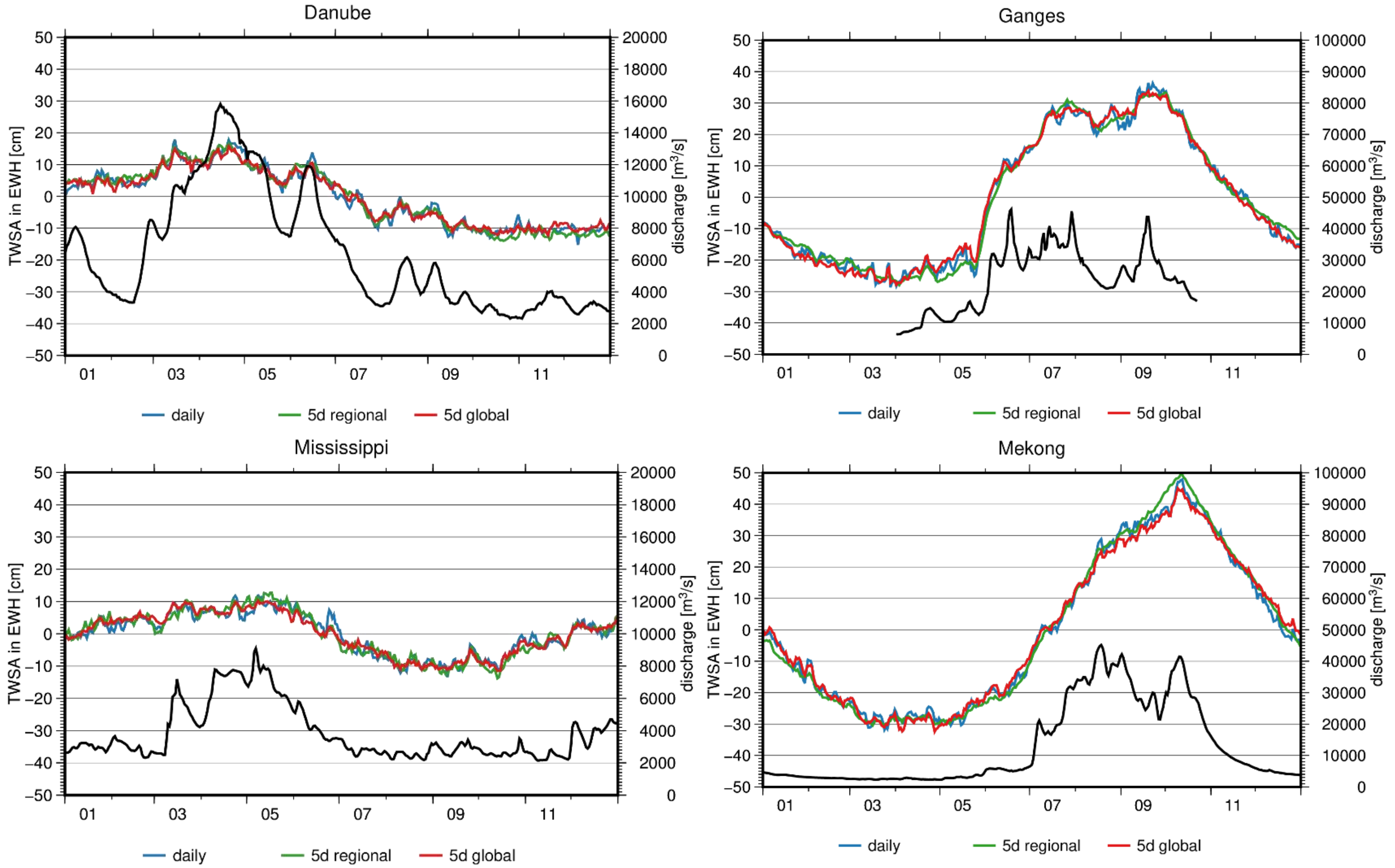
- Picking up on the idea of E2, regionally adapted regularization was implemented
  - Independent isotropic noise model for ocean and land
  - Noise level estimated through variance component estimation
  - Only prior information is land/ocean mask!

- Companion solution: same normal equations, one global variance factor

- Evaluation of solutions based on comparison of five day moving RBF solutions with Kalman filter output
  - Primary goal is to check the feasibility of this product for operational use

Regional Solutions – E3: regionally adapted regularization

- Point wise evaluation of solutions in discharge stations



Regional Solutions – E3: regionally adapted regularization

- Conclusion (from D5.4):
  - To concede temporal resolution by stacking the normal euqations of five days seems therefore counterproductive, since the Kalman filtered solution exhibits a more dynamical behavior during events with sharply increasing river discharge, without major loss of spatial resolution.

