EGSIEM
European Gravity Service for Improved Emergency Management

HORIZON 2020

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Research and Innovation action

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Deliverable 5.4
REGIONAL SOLUTION PRODUCT REPORT

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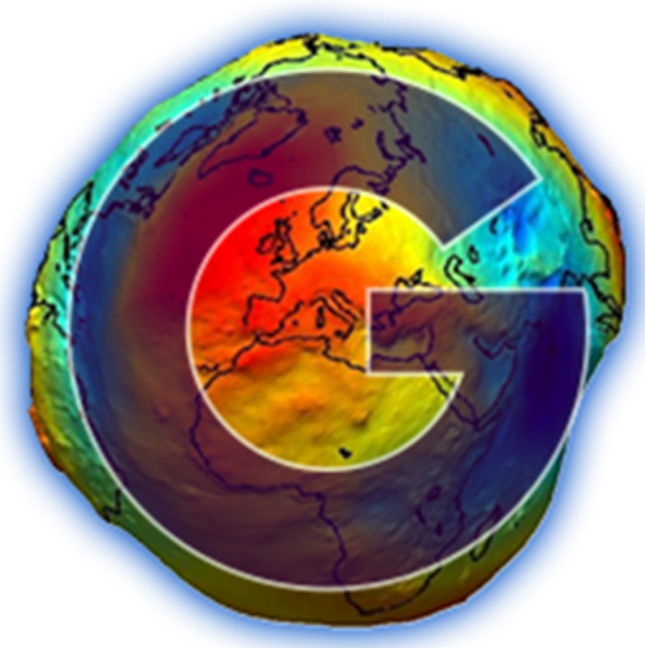

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1. Terms

This document provides the product report of the Regional Gravity Service of EGSIEM (Work Package 5). The contents describe the data product which will be delivered to the Hydrological Service (Work Package 6) and the measures undertaken to ensure reliability and integrity during the operational service run.

2. Regional Service Overview

Background

The nominal time delay of the standard GRACE Science Data System (SDS) Level-1B (L1B) instrument data is 11 days and of derived Level-2 (L2) gravity field products up to 60 days. Therefore, monitoring of hydrological extremes such as floods and droughts currently covers only the ‘confirmation after occurrence’ of an event and estimation of the severity after the event. In order to improve e.g. SAR acquisition planning the latency of GRACE Level-2 products is therefore planned to be drastically reduced.

Objectives

One of the main objectives of EGSIEM is to establish a **N**ear-**R**eal-**T**ime (NRT) and Regional Service that aims a) to reduce the time delay of necessary input data and derived output gravity models to less than 5 days, b) to increase the time resolution of gravity models to just one day and c) to improve their quality by transferring the accuracy level of the monthly fields to the daily ones. This can be done by adequate regularization and constraining of solutions in terms of Bayesian estimation and Kalman filtering on a global scale and by using dedicated space-localizing radial base functions for applications on a regional scale.

By the evaluation of daily batches in a Kalman filter the temporal resolution can be optimally addressed but the spatial resolution on a global scale is limited, due to the sample density of the data and the sparsity of adjacent ground tracks from satellite fly-over events. In order **to enhance the spatial resolution,** it is thus necessary to increase the sampling period, thereby reducing the frequency for the evaluation intervals. During nominal satellite operations, i.e. off periodically occurring repeat cycle orbits, any given location should be re-sampled after 4-5 days. Then an additional solution can be provided that yields a time-average of 5 days in a higher spatial resolution. This will be addressed in the regional service product for defined areas of interest.

The additional product along-side the NRT service (D5.2) will be used to observe and monitor European (and global) water resources and ensures wide access to high level, easy to use products.

For this GFZ will develop indicators (within WP6) as a measure of catchment wetness from gravity-based water storage anomalies and will evaluate their performance for forecasting hydrological extreme events. This evaluation is expected to provide information on the added value of these gravity-based indicators for flood forecasting in terms of accuracy, lead time and skill. The results will be used to provide input to T6.3.

‘Off-line’ performance tests, i.e. post-processing of available data shall be developed based on historical hydrological extreme events (T3.9) covering the GRACE mission period. In the final phase of the project an operational test run, simulating 'real-time' conditions of the service has been performed in cooperation with DLR/ZKI for up to half a year.

