Chapter 6
Comparison of Daily GRACE Solutions to GPS Station Height Movements

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Abstract In Kurtenbach (2011) and Kurtenbach et al. (2012) an approach has been introduced that allows to calculate daily gravity field solutions from GRACE data within the framework of a Kalman filter and smoother estimation. The method utilizes spatial and temporal correlations of the expected gravity field signal derived from geophysical models in addition to the daily observations, thus effectively constraining the spatial and temporal evolution of the GRACE solution. Here, we offer an extended validation of these daily solutions by comparing the derived mass variations to vertical displacements at various permanent GPS stations. The comparison confirms the conclusion that the daily solutions contain significant high-frequent temporal gravity field information, especially in higher latitudes.

6.1 Introduction: The GRACE Kalman Filter Approach

The standard analysis approach for GRACE data aims at the calculation of monthly (Watkins and Yuan 2007; Bettadpur 2007; Flechtner et al. 2010), 10-day (Bruinsma et al. 2010) or weekly (Flechtner et al. 2010) gravity field solutions. A temporal evolution of the mass variations, however, also occurs on much shorter time scales. It is therefore our goal to increase the temporal resolution of GRACE in order to determine these fast changes, which are for example present in atmospheric or barotropic

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ocean variations. Since the data coverage provided by GRACE is not sufficient to allow for a recovery of gravity field snapshots on a day-to-day basis, the introduction of stochastic prior information from geophysical models as described in Kurtenbach et al. (2012) has to be used to stabilize the solutions.

The Kalman filter combines this prior information and the daily GRACE observations in a joint estimation process and delivers an updated state of the gravity field for each day. Stochastic information is introduced in terms of the process model which formulates a prediction of the current state resulting from the state of the previous time step. The process model is constructed from spatial and temporal covariance matrices derived from the output of the geophysical models. The daily solutions described by the present paper are part of the GRACE gravity field model ITG-Grace2010 (Mayer-Gürr et al. 2010) and can be downloaded at http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010. For details of the method, a comparison to other constraint approaches, and some first validation results, please refer to Kurtenbach (2011) and Kurtenbach et al. (2012). In the following, the results will be evaluated more thoroughly by comparison to a larger number of vertical GPS station movements.

6.2 Validation of Daily Solutions

In order to evaluate the temporal high frequency information content of the daily GRACE models, they have to be compared to independent data sets. Mass variations at the Earth's surface result in geometrical deformations of the Earth's crust which can be measured by GPS receivers. Therefore, the global network of permanent GPS stations provides a set of independent observations which can be used for comparing with GRACE gravity field models. Vertical station displacements of the reprocessed time series of the International GPS Service (IGS), see Steigenberger et al. (2006), were compared on a daily basis to the GRACE Kalman solutions after transforming them to vertical loading using the load Love numbers of Gegout (2005). For a detailed description of the method for comparing GRACE and GPS, including the treatment of the degree 1 coefficients, see Tesmer et al. (2011).

Figure 6.1 shows the time series for four exemplary GPS stations. The in-situ GPS observations are plotted in the black curve, the GRACE time series is given by the red curve. As a comparison vertical loading as computed from the de-aliasing product (AOD1B RL04, blue line) used in the GRACE L1B data analysis (Flechtner 2007) is displayed by the green line. The AOD1B RL04 product represents our knowledge of global temporally high-frequent mass variations before the calculation of daily GRACE solutions. The left part of each figure shows the time span 2003–2007, while the right part presents a zoom-in on the year 2004. The top three images Fig. 6.1a–c reveal a better agreement between the daily GRACE solutions and the independent GPS observations than between GPS and AOD1B RL04. This implies that, here, significant gravity field information has been recovered that is not present in the AOD1B RL04. The three stations are located in the mid to high latitude region where

