# Validation of static global gravity field models from CHAMP, GRACE and GOCE with ground data in Poland

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## INTRODUCTION

The main objective of our research is a comparison and validation of different models from satellite missions CHAMP, GRACE and GOCE with ground-based gravimetric measurements. Our analyses concern **Bouguer gravity anomalies**. As a reference dataset for validation of the models, we used ground-based gravity measurements for points located in Poland. These stations are divided into three groups: 1) points of POLish REFerence network POLREF (with relative gravity measurements), 2) points of Polish National Gravimetric Network POGK (with absolute gravity measurements) and 3) points located in Tatra Mountains (with relative gravity measurements). First two groups contain stations from the whole area of the country while the last one covers only a small highlands region.

In this study we compute the Bouguer's anomalies for every point in two ways: 1) with the use of different GGMs – we call them **calculated anomalies** and 2) with the use of ground-based gravimetric observations – we call them **measured anomalies**. Next we determine the differences between calculated and measured values as well as their basic statistics (minimum, maximum, mean, standard deviation). The evaluation of the accuracy of each model is based on the analysis of these differences. The use of CHAMP, GRACE and GOCE-based GGMs for modelling the gravity field over Poland is discussed here.

## DATA USED

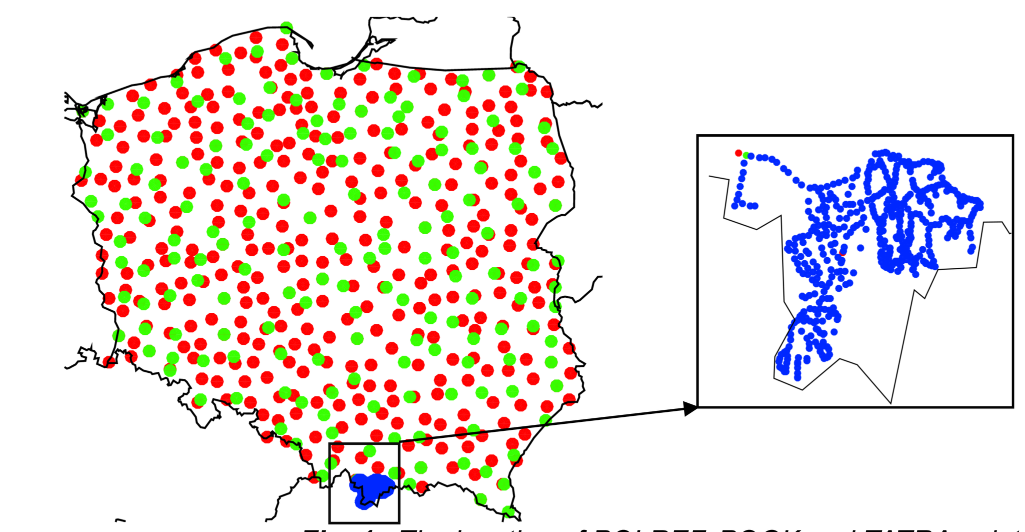
### 1) CHAMP, GRACE and GOCE-based GGMs – with different $N_{max}$, spatial resolution and input data

