EGSIEM

European Gravity Service for Improved Emergency Management

HORIZON 2020

***EO-1-2014: New ideas for Earth-relevant space applications***
***Research and Innovation action***


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# Deliverable 3.3:
# NRT product validation report

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# 2. Introduction

## Background

One of the main objectives of the EGSIEM project is to establish a near-real-time regional service which aims at reducing the latency to less than 5 days and increasing the temporal resolution to daily. Meanwhile, the quality of the daily gravity solutions is expected to be kept at the comparable accuracy level of the monthly gravity fields. To this end, post-processing of the available GRACE data has been done by GFZ and TU Graz to produce continuous daily gravity fields since 1st April, 2002, see more processing details in Deliverable 5.2.

To validate the post-processed daily gravity fields, we follow the same validation concepts as presented in Deliverable 3.2 by using the daily GNSS time series and the ocean bottom records. The same evaluation metrics are used. Therefore, the concepts of validation are not repeated in this report.

During the generation of the daily gravity fields by GFZ, several versions has been produced, i.e. GFZ RBF daily v100, GFZ RBF daily v101, GFZ RBF daily v200, GFZ RBF daily v201, GFZ RBF daily v211, GFZ RBF daily v221 and modified GFZ RBF daily v221 (after the project meeting in Munich in June 2017). During each project meeting, we have forwarded the validation feedback to the analysis centers.

The first round validation feedback for the first three versions have been presented in the project meeting on 19th January 2017 by UL and GFZ using the GNSS time series and the ocean bottom pressure (OBP) records, respectively.

The second round validation feedback regarding the following three versions, i.e. GFZ RBF daily v201, GFZ RBF daily v211 and GFZ RBF daily v221 have been presented again using the GNSS time series by UL during the project meeting in Munich on 9th June 2017. The final version of the GFZ RBF daily gravity fields were generated in July 2017 after the project meeting. During the intermediate project meeting on 4th October 2017 in Munich, the final version of the GFZ RBF daily v221 has been validated and shown using the GNSS time series by UL. Therefore, in this report, we include the validation of the gravity fields using GNSS time series only for the ITSG2016 daily gravity field solutions and the final version of the GFZ RBF daily gravity field solutions.

For validation using the OBP records, the validation results for the ITSG2016 daily gravity solutions and the GFZ RBF daily v100 daily gravity solutions have been presented in this report. Although the first version of the GFZ RBF daily solutions are used, promising results from the GFZ RBF daily gravity products are obtained.

## Outline

The report consists of two parts. The validation part using the GNSS time series is described in Section 3 including the post-processing of the daily gravity fields, which is not the same as the monthly fields. Corresponding validation results are presented in this section. Validation using the OBP records is presented in Section 4.

# 3. Validating daily gravity fields using GNSS

## *3.1 Post-processing of daily gravity fields*

**Table 3-1** lists the daily gravity fields used in the validation with GNSS. The maximum degree for the GFZ daily solutions is 50 while ITSG2016 daily has maximum degree 40. Both gravity fields span the same period, i.e. from 1st April 2002 up to the end of 2016.

**Table 3-1 Daily gravity fields uses in the validation**

| | Time span | Maximum degree |
|---|---|---|
| GFZ RBF daily v221 | 2002.04.01~2016.12.31 | 50 |
| ITSG2016 daily | 2002.04.01~2016.12.31 | 40 |

Post-processing of daily gravity fields is not the same as for the monthly solutions. $C_{20}$ terms are not replaced for the daily gravity fields as there are currently no daily $C_{20}$ time series available. To restore the degree-1 coefficients, we need to interpolate the monthly degree-1 coefficients from external sources, e.g. monthly degree-1 coefficients from Swenson et al. (2008), to the daily degree-1 coefficients. We have experimented with two interpolation techniques. The first is the simple spline interpolation and the second is the harmonic series suggested by Dr. Christian Gruber (GFZ). The harmonic series for $C_{1,0}$ is written as $C_{1,0} = A * \cos\left(\frac{2*\pi}{wz}\right) * dday - phz$, where $A, wz, phz$ are constants listed in Table 3-2 and $dday$ is the decimal time of the specific day, for example, $dday = 2017.00136986301$ for 1.1.2017 (noon). The formula is also applied for the $C_{1,1}$ and $S_{1,1}$ terms except these constants are different, see Table 3-2. We find that the interpolated harmonic series perform slightly better than degree-1 coefficients determined using the simple spline interpolation. Therefore, we restore the interpolated degree-1 harmonic series back to the daily gravity fields.

**Table 3-2 Constants for interpolating the degree-1 harmonics.**

| | $A$ | $wz$ | $phz$ |
|---|---|---|---|
| $C_{1,0}$ | 1.008979156830368e-10 | 0.998245271982843 | -1.490451013729841 |
| $C_{1,1}$ | 6.701850615794752e-11 | 0.998829496683574 | -2.342642651858799 |
| $S_{1,1}$ | 1.349493530967875e-10 | 1.001760907845823 | 1.621254226970130 |

As the daily gravity fields have been stabilized by certain constraints during data processing, no filtering is required at the post-processing stage. Regarding the dealiasing products, we add the daily GAC products averaged from the 6-hourly AOD1B release 5 back into the daily gravity fields. The last step in post-processing is to convert the daily fields into the vertical displacements in the center of figure (CF) reference frame at the GNSS stations using the spherical harmonic approach. We fit and remove the mean and the trend of the vertical displacements.

