Comparison of GRACE Level-3 Data with Superconducting Gravimeters in Europe By Means of Signal Decomposition Analysis

Miguel Ángel Izquierdo Pérez[1], Christian Voigt[2], Elmas Sinem Ince[2], and Frank Flechtner[1,2]

1. Institute of Geodesy and Geoinformation Science, Technische Universität Berlin (TUB), Berlin, Germany
2. German Research Centre for Geosciences (GFZ), Potsdam, Germany
[maizquierdop@correo.udistrital.edu.co]

Introduction

The validation of the GRACE(FO) observations is a challenging task due to the lack of alternative methods to obtain in-situ measurements that are directly comparable. Therefore, one appropriate approach for this endeavor consists of comparing the GRACE derived residuals against Superconducting Gravimeter (SG) residuals, which provide long term stability, allowing an assessment of the observed time series (Hinderer, et al., 2006). This method has been proven to be effective for the validation purpose, despite the limitations related to the different nature of both data sources. Some additional remarkable studies of this problem include the work of Neumeyer, et al. (2008), Weise, et al. (2012), Crossley, et al. (2012) and Abe, et al. (2012). From these studies, it is evident that the inclusion of the Principal Component Analysis (PCA) represents a significant improvement for the comparison of the common signals present in the gravity residuals.

In this project, two additional matrix decomposition methods, namely Spatiotemporal Independent Component Analysis – stICA (Stone, et al. 2002) and Multivariate Singular Spectral Analysis – MSSA (Allen & Robertson 1996), are used to evaluate the impact of different GRACE data improvements and processing standards. More specifically, the corrections applied to the coefficient C_{20}, the coefficients of degree and order one (d/o=1), and the Glacial Isostatic Adjustment (GIA) effect. In addition, the DDK, VDK and Gaussian filtering techniques are evaluated. An important constrain for this project is the automatic pre-processing of the data, which limits the time span of the ground truth residuals corrected for local hydrology effects and instrumental drift. Nonetheless, the methods tested here proved to cope with these issues up to an extend that allows an objective evaluation of the data.

Objectives

The general objective is to perform analysis of different decomposition methods in the evaluation of various GRACE solutions on the basis of SG gravity residuals.

The specific objectives of the project are:

- Extracting and analyzing the main common signals from SG and GRACE data
- Comparing the results obtained when applying the decomposition methods of PCA, stICA and MSSA
- Evaluating the impact of the corrections when applied individually to GRACE data, considering the SG common signals as ground-truth data for validation
- Evaluating the impact of the different GRACE filtering techniques, considering the SG common signals as ground-truth data for validation
- Proposing a methodological procedure for future related projects

SG Data

A preliminary test analysis was performed with the same data used by Abe, et al. (2012), obtaining positive results for the comparison of release 4 and release 6 GRACE solutions. After that, we used IGETS Level-3 data in order to extend the length of the time series and include additional stations, with the limitation of the automatic pre-processing of this data.

Stations: Schiltach* (BF) – Bad Homburg (BH) – Conrad (CO) – Medicina (MC) – Moxa* (MO) – Onsala (OS) – Pecny (PE) – Strasbourg* (ST) – Wettzell (WE)

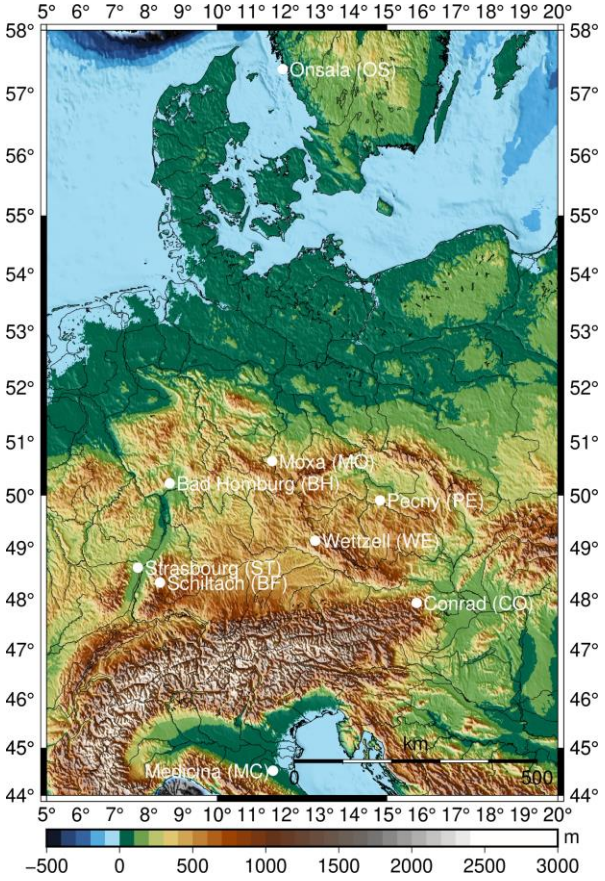
Time of interest: January 2010 to March 2017 (87 months)

Corrections in the data (Boy, et al., 2020): solid Earth tides and ocean tidal loading – atmospheric loading – polar motion and length-of-day induced gravity changes – instrumental drift

Note: The instrumental drift is not properly reduced due to the lack of updated calibration data for most of the instruments.