- However: moving five day solutions are however a useful tool in evaluting the temporal behavior of the Kalman solutions
  - No explicit temporal constraint needs to be applied
  - During TUGs NRT run, five day moving solutions (with isotropic noise constraint) were used as offline evaluation tool

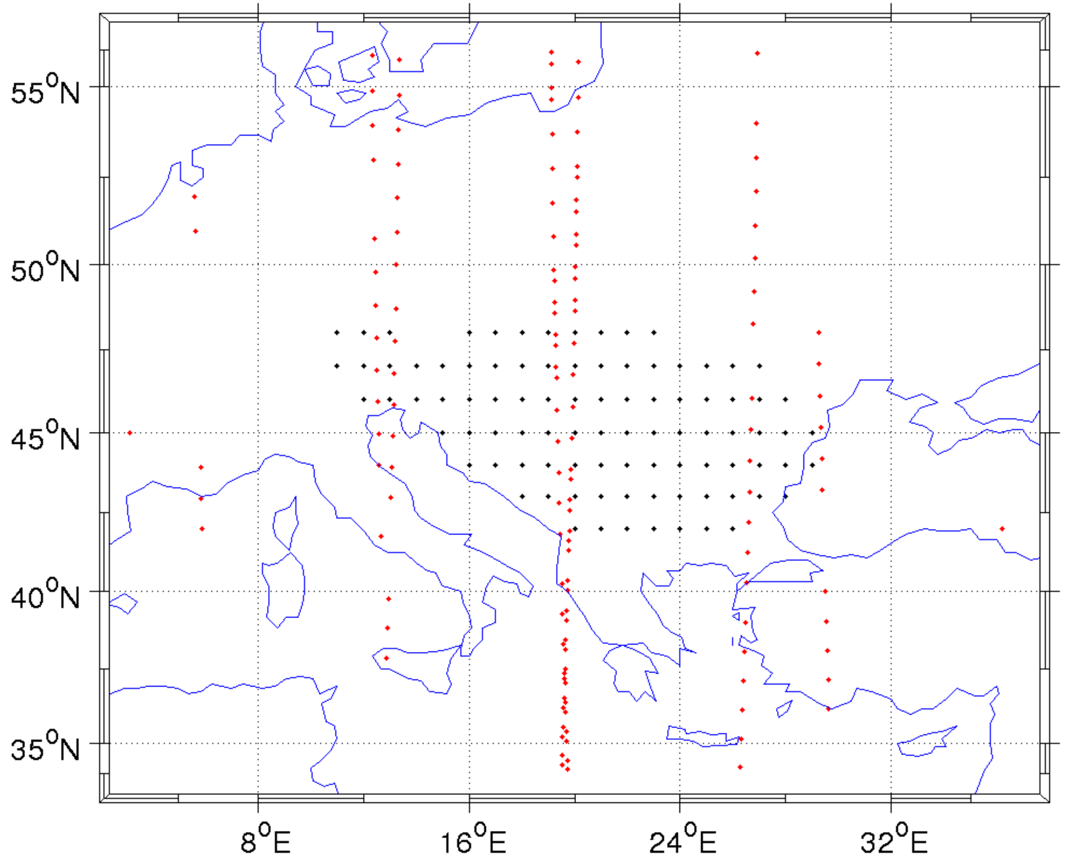
Regional Solutions – Results at GFZ

- Idea: accumulate observations in a specified region from multiple fly-overs
  - Region of interest can be a river basin with a buffer, e.g. a spherical cap

- As the GRACE ranging observations are not fully localizing, the daily Kalman solutions are removed as additional background field to reduce far zone effects

- Within the area of interest, the gravity field is parametrized as space-localizing basis function