## 3.2 *External datasets*

### GNSS time series

To validate the daily gravity fields, we use the same ITRF2014 residuals from Rebischung et al. (2016) as used in Deliverable 3.2 and Deliverable 4.3. As demonstrated in D3.2, the ITRF2014 residuals can be considered as the most precise GNSS time series to date. These are daily GNSS time series free of outliers, offsets and linear trends. For the ITRF2014 residuals, a selection of 394 global GNSS stations are used.

### Hydrological models

During the validation process of the daily gravity fields, five hydrological models have been tested as references. Four of them are WGHM models of different versions and another is the GLDAS model. In this report, we include only the best WGHM model out of the four versions, i.e. WGHM (CRU) model, and the GLDAS model. The WGHM model has a temporal resolution of daily and a spatial resolution of a half degree globally. The GLDAS model has the same temporal resolution as WGHM but a spatial resolution of one degree globally. Vertical displacements from the hydrological models are computed at the GNSS stations in the CF reference frame using the Green's functions approach (Farrell et al., 1972). As with the gravity fields, we fit and remove the mean and the trend from the computed displacements.

## 3.3 *Full signal level*

In line with the validation process as described in D3.2, we commence the validation of the daily gravity fields by analyzing the degree WRMS reductions and accumulative degree WRMS reductions. **Figure 3-1** shows that the ITSG2016 daily solutions reduce the RMS of GNSS time series to a greater extent than the GFZ RBF daily gravity solutions at low degrees, especially at degree 2 and degree 3, which leads to the better performance of the ITSG2016 daily solutions in terms of the mean accumulative degree WRMS reductions. **Table 3-3** lists the statistical results according to the minimum, maximum, mean, median and positive WRMS reductions. As reference, median and positive WRMS reductions with respect to the same GNSS time series from Li et al. (2016) who used a combination of the non-tidal atmospheric model (NCEP), the non-tidal oceanic model (ECCO) and the hydrological model (GLDAS) are shown as well (personal communication).

Comparing to the monthly gravity fields which are smoother than daily solutions, we find that a maximum of 66.8% WRMS reduction can be reached using the ITSG2016 daily solutions. Similarly, the maximum WRMS reduction for the GFZ RBF daily v221 is 64.7%. With both daily solutions, a mean reduction of the WRMS of more than 15% can be achieved, which is higher than Gu et al. (2017) who compared monthly GNSS and GRACE products.

Comparing the combined daily models from NCEP, ECCO and GLDAS, both ITSG2016 daily solutions and the GFZ RBF daily v221 solutions with GAC restored show better median WRMS reductions. In particular, the ITSG2016 daily solutions show both higher median WRMS reductions as well as positive WRMS reductions.

