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ACCURACY ANALYSIS OF GRAVITY FIELD CHANGES FROM GRACE RL06 AND RL05 DATA COMPARED TO IN SITU GRAVIMETRIC MEASUREMENTS IN THE CONTEXT OF CHOOSING OPTIMAL FILTERING TYPE

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ABSTRACT. Global satellite gravity measurements provide unique information regarding gravity field distribution and its variability on the Earth. The main cause of gravity changes is the mass transportation within the Earth, appearing as, e.g. dynamic fluctuations in hydrology, glaciology, oceanology, meteorology and the lithosphere. This phenomenon has become more comprehensible thanks to the dedicated gravimetric missions such as Gravity Recovery and Climate Experiment (GRACE), Challenging Minisatellite Payload (CHAMP) and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE). From among these missions, GRACE seems to be the most dominating source of gravity data, sharing a unique set of observations from over 15 years. The results of this experiment are often of interest to geodesists and geophysicists due to its high compatibility with the other methods of gravity measurements, especially absolute gravimetry. Direct validation of gravity field solutions is crucial as it can provide conclusions concerning forecasts of subsurface water changes. The aim of this work is to present the issue of selection of filtration parameters for monthly gravity field solutions in RL06 and RL05 releases and then to compare them to a time series of absolute gravimetric data conducted in quasi-monthly measurements in Astro-Geodetic Observatory in Józefosław (Poland). The other purpose of this study is to estimate the accuracy of GRACE temporal solutions in comparison with absolute terrestrial gravimetry data and making an attempt to indicate the significance of differences between solutions using various types of filtration (DDK, Gaussian) from selected research centres.

Keywords: GRACE, DDK, Gaussian filter, FG5

1. INTRODUCTION

The twin GRACE satellites, launched in 2002, had taken detailed measurements of the Earth's gravitational field changes for 15 years. This has revolutionised research on land water resources, glaciology, earthquakes and deformation of Earth's crust. The benefits of continuous observation of our planet through GRACE satellites have led to rerun the project, this time named GRACE Follow-On (GRACE-FO), which was initiated in 2018.

In order to present the distribution of the Earth's gravitational field, the most common representation is to expand gravitational potential function in series of spherical harmonics

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functions. Gravity potential V in any point on the surface of the Earth can be described as a function of spherical coordinates $= 90 - \varphi, \lambda$:

$$V(r,\theta,\lambda) = \frac{GM}{R}\sum_{n=0}^{n_{max}}\left(\frac{a}{r}\right)^{n+1}\sum_{m=0}^{n}(\bar{C}_{nm}\cdot\cos m\lambda + \bar{S}_{nm}\cdot\sin m\lambda)\cdot\bar{P}_{nm}(cos\theta) \quad (1)$$

where φ is a geodetic latitude, (θ,λ) are the spherical coordinates of this point, r stands for radius vector, GM is the geocentric gravitational constant, a is the semi-major axis of reference ellipsoid defined in International Earth Rotation and Reference Systems Service Convention (IERS2010), $\bar{C}_{nm}\bar{S}_{nm}$ are the normalised harmonic coefficients of the gravity potential expansion (Stokes' coefficients) and $\bar{P}_{nm}(cos\theta)$ are the Legendre polynomials of n-th degree and m-th order (Wahr, 1998). To ensure a consistent long-term time series of the gravitational field of the highest possible quality, the values of geopotential coefficients are reprocessed by major scientific centres, the latest solution known as RL06 has replaced the predecessor RL05a. As compared to the previous version, the following components have been changed in RL06: ocean tides models, time-variable a priori gravity field, non-tidal atmospheric and oceanic mass variations (Atmosphere and Ocean De-aliasing Product [AOD1B]), as well as a strategy of data processing described in Dahle et al. (2019). Before interpreting the variability of the field of gravity from GRACE data, it is necessary to reduce the effects of the specific inclination of the orbit of GRACE satellites (that is equal to 89.5°). It usually occurs as characteristic meridional 'stripes' when visualising spatial distribution. There are several methods to dispose this issue in the form of spatial signal filtering. Unfortunately, throughout this process, it is possible to miss some information about the geodynamic signal. To choose an optimal filter, a common method is the comparison of filtered data with terrestrial results from gravimetric and geodetic measurements (e.g. SG, AG).

In Poland, such research was conducted in, e.g. Kuczynska-Siehien et al. (2019), whereby decomposing the signal with periodic functions, GRACE data was compared with hydrological and gravimetric in situ data. In Godah and Krynski (2017), principal component analysis (PCA) method was used to decompose the periodic signal and then to compare the RL05 data to changes in normal and orthometric heights on the territory of Poland. The article Godah et al. (2018) presents a comparison of satellite-only global geopotential models (GGMs) with quasigeoid undulation derived from levelling and Global Navigation Satellite Systems (GNSS) measurements. The article Godah et al. (2015) presents a comparison of non-isotropic decorrelation filters (denoted by DDK) and Gauss filtration for the Vistula and Odra river basins based on data from the RL05 solution. In a comparison of RL04 data with Global Land Data Assimilation System (GLDAS) time series, described in Kloch-Glowka et al. (2012), DDK1 filter turned out to be the most effective in the noise from observations. Further research on GRACE data compared with gravimetric measurements in Eastern and Central Europe has been outlined in Crossley et al. (2012), Neumeyer et al. (2005) and Abe et al. (2012).

This paper will assess how compatible are terrestrial measurements with satellite signals in the context of filtering GRACE data. The research is based on entire GRACE time series and the last two absolute gravity measurement campaigns performed in the Astro-Geodetic Observatory located in Józefosław (AGO JOZE).

2. GRACE SIGNAL FILTRATION

2.1. Applied algorithms

The source of meridional (North–South oriented) stripes is geometry of the twin-satellites system. They moved in at an altitude of approx. 450 km, separated by 220 km along their orbit track. GRACE consisted of only one pair of satellites at near-polar orbit. The creators' intention was to provide monthly solutions of GRACE results. The number of observations made on average over 30 days is limited. Hence, there are areas without any numerical information in a month. To succeed in delivering a global solution for every period, an interpolation of the data is necessary.

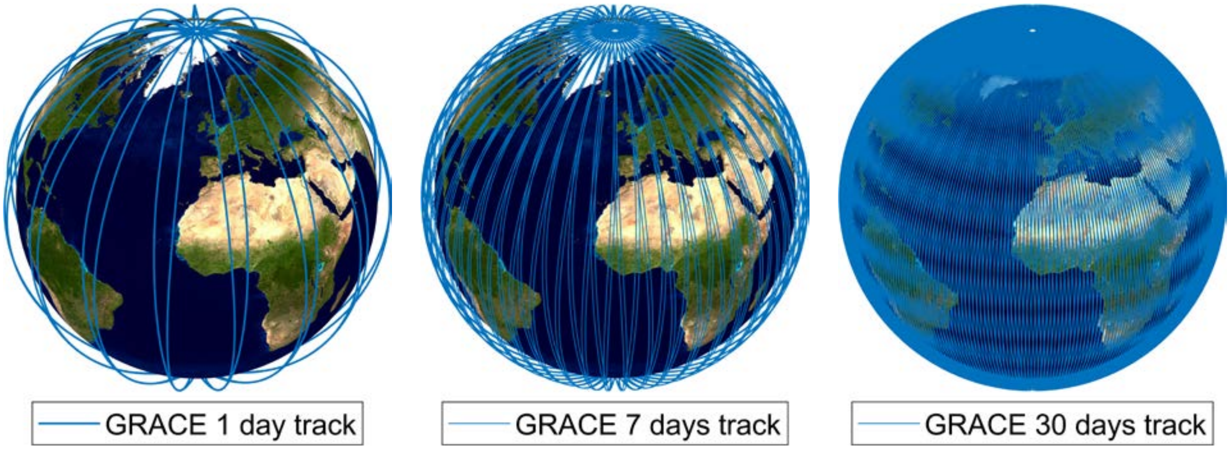


Figure 1. (a–c) GRACE ground track simulation. Source: own study

However, it causes highly correlated errors in spherical harmonic coefficients due to their orthogonality that appears in Level-1 solutions. In order to reduce this kind of observational noise, spatial smoothing by Gaussian function is used (Jekeli, 1981). Swenson and Wahr (2006) had observed a unique property of spherical harmonic coefficients associated with their decomposition. They also had designed a set of filters to eliminate the problem. Nevertheless, the provided method is not perfect. Due to the orbit inclination of 89.5°, there is a significant accumulation of data in the polar region, while in the equatorial area its spatial resolution is lower (as shown in Figure 1). Gauss filtration smooths the data equally in every direction.