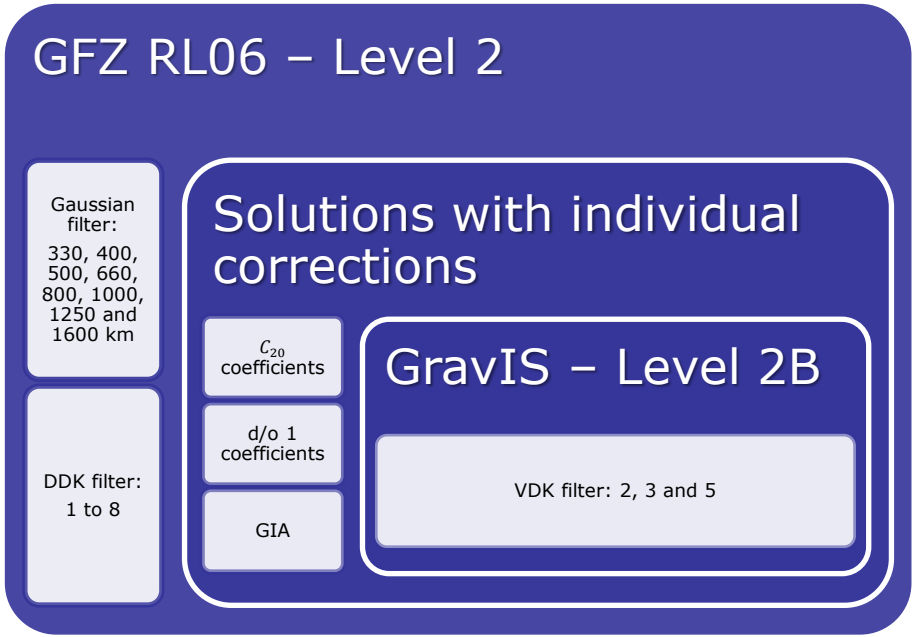
These data sets are publicly available from the IGETS database at GFZ: https://isdc.gfz-potsdam.de/igets-data-base/

* Underground stations



Location of the 9 SG stations considered for the study.

GRACE Data



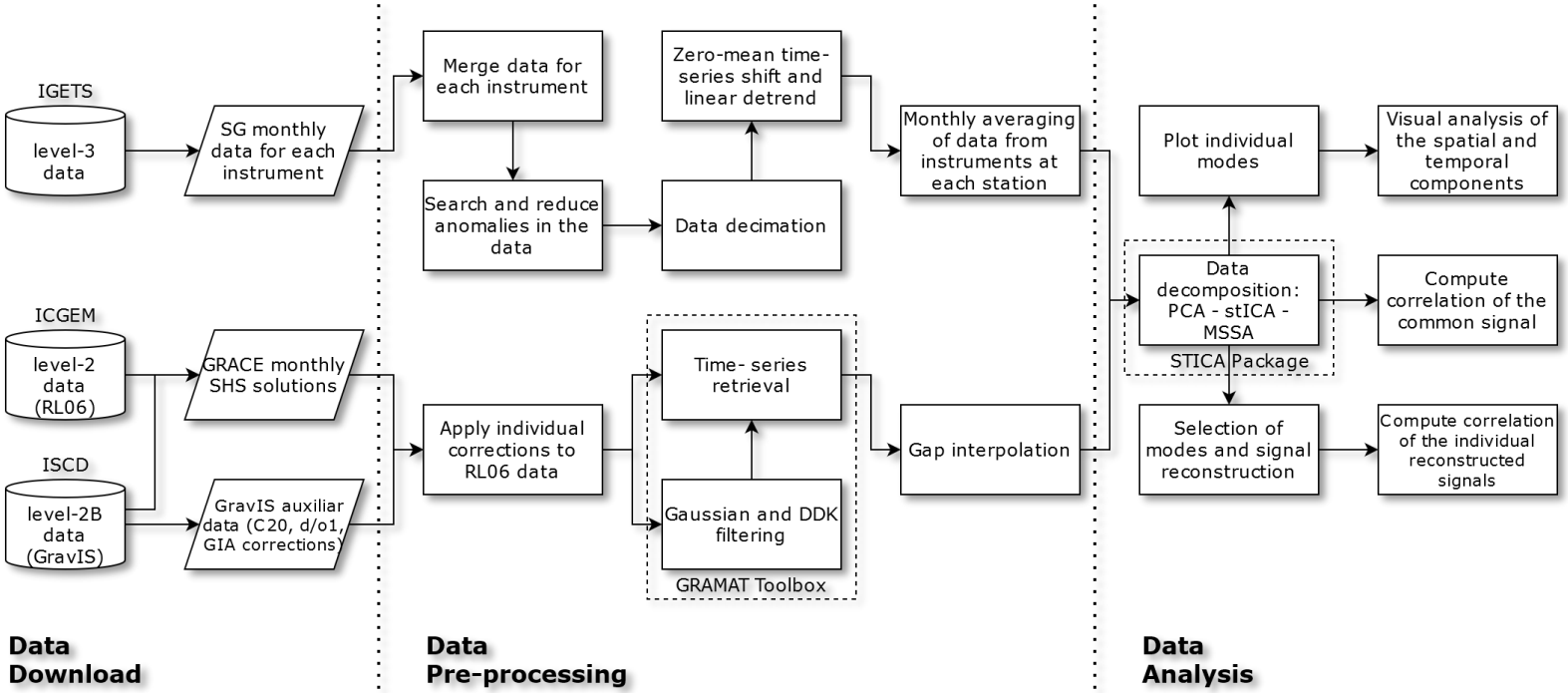
The dataset to be validated comprises the Release 06 (RL06) level-2 GRACE monthly solutions computed by GFZ and the further corrected level-2B solutions provided by GravIS. The level-2B corrections include:

- Replacing the C_{20} coefficient with the Satellite Laser Ranging (SLR) data provided by Koenig, Schreiner, & Dahle (2019)
- Replacing the degree/order 1 coefficients with the data provided by Dahle & Murböck (2019)
- Reducing the linear deformation of the solid Earth surface associated to the Glacial Isostatic Adjustment (GIA), using the model ICE-6G_D (VM5a) (Peltier et al., 2018)

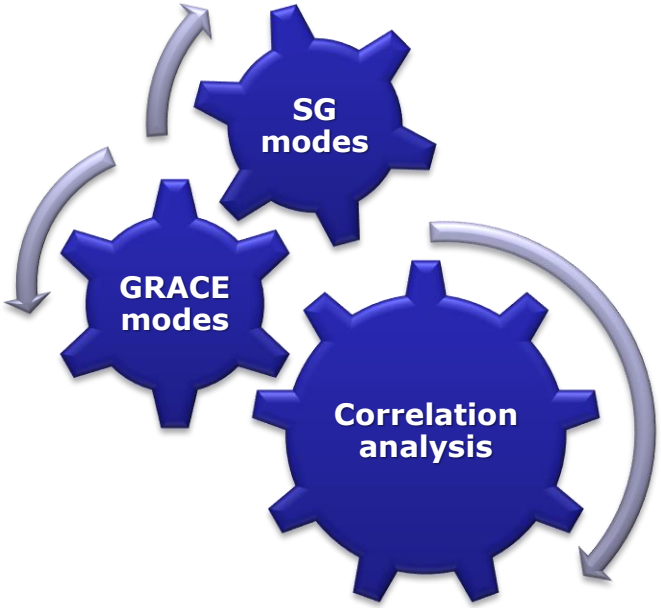
These corrections were also applied individually to RL06 data in order to assess their impact.

In the case of level-2B solutions, VDK filtered data is available in addition to DDK and Gaussian filtered solutions.

Methodology



Structure of the results



The results are presented in three individual sections for each decomposition method. Every section contains a visualization of the most important modes retrieved, as well as the correlation curves computed for the different solutions.

The following remarks are provided for an easy reading of the outcomes:

- For simplification, the modes obtained from the GRACE signal decomposition are illustrated only for the fully corrected data (GravIS), filtered with the Gaussian filter of 500 km.
- Each mode is illustrated in a three-module format: At the top of each figure, the temporal components are displayed with the signals in both time (red) and frequency (black) domains. At the bottom-left side, the spatial components are illustrated for each individual location. The bottom-right side contains a partial reconstruction of the data obtained from the components displayed.
- In the case of MSSA decomposition, the modes are displayed in pairs and the partial reconstruction is built from both pairs.
- For the correlation analysis, a specific data group is considered comparatively better if the correlation values are higher, and/or a shorter filter bandwidth is required.