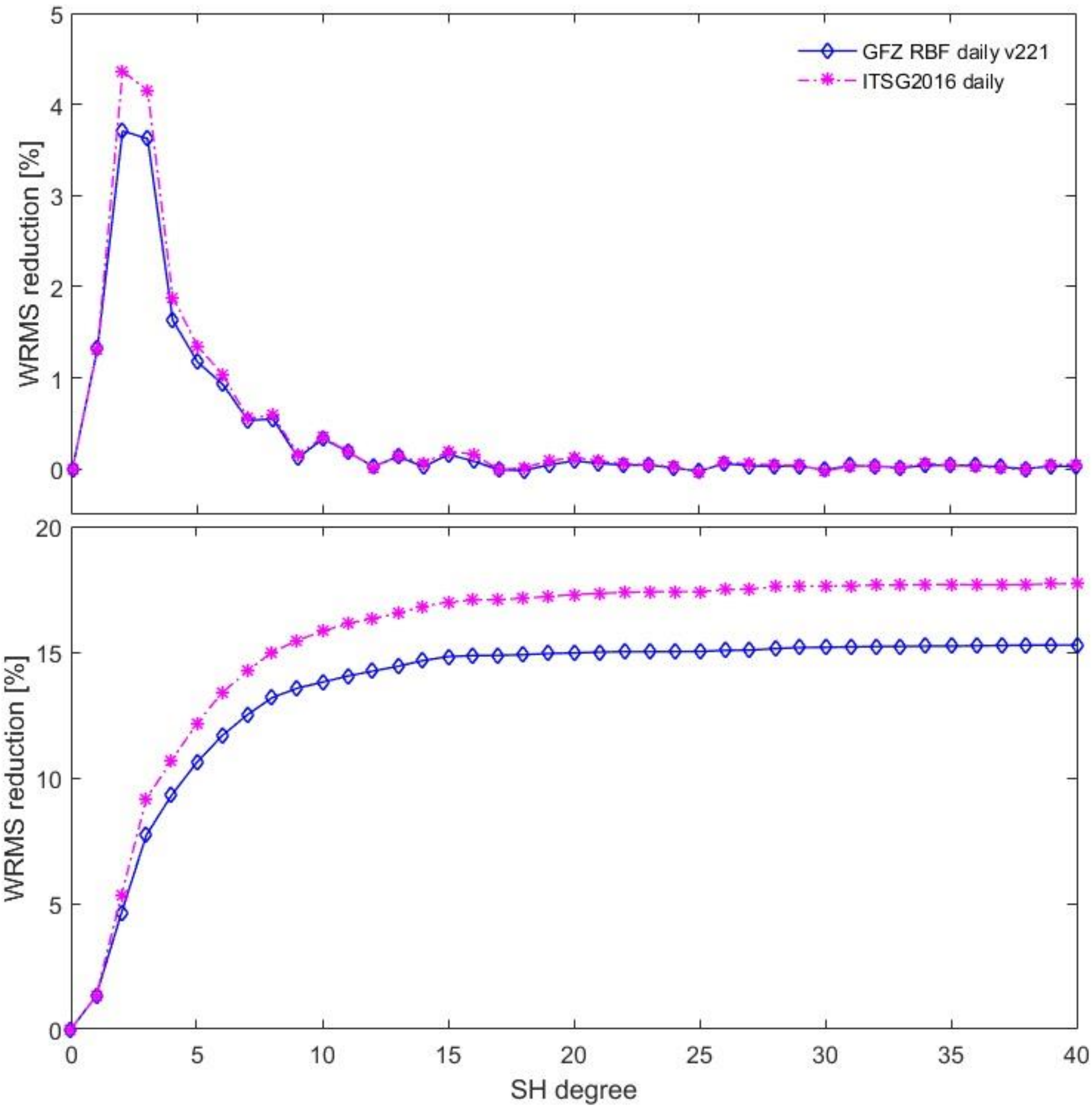


**Figure 3-1: Mean degree WRMS reductions (top) and accumulative degree WRMS reductions (bottom) of two daily gravity solutions using the ITRF2014 residuals at the full signal level over 394 GNSS stations globally. GAC products have been restored back.**

**Table 3-3 WRMS reductions with respect to the ITRF2014 residuals at the full signal level. GAC prodcuts have been restored back to the daily gravity fieelds.**

| | WRMS reduction [%] | | | | Positive WRMS reduction [%] |
|---|---|---|---|---|---|
| | min | max | mean | median | |
| GFZ RBF daily v221 | -10.7 | 64.7 | 15.3 | 15.0 | 90.6 |
| ITSG2016 daily | -12.2 | 66.8 | 17.7 | 16.9 | 94.4 |
| Combination of models | - | - | - | 11.5 | 90.7 |

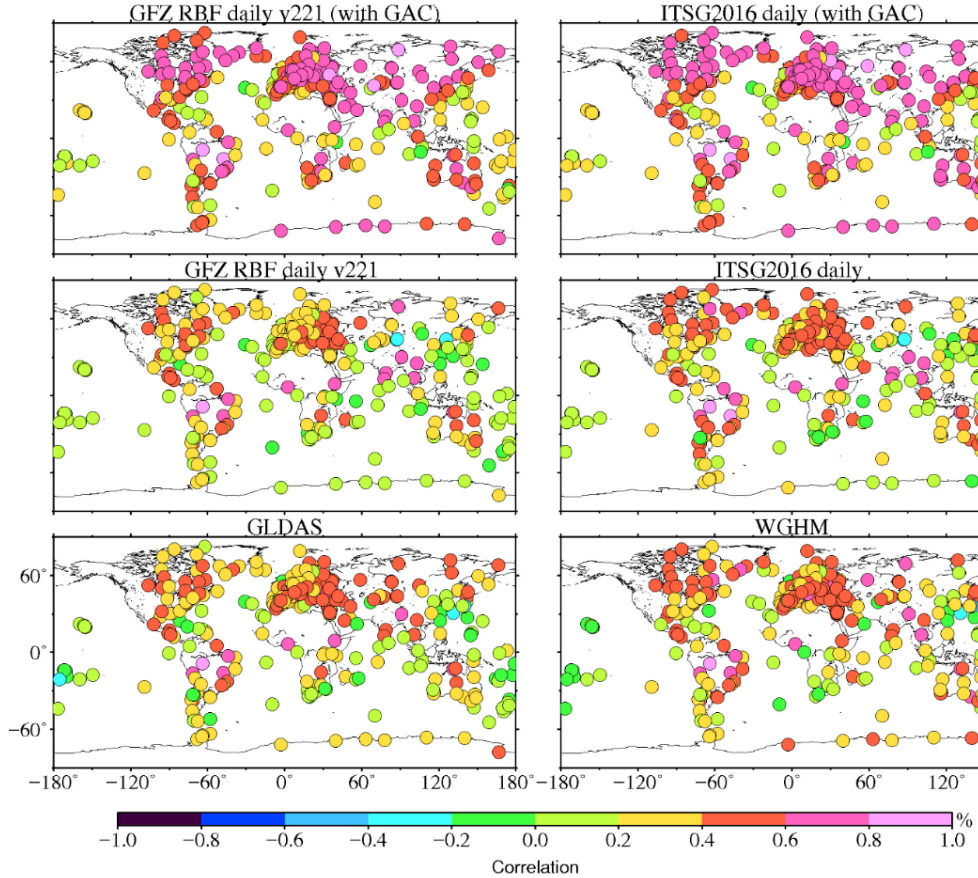


**Figure 3-2: Correlations between GNSS-observed and daily gravity fields derived displacements over 394 GNSS stations using the ITRF2014 residuals. Daily gravity fields up to their full spectrum are used to compute the displacement. GLDAS and WGHM are illustrated as reference.**

The spatial correlation plots of the two daily gravity solutions and the two hydrological models with respect to the ITRF2014 residuals are illustrated in **Figure 3-2**. The correlation of the daily gravity fields with or without the GAC products restored back are shown separately. Visually, similar patterns are observed in the bottom four subplots in **Figure 3-2** when the GAC products have not been added back to the daily gravity fields. However, when the GAC are restored back to the daily gravity fields, the top two subplots display much higher correlations, especially over the regions with high daily atmospheric and oceanic mass variations. For example, significant improvements can be observed over Siberia where strong atmospheric mass variations exist. **Figure 3-2** demonstrates the importance of the GAC products when compared with the GNSS-observed and daily gravity field derived vertical displacements.