Hence, other solutions are proposed, e.g. filtering with latitude-dependent filters. A decorrelation of monthly global solutions was suggested by J. Kusche. It is based on a priori assumptions of error budget and was tested using hydrological models (Kusche et al., 2009). A similar solution has been presented in Horvath et al. (2018) using full covariance matrix determined in two ways: stochastic and deterministic. Anisotropic DDK filters proved to be a satisfying method that preserves geophysical details from GRACE level 2 products the best (Chen et al., 2006; Kusche, 2007). DDK1-8 filters have become the primary tool used in GRACE data processing over time. Another proposed method is a reduction of the correlation between spherical harmonic coefficients and errors using quadratic polynomials (with a moving window) to fit the resulting function between original and decorrelated C_{nm} coefficients (Duan, 2009). Empirical decorrelation of coefficients is a wide group of methods and will not be analysed in this paper. Despite the large number of filtering approaches, none is stated as universal. This is because the quality of the final solution depends on the latitudes of an examined area and the power of a chosen filter.

2.2. Gaussian filter

Gauss filtration is based on the regular smoothing of variance of the observed gravity field changes by the following kernel function:

$$F(cos\psi) = \frac{2b}{1-e^{-2b}} e^{-b(1-cos\psi)} \tag{2}$$

where $\boldsymbol{\psi}$ stands for a spherical distance from the given point and b is calculated by the formula:

$$b = \frac{\ln(2)}{1-\cos\left(\frac{d}{R}\right)} \tag{3}$$

with d meaning a radius value and R is the equatorial radius, both expressed in kilometres. The filtration process is based on multiplying all spherical harmonic coefficients by a predefined filtration factor. Because the filtering domain depends on the spatial resolution of the data, it is possible to express the Gauss weighting coefficients as:

$$F(cos\psi) = w_n \tag{4}$$

where w_n value defines the dependence on n-th degree of spherical harmonic function as follows:

$$w_n = \frac{2n-1}{b} w_{n-1} + w_{n-2} \tag{5}$$

These weighting coefficients must be included in the function describing the Earth's gravity field (expanding equation (1)):

$$V(r,\theta,\lambda) = \frac{GM}{R} \sum_{n=0}^{n_{max}} \left(\frac{a}{r}\right)^n w_n \sum_{m=0}^{n} (\bar{C}_{nm} \cdot \cos m\lambda + \bar{S}_{nm} \cdot \sin m\lambda) \cdot \bar{P}_{nm}(cos\theta) \tag{6}$$

The size of the radius is crucial. The larger it is, the more it blurs geophysical information contained in coefficients of higher degree, as shown in Figure 2.

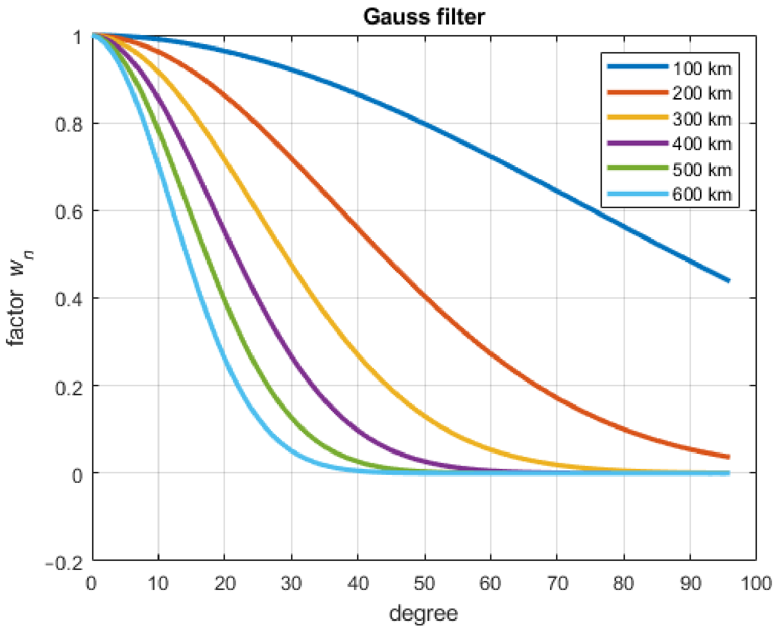


Figure 2. Gauss filter spectral scale of factor w_n. Source: own study

According to the Center for Space Research (CSR) standards for processing GRACE Level-2 RL05 and RL06 data (Savannah et al., 2019), different radii are chosen for sea/ocean and land areas, equal to 500 and 300 km, respectively. Examples of applying Gauss filter with various radii are presented in Figure 3a–d.

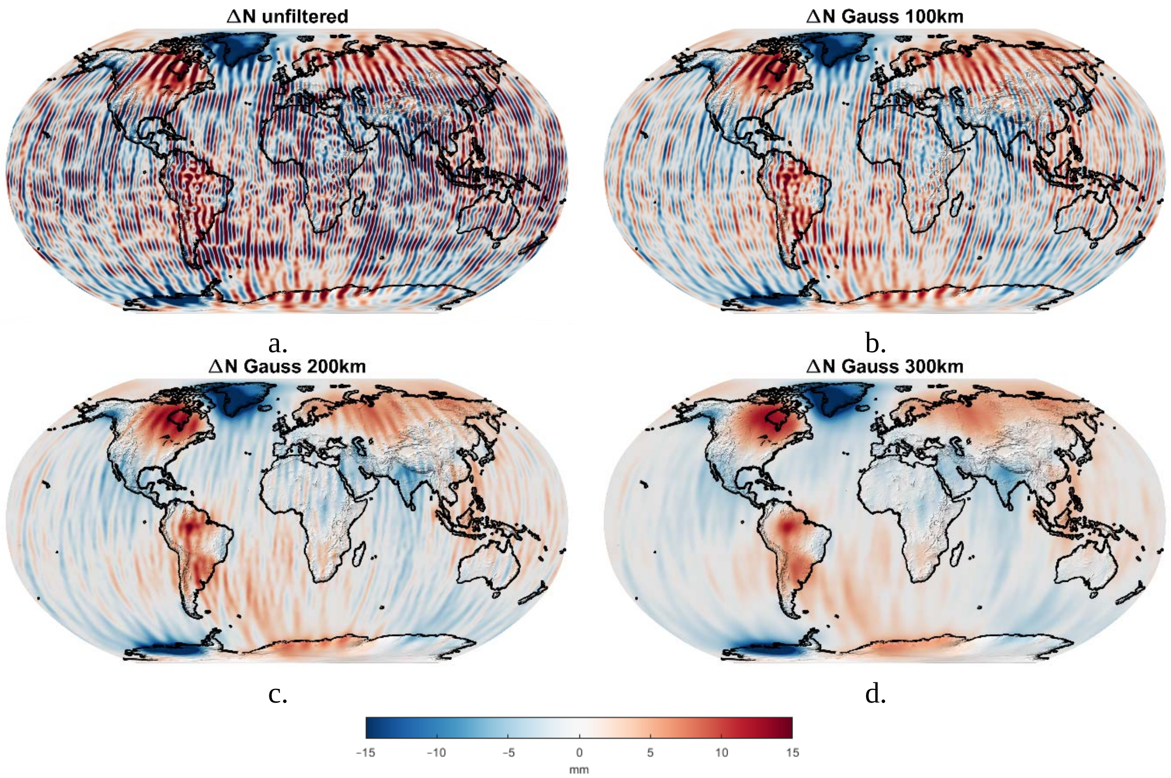
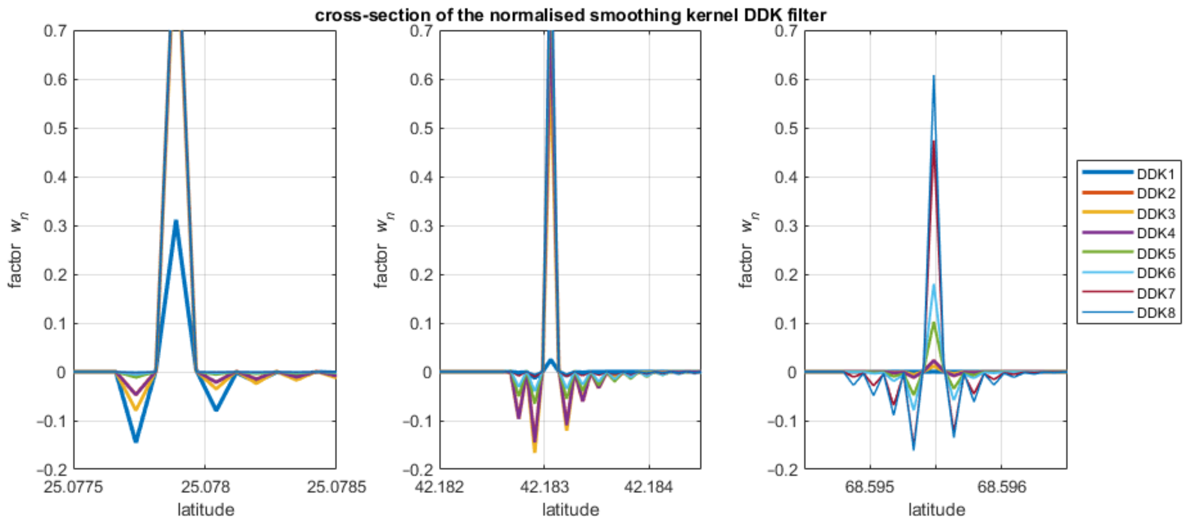


