EGSIEM
European Gravity Service for Improved Emergency Management

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Deliverable 5.3
OPERATIONAL NRT SERVICE PRODUCT REPORT
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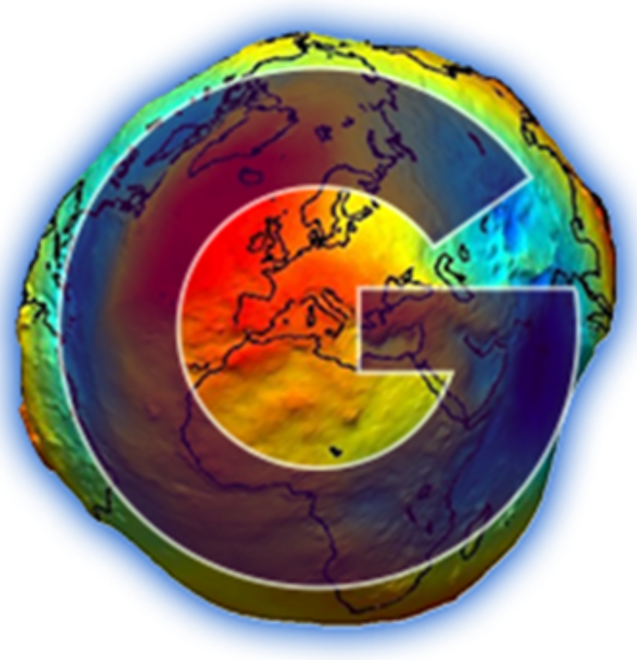

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1. Change Record

Name	Author(s)	Date	Document ID
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2. Terms

This document provides the product report of the Near Real-Time and Regional Service of EGSIEM (Work Package 5). The contents describe the data product which was delivered to the Hydrological Service (Work Package 6) and the measures undertaken to ensure reliability and integrity during the operational service run.

3. NRT and Regional Service Overview

Background

The nominal time delay of the standard GRACE Science Data System (SDS) Level-1B (L1B) instrument data is 11 days and of derived Level-2 (L2) gravity field products up to 60 days. Therefore, monitoring of hydrological extremes such as floods and droughts currently covers only the ‘confirmation after occurrence’ of an event and estimation of the severity after the event. In order to improve e.g. SAR acquisition planning the latency of GRACE Level-2 products is therefore planned to be drastically reduced.

Objectives

One of the main objectives of EGSIEM is to establish a **N**ear-**R**eal-**T**ime (NRT) and Regional Service that aims a) to reduce the time delay of necessary input data and derived output gravity models to less than 5 days, b) to increase the time resolution of gravity models to just one day and c) to improve their quality by transferring the accuracy level of the monthly fields to the daily ones. This can be done by adequate regularization and constraining of solutions in terms of Bayesian estimation and Kalman filtering on a global scale and by using dedicated space-localizing radial base functions for applications on a regional scale. The product of the NRT service will be used to observe and monitor European (and global) water resources and ensures wide access to high level, easy to use products. GFZ will develop indicators as a measure of catchment wetness from gravity-based water storage anomalies and will evaluate their performance for forecasting hydrological extreme events. This evaluation is expected to provide information on the added value of these gravity-based indicators for flood forecasting in terms of accuracy, lead time and skill. The results will be used to provide input to T6.3.

‘Off-line’ performance tests, i.e. post-processing of available data shall be developed based on historical hydrological extreme events (T3.9) covering the GRACE mission period. In the final phase of the project an operational test run, simulating ‘real-time’ conditions of the service was performed in cooperation with DLR/ZKI for half a year (1.4.-30.9.2017).

Near-Real-Time & Regional Service Timeline

NRT and Regional software and output products were developed based on individual approaches at GFZ and TUG within M04-M27. The concepts and strategies were refined and improved during this implementation phase which led to minor adaptions to the NRT processing strategy as defined in deliverable D5.1.

Milestones, Documents & Reports to be provided by the Service

Table 1: Deliverables and Milestones for WP5.