Regional Service Timeline

NRT and Regional software and output products were developed based on individual approaches at GFZ and TUG within M04-M27. The concepts and strategies were refined and improved during this implementation phase which led to minor adaptions to the NRT processing strategy as defined in deliverable D5.1.

Milestones, Documents & Reports to be provided by the Service

Deliverable D5.4 was postponed by 6 months due to the severe conditions of the GRACE satellite system (battery problems and related instrument switch-offs).

Table 1: Deliverables and Milestones for WP5.

	Item Name	**Date**
D5.1	Concept of NRT Service	M03
MS2	Implementation and Preparation Review	M10
MS3	Service Readiness	M18
D5.2	NRT Service Product Report	M27
D5.4	Regional Solution Product Report	**M33**
MS4	Operational NRT Service Readiness	M27
D5.3	Operational NRT Service Product Report	M33
D5.5	NRT Validation Report	M36
MS5	Final Review	M36

Document overview

In chapter 4 of this document, the data product provided to the Hydrological Service and quality assurance measures is described. In chapter 5 and 6 the work undertaken during the implementation phase of the NRT and regional service is outlined for TUG and GFZ respectively. The document is completed by a summary, references, and a glossary.

3. Regional Service Product

The main output of the NRT service are two independent estimates of water storage anomalies given in center of figure frame and corrected for global isostatic adjustment (GIA), computed at GFZ and TUG respectively. The data is provided to the Hydrological Service through well-defined grid files which in addition to the estimated solution contain metadata that describe the GRACE contribution to and overall quality of the solution. Data exchange is realized through FTP server infrastructure at GFZ and University of Bern.

3.1 Regional Processing at TUG

3.1.1 Method Description

The representation of the gravity field with space localizing basis functions (RBF) at TUG is based on the approach developed by Eicker (2008). The following paragraphs will give a short summary of the approach and its relation to the spherical harmonic parametrization.

The basis functions used to represent the gravity field are radially symmetric splines which are distributed on a sphere following a (generally uniform) grid and can be expressed by

$$s(\boldsymbol{r_i},\boldsymbol{r}) = \sum_{n=2}^{N} \sqrt{2n+1}k_n P_n(\boldsymbol{r}\cdot\boldsymbol{r}_i). \tag{1}$$

Here, r_i is the nodal point of the basis function, k_n are the kernel coefficients which determine the shape of the function and P_n is the Legendre polynomial of degree n. The inner product $\boldsymbol{r}\cdot\boldsymbol{r}_i$ represents the spherical distance between nodal and evaluation point. Earth's gravitational potential in terms of spline functions can be represented as follows,

$$V(\boldsymbol{r}) = \sum_{i=1}^{I} a_i s(\boldsymbol{r}_i,\boldsymbol{r}). \tag{2}$$

In equation (2) a_i are the unknown scaling coefficients which are to be estimated. A useful property of the spherical splines is that these coefficients can be transformed into spherical harmonic coefficients using the linear relation

$$c_{nm} = \sum_{i=1}^{I} a_i k_n Y_{nm}(\boldsymbol{r}_i), \tag{3}$$

where Y_{nm} is the surface spherical harmonic of degree n and order m, evaluated at the nodal points r_i.

3.1.2 Implementation and computational results

To evaluate a possible performance gain by using space localizing basis function historical GRACE data was reprocessed and compared to a spherical harmonic solution which serves as reference. The kernel coefficients k_n were determined by fitting an isotropic noise model to the empirical auto-covariance of the process model. A triangle-vertex grid of order 11 was used for the nodal points of the splines. This resulted in a gravity parameter count of 1442, compared to 1677 when expanding the potential in a spherical harmonic series up to degree and order 40. Three years of GRACE data from 2005 to 2007 were processed by applying the Kalman smoother to the computed RBF normal equations.

Looking at individual river basins, both solutions perform similarly.