Corresponding WRMS reductions are shown in **Figure 3-3**. Clearly, yellow colors dominate the pattern in the bottom four subplots indicating WRMS reductions of most of stations range from 0 to 10% with the maximum value of ~60% at the POVE station located in Porto Velho, Brazil. The top two panels demonstrate the significant increase of the WRMS reductions when the GAC products have been added back to the daily gravity fields. For instance, the mean WRMS reduction using the GFZ RBF daily v221 gravity solutions is improved from 5.6% shown in **Table 3-4** to 15.2% shown in **Table 3-3** with GAC restored. As for the ITSG2016 daily gravity solutions, the mean WRSM reduction is increased by 11.2%.

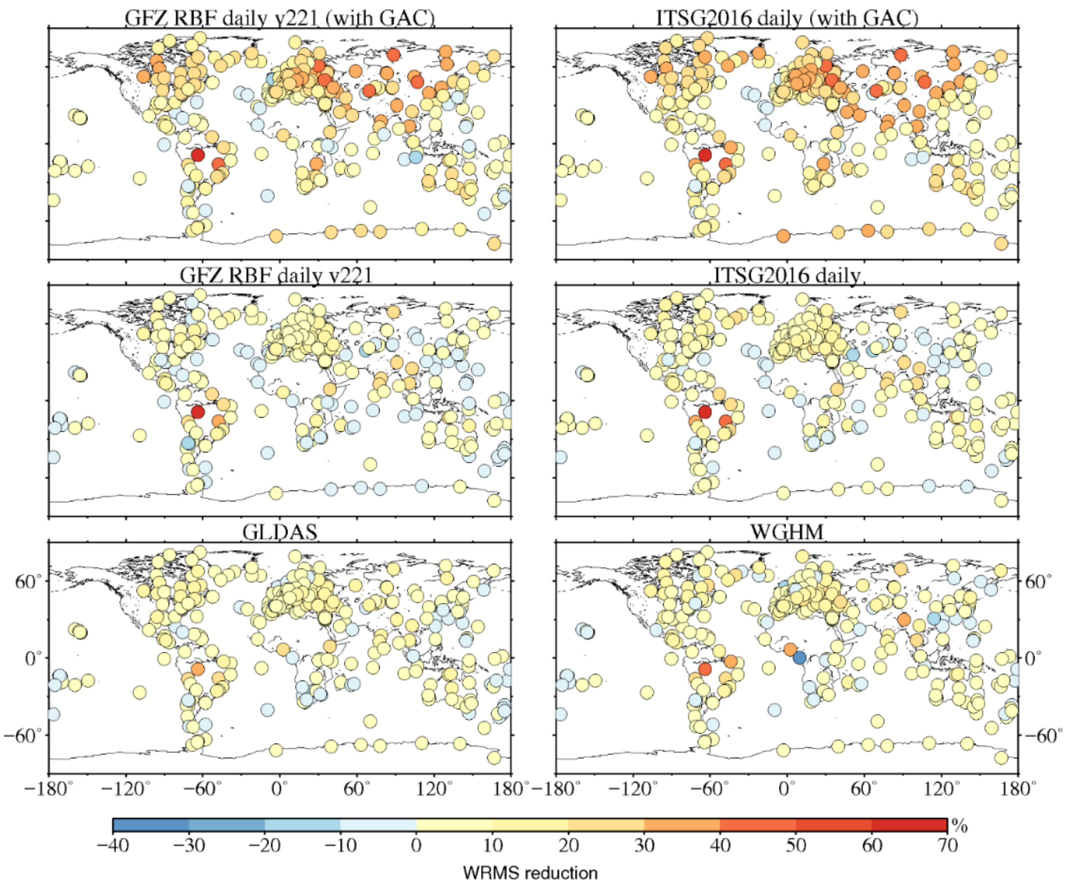


**Figure 3-3: WRMS reduction at the full signal over 394 GNSS stations using the ITRF2014 residuals. Daily gravity solutions up to their full spectrum are used to compute the displacements.**

Meanwhile, **Table 3-4** lists the statistics of the WRMS reductions from the pure daily gravity fields without GAC along with the two hydrological models. **Table 3-4** conveys the information that both daily gravity fields are better than models with higher maximum, mean and median WRMS reductions. We also observe that WGHM provides relatively better performance than GLDAS, which is due to the fact that WGHM contains the groundwater and surface water components while GLDAS does not.

**Table 3-4 WRMS reductions with respect to the ITRF2014 residuals at the full signal level. GAC products are not restored back to the daily gravity fields.**

| | WRMS reduction [%] | | | | Positive WRMS reduction [%] |
|---|---|---|---|---|---|
| | min | max | mean | median | |
| GFZ RBF daily v221 | -16.7 | 62.6 | 5.6 | 4.5 | 82.2 |
| ITSG2016 daily | -17.2 | 64.6 | 6.5 | 5.7 | 82.7 |
| WGHM | -14.8 | 42.80 | 5.5 | 4.4 | 84.5 |
| GLDAS | -12.5 | 33.4 | 5.1 | 3.5 | 80.9 |

Apart from the statistics in **Table 3-4**, **Figure 3-4** shows the derived vertical displacements from the daily gravity fields with or without restoring the GAC products in comparison to the ITRF2014 residuals at three representative GNSS stations. The top panel of the figure shows the comparison of vertical displacements at POVE where we have the most significant continental water mass variations. Strong annual signals are observed from both the GNSS observed and daily gravity field derived displacements. In addition, adding back GAC or not does not affect the WRMS reduction significantly, see maximum values in **Table 3-3** and **Table 3-4**.