Figure 3. (a–d) Geoid height changes in metres compiled for GRACE data from the 2002.123 to 2002.137 period published by CSR RL06. Development in relation to the GOCO05S static model with a degree of development of n = 90, unfiltered, blurred by a Gaussian filter with 100, 200, 300 km radii. Source: own study

Apparently, Gauss filtration is not an ideal solution to the meridional stripes issue. Due to the frequent passage of satellites around the pole, this region is better covered with data than the equatorial zone. It should be considered if there is a method including the different distance ranges between the stripes at a given latitude.

2.3. Anisotropic DDK filters

The anisotropic filtration method differs from Gaussian filters in that it uses approximate coefficient errors, a full matrix of covariance errors and normalised values of spherical harmonics. A kernel function determines the way of eliminating errors resulting from the orbit path by azimuth-weighted coefficients: narrower in the N–S direction and wider in the E–W direction. The spectrum of a given filter was created as a result of empirical mathematical modelling of error covariance matrix and the methods for developing observations from level 1 to 2 based on distance measurements between GRACE satellites using a K-band inter-satellite sensor. The entire method is described in Kusche (2007). Examples of kernel functions for selected geodetic coordinates in the N–S direction are presented in Figure 4a–c.



a. b. c.

Figure 4. (a–c) Examples of DDK base filtration function depending on latitude. Source: own study

For a better understanding of the problem, the maps presented in Figure 5a–h show an application for subsequent types of DDK filtration – geoid undulation changes for a declared period.

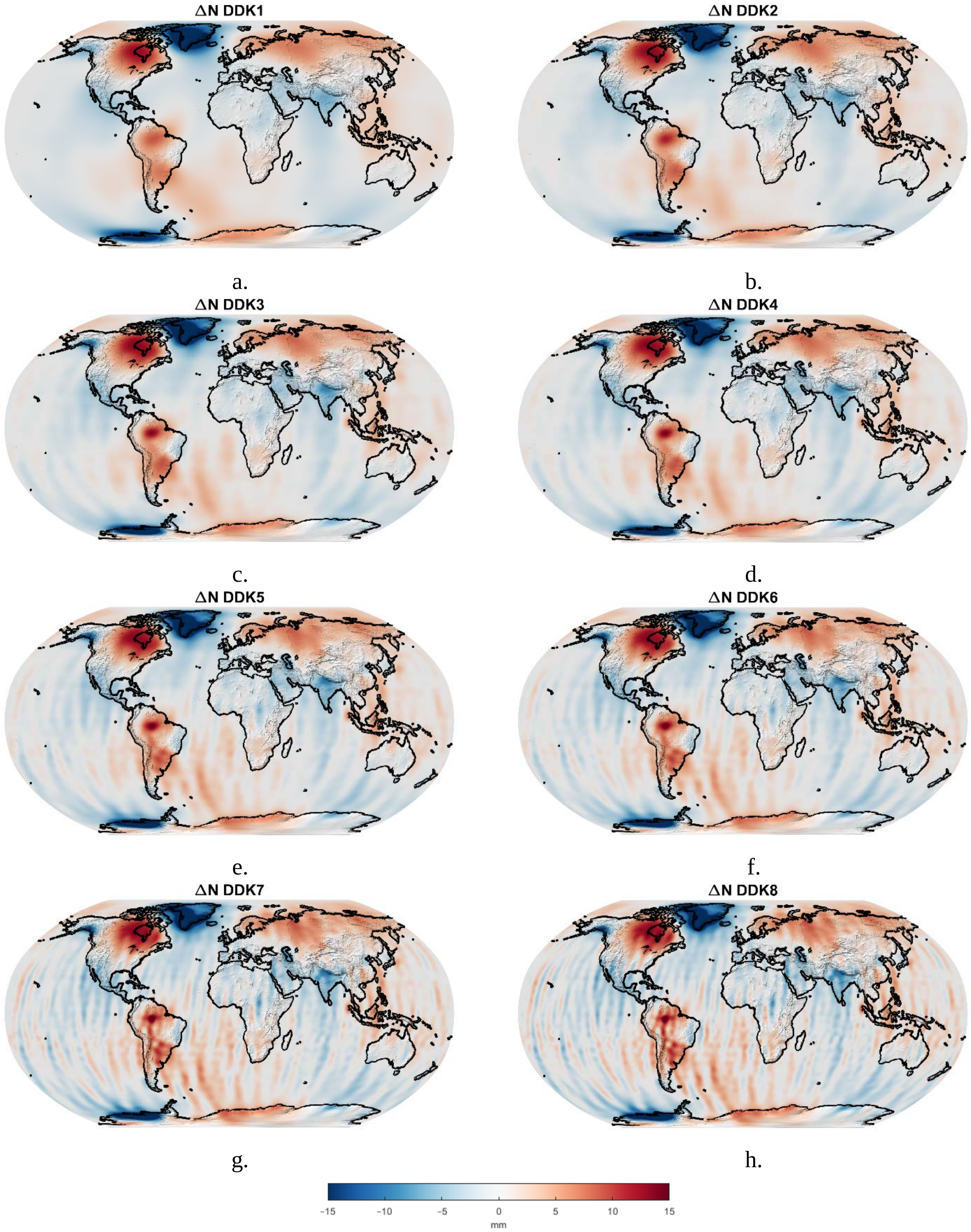


Figure 5. (a–h) Geoid height changes in metres compiled for GRACE data from the 2002.123 to 2002.137 period published by CSR RL06. Development in relation to the GOCO05S static model with a degree of development of n = 90, filtered by non-isotropic DDK1-8 filters. Source: own study

The full difference between the filtration types used is shown in Figure 6 in terms of the *square root of degree variance of spherical harmonics* depending on their degree. It is well noticeable that the variance of data filtered by Gaussian method with 100 km radius practically coincides with the variance of unfiltered coefficients. In turn, Gaussian filter with a radius of 600 km ceases to be useful for monthly solutions above 75–77 degree of harmonic function. DDK1-5 filters are on a similar level as Gaussian filter with a radius R = 300 km (recommended by the CSR).