*Table 1. Global Gravity Field Models (GGMs) used for analysis*

| Mission(s) | Model | Max degree ($N_{max}$) | Year | Type of data* |
|---|---|---|---|---|
| CHAMP | 1. ULUX_CHAMP2013s | 120 | 2013 | S (CHAMP) |
| | 2. EIGEN-CHAMP05s | 150 | 2010 | S (CHAMP) |
| GRACE | 3. ITG_GRACE2010s | 180 | 2010 | S (GRACE) |
| | 4. GGM05s | 180 | 2014 | S (GRACE) |
| | 5. ITSG_GRACE2014s | 200 | 2014 | S (GRACE) |
| | 6. EIGEN_GL04c | 360 | 2006 | S (GRACE, SLR) + G + A |
| | 7. GGM03c | 360 | 2009 | S (GRACE) + G + A |
| | 8. EGM2008 | 2190 | 2008 | S (GRACE) + G + A |
| GOCE | 9. DIR-R2 | 240 | 2011 | S (GOCE) |
| | 10. TIM-R5 | 280 | 2014 | S (GOCE) |
| | 11. SPW-R4 | 280 | 2014 | S (GOCE) |
| | 12. SPW-R5 | 330 | 2017 | S (GOCE) |
| | 13. JYY_GOCE04s | 230 | 2014 | S (GOCE) |
| | 14. GECO | 2190 | 2015 | S (GOCE) + EGM2008 |
| GOCE + GRACE | 15. EIGEN_6s | 240 | 2011 | S (GOCE, GRACE, SLR) |
| | 16. EIGEN_6c | 1420 | 2011 | S (GOCE, GRACE, SLR) + G + A |
| | 17. GOGRA04s | 230 | 2014 | S (GOCE, GRACE) |
| | 18. GGM05c | 360 | 2016 | S (GOCE, GRACE) + G + A |
| CHAMP + GRACE + GOCE | 19. GOCO02s | 250 | 2011 | S (GOCE, GRACE, CHAMP, SLR) |
| | 20. GOCO05s | 280 | 2015 | S (GOCE, GRACE, CHAMP, SLR, K) |
| | 21. GOCO05c | 720 | 2016 | S (GOCE, GRACE, CHAMP, SLR, K) + G + A |
| | 22. XGM2016 | 719 | 2017 | S (GOCE, GRACE, CHAMP, SLR, K) + G + A |

*S – satellite data, G – ground-based gravimetric measurements, A – altimetry measurements, K – kinematic orbits of satellites: Swarm A+B+C, TerraSarX, Tandem-X, CHAMP, GRACE A+B, GOCE*

### 2) Ground-based gravity measurments for points in Poland - POLREF, POGK and TATRA



- POLish REFerence network (POLREF) – 353 points
- Polish National Gravimetric Network (POGK) – 167 points
- Points in Tatra Mountains (TATRA) – 479 points

Total – 999 points

*Fig. 1 . The location of POLREF, POGK and TATRA points in Poland, Central Europe*

## METHODOLOGY

1) **Bouguer anomalies have been obtained from GGMs** as follows (Barthelmes, 2013):

$$\Delta g_B(r,\varphi,\lambda)=\frac{GM}{r^2}\sum_{n=0}^{n_{max}}\left(\frac{R}{r}\right)^n(n-1)\sum_{m=0}^{n}\bar{P}_{nm}(sin\varphi)(\bar{C}^T_{nm}cos\,m\lambda+\bar{S}^T_{nm}sin\,m\lambda)\;-2\pi G\rho R\sum_{n=0}^{n_{max}}\sum_{m=0}^{n}\bar{P}_{nm}(sin\varphi)(\bar{C}^{topo}_{nm}cos\,m\lambda+\bar{S}^{topo}_{nm}sin\,m\lambda)$$

where: $\bar{C}^T_{nm}$ i $\bar{S}^T_{nm}$ – fully normalized Stokes' coefficients of gravity disturbance, $\bar{C}^{topo}_{nm}$ i $\bar{S}^{topo}_{nm}$ – fully-normalized coefficients of topography model, $\bar{P}_{nm}$ – fully-normalized Legendre functions

2) **Bouguer anomalies from ground-based measurements** have been computed using formula: $\Delta g_B = g-\gamma_0+R_B+R_{fa}$, where $R_B = 2\pi G\sigma H$ is a Bouguer correction and $R_{fa}=0.3086\cdot H$ s a free-air correction

## REFERENCES

Barthelmes F. (2013). Definition of functionals of the geopotential and their calculation from spherical harmonic models: theory and formulas used by the calculation service of the International Centre for Global Earth Models (ICGEM). Scientific Technical Report STR09/02. GFZ German Research Centre for Geosciences. Potsdam, Germany, http://icgem.gfz-potsdam.de/ICGEM/