Results – Principal Component Analysis (PCA)

<u>Decomposition remarks</u>

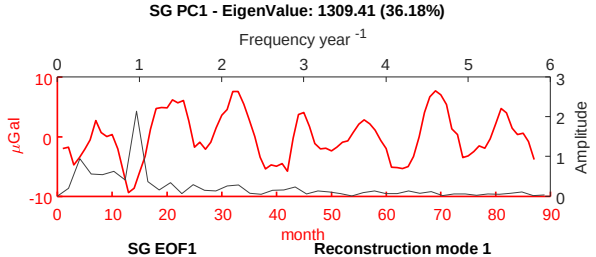
Annual signal:
- SG -> 1st mode
- GRACE -> 1st mode

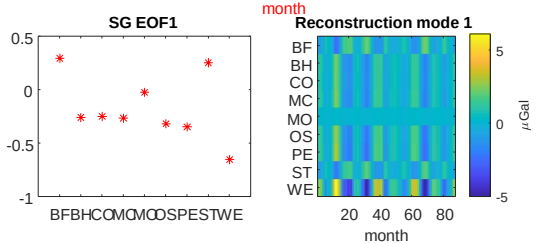
Data variability of the annual signal:
- SG -> 36%
- GRACE -> 99%

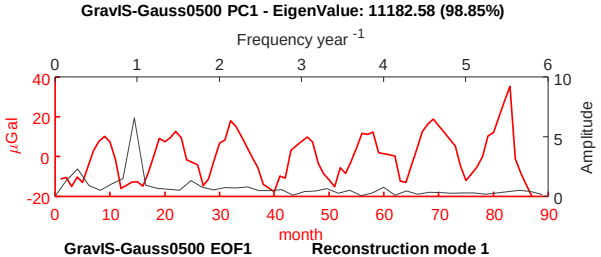
SG – Empirical Orthogonal Function: Due to local hydrology effects, the EOF presents values with opposite sign at Schiltach and Strasbourg, and it is close to zero at Moxa.

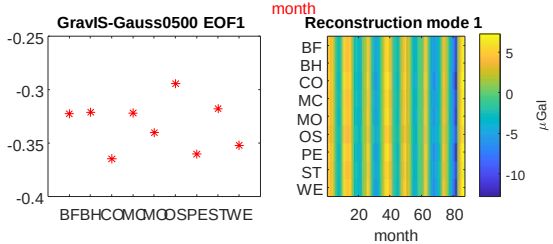
<u>Correlation analysis remarks</u>

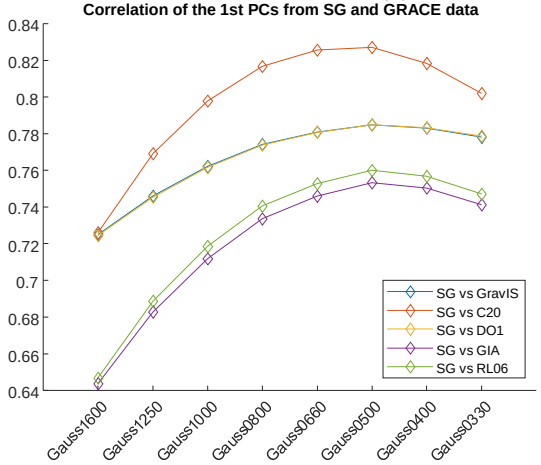
The correction of C_{20} results in the highest correlations, followed by the d/o=1 correction. In the case of GIA, the lower correlation obtained (with respect to RL06) might be a consequence of the linear detrending step applied to the SG data to avoid the influence of instrumental drift.











Top-left: 1st PCA mode and partial reconstruction computed for SG data.
Top-right: 1st PCA mode and partial reconstruction computed for fully corrected GRACE data (Gaussian filter 500 km).
Bottom: correlation curves (in function of the filter bandwidth) computed between the first PCs from SG and the GRACE solutions.

Results – Spatiotemporal Independent Component Analysis (stICA)

<u>Decomposition remarks</u>

Relative weighting used: $\alpha = 0.5$

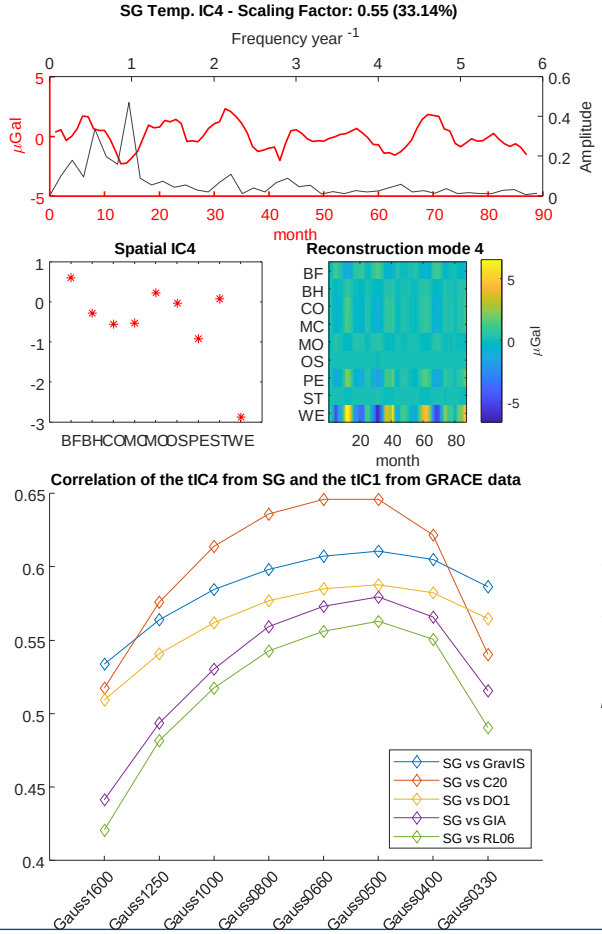
Annual signal:
- SG -> 4th mode
- GRACE -> 1st mode