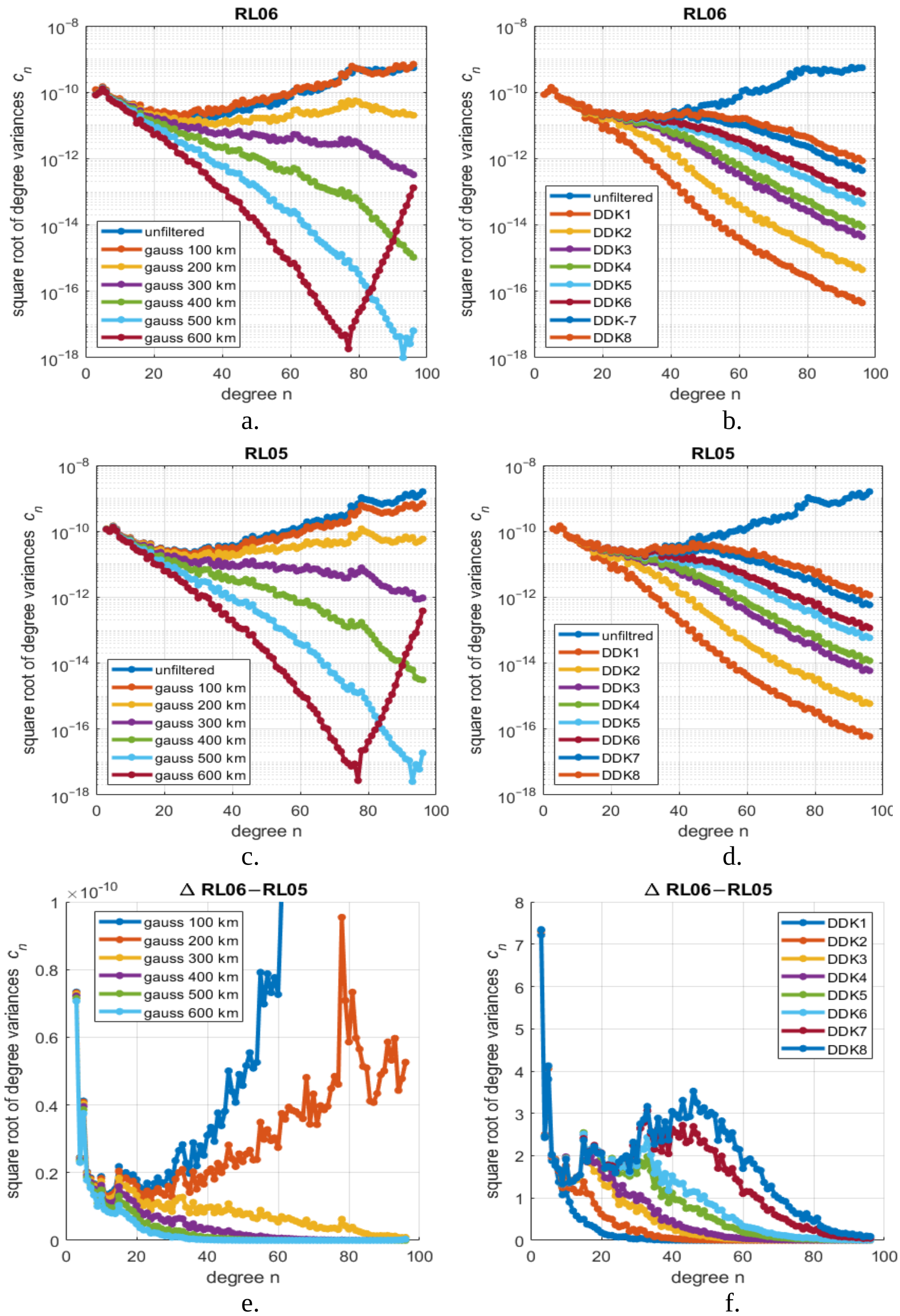


Figure 6. (a–f) Square root of Degree Variance of Spherical harmonic from period 2002.123-2002.137 for RL05, RL06 and difference between RL06-RL05. Source: own study

On comparing the Gauss filter to DDK, it can be seen that DDK shows better stability for higher degree/order of spherical harmonic coefficients. Regarding the differences between the RL06 and RL05 versions, slight discrepancies can be noticed, up to 60 harmonic degree. Better compatibility between RL06 and RL05 is preserved by Gaussian filters with radii 500 and 600 km, while in the case of anisotropic filters, DDK 1–4 types show compatibility. All examples discussed above present only one epoch of GRACE mission solutions. Results may vary over time. Presenting the differences between official centres from different epochs over the 15 years may be complicated. One of the possibilities has been presented in Sakumura et al. (2014). It has revealed a clear similarity between the CSR and GeoForschungsZentrum, German Research Centre for Geosciences (GFZ) solutions. Also, a significant difference between the CSR and the GFZ solutions compared to Jet Propulsion Laboratory (JPL) is observed in the basins of Amazon and Congo rivers. In both cases, there is a slight discrepancy in the equivalent water height (EWH) in the polar regions, where it reaches about ±2 mm/year. In the ocean, the differences are minor and the mean squared error of EWH varies from 12 to 16 mm/year. It is worth mentioning that terrestrial and oceanic areas are developed separately. Solutions for oceans are comparable for each processing centre. Moreover, each of them suggests a comparable radius of filtration as the most effective for these areas. Thus, GRACE results on continents are crucial in comparing the computing strategies of individual data centres. The next section presents an example of local comparison of different GRACE data filtration types derived from three official processing centres.

3. SELECTING AN APPROPRIATE FILTERING TYPE FOR AGO JOZE LOCATION

3.1. Data processing

This part presents a comprehensive comparison of the gravity fluctuations determined from GRACE periodic models and absolute gravimetric measurements at the AGO JOZE. The main goal of the study is to estimate the accuracy of GRACE temporal solutions in comparison with terrestrial gravimetry data. Furthermore, the authors attempted to evaluate the discrepancies between various solutions that were based on numerous DDK and Gauss filters and that were computed in different research centres. A simplified scheme of this experiment is presented in Figure 7.

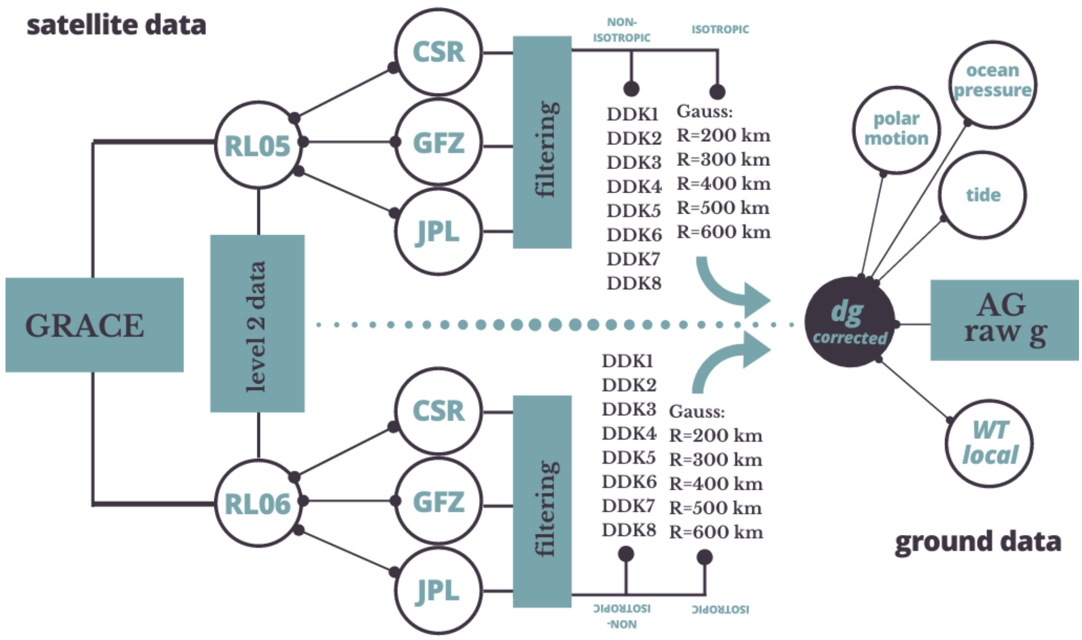


Figure 7. Scheme of the experiment. Source: own study

Time series analysis was carried out for selected monthly solutions of GRACE missions produced by GFZ, CSR, and JPL. RL06 data (Dahle et al., 2013) from April 2002 to March

