Project work – Analysis of time variable gravity data

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The satellite gravity mission *Gravity Recovery and Climate Experiment* (GRACE) and its successor *GRACE Follow On* (GRACE-FO) provide monthly snapshots of the gravity field allowing us to study the temporal variations of the gravity field. For the first time, we know how much mass is being lost to the oceans from the polar ice caps, the usage of fossilized water in the form of groundwater extraction and the amount of ocean mass storage change have all been made possible by GRACE.

In this project, you can choose to study either total water storage changes in India, or the ice mass loss in Greenland and Antarctica. Prior to using GRACE data for any study it has to be filtered due to the heavy noise content in the dataset. In the sequel, GRACE data processing will be discussed using the `GRACE Bundle`. After which we will discuss the tasks that have to be carried out.

1 GRACE data processing

The GRACE/GRACE-FO data is disseminated as spherical harmonics like the static gravity field that was used in Lab 5. The format is called the ICGEM format. The data can be parsed using the `parse_icgem` function in `SHbundle`. An elaborate tutorial on GRACE data processing is given in the `GRACE Bundle` website. Please peruse that for further details.

Theory

The monthly changes in the gravity field is brought out by mass changes on earth caused by atmospheric and ocean circulation, tides, hydrological cycle, ice mass changes and the mass changes in the interior of the earth. The mass changes can be discerned as surface mass density changes given by

$$\Delta\sigma(\theta,\lambda,t) \;=\; \frac{a_{\mathrm{e}}\,\rho_{\mathrm{e}}}{3}\sum_{l=0}^{\infty}\frac{2l+1}{1+k_l}\sum_{m=-l}^{l}Y_{lm}(\theta,\lambda)\,\delta K_{lm}(t) \tag{1}$$

where $\Delta\sigma(\cdot)$ (kg/m^2) is the surface mass density anomaly, ρ_{E} is the average density of Earth ($5515\,\mathrm{kg}/\mathrm{m}^3$), k_l is the load Love number for the spherical harmonic degree l, $Y_{lm}(\cdot)$ are the spherical harmonic coefficients and δK_{lm} are monthly anomalies of spherical harmonics with respect to a long-term mean. The surface mass density can also be represented in terms of equivalent water height by dividing it with the density of water ρ_{w}.

$$h_{\mathrm{w}}(\theta,\lambda,t) = \frac{\Delta\sigma(\theta,\lambda,t)}{\rho_{\mathrm{w}}}\,, \tag{2}$$

The quantity allows us to study changes in mass as changes in a column of water. For ocean mass changes, the sea water density can be used and for ice mass changes the density of ice can be used.

Steps for GRACE data processing

1. Download GRAC/GRACE-FO data from ICGEM website. There are many flavours of GRACE monthly solutions. ITSG-GRACE2018 monthly solutions of maximum degree $L = 96$ are strongly recommended.

2. Parse the data set and store all the monthly files.
3. Compute a mean of the monthly fields such that integer number of years are used. For example, if you start from 2002 August, then the last data point must be July of any of the subsequent years. This will account for the strong annual signal in the dataset. Also, the years after 2011 are very noisy, so it is recommended to take a mean from 2004 January to 2010 December (seven years of data).

$$\bar{K}_{lm} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} K_{lm}(t)\,\mathrm{d}t \tag{3}$$

4. Remove the mean $\bar{K}_{lm}$ from the monthly solutions $\delta K_{lm}(t) = K_{lm}(t) - \bar{K}_{lm}$.
5. Filter the coefficients using the destriping filter, followed by a Gaussian filter or the cosine filter available in `GRACE Bundle`.

$$\delta\tilde{K}_{lm}(t) = B_l \sum_{n=m}^{L} B_{lm}^{nm}\,\delta K_{lm}(t) \tag{4}$$

   where B_l is the Gaussian or the cosine filter and B_{lm}^{nm} is the destriping filter. For further details refer `http://gracebundle.tuxfamily.org/filter-grace`.
6. Now, the filtered GRACE coefficients can be synthesised either to global grids or regional grids.