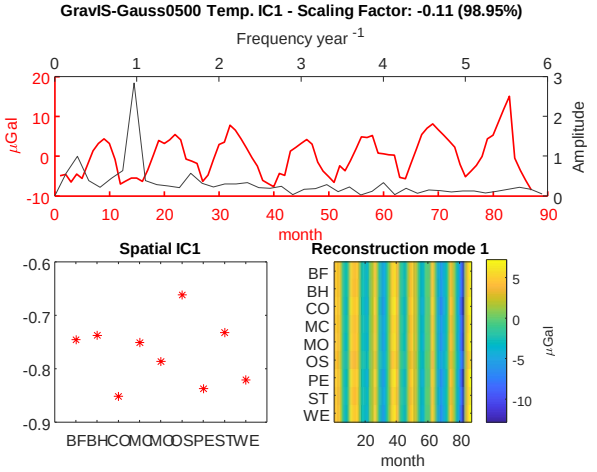
Data variability of the annual signal:
- SG -> 33%
- GRACE -> 99%

SG – temporal Independent Component: Underground stations (BF, MO, ST) present values with opposite sign, due to local hydrology effects. Onsala and Strasbourg are the locations with the shortest tIC values.

<u>Correlation analysis remarks</u>

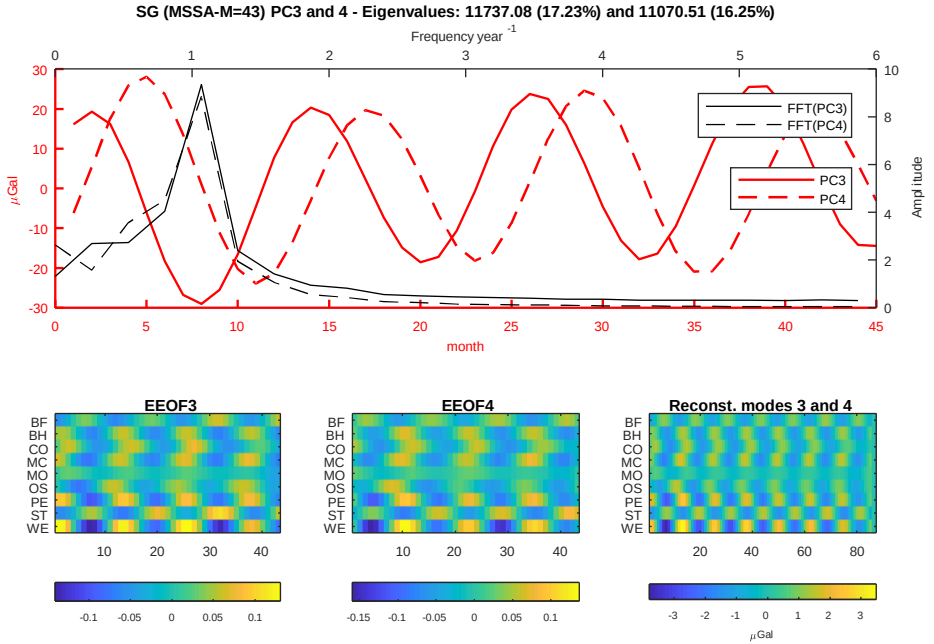
The C_{20} correction provides the highest correlations, followed by the d/o=1 and GIA. In comparison to PCA, the correlation values are in general lower, but the GIA correction shows a better performance.





Top-left: 4th stICA mode and partial reconstruction computed for SG data.
Top-right: 1st stICA mode and partial reconstruction computed for fully corrected GRACE data (Gaussian filter 500 km).
Bottom: correlation curves (in function of the filter bandwidth) computed between the temporal Independent Components (tICs) 4 and 1 from SG and the GRACE solutions, respectively.

Results – Multivariate Singular Spectral Analysis (MSSA)



Third and Fourth MSSA modes obtained from SG data, and their respective partialreconstruction.