The middle panel in **Figure 3-4** shows the displacements at ARTU located in Siberia where the atmospheric signals play an important role. Amplitude increases and phase shifts are visible after restoring the GAC products. Certainly, a big increase in terms of the WRMS reduction is expected. For example, the WRMS reduction at ARTU is improved from 8.2% using the GFZ RBF daily v221 without GAC up to 39.4% with GAC restored.

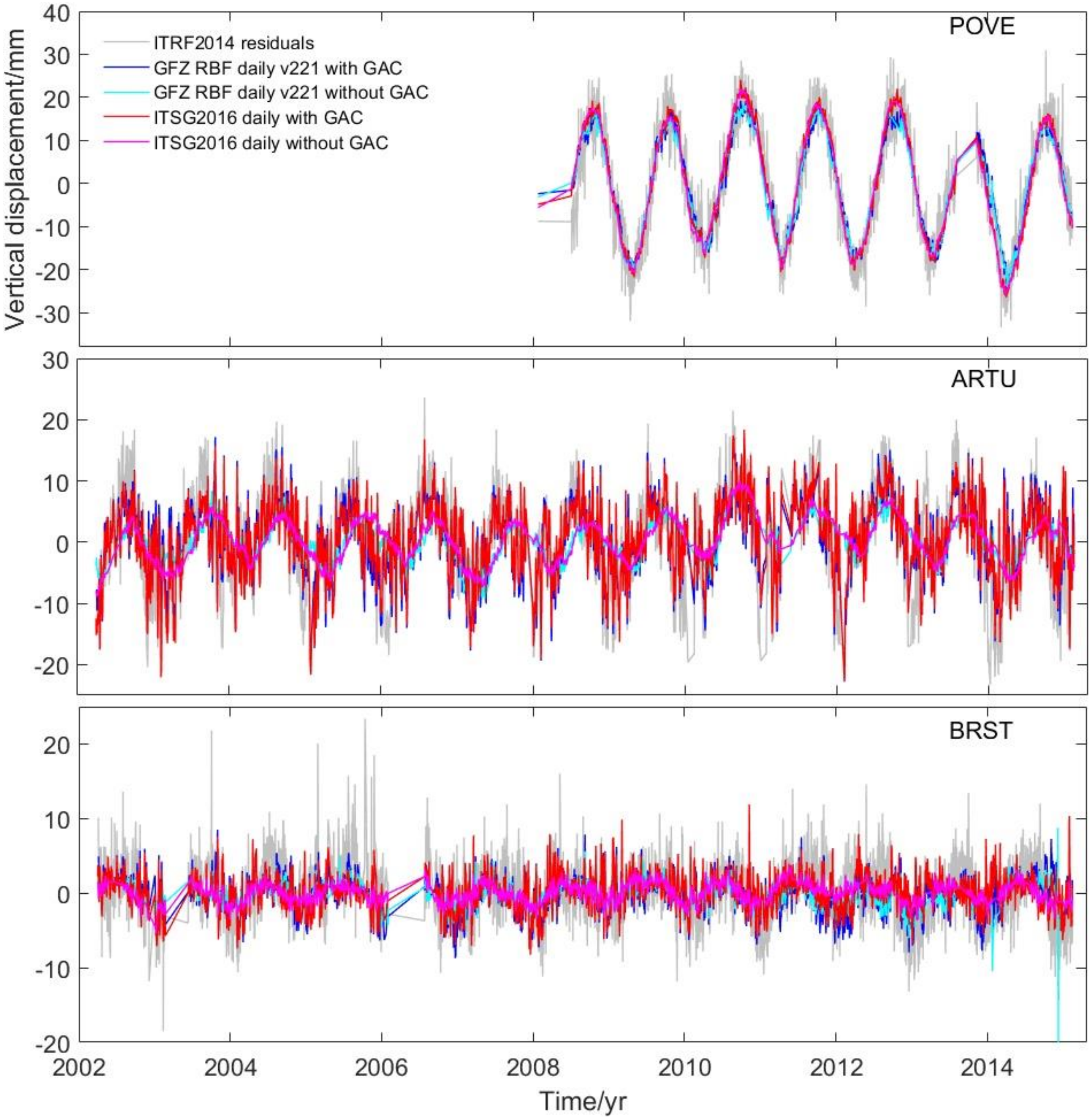


**Figure 3-4: Comparison of vertical displacements from the GNSS-observed, i.e. ITRF2014 residuals, and the daily gravity fields derived at three selected GNSS stations.**

The bottom panel in **Figure 3-4** presents the vertical displacements at BRST located in the city of Brest, France, close to the coast. At this station, both the GFZ RBF daily v221 and the ITSG2016 daily gravity solutions show relatively low WRMS reductions, 4.6% and 10.9%, respectively, when GAC has not been restored. Surprisingly, the WRMS reductions are decreased using both of the two daily gravity fields with GAC added back, down to -1.5% and 3.4%.

In summary, by comparing the daily gravity fields with the combined daily environmental loading models and the pure hydrological models, we can conclude that both daily gravity models from

GFZ and TU Graz demonstrate good performances at the full signal level. ITSG2016 daily solutions present marginally better statistics than the GFZ RBF daily v221 solutions.