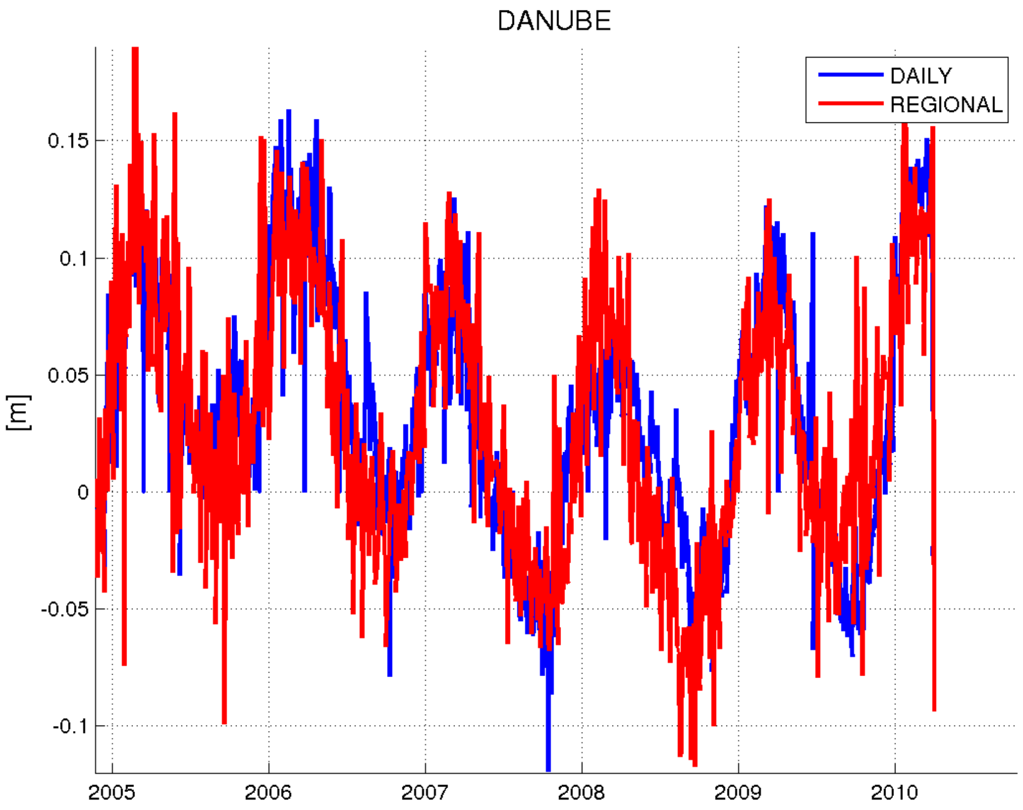
- Integrating only the region of interest allows for estimating the unconstrained basin average from from 4 to 5 days of data