Decomposition remarks

Lag used: 43 months

Annual signal:
- SG -> modes 3 and 4
- GRACE -> modes 1 and 2

Data variability of the annual signal:
- SG -> 34%
- GRACE -> 85%

SG – Extended Empirical Orthogonal Function: The signal at Moxa has an amplitude closer to zero, while Schiltach and Strasbourg present an anticorrelated pattern. In general, the signals tend to show phase shift differences.

The GRACE modes 1-2 (not shown here) are similar in shape to SG modes 3-4, with the difference that the EEOFs are in phase for all the stations.

Correlation analysis remarks

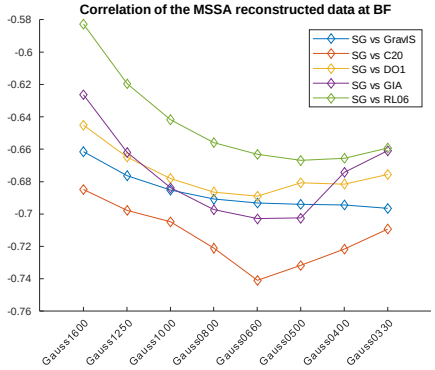
The correlation values (slides 11-12) were computed between SG data reconstructed with the modes 3 to 9, and GRACE data reconstructed with the mode pairs that add at least 95% of the variability (usually 6 to 8). The modes 1 and 2 were excluded for SG as they represent long term signals that might not contain a geophysical meaning due to the automatic pre-processing constraint.

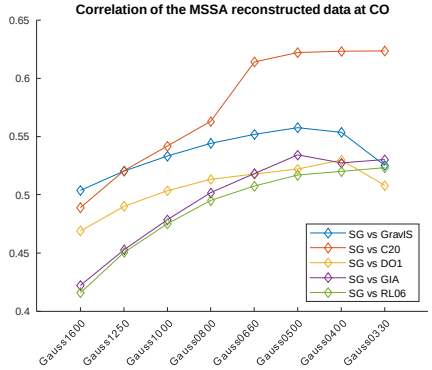
Results – Multivariate Singular Spectral Analysis (MSSA)

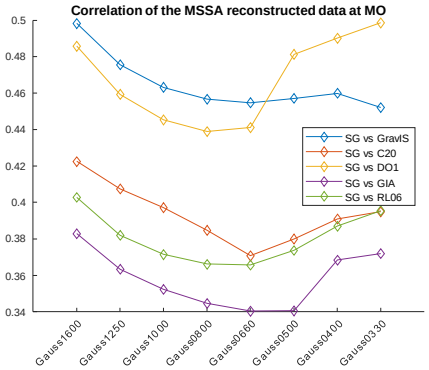
The correlations obtained for the different stations show that the correction of C_{20} is mainly representative at the stations of Schiltach, Conrad, Medicina and Wettzell, for the solutions filtered with bandwidths up to 660 km.

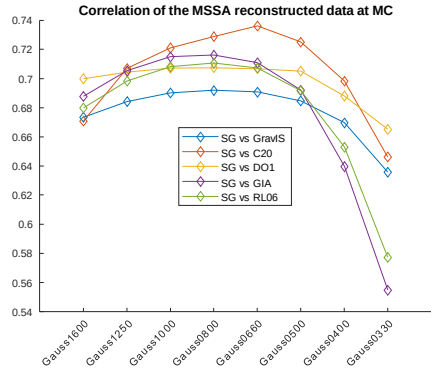
The case of Moxa is more complex to analyze considering that the correlations are lower, and the curves computed tend to follow a pattern expected for negative correlations. This behavior is a consequence of the phase-shift that the reconstructed SG signal has at this station, most likely related to local hydrology effects.

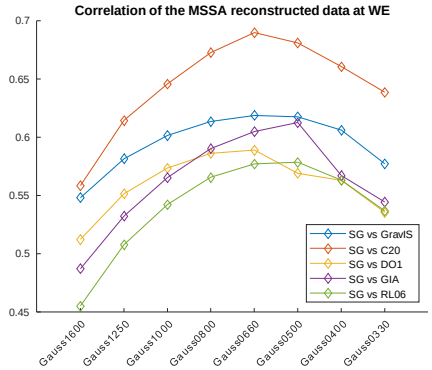
Correlation curves computed for the reconstructed signals at Schiltach (top-left), Conrad (top-right), Moxa (bottom-left), Medicina (bottom-center) and Wettzell (bottom-right).