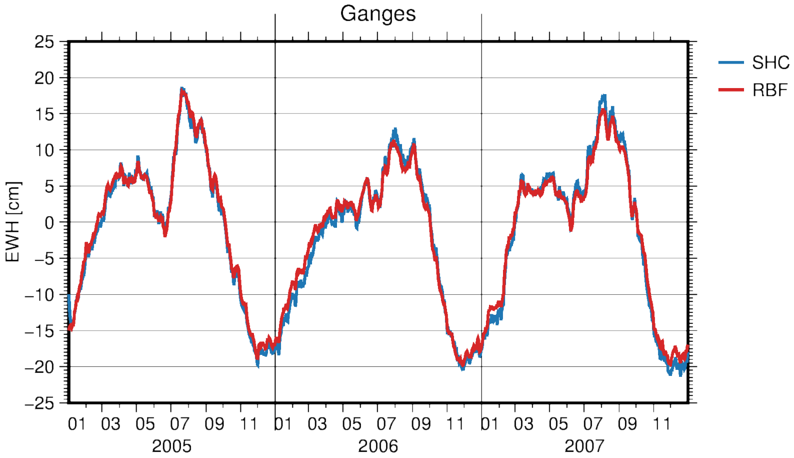


Figure 1: Area mean time series of the Ganges basin (annual/secular signals removed).

Figures 1 and 2 show an example area mean time series for the Ganges (annual and secular signals removed) and the corresponding power spectral density. As can be seen, both representations yield similar results. The power spectral density reveals that the radial basis function solution seems to be less noisy than the reference spherical harmonic solution. This might however be more attributed to the lower parameter count in the RBF solution (approximately 10% lower parameter count), rather than the different representations.

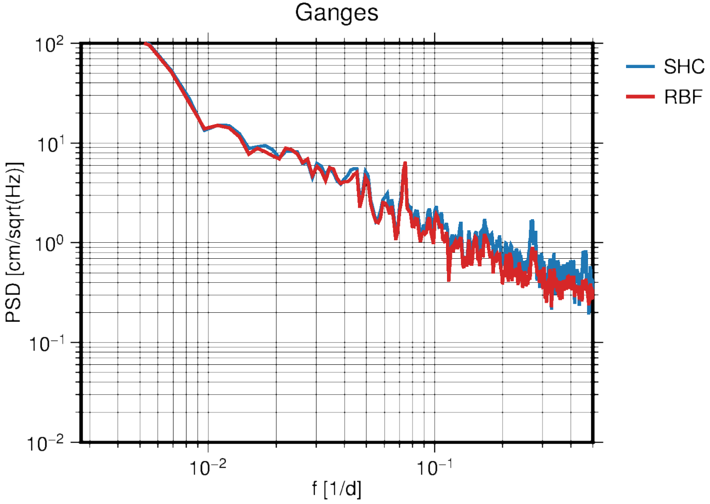


Figure 2: Power spectral density of the Ganges basin area mean time series.

In conclusion, the parametrization of the gravity field in space domain as opposed to the spherical harmonic domain does not offer improvements when considering global gravity field solutions.

Tailored RBF Kernels

An extension to the experiment outlined above was conducted by tailoring the kernel functions to the expected signal in different spatial domains. Specifically, different kernel shapes (c.f. figure 3) and spatial resolutions were introduced for oceans and continents. Looking at the expected signal covariance derived empirically from WGHM and AOD1B RL05 GAD, one can observe that for the ocean a smoother signal can be expected compared to land.

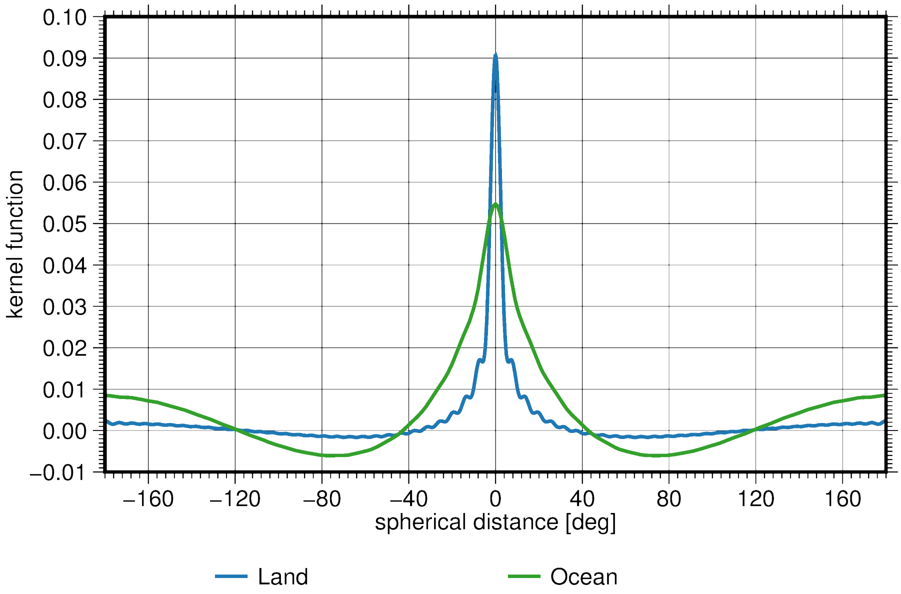


Figure 3: Expected signal covariance expressed as kernel functions (cross section).