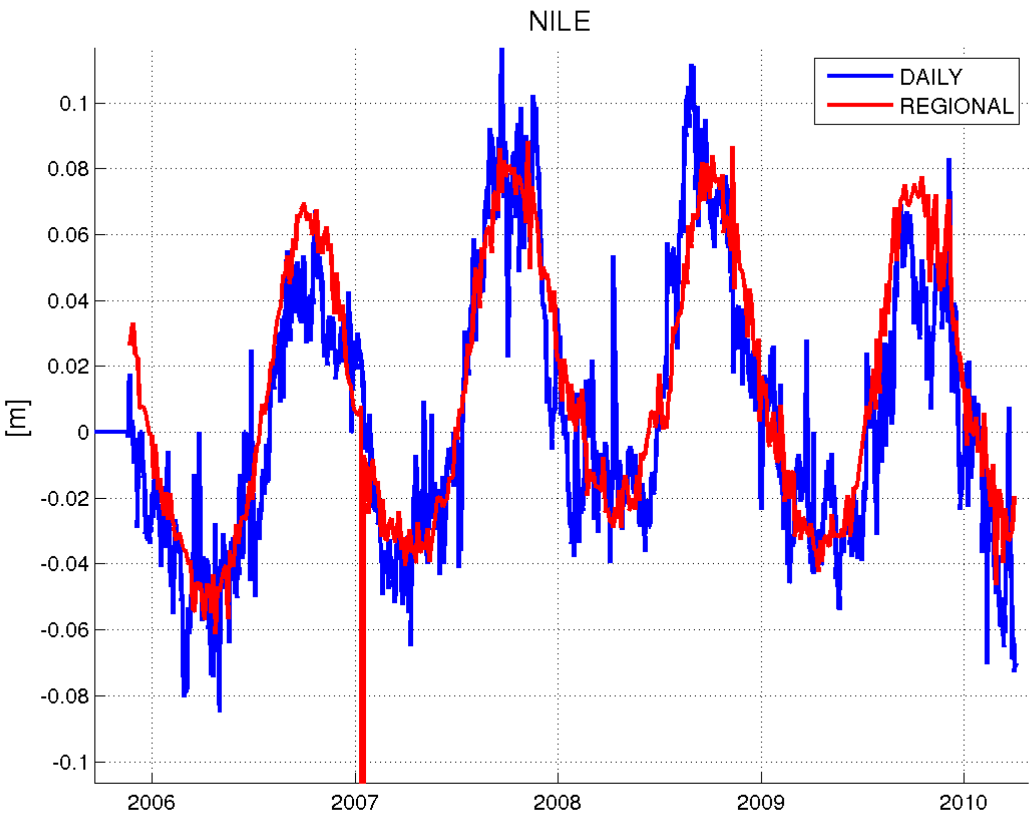


EGSIEM

Regional Solutions – Results at GFZ

- Results: comparison of unconstrained basin average estimate (red) with the Kalman filtered solution (blue)

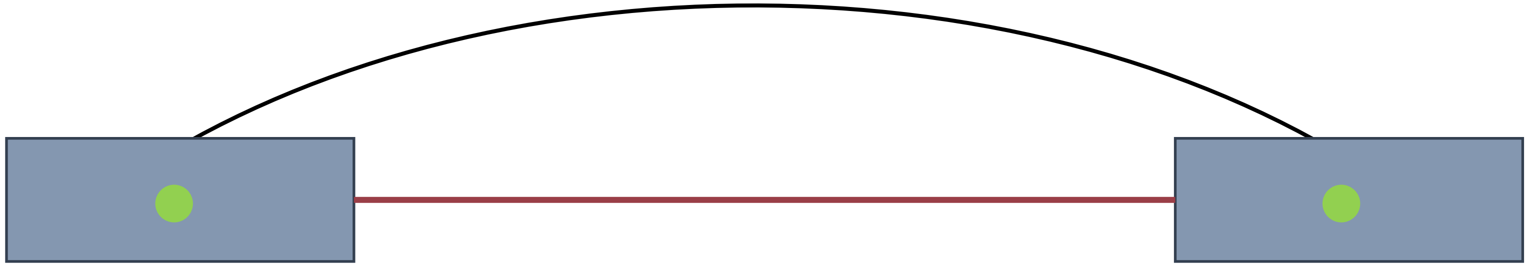




Backup – GRACE Satellite Health

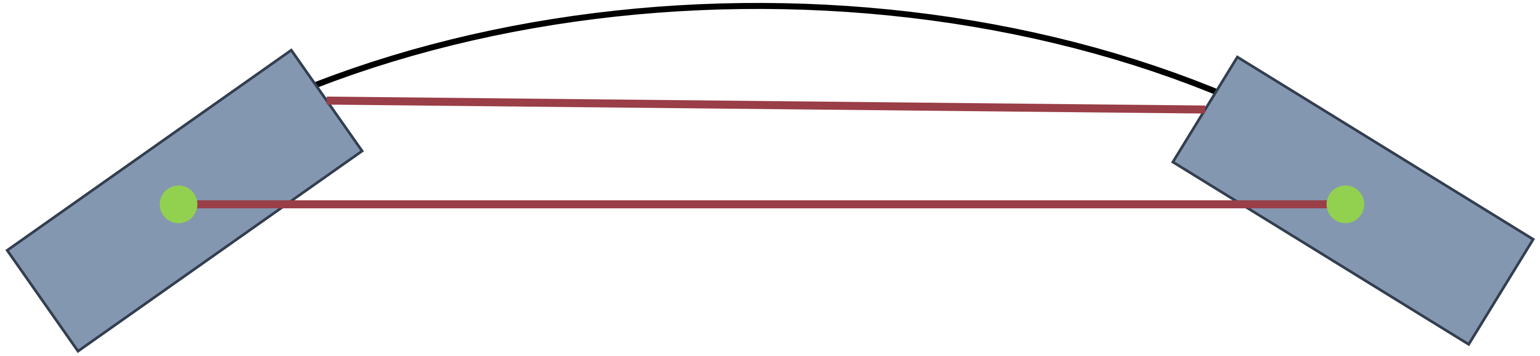
Impact of Pitch Bias Removal

- During science operations, the GRACE satellites directly face each other
  - K-band antenna center and satellite center of mass (approximately) lie on the line-of-sight