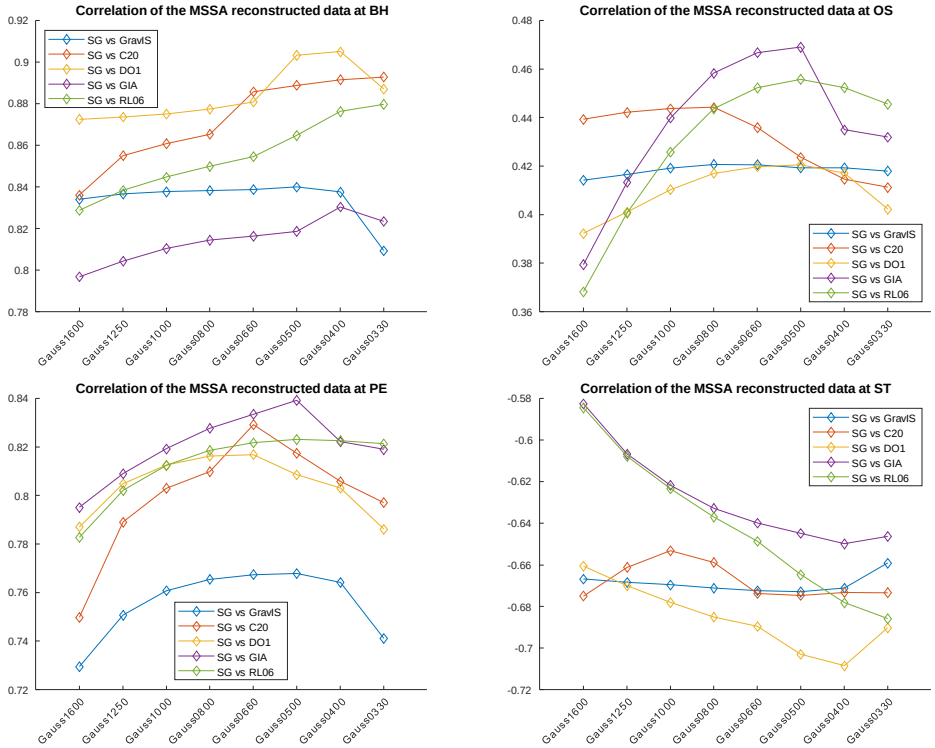




Results – Multivariate Singular Spectral Analysis (MSSA)

The d/o=1 coefficient correction shows an improvement mainly at the stations of Bad Homburg and Strasbourg, after filtering with 400 km bandwidth. Finally, the GIA correction has the greatest impact at the locations of Pecny and especially Onsala. One remarkable characteristic of this correction is that the largest correlations are found usually for solutions filtered with 500 km bandwidth, but a significant decrease in the numbers are seen for shorter bandwidths. This effect is as well visible in Schiltach and Wettzell.

Correlation curves computed for the reconstructed signals at Bad Homburg (top-left), Onsala (top-right), Pecny (bottom-left), and Strasbourg (bottom-right).



Results – GRACE filtering assessment

In a similar way to the previous analysis, the correlation values were computed between SG and GRACE data, considering in this case more filtering techniques in order to evaluate their performance with different bandwidths.

In general, the correlations obtained for the main signals extracted from PCA and stICA, as well as the (absolute valued) average correlations of the MSSA reconstructed data, show an agreement concerning the relative performance of the filters. Thus, the best performance is observed for DDK, followed by VDK and finally the Gaussian filter with the lowest values. The best bandwidths for each case are DDK1, VDK2 and Gaussian of 500 km, respectively.

Furthermore, one important difference between these filters is the range of the correlation values. Variations in the filter bandwidth for DDK cause larger correlation differences than VDK and Gaussian filters.

Filter	PC1 Corr.	tIC4-1 Corr.	MSSA Correlation Modes [95%]	MSSA Correlation mean(|r|)
unfiltered	0.1151	0.1347	9	0.2172
Gauss0800	0.7742	0.5982	6	0.6325
Gauss0660	0.7809	0.6072	6	0.6343
Gauss0500	**0.7849**	**0.6106**	6	**0.6346**
Gauss0400	0.7830	0.6049	6	0.6307
Gauss0330	0.7781	0.5865	6	0.6127
DDK1	**0.8397**	**0.6703**	8	**0.6711**
DDK2	0.8300	0.5051	8	0.6644
DDK3	0.7918	0.5880	8	0.6488
DDK4	0.7660	0.5592	8	0.6135
DDK5	0.6055	0.4531	9	0.5433
VDK2	**0.8103**	**0.6366**	6	**0.6438**
VDK3	0.7958	0.6220	6	0.6415
VDK5	0.7836	0.6022	6	0.6369

Table of correlation values computed between the main PCA and stICA modes, and the average absolute correlations obtained from the reconstructed MSSA signals, including the number of modes used.