	Item Name	Date
D5.1	Concept of NRT Service	M03
MS2	Implementation and Preparation Review	M10
MS3	Service Readiness	M18
D5.2	NRT Service Product Report	M27
D5.4	Regional Solution Product Report	M27 (deferred to M33)
MS4	Operational NRT Service Readiness	M27
D5.3	Operational NRT Service Product Report	M33
D5.5	NRT Validation Report	M36
MS5	Final Review	M36

Document overview

In chapter 4 of this document, the satellite health and data quality during the operational phase of the NRT service is outlined. Chapter 5 contains a summary of the operational gravity field generation. Evaluations of gravity field solutions computed by GFZ and TUG during the NRT service run with GNSS loading displacements, as well as a comparison to historical (post-processing) GRACE time series can be found in Chapter 6.

4. State of the GRACE satellites during the operational service run

Following a battery cell failure on October 25th 2016 the accelerometer on board the GRACE-B spacecraft was turned off on September, 3 2016. Its data stream has subsequently been replaced with a “transplant” data product, where the accelerometer measurements of GRACE-A are shifted in time and rotated to substitute the missing measurements on GRACE-B. Furthermore, to shed load on the GRACE batteries, since 2011 inter-satellite K-Band ranging (KBR) data have only been collected in orbit segments where the satellites are fully exposed to the sun. These events are correlated with the β’ angle between the orbit plane and the Earth-Sun line and have a periodicity of 161 days. Near β’=0° the KBR data are completely missing due to switch-off of the Microwave Assemblies. Further details can be found at http://www.csr.utexas.edu/grace/operations/mission_status/.

Since March, 17 2017 inter-satellite observation between the GRACE spacecraft have been available again. The pitch angle of both spacecraft relative to the line of sight was increased from zero to approximately one degree (Himanshu Save, Gerhard Kruizinga, personal communication) on March, 30 (Fig. 1, left). This means that the cross section of the spacecraft move through the atmosphere at approximately the same angle which in turn alleviates the transplant process. The resulting increased KBR antenna phase center correction (PCC) magnitude (Fig. 1, right) has also led to an increase of the errors in spacecraft attitude that prominently propagate into the gravity field solutions. These errors typically manifest in horizontal striping patterns. While TUG computed and applied its own PCC solution, at GFZ the JPL provided PCC solution was first low-pass filtered in order to reduce the impact on the error covariance estimation for the KBR. The Kalman filter is weighting the actual data contribution with the previous state such that high error variances within the measurement update leads to a low contribution in the solution. Therefore, data error needs to be reduced as much as possible to keep the Kalman process dynamic.

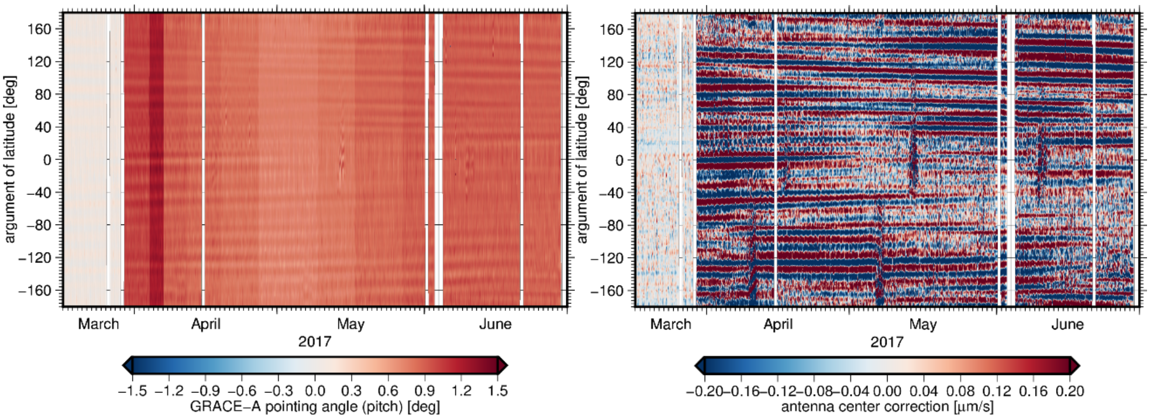


Figure 1: Pointing angle (pitch component) of GRACE-A relative to the line of sight and antenna center correction (expressed as range rate) during the beginning of the operational NRT service run.