Impact of Pitch Bias Removal

- During science operations, the GRACE satellites directly face each other
  - K-band antenna center and satellite center of mass (approximately) lie on the line-of-sight
- This pitch bias was removed on March 29 to alleviate accelerometer transplant
  - Both spacecraft hit the atmosphere at the same angle
  - Drag acts primarily along one accelerometer axis



- The drawback of this measure is an increase in magnitude of the K-band antenna center correction (ACC)
  - Attitude and ACC errors more prominently propagate into the ranging observations

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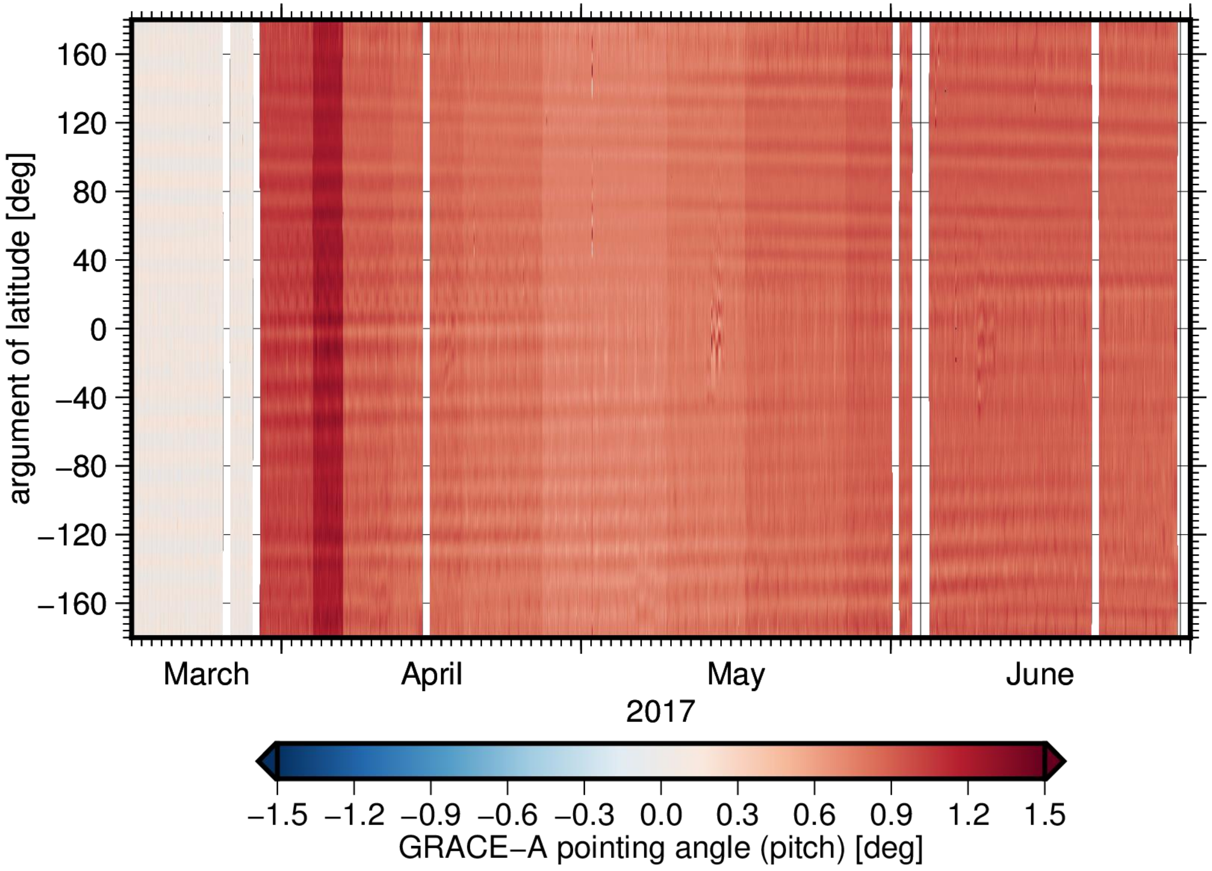