## RESULTS

### 1) Spatial distribution of measured and calculated anomalies

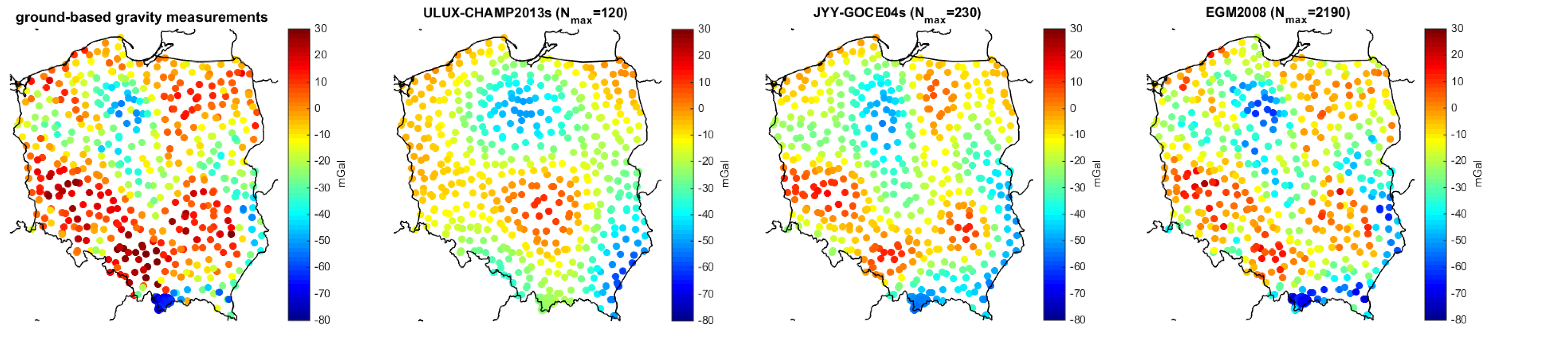


*Fig. 2. Example of Bouguer's anomalies distribution over area of Poland - obtained from ground-based gravity measurements and three GGMs with different $N_{max}$ (ULUX_CHAMP2013s, JYY_GOCE04s and EGM2008). The Bouguer anomalies are given in mGal.*

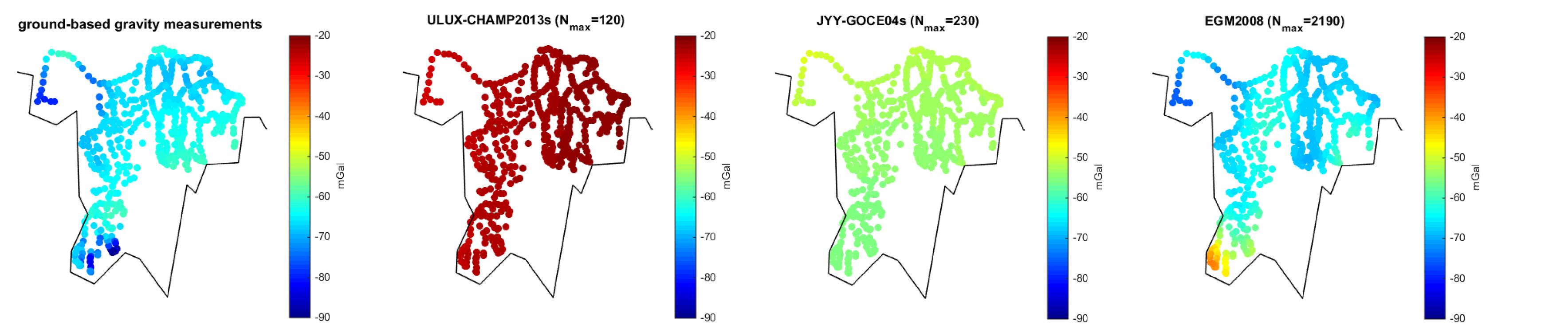


*Fig. 3. Example of Bouguer anomalies distribution for area of Tatra Mountains - obtained from ground-based gravity measurements and three GGMs with different $N_{max}$ (ULUX_CHAMP2013s, JYY_GOCE04s and EGM2008). The Bouguer anomalies are given in mGal.*