KBR data collection was steadily increased from sunlight-only orbital segments (approximately 50% reduction of the observation count) back to full revolutions with nearly 100% observation count. On May, 2 the accelerometer on GRACE-B was switched on again for 22 days. During this time the nominal set of GRACE science data was available. A scheduled position swap of leading and trailing satellites meant that the KBR was turned off on June 30th and remained inactive throught the remaining service run. On September 3 another battery cell failed aboard GRACE-B which forced the satellite into a passive state with data collection suspended until the end of September (the end of the test run). The effective length of the operational service test run was therefore limited from April, 1st to June, 29 where in principle only nominal results can be expected from May, 4 until May, 25.

5. Summary of NRT gravity field product generation

Estimation of Instrument Noise Covariance at TUG

The gravity field product generation at TUG followed the processing steps described in deliverables 5.1 and 5.2. A key feature of the processing at TUG is the empirical estimation of noise covariance functions for KBR range-rates and kinematic orbits from the residuals of an unconstrained monthly solution. One fundamental assumption in this procedure is that the noise behavior is stationary within the given month, which was partly violated during the service run due to rapid changes in data characteristics outlined in chapter 4. It was therefore necessary to move from automated weekly updates of the noise covariance functions using the last 30 days, to manual updates where only days of similar data quality are used. The definition of these manually chosen time spans was based on the attitude control of the satellites, the availability of accelerometer data, as well as the data coverage along the orbit. These criteria resulted in four segments of similar data characteristics which can be found in table 2. While this approach minimizes the days with varying stochastic properties in each covariance update, the requirement of 7-10 days of data to derive a global GRACE gravity field solution still induced edge effects.

Table 2: Defined Segments of similar data characteristics for the estimation of instrument noise covariance functions

Start	End	Features
2017-03-17	2017-03-29	Pointing Angle approximately zero degrees, accelerometer transplant
2017-03-30	2017-05-01	Pointing Angle approximately one degrees, accelerometer transplant
2017-05-02	2017-05-22	Pointing Angle approximately one degrees, measured accelerometer data on GRACE-B
2017-05-23	2017-06-29	Pointing Angle approximately one degrees, accelerometer transplant

Estimation of Instrument Noise Covariance at GFZ

The instrument noise estimates at GFZ are based on a multi-step derivation strategy starting from averaged auto-correlations derived from nominal sensor characteristics. After computation of primary signal estimates the residuals are re-analyzed for the derivation of the actual error covariance for each subsequent data set being processed through the Kalman filter. The noise estimates are thereby being altered throughout data processing and automatically adapting to changing error properties from different data qualities.

Operational Gridded Water Storage Anomalies

Since the flood indicators rely on gridded water storage anomalies as input, and operational level 3 (gridded gravity products) was implemented as outlined in deliverable 5.2, the main features of this processing chain was the transformation of the GRACE solution from center of mass to center of figure frame and the reduction of GIA induced mass change by removing the model of A, et al. 2013. As no degree one estimates are available in near-real time, these coefficients were estimated from a combination of GRACE and an ocean model (AOD1B RL06) as proposed by Swenson et al. (2008). The replacement of C20 of GRACE solutions with SLR derived values is also common, however, no suitable substitute with operational capability was found. The final grid provided to the Hydrological Service therefore consisted of GIA corrected water storage anomalies transformed to center of figure.

Latency of NRT Gravity Field Solutions

Throughout the service run, the latency of the gravity field solutions was tracked. Latency in this case was defined as the time span between the last measured epoch and the upload of the gridded solution. The daily latency of the solutions can be seen in figure 2, which highlights that for most days the solution could be uploaded within 20h after the last measured epoch, with some periods exceeding two or even three days. These spikes were caused by FTP server and network outages (May 22, June 1 and June 20), which meant the necessary input data could not be downloaded. As the employed Kalman filter approach introduces dependencies between consecutive epochs, the latency only gradually decreases such events. Generally, the processing duration was low enough to fulfill the goal of five day latency for the derived flood indicators.