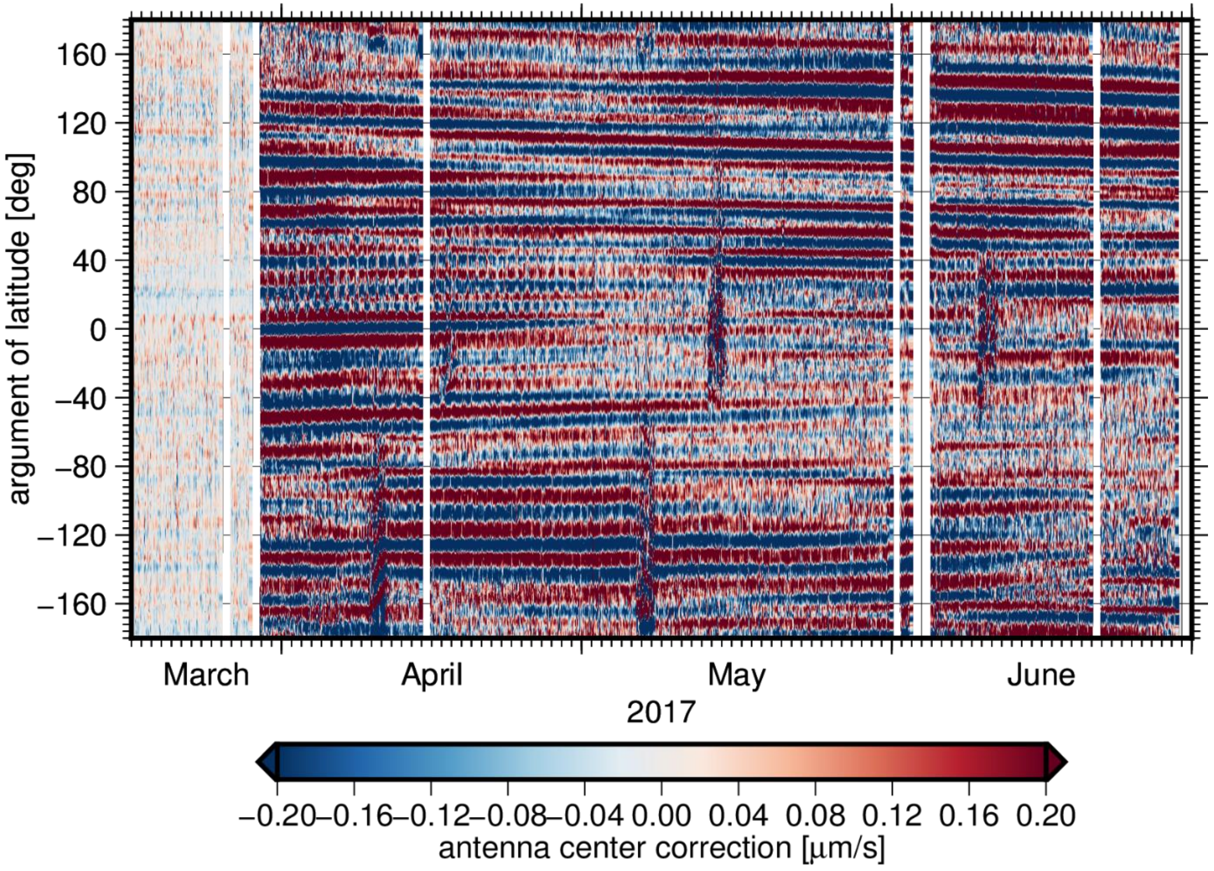

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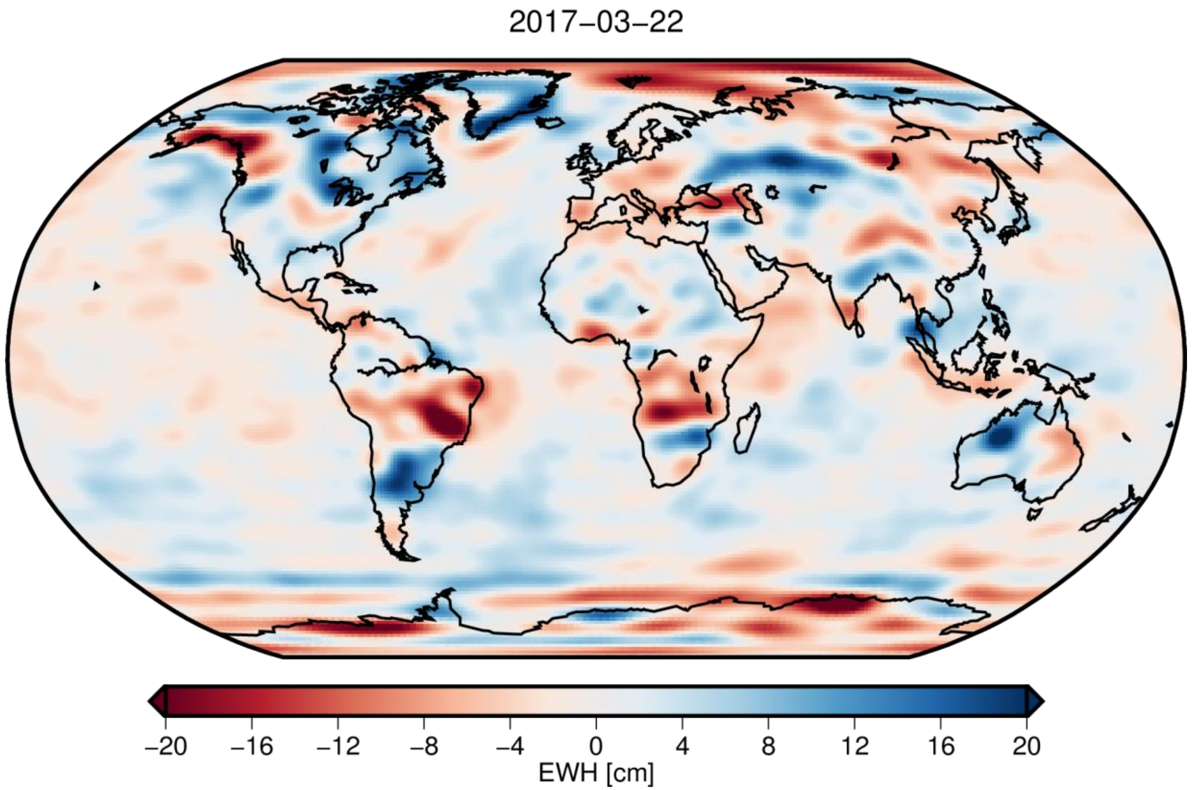