Discussion and conclusions

- For the analysis of temporal gravity variations from GRACE and SG, publicly available IGETS Level-3 data sets were used from 9 European SG stations for the common period from January 2010 to March 2017. Despite included local hydrology, instrumental drifts and imperfect processing, these data sets show reasonable and meaningful results when their common signals are analyzed.
- For future studies, the analysis methods used in this project will be more advantageous with the addition of the new SG stations that the GFZ-Potsdam and the EOST-Strasbourg have been setting up during the last years in Germany and France. However, underground stations should be excluded from the analysis, especially if no local hydrological modelling is considered, due to the resulting anticorrelations with GRACE.
- The usage of stICA and MSSA decomposition methods proved to be valid alternatives to the traditional PCA for the SG-GRACE data comparison. Bearing in mind that the main aim of stICA is to unmix a set of signals that are similar to each other, better results are expected from its application on SG data corrected for local hydrology. On the other hand, MSSA is comparatively less sensitive to the presence of noise in the data and provides a larger set of modes with common signals, even for GRACE data. One of the most remarkable advantages of its implementation is found in the EEOFs computed, which indicate the particularities of the signals in terms of amplitude, phase and frequency.
- Regarding the improvements to the GRACE data, the correction of the C_{20} coefficient causes in general the greatest positive impact on the time-series, followed by the correction of the d/o=1 coefficients. The GIA correction is not so significant in general, but it demonstrates to be relevant for northern locations like Onsala. However, further research must be carried out to effectively evaluate the impact of this correction, considering that it is modelled as a linear trend in time and the SG data was detrended as part of the pre-processing steps.
- Concerning the filtering techniques, The DDK filter provides the best results but it also shows the largest differences between the different bandwidths. On the other hand, the VDK filter tend to present smaller variations between the different bandwidths. These two filters show higher correlations with SG data than the Gaussian filter. However, the values obtained for the filter bandwidth of 500 km are still acceptable for its application.

References

Abe, M., Kroner, C., Förste, C., Petrovic, S., Barthelmes, F., Weise, A., . . . Wziontek, H. (2012). A comparison of GRACE-derived temporal gravity variations with observations of six European superconducting gravimeters. Geophysical Journal International, 191, 545–556. doi:10.1111/j.1365-246X.2012.05641.x

Allen, M. R., & Robertson, A. W. (1996). Distinguishing modulated oscillations from coloured noise in multivariate datasets. Climate Dynamics, 12: 775–784.

Boy, J.-P., Barriot, J.-P., Förste, C., Voigt, C., & Wziontek, H. (2020). Achievements of the First 4 Years of the International Geodynamics and Earth Tide Service (IGETS) 2015–2019. International Association of Geodesy Symposia. Berlin, Heidelberg: Springer. doi:https://doi.org/10.1007/1345_2020_94

Crossley, D., Linage, C. d., Hinderer, J., & Boy, J.-P. (2012). A comparison of the gravity field over Central Europe from superconducting gravimeters, GRACE and global hydrological models, using EOF analysis. Geophysical Journal International, 189, 877-897. doi:10.1111/j.1365-246X.2012.5404.x

Dahle, C., & Murboeck, M. (2019). Post-processed GRACE/GRACE-FO Geopotential GSM Coefficients GFZ RL06 (Level-2B Product) V. 1.0. GFZ Data Services. doi:http://doi.org/10.5880/GFZ.GRAVIS_06_L2B

Hinderer, J., Andersen, O., Lemoine, F., Crossley, D., & Boy, J.-P. (2006). Seasonal changes in the European gravity field from GRACE: A comparison with superconducting gravimeters and hydrology model predictions. Journal of Geodynamics, 41, 59-68. doi:10.1016/j.jog.2005.08.037

Koenig, R., Schreiner, P., & Dahle, C. (2019). Monthly estimates of C(2,0) generated by GFZ from SLR satellites based on GFZ GRACE/GRACE-FO RL06 background models V. 1.0. GFZ Data Services. doi:https://doi.org/10.5880/GFZ.GRAVIS_06_C20_SLR

Neumeyer, J., Barthelmes, F., Kroner, C., Petrovic, S., Schmidt, R., Virtanen, H., & Wilmes, H. (2008). Analysis of gravity field variations derived from Superconducting Gravimeter recordings, the GRACE satellite and hydrological models at selected European sites. Earth Planets Space, 505-518.

Peltier, W., Argus, D., & Drummond, R. (2018). Comment on 'An Assessment of the ICE-6G_C (VM5a) Glacial Isostatic Adjustment Model' by Purcell et al. Journal of Geophysical Research: Solid Earth, 2019-2028. doi:https://doi.org/10.1002/2016JB013844

Stone, J., Porrill, J., Porter, N., & Wilkinson, I. (2002). Spatiotemporal Independent Component Analysis of Event-Related fMRI Data Using Skewed Probability Density Functions. NeuroImage, 15, 407–421.

Weise, A., Kroner, C., Abe, M., Creutzfeldt, B., Förste, C., Güntner, A., . . . Petrovic, S. (2012). Tackling mass redistribution phenomena by time-dependent GRACE- and terrestrial gravity observations. Journal of Geodynamics, 82– 91. doi:10.1016/j.jog.2011.11.003