### 2) Differences between anomalies obtained from ground-based gravity measurements and calculated from GGMs

*Table 2. Basic statistics of differences between calculated (from model) and measured (from ground-based gravity mesurements) Bouguer anomalies. The values are given in mGal.*

| Model | min | | | max | | | mean | | | std | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | POGK | POLREF | TATRA | POGK | POLREF | TATRA | POGK | POLREF | TATRA | POGK | POLREF | TATRA |
| 1. ULUX_CHAMP2013s | -59.93 | -70.09 | 34.76 | 37.16 | 31.25 | 68.52 | -10.88 | -14.25 | 43.10 | 18.83 | 4.10 | 19.30 |
| 2. EIGEN-CHAMP05s | -45.67 | -67.63 | 14.16 | 29.47 | 25.95 | 49.60 | -8.44 | -12.54 | 24.50 | 15.96 | 5.53 | 17.07 |
| 3. ITG_GRACE2010s | -38.87 | -77.42 | 14.94 | 21.40 | 21.21 | 46.95 | -9.54 | -12.90 | 22.04 | 11.50 | 4.32 | 13.91 |
| 4. GGM05s | -46.34 | -75.34 | 8.54 | 30.50 | 22.20 | 39.86 | -9.94 | -13.12 | 19.89 | 15.96 | 4.97 | 17.19 |
| 5. ITSG_GRACE2014s | -40.64 | -75.23 | 0.76 | 24.42 | 21.91 | 31.70 | -9.33 | -12.36 | 11.92 | 14.41 | 5.10 | 16.14 |
| 6. EIGEN_GL04c | -30.17 | -82.88 | -15.51 | 14.11 | 8.20 | 15.83 | -9.16 | -12.60 | -1.71 | 7.22 | 6.49 | 11.34 |
| 7. GGM03c | -30.12 | -81.83 | -13.55 | 7.82 | 12.43 | 18.20 | -9.39 | -12.85 | -0.73 | 7.16 | 6.10 | 11.73 |
| 8. EGM2008 | -24.51 | -73.62 | -8.49 | 10.85 | 5.48 | 39.22 | -9.66 | -13.34 | 1.56 | 4.38 | 8.23 | 10.25 |
| 9. DIR-R2 | -38.76 | -71.81 | 16.49 | 21.54 | 18.88 | 48.87 | -9.04 | -12.68 | 25.34 | 11.44 | 4.15 | 12.95 |
| 10. TIM-R5 | -28.04 | -68.95 | -1.74 | 14.11 | 14.43 | 32.91 | -9.31 | -12.97 | 9.17 | 8.78 | 5.88 | 12.26 |
| 11. SPW-R4 | -29.36 | -69.65 | -1.73 | 15.47 | 11.87 | 30.34 | -9.31 | -12.83 | 9.32 | 9.43 | 6.05 | 12.46 |
| 12. SPW-R5 | -30.51 | -64.92 | 2.33 | 18.82 | 14.85 | 33.03 | -9.08 | -12.95 | 14.00 | 10.24 | 6.07 | 12.61 |
| 13. JYY_GOCE04s | -32.93 | -74.62 | 4.70 | 15.92 | 13.66 | 36.83 | -9.07 | -12.92 | 12.28 | 9.60 | 4.61 | 12.75 |
| 14. GECO | -24.60 | -73.61 | -8.62 | 10.61 | 4.69 | 38.68 | -9.50 | -13.21 | 1.67 | 4.38 | 8.08 | 10.07 |
| 15. EIGEN_6s | -38.43 | -72.27 | 16.24 | 21.17 | 18.05 | 48.72 | -8.96 | -12.64 | 25.27 | 11.42 | 4.14 | 12.97 |
| 16. EIGEN_6c | -24.27 | -80.87 | -7.82 | 10.47 | 5.92 | 39.68 | -9.57 | -13.02 | 0.92 | 4.22 | 8.00 | 10.31 |
| 17. GOGRA04s | -33.11 | -74.72 | 4.94 | 15.89 | 13.83 | 37.07 | -9.08 | -12.93 | 12.47 | 9.59 | 4.60 | 12.76 |
| 18. GGM05c | -28.97 | -75.53 | -4.45 | 12.46 | 10.32 | 28.19 | -9.66 | -13.25 | 3.74 | 6.80 | 4.88 | 11.29 |
| 19. GOCO02s | -33.97 | -70.68 | 10.25 | 20.94 | 14.96 | 41.58 | -9.40 | -12.65 | 18.72 | 10.85 | 4.88 | 12.93 |
| 20. GOCO05s | -28.70 | -70.11 | -3.06 | 15.09 | 15.51 | 31.74 | -9.34 | -12.94 | 8.11 | 8.96 | 5.97 | 12.36 |
| 21. GOCO05c | -30.16 | -71.34 | -0.09 | 9.02 | 4.40 | 35.20 | -9.95 | -13.32 | 6.79 | 4.80 | 4.19 | 10.01 |
| 22. XGM2016 | -31.35 | -71.64 | -1.40 | 9.21 | 5.15 | 31.89 | -9.95 | -13.21 | 5.67 | 4.74 | 4.28 | 10.12 |