### *3.4 Annual signal level*

In terms of annual signals, median degree WRMS reductions and accumulative degree WRMS reductions are shown in **Figure 3-5**. Surprisingly, both daily gravity solutions present comparable good median degree WRMS reductions at low degrees, e.g. degree 2 and degree 3, with regard to the monthly solutions. This observation may be due to the constraints by the hydrological model applied during daily data processing, see details in Deliverable 5.2. In particular, the GFZ RBF daily v221 solutions show significantly higher WRMS reduction than the ITSG2016 daily solutions at degree 2 at the annual period, which is 30.6% WRMS for the GFZ RBF daily solutions and 22.2% for the ITSG2016 daily solutions. At other SH degrees, the two daily gravity solutions have comparable WRMS reductions.

The extent of the degree WRMS reductions illustrated in the top panel of **Figure 3-5** are directly transferred into the cumulative degree WRMS reductions in the bottom panel of **Figure 3-5**. Both the two daily gravity solutions have a very high median cumulative WRMS reductions, i.e. 80.1% from the GFZ RBF daily v221 and 79.9% from the ITSG2016 daily, respectively, comparing to the monthly gravity solutions with the median values around 70%.

The spatial distribution of WRMS reductions at the annual period are shown in **Figure 3-6**. When the GAC products are not restored to the daily gravity fields, similar patterns are found in the bottom four panels. Low WRMS reductions at annual signal level are seen in the bottom four figures over GNSS stations located in islands, coast, Antarctica and the Siberian region. When the GAC products are added back, significant improvements can be observed in the top two figures with dark red dots being dominant. Remarkable annual WRMS reductions are noticed over islands, coast, Siberia and Antarctica when the daily non-tidal atmospheric and oceanic products are added back to the daily gravity fields.

**Table 3-5** summarizes the spatial annual WRMS reduction maps in terms of median and positive WRMS reductions. The two daily gravity solutions without GAC display slightly worse median WRMS reductions than the WGHM model at the annual signal level while much better than GLDAS. In terms of positive WRMS reductions, the four models show comparable results, i.e. more than 80%.

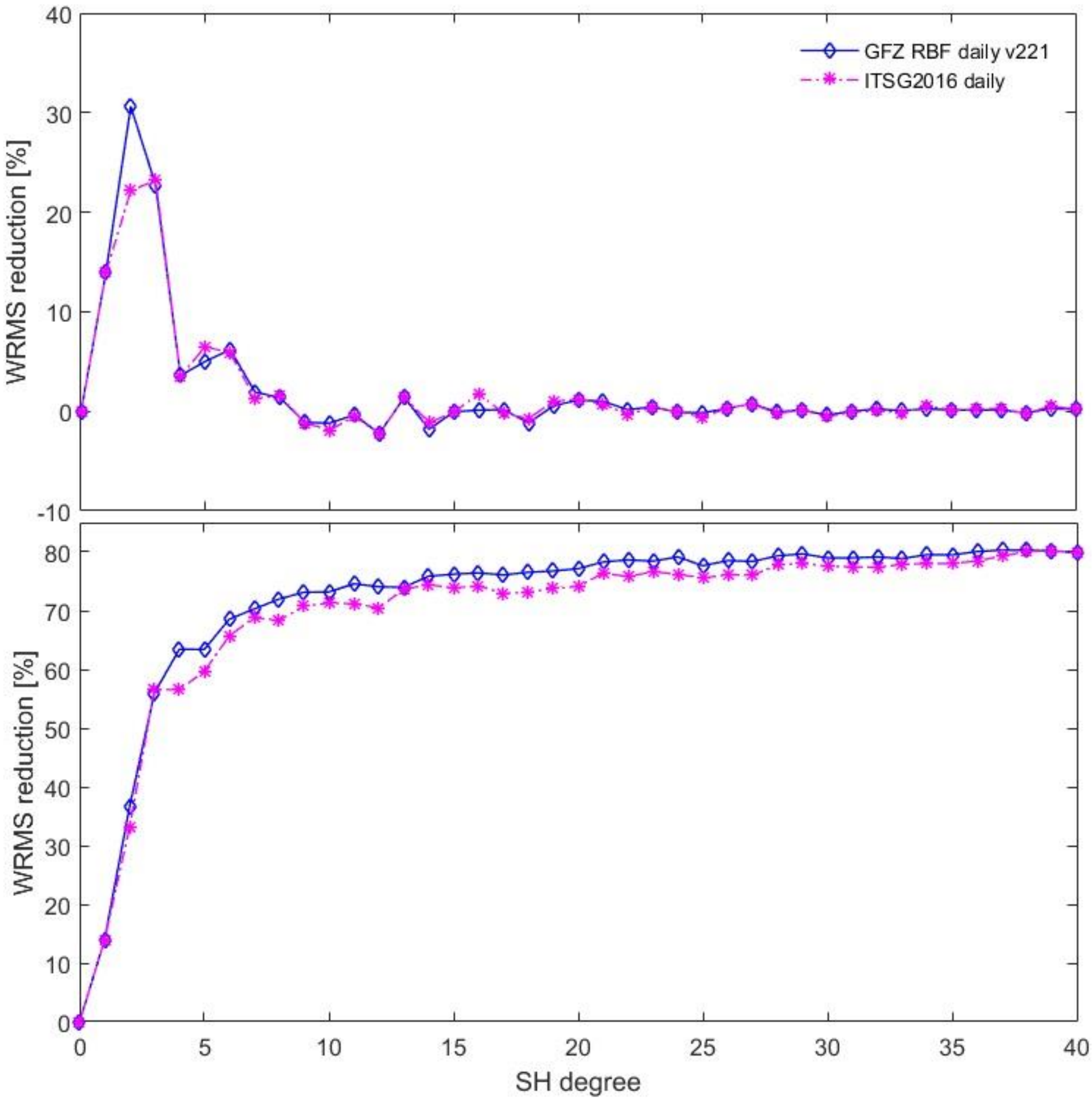


**Figure 3-5: Median degree WRMS reductions (top) and accumulative degree WRMS reductions (bottom) of two daily gravity solutions using the ITRF2014 residuals at the annual signal level over 394 GNSS stations globally.**

**Table 3-5** demonstrates again the importance of the daily GAC products when we compare daily displacements from GRACE and GNSS. Both the median and positive WRMS reductions are increased in the case where the daily atmospheric and oceanic mass variations are restored.