This led to a representation of the gravity field with wider kernel functions for oceans based on the expected signal covariance up to degree 30 and continental hydrology up to degree 60, both on Reuter grids which reflect the corresponding spatial resolution. Since the coverage of the comparably sparse ocean grid exceeds the continental area with a ratio of 3:1, the overall parameter count of approximately 1800 is only slightly higher than a global representation in spherical harmonics up to degree and order 40. Using this representation, one year of GRACE data was processed and five day moving solutions were estimated. The results were filtered with a 350km Gaussian filter and compared in terms of global temporal RMS.

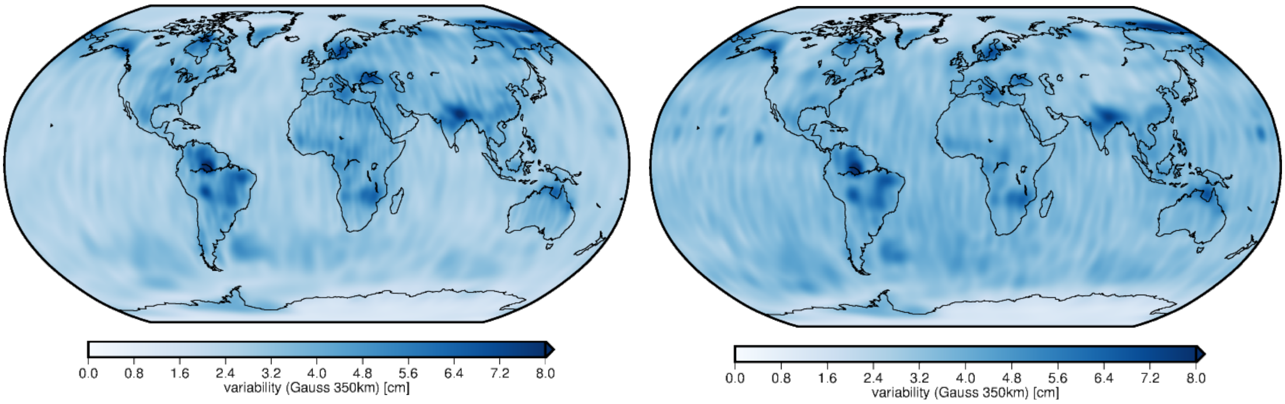


Fig 4: Temporal variability of RBF solutions (left) and spherical harmonic solution (right) in equivalent water height (350km Gauss filter applied).

As can be seen in Figure 4 , the temporal RMS over the oceans is high in the spherical harmonic solution. This can be attributed to the fact that the truncation of the kernel shape at degree 30 acts as a low pass filter. Similarly, on the continents the RBF solution allows for higher spatial resolution due to the denser spacing of the basis functions. The increased noise which this induces can be appropriately treated with regularization or incorporation into the Kalman filter. Given that RBFs and spherical harmonic coefficients can be converted into one another, the solutions are very similar up to degree and order 30.

To capture the same signal content with spherical harmonics, the full spectrum up to degree and order 60 would have to be estimated. Similarly, for possible constraints on the parameters, the global carrier of the spherical harmonics requires dense regularization matrices despite geographically independent domains. It is however important to note that because a linear relation between RBF and spherical harmonics exist, analytically identical solutions can be computed. Therefore, from a practical point of view give the possibility of tailoring the parametrization of the gravity field to different spatial domains. For the problem at hand, these gains are rather small due to the moderate size of the normal equations and the comparably slow computation of the kernel function when assembling observation equations.