2016 was used in the maximum degree/order of expansion equal to 96 and for RL05a data, the values are CSR – d/o 96, GFZ – 90 and JPL – 90, respectively (for certain solutions up to 60). It results in a spatial resolution of about 330 km. This value may vary depending on the selected version and the method of smoothing the signal. GRACE is effective for the study of phenomena in the continental scale. For examined areas smaller than 100,000 km^2, the signal-to-noise ratio may be weak. Thus, the resulting errors (especially those from smoothing and signal leakage) require user's attention. Despite averaging observations from GRACE, appropriate post-processing methods can preserve geophysical information for areas of about 10,000 km^2 (Vishwakarma and Devaraju, 2018).

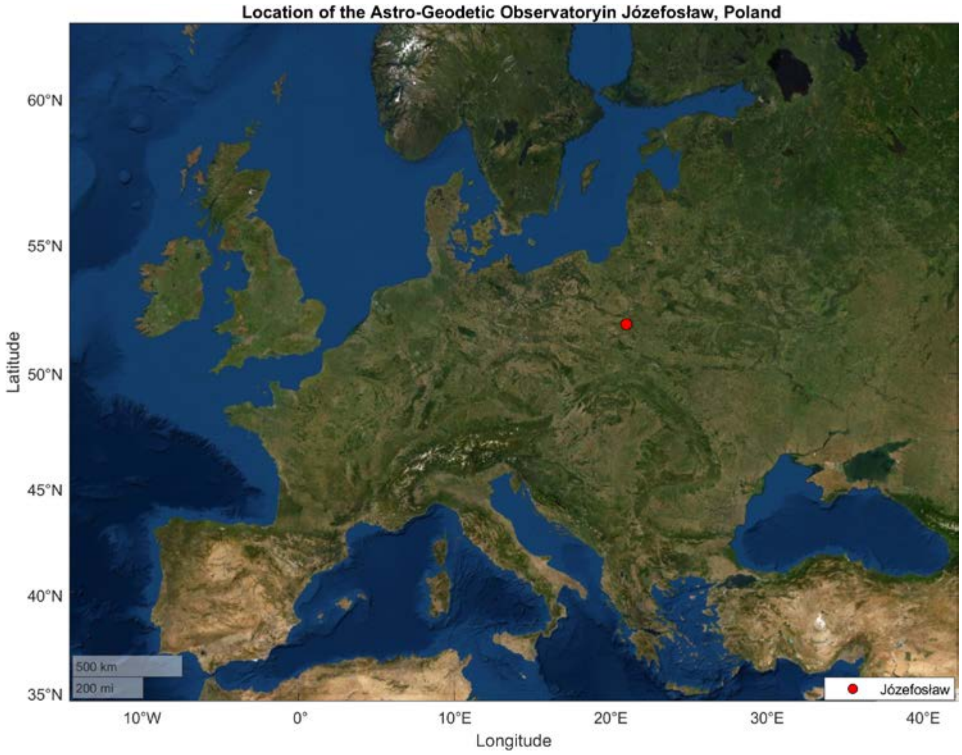


Figure 8. Location of the case study. Source: own study

The gravimetric JOZE station (general location in Figure 8) is in the basement of AGO building, i.e. 5.7 m below the ground, on a 2 × 2 m concrete pole. Absolute measurements were conducted in roughly monthly routine from May 2005 to November 2016 using the FG-5 gravimeter No. 230. This is the longest and homogeneous (considering both accuracy and spatial resolution) time series of gravity values in Poland. The total uncertainty in determining the gravity field force is ±2 μGal. Results from the absolute measurements are corrected for the effects related to Earth tides (Wenzel model) and oceanic tides (FES2004 model), changes in atmospheric pressure and polar motion. In addition, gravity values are corrected by the results of international comparison campaigns. Metrological factors (resulting from clock and laser frequency changes) are also considered.

Results measured by an absolute gravimeter are not only affected by systematic geodynamic factors removed during data processing, but also by local hydrological influence. In AGO JOZE, parallel to the gravity data measurements, groundwater level was recorded by a piezometer. After calculating the impact of local subsurface water masses, it was possible to compare terrestrial data with satellite ones. To obtain the desired results, the approach presented in Kuczynska-Siehien et al. (2019) was used. Piezometric measurements of groundwater level fluctuations made it possible to estimate the hydrological effect on gravity according to the formula (Creutzfeldt, 2010):

$$\Delta g_{hyd} = 41.92 \cdot Sy \cdot \Delta h \tag{7}$$

Sy (specific yield) means the water content in the pores of a given aquifer and Δh is the change in groundwater level obtained from piezometer readings. In this case, $Sy = 0.13$ was determined on the basis of simple regression of piezometric and gravimetric observations.

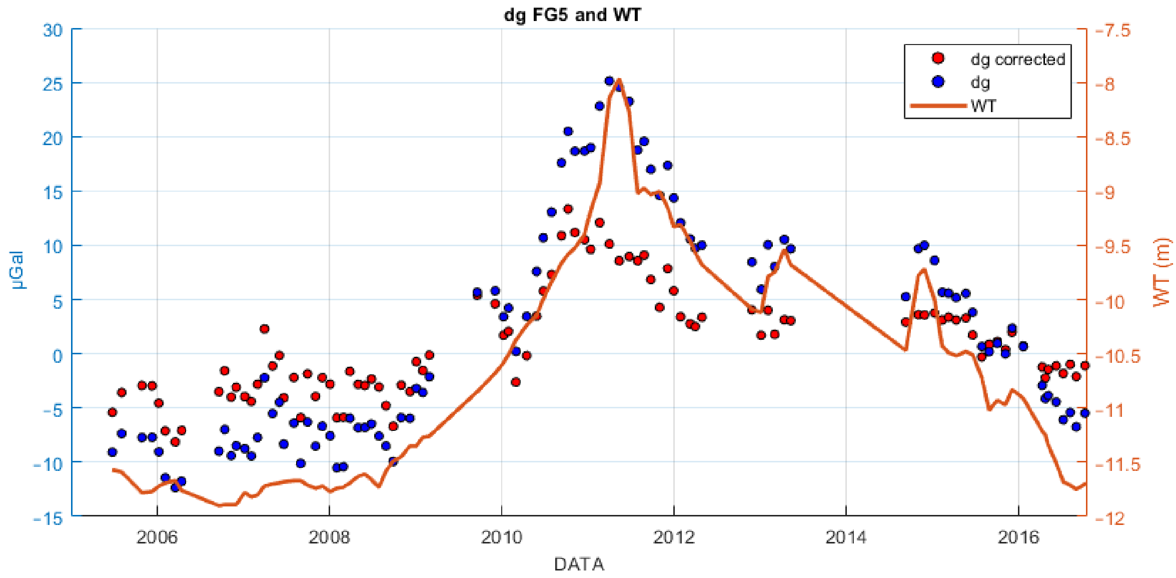


Figure 9. Graph of observed dg changes by absolute gravimeter before and after hydro correction against the background of changes in groundwater level. Source: own study

On analysing the graph in Figure 9, is it noticeable that gravimetric measurements are highly dependent on groundwater level fluctuations. The Δg_{hyd} correction reduced the amplitude of the observed g values from 25 to 14 μGal. Compared to the total uncertainty of absolute measurement at ±2μGal, it is clearly seen how sensitive equipment is to changes in local mass distribution.