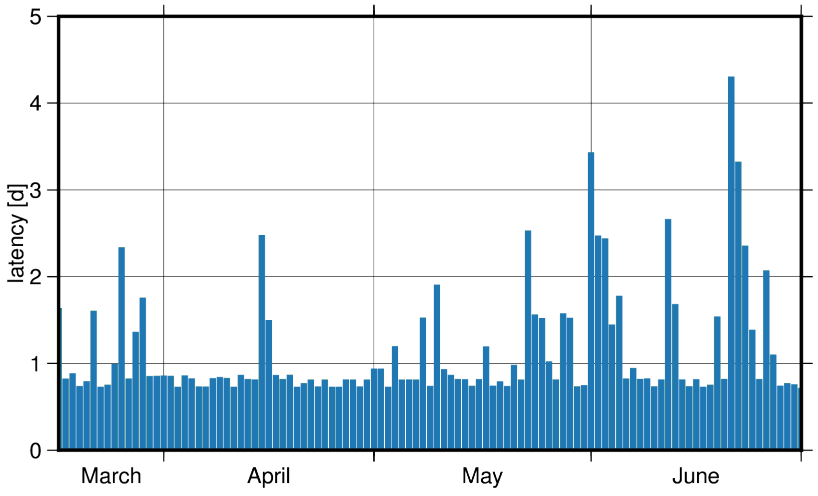


Figure 2: Latency of the computed gravity field from last measured epoch to upload.

6. Evaluation of the NRT gravity field solutions

6.1 *Inter-comparison of historical time series*

To get an idea on how well the processing strategies of GFZ and TUG fit, an analysis of historical data from 2002 was undertaken. Here the GSM coefficients are compared and an independent evaluation of the time series using GNSS displacements provided by JPL is performed. For GFZ, three time series are available, denoted v201, v211 and v221 which differ in the applied Kalman filter process model and prediction, as well as in terms of background modeling. These differences were relatively minor, starting from deploying continuous predictions for those cases where no KBR data have been available (v201-> v211) as well as the introduction of a stepwise modeling of trends with the following breakpoints applied: 26.12.2004, 30.06.2008 and 11.03.2011 due to singular events such as major earthquakes (Fukushima, Tohoku) or an apparent change in global trends during 2008.
A second modification was applied from v211 to v221, with an amplification of the error estimates for atmosphere and non-tidal ocean signal contribution. For TUG the ITSG-Grace2016 daily (Mayer-Gürr et al. 2016) solutions are used.

Inter-comparison of Gravity Field Solutions

To determine the overall fit of the different time series each GFZ time series is compared to the ITSG-Grace2016 release which is taken as reference in this case. In order to determine the coherence for short term temporal variations, the annual and secular signal has been removed from each time series. Additionally, only epochs which contain GRACE contributions common to all four time series are used in this analysis.

Figure 3 shows the global difference RMS in terms of equivalent water height for all three GFZ time series compared to the TUG solution. The solutions fit best during the interval from 2003 to 2010, where no large data gaps occur and the GRACE data quality was very high.

The most striking feature is the large deviation between the solutions in 2015. This may be attributed to different warm up behavior of the individual Kalman filter implementations, since the large RMS differences occur on the edges of long data gaps. Overall the RMS between the time series averages approximately 2.5 cm of equivalent water height over all considered epochs.