Regionally Adapted Regularization

As mentioned in the previous section, the representation of the gravity field in terms of radial basis functions makes the construction of tailored constraints easier, since the matrices involved are usually sparse or even diagonal. This means that individual constraints can be applied to geographically separate areas or geophysical subsystems such as land/ocean or (large) river basins. While the geographical location and extent of these regions is assumed to be known, no information about the expected signal magnitude will be introduced. Rather the level of constraint will be determined within the gravity field adjustment process by variance component estimation. For this experiment the gravity will be represented in time as a five day moving window solution with the central epoch as reference. The spatial representation will be split into a global part in spherical harmonics up to degree and order 40 and a regional augmentation to represent small scale features represented by RBF in a frequency band from degree 41 to 60. The time series are evaluated by point wise evaluation with discharge measurements. The assumption here is that a higher spatial resolution should reflect in higher dynamics of the time series.

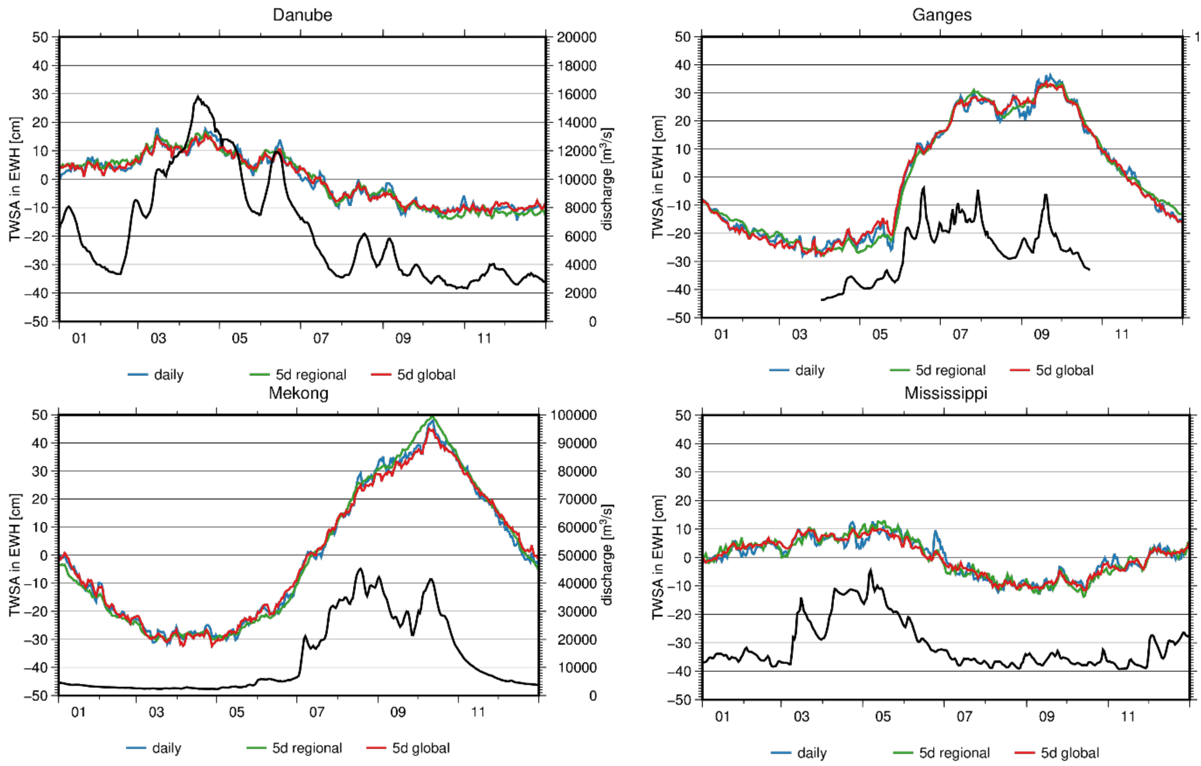


Figure 5: Comparison of daily Kalman filtered and five day moving solutions with uniform global and regional regularization.