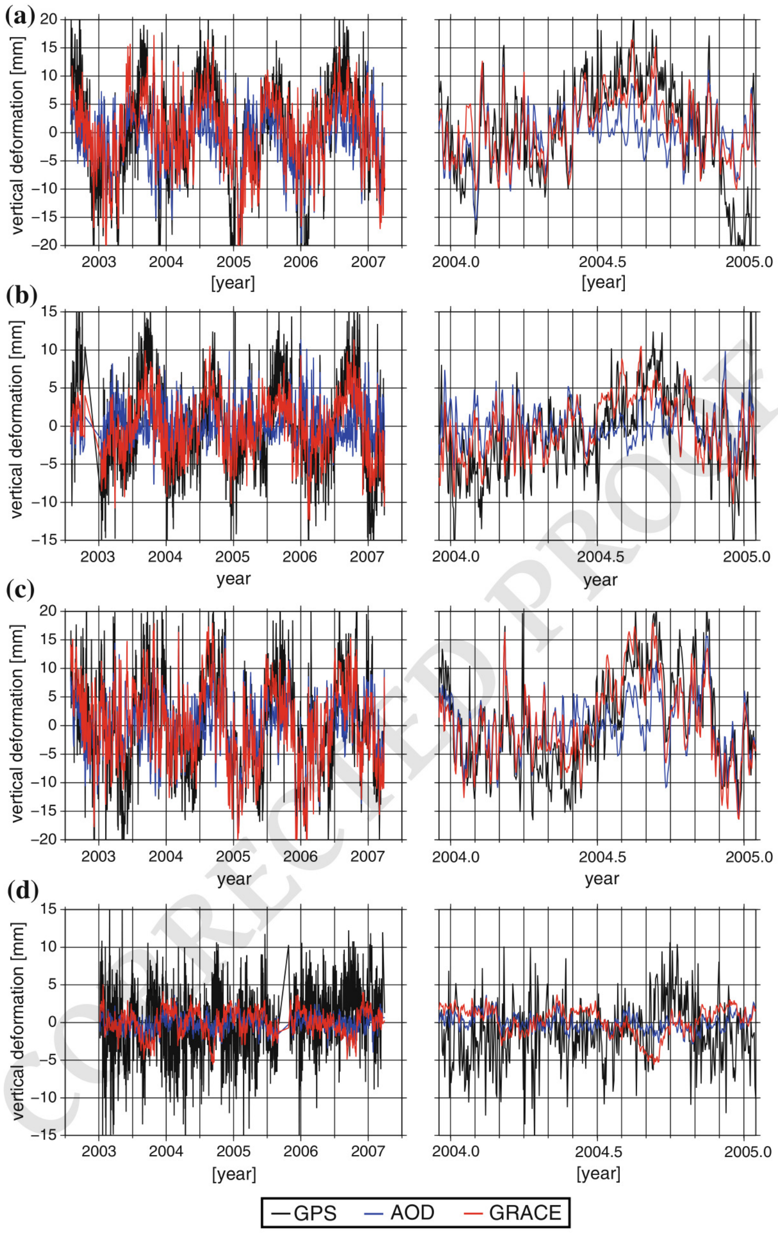

Fig. 6.1 Time series of observed vertical GPS station movements (*black*) compared to ITG-Grace daily solutions (*red*) and the AOD1B RL04 dealiasing product (*blue*). *Left* complete time series. *Right* zoom-in for one year. **a** ARTU—Arti (Russia)—$\lambda = 58.6^\circ$, $\varphi = 56.4^\circ$, **b** NANO—Nanoose Bay (Canada)—$\lambda = 235.9^\circ$, $\varphi = 49.3^\circ$, **c** NRIL—Norilsk (Russia)—$\lambda = 88.4^\circ$, $\varphi = 69.4^\circ$, **d** GLPS—Puerto Ayora (Galapagos Islands)—$\lambda = 269.7^\circ$, $\varphi = -0.7^\circ$