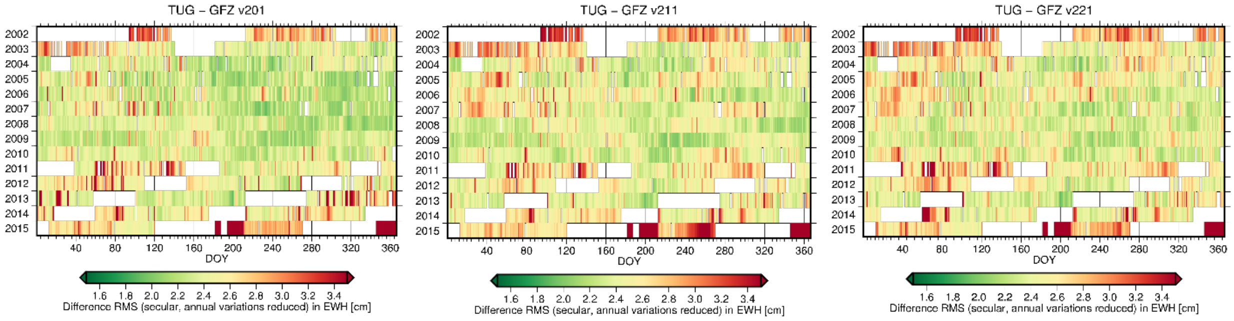
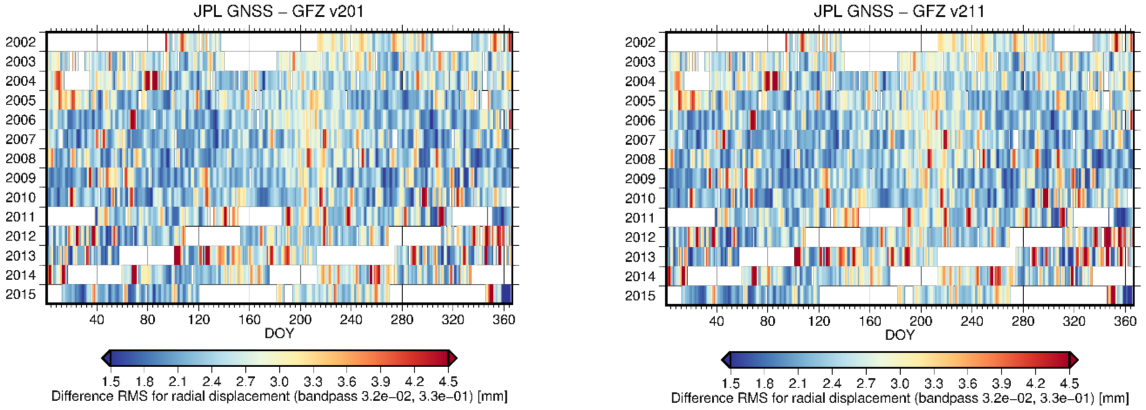


Figure 3: Global difference RMS of GFZ solutions v201 (left, 2.48cm), v211 (middle, 2.53cm) and v221 (right, 2.58) compared to TUG solution.

Comparison with GNSS displacements

An evaluation with independent data was performed by comparing the GRACE time series with station displacements observed by GNSS. The measured station displacements were provided by JPL and divided into secular, annual/semi-annual and residual parts. Breaks and discontinuities have also been removed. Stations with short observation periods or long data gaps have been excluded, which meant a network of 257 stations remained for this analysis. As the measured GNSS displacements also contain atmospheric and ocean loading, AOD1B RL06 was removed from the observations to be comparable with the GRACE gravity fields. A band pass filter was applied to both the GNSS time series as well as the GRACE derived radial displacements to evaluate only the high frequency temporal content. The frequency band was chosen to range from 31 days to capture only sub-monthly variations and three days since noise starts to increase in both GNSS and GRACE time series beyond this limit.

Figure 4 shows the daily difference RMS between the observed displacements and the GRACE derived values. Similar to this comparison, the RMS is lowest in the years 2003 to 2010. Generally, all four time series exhibit similar behavior throughout the observation period with overall RMS values ranging from 2.66 mm to 2.68 mm for GFZ and 2.59 mm for TUG.