### 3) Spatial distribution of differences between measured and calculated anomalies - Tatra Mountains

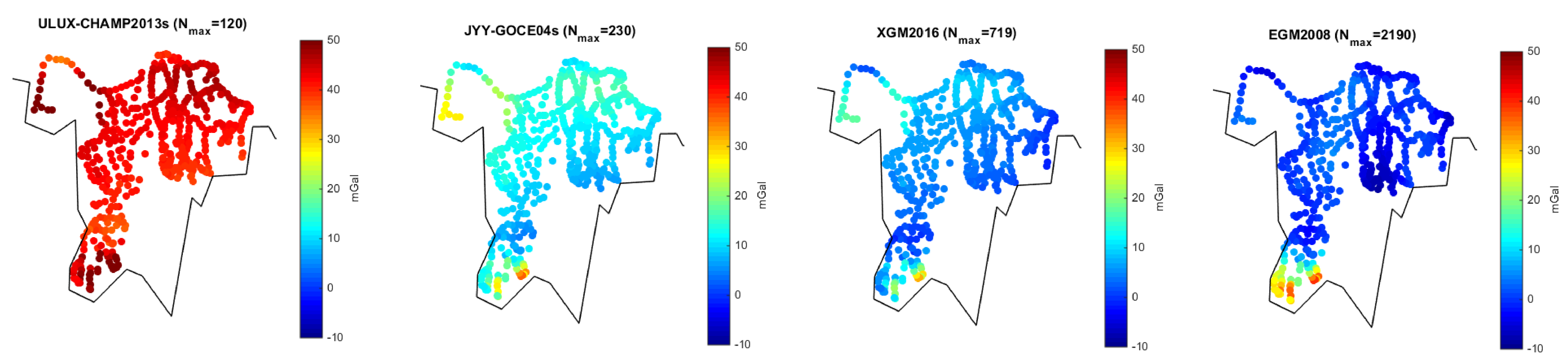


*Fig. 4. Example of differences distribution for area of Tatra Mountains for four GGMs (ULUX_CHAMP2013s, JYY_GOCE04s, XGM2016 and EGM2008). The highest differences correspond to the biggest heights of the stations (southern part of the area).*

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### 4) The impact of $N_{max}$ on the differences between Bouguer anomalies computed from GGMs and the respective ones from ground-based gravity measurements