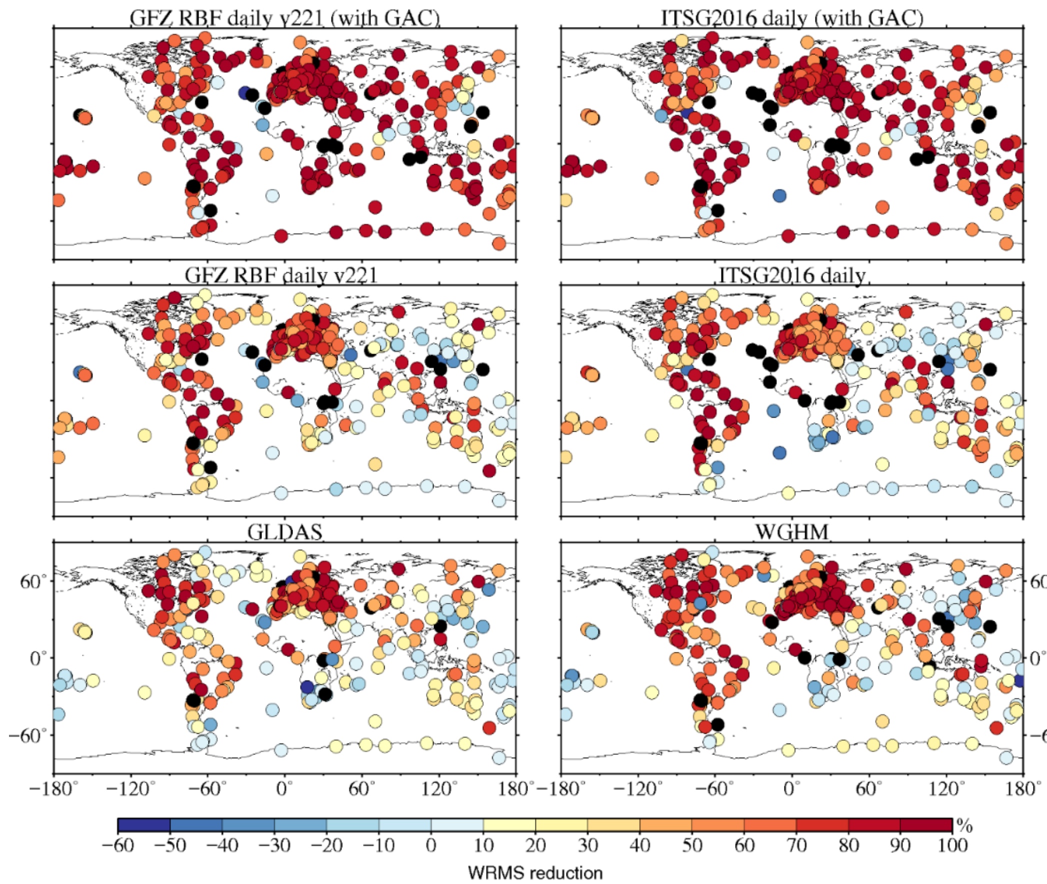


**Figure 3-6: WRMS reduction at the annual signal over 394 GNSS stations using the ITRF2014 residuals. Daily gravity fields up to their full spectrum are used to compute the displacements.**

**Table 3-5 WRMS reductions with respect to the ITRF2014 residuals at the annual period.**

| | Median WRMS reduction [%] | Positive WRMS reduction [%] |
|---|---|---|
| GFZ RBF daily v221 (with GAC) | 80.1 | 90.1 |
| ITSG2016 daily (with GAC) | 79.9 | 90.1 |
| GFZ RBF daily v221 | 44.8 | 87.8 |
| ITSG2016 daily | 45.9 | 82.0 |
| WGHM | 47.2 | 81.4 |
| GLDAS | 33.8 | 80.9 |

# 4.Validating daily gravity fields using OBP

Ocean bottom pressure (OBP) recorders measure the variations of the combined oceanic and atmospheric mass above the sensor. These data are therefore directly comparable with the gravity fields and thus suitable for use in validation. We use in situ data from a set of globally distributed OBP recorders as compiled by Macrander et al. (2010).

Before using the in-situ data for validation, it has to be pre-processed: drifts, jumps present in some time series due to recovery and re-deployment of sensors and trends are removed and the data is checked for outliers; temporal sampling is changed to 1 hour in all time series to ensure uniformity, tidal signal is removed with the T_TIDE Matlab package for classical harmonic analysis (Pawlowicz et al., 2002) and the time series from the same stations are stacked. For each in-situ OBP measuring station, data from the four closest grid points in the GRACE gravity field solution is extracted and bilinearly interpolated to the station's location. Daily means are then calculated from the in situ time series and compared to the daily means of the GRACE gravity fields. To focus on specific frequency bands, we filter both in situ and GRACE time series with a series of Butterworth low-pass filters.