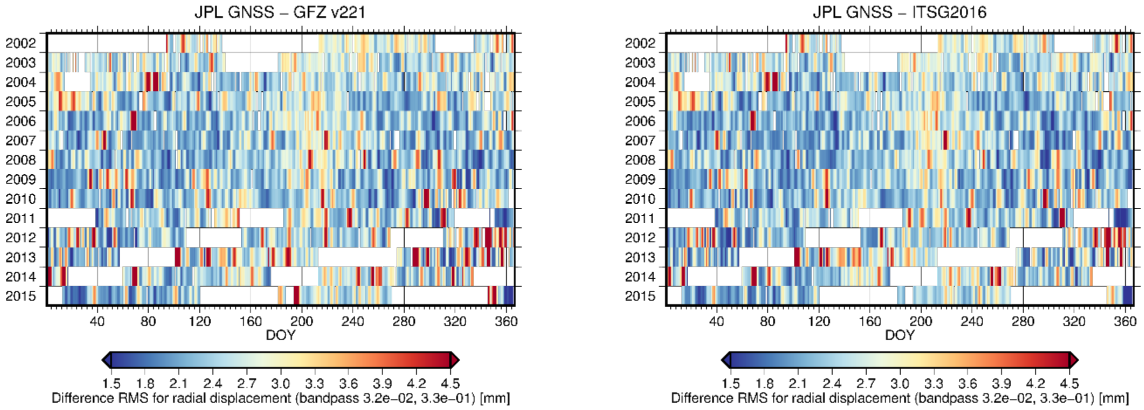


Figure 4: Daily difference RMS of radial displacements observed by GNSS and GRACE for GFZ solution v201 (top left, overall 2.66mm), v211 (top right, overall 2.67mm), v221 (bottom left, overall 2.68mm) and TUG (bottom right, overall 2.59mm).

The inter-comparison of the time series shows that, except for periods which experienced long data gaps, the time series are homogeneous despite very different processing approaches and parametrizations. This is underlined by the relative RMS increase/decrease shown in figure 5, which only ranges from 6.9% to 7.9% for the whole time span.

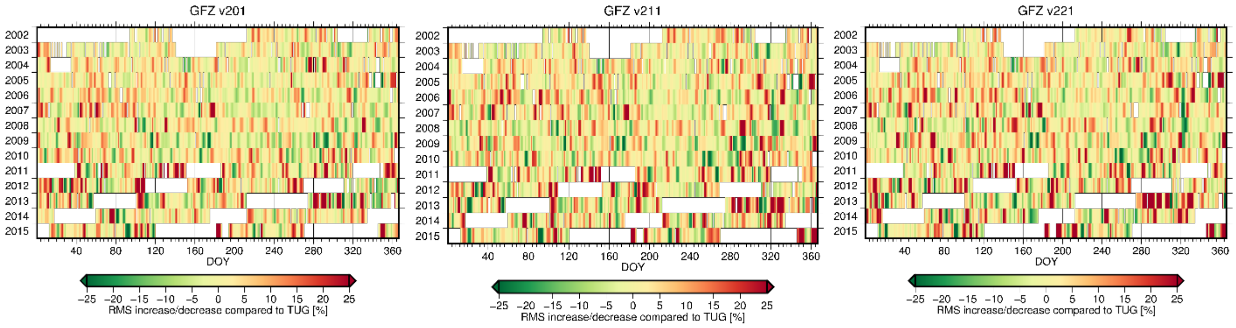


Figure 5: Relative RMS increase of GFZ solution v201 (left, +6.9%), v211 (middle, +7.5%) and v221 (right, +7.9%) compared to TUG.

6.2 Evaluation of NRT gravity products

As mentioned in Chapter 4, the effective duration of the EGSIEM NRT Service test run was April 1 to June 30 (with the limitations as mentioned in Chapter 4). This means that approximately 90 daily gravity field solutions are available for evaluation. In accordance with the inter-comparison of the historical time series, the NRT gravity field products are evaluated by comparing the GFZ and TUG solutions as well as both time series to GNSS displacements. Since the time series is comparatively short, GNSS station with no data gaps during the NRT service test run have been chosen, leaving 992 stations (distributed mostly in North America and Europe). Again, to be comparable to the GRACE fields, AOD1B RL06 has been reduced from the measured displacements.

Inter-comparison of Gravity Field Solutions

The inter-comparison of both near real-time solutions shows daily global RMS differences of about 2.65 cm equivalent water height (cf. Figure 6), which is slightly higher than for the historical data sets. This can be attributed to the overall reduction in observation count as well as the challenging data characteristics (see Chapter 4).