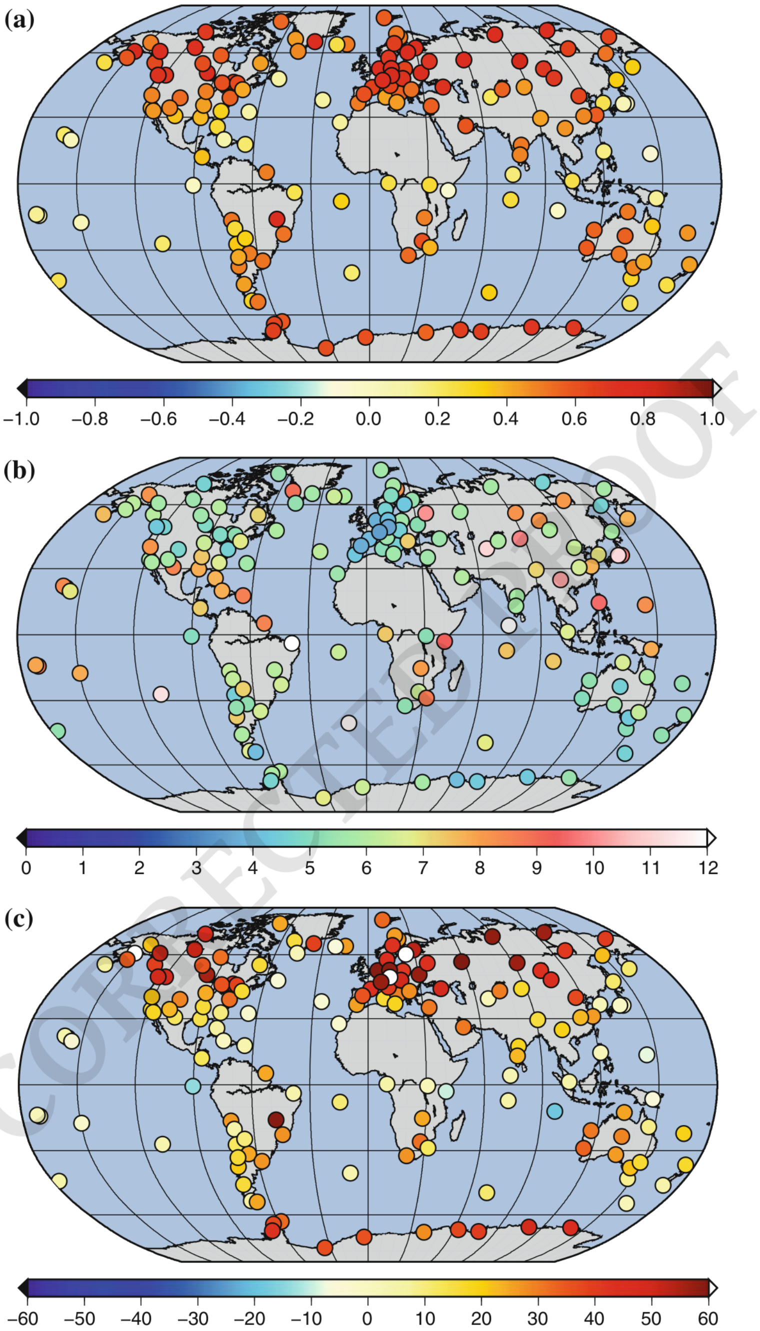

Fig. 6.2 Quality measures for the correspondence of daily GRACE solutions with global GPS station displacements. (**a**) correlation coefficient, (**b**) error RMS, (**c**) signal reduction

the GRACE data coverage is dense due to the orbit geometry and the high-frequent temporal signal is strong due to large atmospheric mass variations. Figure 6.1d displays the vertical motion of a station near the equator, where the data coverage is less dense and the mass signal exhibits a lower amplitude. The evaluation of the curves leads us to the conclusion that at this station no significant gain in information can be obtained from GRACE. The differences between GPS and GRACE, however, cannot only be addressed to errors in the gravity field determination, as it is known (see for example van Dam et al. 2007) that the quality of GPS time series is quite inhomogeneous; i.e. other signals (e.g. troposphere, station movements, antenna effects) may be affecting the comparison.

Figure 6.2 shows different accuracy measures for all the compared global GPS stations. Figure 6.2a illustrates the correlation coefficient between GRACE and GPS. As expected, a high correlation can be found in the higher latitudes, whereas the correlation along the equator is low. Obviously, the correlation is in particular low at stations located on islands in the Atlantic and Pacific ocean. This can be attributed to the fact that the ocean reacts to atmospheric mass changes by the inverse barometer effect and therefore mass variations at island stations are particularly small, as is also the case for the station GLPS in Fig. 6.1d. As second quality measure, Fig. 6.2 displays the error RMS between the GPS and GRACE time series for each station, i.e. representing the mean squared differences between the two time series. Again it can be observed that the errors are smaller in higher latitudes with values around 4–6 mm, whereas in the lower latitudes values up to 12 mm can be reached. As the correlation coefficient is only sensitive to phase shifts and the error RMS depends strongly on the magnitude of the signal, a third quality measure is introduced in Fig. 6.2c. The signal reduction represents the percentage of the signal of each at the stations that can be explained by the GRACE observations. It can be interpreted as the ratio between error RMS and signal RMS. Again the conclusion is confirmed that especially in the higher latitude regions a large part of the temporally high-frequent gravity field signal can be explained by the daily GRACE solutions.

6.3 Conclusions and Outlook

We note that the gravity field variations observed independently by GRACE and GPS show a good agreement for a large part of the global IGS stations. This allows the conclusion that the GRACE Kalman filter approach is able to recover temporally high-frequent gravity field variations. These variations can be considered as an improved de-aliasing product. The improvement can be attributed to two effects which cannot easily be separated: First of all the daily GRACE solutions represent, beside the atmospheric and oceanic variations contained in the AOD1B RL04 product, also high-frequent hydrological mass changes. Furthermore, they also account for model errors in the atmosphere and ocean models, as was independently proven by Bonin and Chambers (2011).

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