The agreement of the GRACE solution with the in situ ocean bottom pressure measurements is expressed in relative explained variance:

$$REV = \frac{Var(insitu) - Var(insitu - GRACE)}{Var(insitu)}$$

Relative explained variance is the variance of the in situ measurements explained by the GRACE gravity field solution. REV is negative in the case that GRACE increases the variance; REV is zero when GRACE does not alter the variance of the in situ data, and the REV is 100% when the GRACE signal perfectly coincides with the OPB observed in-situ signals. In view of the area-averaging properties of GRACE, an achievement of 100% is highly unlikely.

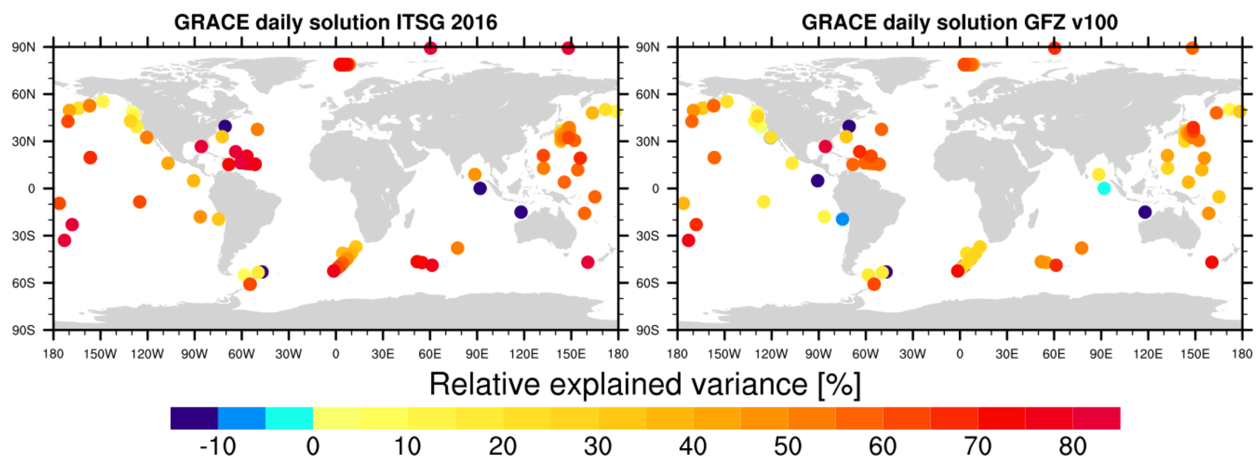


**Figure 5.1: Relative explained variance for ITSG 2016 and GFZ v100 daily solutions against in situ ocean bottom pressure for the 3-10 days frequency band.**

Two GRACE gravity field daily solutions are validated against in situ observations: ITSG-Grace2016 Kalman smoothed daily solution (Mayer-Gürr et al., 2016) and GFZ v100 daily solution (Gruber and Rudenko, 2014). We in particular focus on the frequency band between 3 and 10 days, which sets the daily solutions most prominently apart from the conventional monthly-mean GRACE gravity fields.

Both solutions considered here demonstrate very good agreement with the in situ data (**Figure 5.1**): with the exception of a few stations, relative explained variance is positive in all regions and it predominantly ranges between 30 and 60%. The lowest relative explained variances are for both solutions along the western coast of the Americas, where they are, on average, as low as 20% for the GFZ v100 and 40% for the ITSG 2016 solution. In the North Atlantic and the Arctic Ocean, on the other hand, both solutions show the best agreement with the in situ data and the relative explained variances for the ITSG 2016 solution exceed 80% for many stations in those regions.

# 5.Summary

In conclusion, this report presents the validation of daily gravity fields from two EGSIEM ACs, i.e. GFZ and TU Graz, using the GNSS time series and the OBP records, respectively. Generally, both validation techniques provide promising and positive feedback to the daily gravity fields.

Using the GNSS time series, the daily gravity fields are contrasted with the environmental models, especially hydrological models. The good quality of the daily gravity fields is demonstrated and the good consistency between two daily gravity fields is confirmed. In particular, when the GAC products are restored, high agreement at the annual period between GNSS-observed and daily gravity field derived displacements is obtained.

In-situ OBP records have shown the very good agreement with the daily gravity fields on the frequency band between 3 and 10 days.

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# 7.Glossary

| | |
|---|---|
| AIUB | Astronomical Institute, University of Bern |
| CSR | Center for Space Research, Austin, Texas |
| EGSIEM | European Gravity Service for Improved Emergency Management |
| ECCO | Estimating the Circulation & Climate of the Ocean |
| GAC | Geopotential coefficients of averaged combination of non-tidal atmosphere and ocean |
| GFZ | Helmholtz Centre Potsdam, German Research Centre for Geosciences |
| GLDAS | Global Land Data Assimilation System |
| GNSS | Global Navigation Satellite System |
| GRACE | Gravity Recovery and Climate Experiment |
| GSM | Geophoten coefficients of GRACE-derived static gravity field |
| ITRF | International Terrestrial Reference Frame |
| JPL | Jet Propulsion Laboratory, Pasadena, California, USA |
| NCEP | National Centers for Environmental Prediction |
| OBP | Ocean Bottom Pressure |
| RBF | Radial Basis Functions |
| RMS | Root Mean Square |
| SHC | Spherical Harmonic Coefficient |
| SLR | Satellite Laser Ranging |
| TU Graz | Technical University of Graz |
| UL | University of Luxembourg |
| WGHM | WaterGap Hydrological Model |
| WRMS | Weighted RMS |