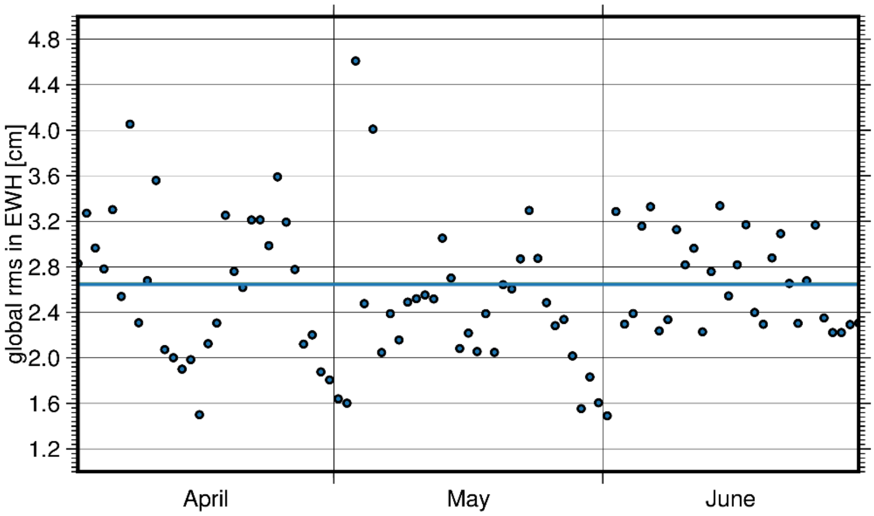


Figure 6: Daily difference RMS in equivalent water height between GFZ and TUG solution during the NRT service test run.

Comparison with GNSS displacements

Comparison of the NRT gravity field solutions with GNSS station displacements shows a similar picture to the historical time series. Both solutions exhibit a similar spatial with an overall difference in RMS of 3.0mm (TUG) and 3.3mm (GFZ). As with the inter-comparison, this value is higher compared to the historical time series (it shows an increase of about 18%). The overall RMS of both time series deviates on average by 11.7% (increase of GFZ solution compared to TUG).

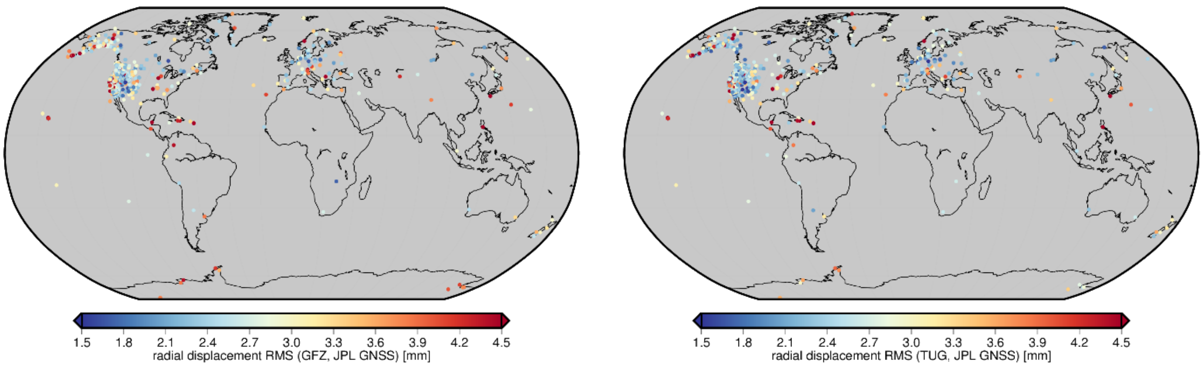


Figure 7: Difference RMS of radial displacements observed by GNSS and GRACE for GFZ (left, 3.3mm) and TUG (right, 3.0mm).