Data from the GRACE mission was collected as spherical harmonics (*.gfc* file from the International Center for Global Earth Models [ICGEM] website) in RL06 and RL05a releases. The changes denoted as ΔC_{nm} and ΔS_{nm} were calculated by removing the static part of the gravity field using GGM05C model (Ries et al., 2016) for each monthly solution. According to the valid conventions (technical notes TN-11 and TN-07), GRACE coefficients C_{10}, C_{11}, S_{11} denoting the centre of mass and C_{20} denoting the gravimetric flattening of the Earth (Swenson et al., 2008) have been replaced with the coefficients determined using satellite laser ranging (SLR) measurements (Cheng et al., 2013). Additionally, due to problems with the GRACE-B accelerometer, a significantly higher variance of the C_{30} coefficient could have been observed in the last 7 months of the mission, therefore it was also substituted by a corresponding value from SLR. For the RL06 data, a linear model of polar motion has been introduced, which is consistent with the IERS2010 convention. Hence, it is not recommended to introduce any corrections to the C_{21} and S_{21} coefficients (according to Dahle et al., 2019).

GRACE and FG5 observations were recorded for different epochs. To be able to compare them, it was necessary to interpolate the data. The choice of interpolation method was important because of possible overestimation with a too aggressive approach. Several popular ways were tested in this study and the best one turned out to be a moving average with a window size of 5 months. This allowed to faithfully reflect the original signal without excessive smoothing and the appearance of gross errors.

The comparison of gravity field changes data determined by GRACE sensors and absolute measurements with the FG5 gravimeter was based on gravimetric disturbances. The gravity disturbance is understood here as the difference between the real and normal (referred to ellipsoid) acceleration of gravity on the physical surface of the Earth. It was determined from GRACE data, taking into account the elastic deformation of the Earth as a result of loading (Crossley et al., 2012) according to the following formula:

$$\delta g(\theta,\lambda) = \frac{GM}{R^2}\sum_{n=0}^{\infty}\left(n+1-\frac{2h_n}{1+k_n}\right)\sum_{m=0}^{n}(\bar{C}_{nm}\cdot\cos m\lambda + \bar{S}_{nm}\cdot\sin m\lambda)\cdot\bar{P}_{nm}(\cos\theta) \quad (8)$$

where h_n and k_n are the Love numbers for the overall elastic response of the Earth from the preliminary reference earth model (PREM). Due to the correction of the geocenter parameters from GRACE data to the coefficients C_{10}, C_{11} and S_{11}, the corresponding value of k_1 was changed to 0.021. The values of gravity disturbance have also been fixed by the *gain factor* (Landerer and Swenson, 2012) for the examined region, which was equal to 1.06. In our research area, no earthquake with magnitude above 8.5 has been observed. Further, the effect of postglacial uplift is relatively small. Hence, it was decided not to make related corrections.

To analyse the time series of GRACE mission, all eight types of non-isotropic filtration of DDK (DDK1–DDK8) were used, as well as Gaussian filtration with the following radii (*R*): 200, 300, 400, 500 and 600 km. Datasets from RL05a and RL06 releases were considered separately for solutions from CSR, GFZ and JPL centres.

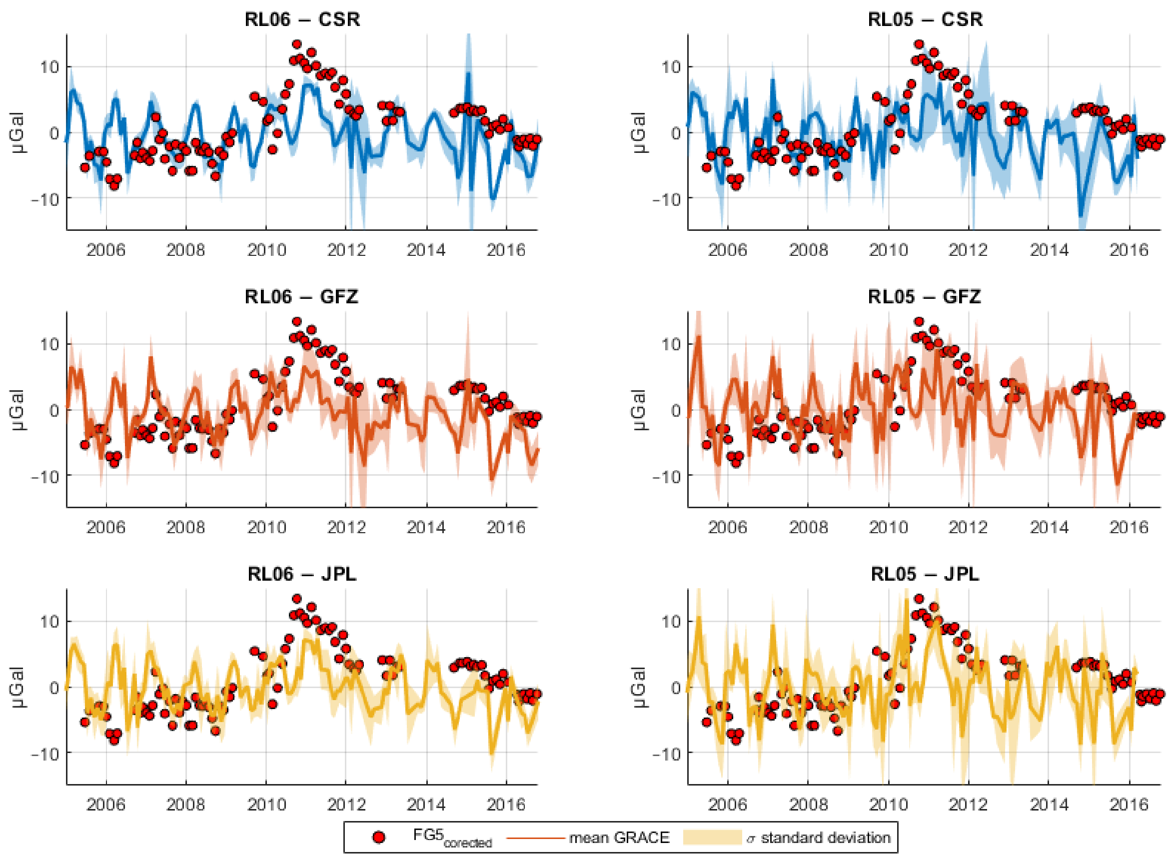


Figure 10. Mean gravity disturbance values and standard deviation (dispersion) based on all types of filtration. Source: own study

On comparing the discrepancies between gravity disturbances observed by GRACE and FG5 (corrected for hydrological effect), a significant difference can be seen between the time series from 2005 to 2009 and from 2010 to 2016 in ground data (red dots in Figure 10), regardless of the type of filtration. The discrepancies observed in these periods result mainly from a major hydrological flood that happened during those times. This rapid increase in dg is not noticed very clearly by GRACE sensors. Substantial seasonal fluctuations in amplitudes, caused by large-scale changes in the water level of the Vistula basin, affect the suppression of information related to the flood in 2010. To compare the data from satellite and terrestrial sensors properly, it is needed to exclude the effects that are modellable and do not appear in local ground observations. These effects are periodic (annual, semi-annual and quarterly) changes of amplitudes in observations recorded by GRACE. Eliminating them allows more effective analysis regarding the comparison of data from different sensors.

To remove the effect caused by seasonal amplitude changes of continental hydrology, the signal had to be approximated with sinusoidal functions. This was done using the least-squares spectral analysis (LSSA) method (Vaníček, 1969, 1971) based on modelling of two waves with annual and semi-annual amplitude parameters determined using the Gauss–Markov model. Decomposition of the observed signal was made in accordance with the methodology proposed in Kuczynska-Siehien et al. (2019). This approach enables eliminating time series periodicity for both GRACE and absolute measurement datasets (Figure 11).