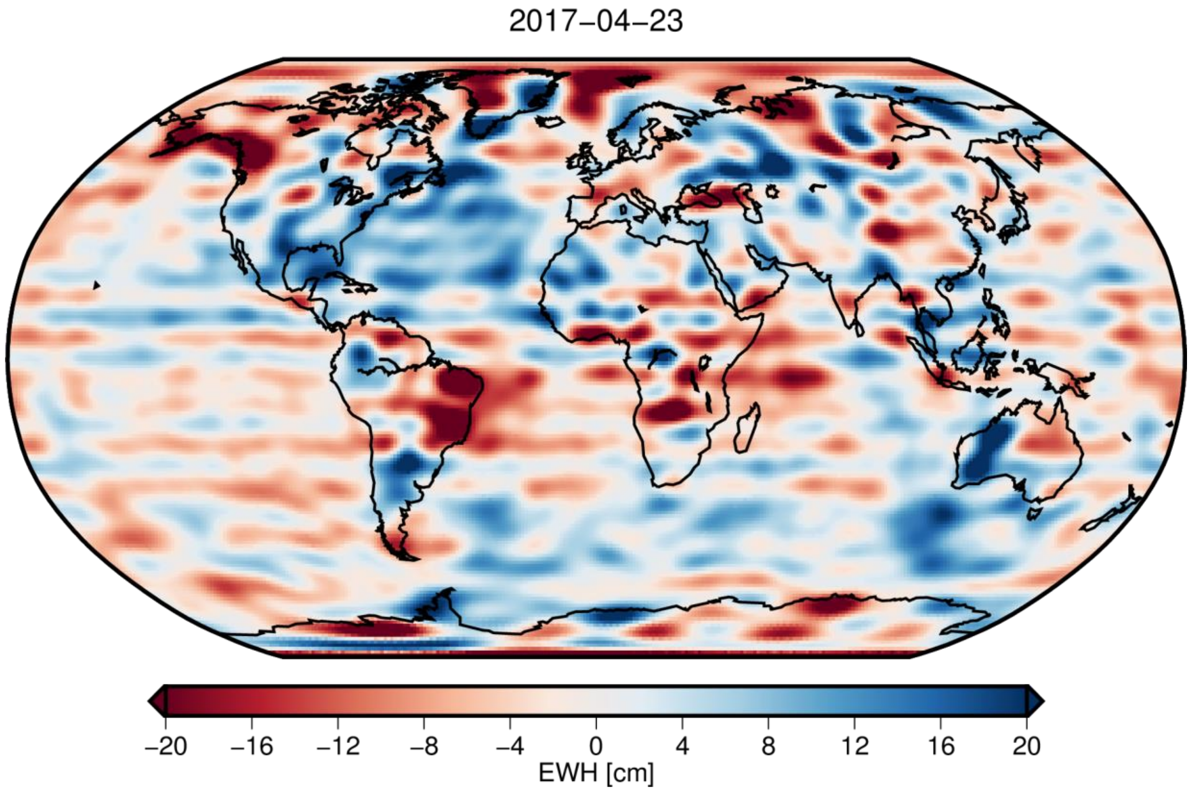

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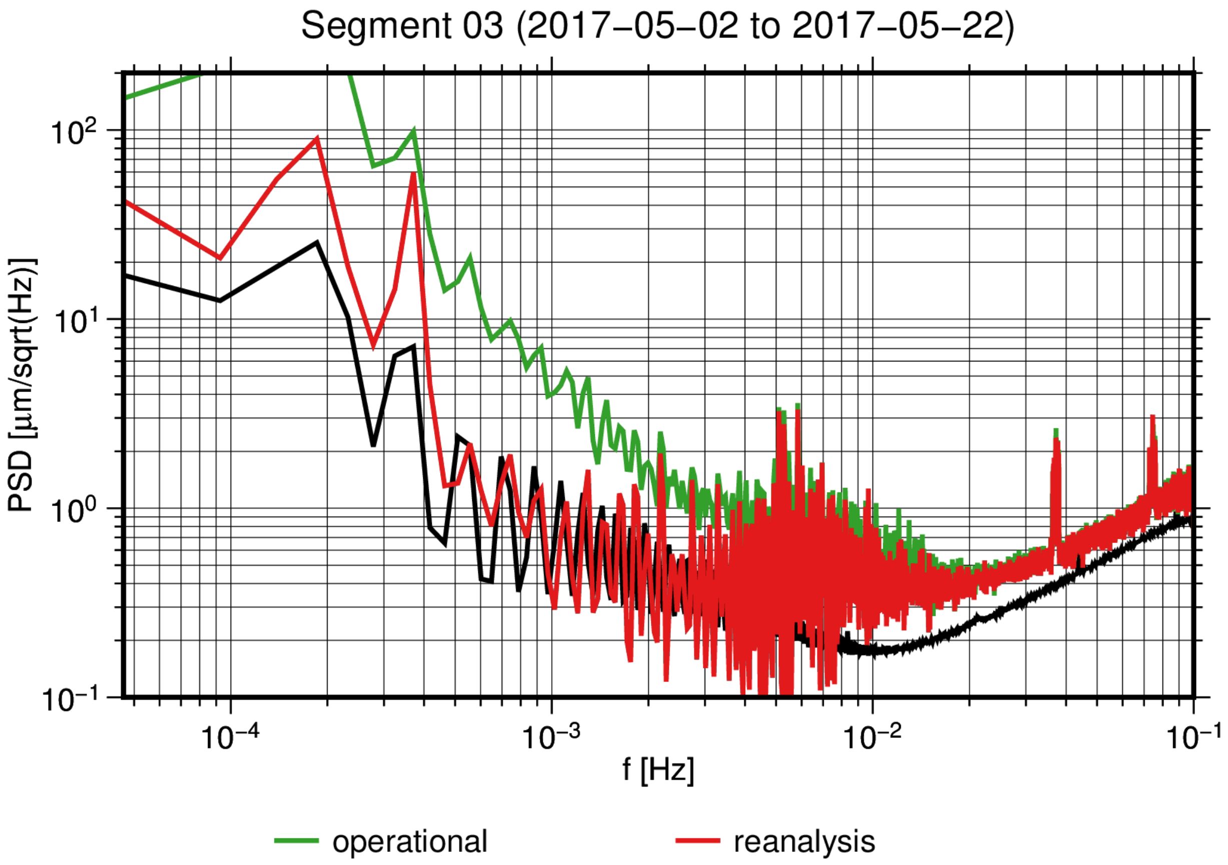

red: GRACE-B accelerometer
green: accelerometer transplant
black: nominal science operations

Impact of Pitch Bias Removal

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  - Attitude and ACC errors more prominently propagate into the ranging observations

- In the frequency band 3 – 10 mHz propagated attitude errors dominate the spectrum
  - Additionally, this effect is non-stationary, which means it cannot be fully captured by TUGs and GFZs (stationary) covariance model