2 Spatio-temporal data analysis

The main goal of the project is to conduct spatio-temporal analysis of the GRACE/GRACE-FO data to understand how the mass variations happen on the surface of the Earth. Spatio-temporal analysis concerns about the study of change in spatial pattern of a phenomenon in time. Typical methods of spatio-temporal analysis are Principal Component Analysis (PCA) using Empirical Orthogonal Functions (EOF), and fitting every grid point with first order polynomial and an annual and semi-annual frequency sinusoid.

$$f(\theta,\lambda,t) = \bar{f}(\theta,\lambda) + \dot{f}(\theta,\lambda)\,t + \sum_{k=1}^{2} A_k(\theta,\lambda)\cos\frac{2\pi}{12}k\,t + B_k(\theta,\lambda)\sin\frac{2\pi}{12}k\,t \tag{5}$$

where $f(\cdot)$ is the spatio-temporal field with $\bar{f}(\cdot)$ being the mean of the field, $\dot{f}(\cdot)$ is the rate of change, commonly called the secular trend, $A_k(\cdot)$ and $B_k(\cdot)$ are the coefficients of the cosine and sine functions fitted to the time-series.

Sometimes instead of fitting functions to individual grid points, they are fitted to spatial average of a group of grid points. For example, spatial averages of grid points within a catchment is typically used for understanding the temporal evolution of mass changes in that catchment.

$$f_\chi(t) = \frac{1}{\mathcal{A}_\chi} \int_\chi f(\theta,\lambda,t)\,\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\lambda \tag{6}$$

where χ is the catchment index and $\mathcal{A}_\chi$ is the area of the catchment. The integration is in fact an area-weighted average, where the area weights are provided by $\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\lambda$ and the sum of the infinitessimal area over the catchment χ is the area of the catchment $\mathcal{A}_\chi$.

3 Project work

For the project, the following three themes are proposed for spatio-temporal analysis:

1. Greenland ice mass loss
2. Antarctic ice mass loss
3. State of the water storage in India

Choose one of the themes, the area masks of these regions are available in the data folder of the `GRACE Bundle` package as `ctchmntindx3.mat`. It is expected that you will explore the spatio-temporal analysis techniques to understand ice mass loss or total water storage evolution. Wahr, Molenaar, and Bryan (1998) is the fundamental article on the theory of GRACE data processing, Wouters et al. (2014) provides an overview of what can be done with GRACE data, Sneeuw et al. (2014) describes the application of GRACE for hydrology, B. Wouters, Chambers, and Schrama (2008) describes the application of GRACE for Greenland ice mass loss and Chen et al. (2006) describes the analysis of GRACE data for understanding the mass loss of Antarctica.

Bonus In order to do a precise analysis of GRACE data, you will have to replace C_{20} and C_{30} in GRACE using estimates from SLR. The polar areas are affected by the glacial isostatic adjustment (GIA), and therefore, ice mass loss estimates must be corrected for GIA effects. Applying these corrections will fetch a bonus.

4 Technical report and software documentation

As per the protocol, you will need to submit a short report (maximum 5 pages including graphs and figures), software written as a toolbox and its documentation. The report must be structured as follows: abstract, introduction, mathemtical details, methods, results, discussion and conclusion. Use the manuscript submission format of International Association of Geodesy Symposia given at `https://www.springer.com/series/1345`. Your project will be evaluated for ease of use of the software, the clarity of your documentation and the scientific quality of your report. All results should be reproducible, and therefore, please submit your code that you used for creating your figures, tables and other results. Otherwise, the results will be considered plagiarised. Plagiarism of any form will be dealt with severely. Since it is a project work, you are also expected to do some literature review and study about the project topic at your end.

References

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