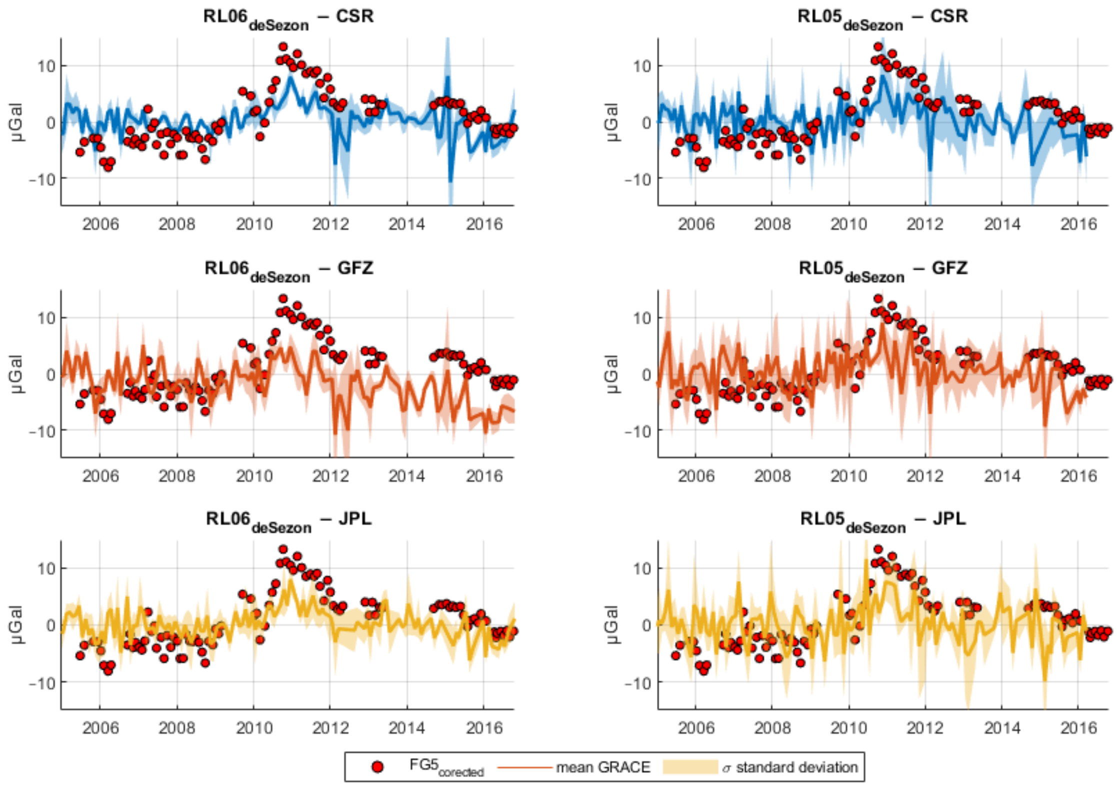


Figure 11. Mean gravity disturbance values after signal decomposition, and standard deviation (dispersion) based on all types of filtration. Source: own study

3.2. Analysis of residuals and time series consistency

After cleaning the datasets, the variability analysis of individual signals was performed in terms of the selected filtration type. To distinguish all discrepancies between FG5 absolute measurements and filtered observations from GRACE, the graphs shown in Figure 12 present the differences between them. The left graph depicts the residues of RL06 release and the right one depicts the residues of RL05a release.

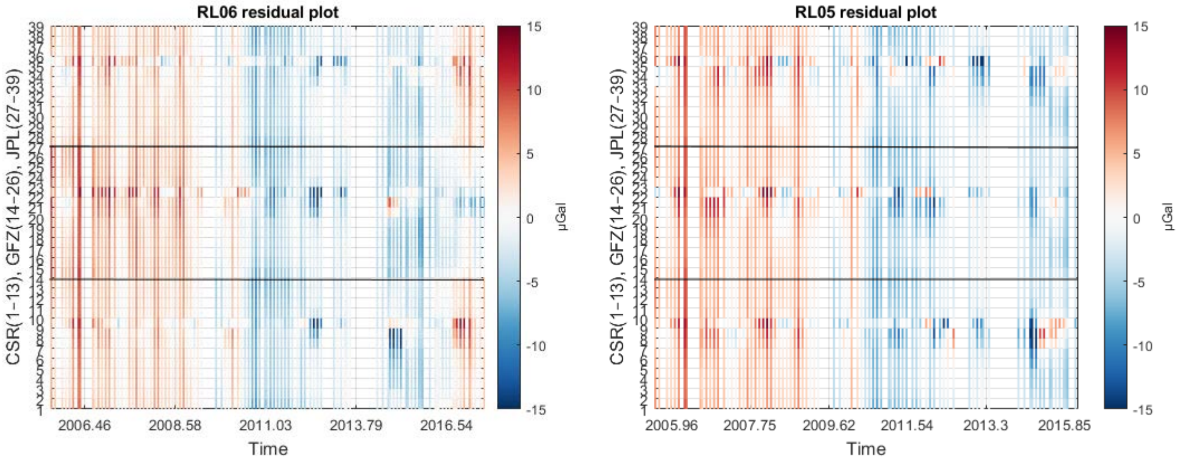


Figure 12 Residual diagram AG-GRACE RL06 (left) and RL05a (right) for DDK1-8 filtration (rows: 1–8, 14–21, 27–34) and Gaussian 200–600 km (rows: 9–13, 22–26, 35–39). Source: own study

The performances of Gaussian filter with smoothing radius equal to 200 km (rows: 9, 22, 35) and DDK8 (rows: 8, 21, 34) are clearly different from others. Furthermore, it can be seen that the discrepancies occurring in 2010 were not fully corrected due to the changes in groundwater level. This is because of the intense floods that occurred in that year. To determine which of the filtered GRACE time series best fits the AG measurements, the mean square error (RMSE) for each of these series was calculated based on the residues according to the formula:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\delta g_n^{GRACE} - \delta g_n^{AG})^2} \quad (9)$$

Subsequently, Pearson's correlation coefficients were estimated for all calculated variants (on account of applied filters, processing centres) of gravimetric disturbance. However, since the GRACE solutions were delivered monthly, there are some phase shifts between the signals observed by satellite and ground sensors. Therefore, the analysis of signal compatibility was completed with the normalised cross-correlation (*Xcorr*) coefficients:

$$xcorr(\delta g^{AG}(t), \delta g^{GRACE}(t+\tau)) = \frac{E[(\delta g_t^{AG} - \mu(\delta g^{AG}))(\delta g_{t+\tau}^{GRACE} - \mu(\delta g^{GRACE}))]}{\sigma(\delta g^{GRACE})\sigma(\delta g^{AG})} \quad (10)$$

where E is the expected value of the given expression, σ is the standard deviation and μ is the average value, all depending on the time shift τ. In our paper, we have chosen an *Xcorr* value that was a maximum in ±3 months interval of possible lags between the examined time series. So, this lag value is less than 3 (months). The results of all the statistics listed above are summarised in Table 1.