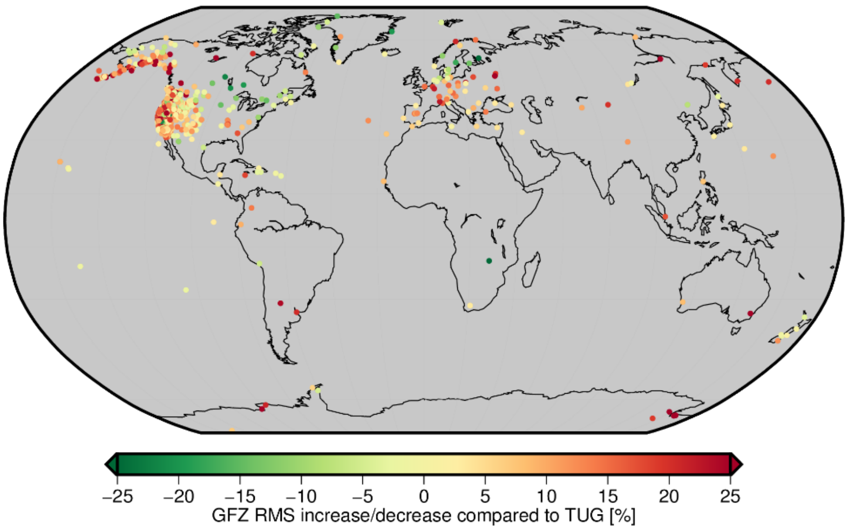


Figure 8: Relative increase/decrease of RMS of GFZ solution compared to TUG (overall +11.7%).

When examining the temporal variations of the time near real-time time series (see Figure 9), for most days both solutions are very similar. GFZ contains some isolated outliers which are the main reason for increased overall RMS. Yet to be explained is the apparent bi-weekly variation in RMS magnitude which is present in both GNSS- and the inter-comparison.

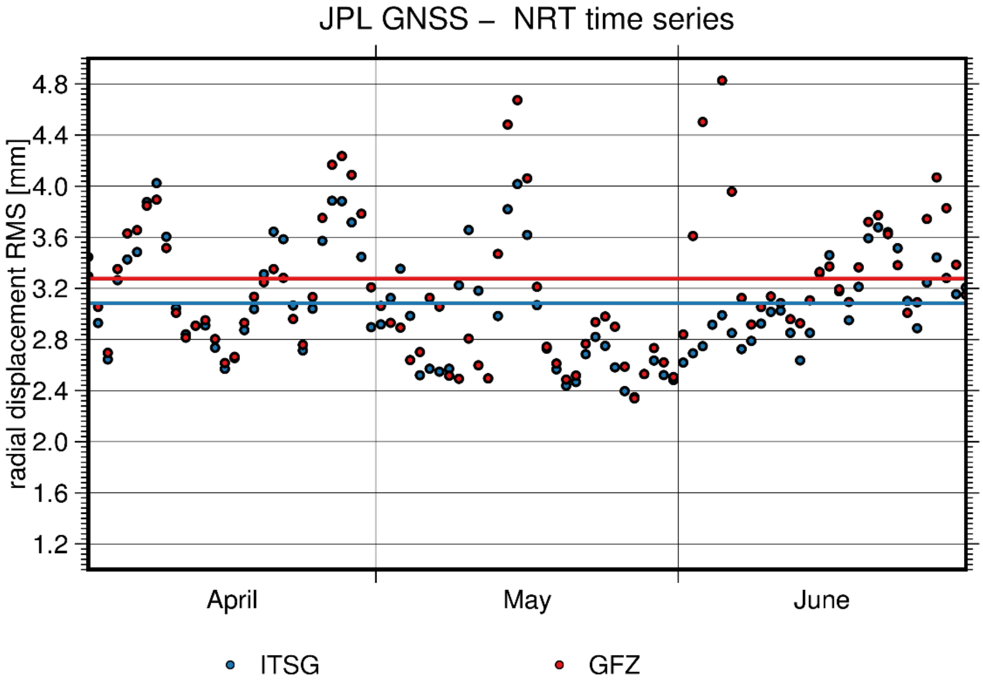


Figure 9: Daily difference RMS of radial displacements observed by GNSS and GRACE for GFZ NRT solution (overall 3.3mm). Right: global difference RMS of TUG and GFZ solutions in equivalent water height (EWH).

7. Summary

Both the near real-time gravity field products and historical time series produced by GFZ and TUG are homogeneous throughout the GRACE observation period, except for time spans with large data gaps. After such gaps, the different warm-up behavior of the Kalman filter process models causes the solutions to deviate for short periods of time.

During the test run, unforeseen changes in satellite attitude required amendments to be made in the proposed processing scheme. However, the difference between RMS to GNSS displacements and between the respective time series increases by about 18% compared to the historical post-processed time series. This can be attributed to both the lower observation coverage during the test run, as well as the degrading satellite health and resulting challenging data characteristics. In terms of operational processing, both processing centers have shown that the computation, internal evaluation and distribution of daily gravity field solutions is possible within the projected five day latency in a fully automated manner.

8. Bibliography

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