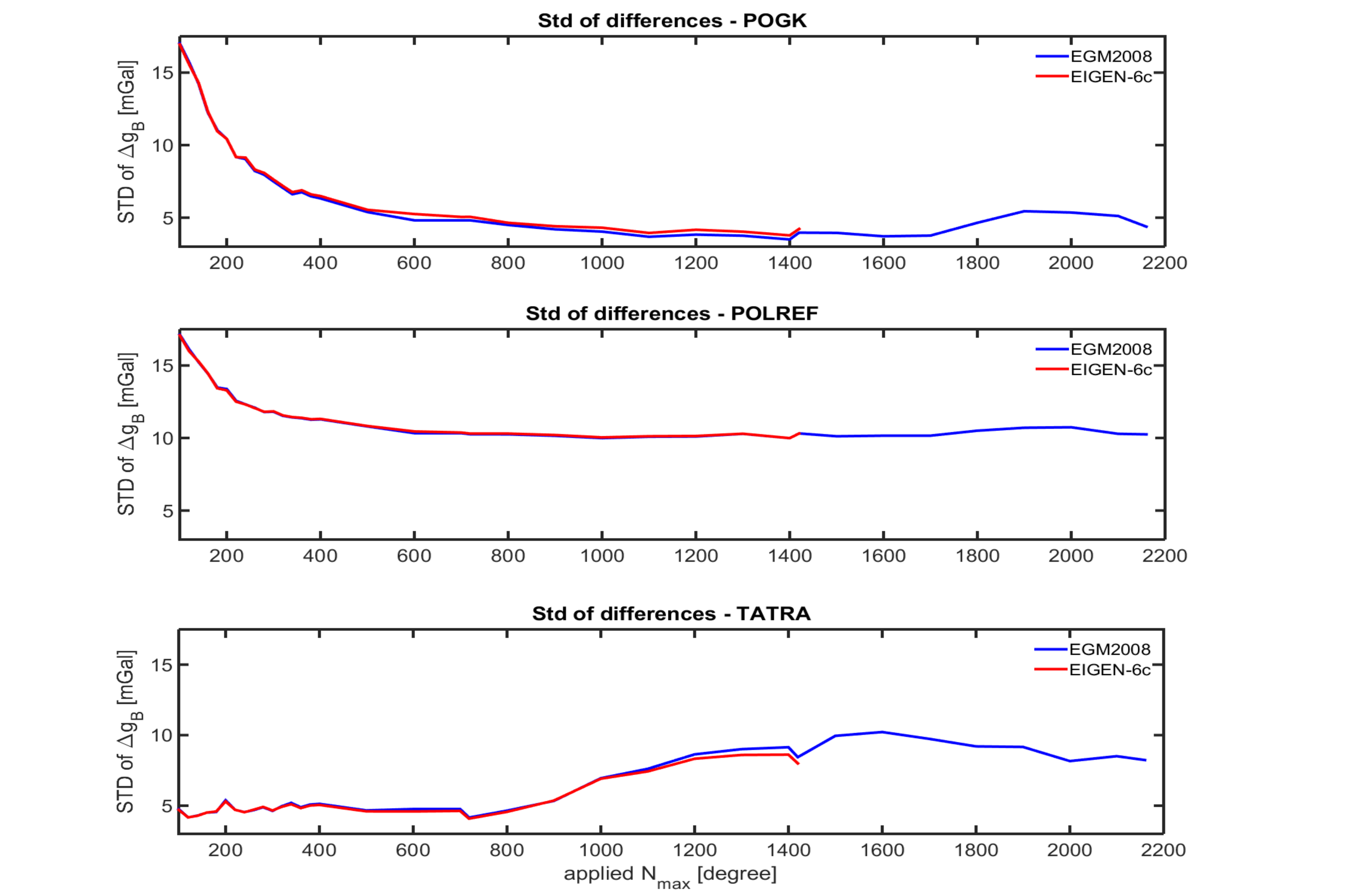


*Fig. 5. Standard deviation of differences between Bouguer anomalies computed from GGMs and the respective ones from ground-based gravity measurements - models EGM2008 and EIGEN-6c*

### 5) Long wave-length components of gravity anomalies

It is obvious that the models with lower $N_{max}$ give bigger differences of gravity anomalies than models that have higher degree of expansion. The first ones show only the long to medium wave-length components of Earth's gravity field while the second ones - also short wave-length changes. Consequently, for an objective comparison of all considered models, we computed Bouger anomalies using the same max degree/order ($N_{max}$ = 120) for all GGMs.