Table 1. The statistics of time series comparison

	RL06										RL05								
	Xcorr			RMS (µGal)			Pearson corr			Filter type	Xcorr			RMS (µGal)			Pearson corr		
	CSR	GFZ	JPL	CSR	GFZ	JPL	CSR	GFZ	JPL		CSR	GFZ	JPL	CSR	GFZ	JPL	CSR	GFZ	JPL
2005-2016	0.39	0.55	0.37	5.15	5.09	5.26	0.15	0.13	0.11	DDK1	0.26	0.52	0.15	5.52	5.19	5.48	0.09	0.20	0.08
	0.60	0.64	0.59	4.74	4.67	4.87	0.33	0.24	0.29	DDK2	0.57	0.71	0.49	5.10	4.77	5.00	0.27	0.38	0.29
	0.77	0.70	0.72	4.59	4.44	4.70	0.40	0.28	0.37	DDK3	0.76	0.80	0.73	4.78	4.51	4.65	0.39	0.47	0.43
	0.79	0.70	0.73	4.59	4.43	4.70	0.40	0.27	0.37	DDK4	0.78	0.80	0.76	4.79	4.56	4.66	0.40	0.46	0.43
	0.81	0.70	0.75	4.65	4.38	4.71	0.39	0.24	0.36	DDK5	0.79	0.78	0.79	5.04	4.98	4.96	0.33	0.33	0.38
	0.81	0.69	0.76	4.76	4.36	4.69	0.36	0.23	0.36	DDK6	0.78	0.76	0.79	5.31	5.32	5.25	0.27	0.24	0.33
	0.78	0.68	0.79	5.26	4.79	4.71	0.27	0.20	0.33	DDK7	0.65	0.63	0.74	6.67	6.52	6.28	0.07	-0.03	0.22
	0.76	0.67	0.78	5.62	5.55	4.91	0.22	0.18	0.29	DDK8	0.48	0.48	0.68	7.75	7.17	6.83	0.00	-0.12	0.18
	0.72	0.67	0.79	6.16	6.90	6.11	0.20	0.09	0.22	GAUSS R= 200 km	0.24	0.78	0.13	7.54	6.69	7.03	0.04	0.26	0.16
	0.75	0.68	0.72	4.63	4.58	4.67	0.34	0.17	0.32	300 km	0.61	0.80	0.73	5.05	4.98	4.95	0.27	0.28	0.31
	0.65	0.64	0.60	4.78	4.70	4.88	0.28	0.16	0.24	400 km	0.50	0.72	0.56	5.07	4.89	5.05	0.24	0.30	0.24
	0.56	0.61	0.54	4.89	4.82	4.99	0.22	0.14	0.17	500 km	0.41	0.64	0.39	5.14	4.88	5.15	0.19	0.30	0.18
	0.50	0.59	0.50	4.99	4.90	5.07	0.16	0.12	0.12	600 km	0.37	0.61	0.30	5.20	4.91	5.23	0.15	0.27	0.13
	RL06										RL05								
	Xcorr			RMS (µGal)			Pearson corr			Filter type	Xcorr			RMS (µGal)			Pearson corr		
	CSR	GFZ	JPL	CSR	GFZ	JPL	CSR	GFZ	JPL		CSR	GFZ	JPL	CSR	GFZ	JPL	CSR	GFZ	JPL
2005-2016 deseasonalised	0.24	0.16	0.41	4.25	4.91	4.27	0.48	0.16	0.48	DDK1	0.25	0.50	0.34	4.56	4.52	4.53	0.42	0.44	0.45
	0.62	0.17	0.70	3.83	4.59	3.88	0.62	0.28	0.61	DDK2	0.58	0.68	0.64	4.27	4.22	4.21	0.53	0.54	0.56
	0.77	0.29	0.74	3.75	4.52	3.75	0.63	0.31	0.63	DDK3	0.73	0.76	0.68	4.15	4.08	4.16	0.56	0.59	0.56
	0.80	0.32	0.74	3.76	4.53	3.77	0.62	0.30	0.62	DDK4	0.77	0.79	0.69	4.17	4.09	4.22	0.56	0.58	0.54
	0.84	0.38	0.76	3.85	4.51	3.83	0.59	0.26	0.60	DDK5	0.82	0.84	0.79	4.38	4.33	4.50	0.49	0.50	0.45
	0.83	0.40	0.79	4.00	4.51	3.87	0.55	0.25	0.59	DDK6	0.81	0.84	0.81	4.62	4.60	4.74	0.40	0.40	0.40
	0.78	0.43	0.79	4.74	5.08	4.18	0.37	0.21	0.49	DDK7	0.72	0.76	0.77	6.00	5.81	5.66	0.11	0.04	0.28
	0.75	0.41	0.75	5.25	5.87	4.55	0.30	0.18	0.39	DDK8	0.62	0.68	0.74	7.10	6.54	6.21	0.01	-0.09	0.23
	0.62	0.49	0.79	5.80	7.09	5.43	0.25	0.09	0.34	GAUSS R= 200 km	0.40	0.77	0.17	6.67	6.79	7.26	0.18	0.23	0.09
	0.73	0.33	0.71	3.89	4.78	3.92	0.61	0.18	0.61	300 km	0.68	0.84	0.78	4.35	4.58	4.44	0.51	0.40	0.46
	0.51	0.09	0.48	4.02	4.81	4.08	0.58	0.18	0.57	400 km	0.41	0.70	0.56	4.38	4.41	4.48	0.51	0.50	0.46
	0.24	0.17	0.35	4.18	4.88	4.21	0.53	0.15	0.53	500 km	0.15	0.42	0.28	4.49	4.45	4.55	0.48	0.49	0.44
	0.11	0.25	0.21	4.31	4.93	4.32	0.48	0.12	0.49	600 km	0.17	0.25	0.11	4.59	4.53	4.63	0.44	0.47	0.42

Performance: good — avg — bad

It can be seen that with RL05a dataset, all processing centres show quite a large consistency of the results. They reveal similar values of both indexes, correlation and RMS. DDK3–6 filters fare very well in this comparison. They are characterised by a cross-correlation coefficient of 0.7–0.8. The RMSE for these sets is approx. 4.5–5.2 µGal before signal decomposition. This values decreases to 4.1–4.7 µGal after removing the seasonal effects. An alternative to these types of filtration may be Gaussian filtration with a smoothing radius of R = 300 or 400 km (in GFZ solution). In all other cases, there is no balance between preserving geophysical information and removing orbital or seasonal hydrological effects. Although RMSE remains at 4.5 µGal, the correlation coefficients drop significantly below 0.5. This means there is no relationship between the signals.

For the RL06 release, DDK3–6 filters are still the best perfsorming ones. The relation between GRACE and FG5 time series remained strong with 0.7–0.8 *Xcorr* values for CSR and JPL centres. This release had also lower RMS error varying in the range of 3.7–4.0 µGal. The amount of observational noise decreased as compared to RL05a. In turn, Gaussian filtration gave satisfactory results only for a smoothing radius of 300 km in any data processing centre.

On comparing the results from the research centres, the dataset from GFZ clearly stands out from the rest. Before removing seasonal impacts, cross-correlation coefficients did not differ much from those obtained for JPL and CSR. However, after eliminating periodicity effects, the values of these factors dropped down. Thus, RL06 data processing strategy provided by GFZ turns out to be inefficient in the case of research in AGO Józefosław area.

4. CONCLUSIONS

When considering the compatibility between terrestrial gravity measurements and GRACE filtered data, it can be noticed that the change in the water table from −11 m to about −8 m below the Earth's surface is not recorded from a satellite's level because the phenomenon is purely local. It should be eliminated at the stage of comparing GRACE solutions with in situ data.

Removing the periodic phenomena of gravity changes associated with different seasons from time series enabled investigation of local environmental changes. To effectively perform this process, it was sufficient to use proper sinusoidal function fit.

In the case of Gaussian filtration, the best results are obtained by a smoothing radius equal to 300 km, which agrees with the recommendations posted by official data processing centres. Other radii of this kind of filtration cause too much data averaging in the study area. Thus, they should not be used because of unsatisfactory performance.

Considering the latest GRACE reprocessed dataset, DDK3–DDK6 filters published by the CSR and the JPL are characterised by a high cross-correlation coefficient at the level of 0.8 and a satisfactory RMSE in the range of 3.7–4.0 µGal, i.e. lower than twice the measurement made by the FG5 gravimeter. For the same filters in the RL05a data version, all three computing centres present good results for both cross-correlation coefficient and RMSE, with values of 0.7–0.8 and 4.1–4.7 µGal, respectively. Therefore, the conclusion is that satellite observations made by GRACE mission properly filtered can be successfully used in studies on the JOZE observatory.

Furthermore, the right selection of data processing strategy is of additional importance. In the RL06 version for GFZ, after signal decomposition, the overall results are worse. Moreover, DDK1–2 filtration types present too intense blurring of geophysical artefacts and could only be used in large oceanic or river basin areas.

The choice of an optimal filtration type and the accuracy of GRACE solutions resulting from it are extremely important in the context of establishing International Geomagnetic Reference Field (IGRF) system and the maintenance of basic gravimetric network in Poland.

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