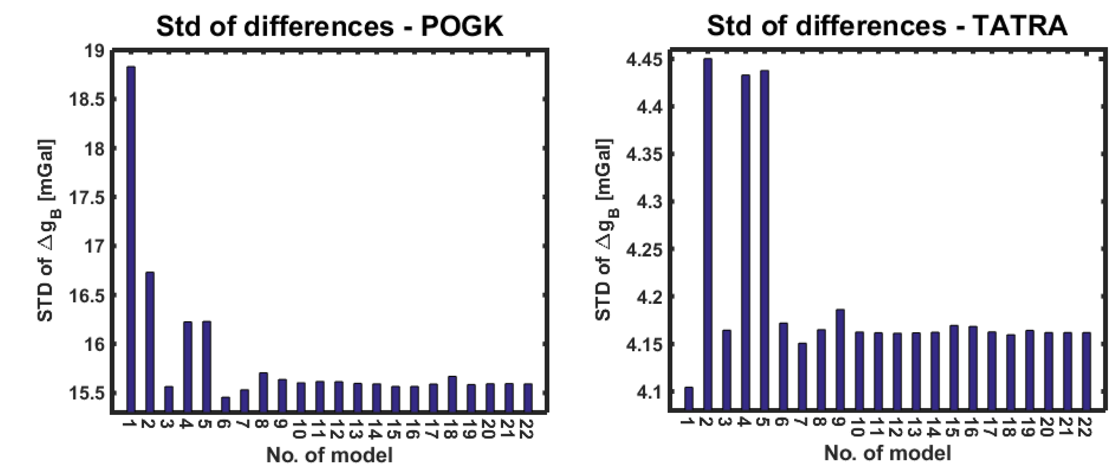


*Fig. 6. Standard deviation of differences between Bouguer anomalies computed from GGMs and the respective ones from ground-based gravity measurements, $N_{max}$ = 120. Points of POGK (left panel) and points located in Tatra Mountains (right panel).*

## DISCUSSION

In this study, the accuracy of GGMs determined from CHAMP, GRACE and GOCE has been estimated over the area of Poland. Bouger gravity anomalies estimated from several models with different spatial resolution and input data (Table 1) have been compared with the corresponding ones obtained from ground-based gravity measurements.

The results obtained show that the variance of modelled anomalies is bigger for the models with higher degree of expansion (Fig. 1). It is clear that higher $N_{max}$ results in lower differences between computed and measured Bouguer anomalies. Obtaining models with high spatial resolution was possible after combining observations from satellite missions CHAMP, GRACE and GOCE with altimetric data and ground-based gravimetric measurements (Table 1).

The discrepancies between examined models are the biggest for the case of Tatra Mountains area (Fig. 2). The varied terrain elevation and geological structure of this region results in high variance of Bouguer anomalies the value of which depends e.g. on the height of the station. The satellites of gravity missions are not sensitive enough to observe ultra-shortwave changes of Earth's gravity field. For this reason, standard deviations of differences between gravity functionals computed using GGMs and based on ground-based measurements are the biggest for this group of points for all considered models. This statistics is the lowest for the models: EGM2008, GECO, EIGEN_6c, GOCO05c and XGM2016 that are distinguished by the highest degree of expansion $N_{max}$ (Table 2). The highest standard deviation of differences is observed for satellite-only models from CHAMP (ULUX_CHAMP2013s and EIGEN-CHAMP05s) and GRACE (GGM05s, ITG_GRACE2010s and ITSG_GRACE2014s) missions. The residuals between measured and computed anomalies are bigger for the stations with higher elevations (Fig. 4).

The comparison of Bouguer anomalies for the points of POLREF and POGK networks shows that standard deviation of differences between observed and computed values are bigger for POLREF for most of combined models (satellite + ground-based measurements as input data) and lower for these stations for most of satellite-only models (only observations from satellite gravity missions) (Table 2, Fig. 5). It is worth mentioning that on the stations of POGK network the gravimetric measurements were made using absolute methods while for the case of POLREF network - with the use of relative measurements. The mean of differences is lower for POGK for all considered models (Table 2).

The maximum degree/order of the model ($N_{max}$) has dominant impact on the accuracy of GGMs (Fig. 5). The biggest increase in quality is observed up to the degree 300. However, further increase in $N_{max}$ also results in decreasing standard deviation of differences between Bouguer anomalies computed using GGMs and obtained from ground-based gravity measurements. For the case of Tatra Mountains area, starting with $N_{max}$ = 700, standard deviation of these residuals increases.

There is no significand difference between long wave-length components of Bouguer gravity anomalies obtained from different Global Gravity Field Models. Only EIGEN-CHAMP05s, GGM05s and ITSG_GRACE2014s models have bigger standard deviation of differences between computed and measured anomalies for both POGK and TATRA points (Fig. 6).