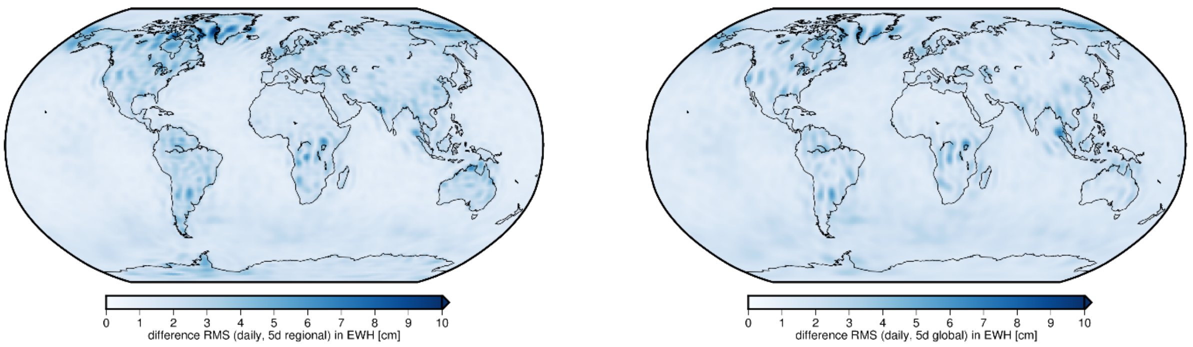


Figure 6: Difference RMS between daily Kalman and five day moving solution with regionally adapted (left, 1.98cm globally) and uniform global regularization (right, 1.88cm globally).

As can be seen in 5 and 6, the differences between the three tested solutions are small (below 2cm equivalent water height RMS globally). The decrease in temporal resolution which comes form stacking the normal equations of five days seems therefore counterproductive, since the Kalman filtered solution exhibits a more dynamical behavior during events with sharply increasing river discharge, without major loss of spatial resolution. The moving five day solutions are however a useful tool in evaluating the temporal behavior of the Kalman solutions, since solutions which are separated five days are fully independent and no prior information in terms of expected signal magnitude is introduced. This has been exploited during the operational service run for calibration parameter tuning.

3.2 Regional Processing at GFZ

3.2.1 Method Description

For the purpose of additional independent estimates in regional applications, the quasi-compact global integration by means of spherical radial basis functions is reduced into local areas, thereby taking into account, that lateral (so called “FAR” zone) attractions need to be reduced beforehand. For this purpose the GFZ (NRT) daily gravity field solutions (see D5.2) are used as quasi background information for the reduction of the lateral impact on the selected data that will be used in the regional refinement for specific regions of interest. The satellite data under further consideration is confined to only those samples which do not exceed the area of interest by a spherical cap size < 10 arc degrees. Any ‘lateral’ contribution of these samples to the refined solution (the “NEAR” zone) is thus neglected and should be contained in the FAR zone. The observation data are then accumulated during subsequent fly-over events, as well as the computation of corresponding observation equations. Next the spherical basis functions are integrated inside the region of interest (the “NEAR” zone) into a basin-specific parameter and the inversion is carried out free of numerical regularization or filtering. This means, that every 4-5 days an independent value for the basin can be computed. The mean of the reduced time-variable background in the specific basin is later restored, in analogy to the daily Kalman solutions.

3.2.2 Required Input Data and Acquisition Strategy

For the regional product the same data products and latencies apply as outlined in D5.2, Table 2.

The data acquisition is based on daily (except for the differential code bias files) download jobs, which are triggered based on the nominal latency of the individual data products. Each download job is repeated until the files have been downloaded successfully or a deadline is reached.

Table 2: Update intervals and projected latencies for the required NRT input data.

Data group	Data product	Provider	Update Interval	Latency
GNSS	Orbits Clocks Differential Code Bias Transmitter Antenna Definitions	CODE CODE CODE IGS	Daily Daily Monthly Daily	17h 17h 4d 17h
GRACE	L1B Q/L	JPL/GFZ	Daily	18h
Background models	AOD1B RL06	GFZ	Daily	10h
Earth Orientation	IERS Rapid EOP	IERS	Daily	17h

3.3 Processing details

The Kalman filtered solutions at GFZ are derived from a differential acceleration approach and surface integral equations are used to map the gravitational signal from the satellites to ground level. The Kalman processing strategy has been outlined in D5.2, Fig 4-9.

The observation error covariances for the regional solutions are isotropically modeled in a matrix $Q_V = E\{v,v\}$ that becomes available after the NRT Kalman filtering. No additional signal covariances have been anticipated for the regional solutions, neither from the results of the Kalman filtering nor from external data sources such as the atmosphere and ocean de-aliasing products (AOD1B) and the continental hydrology (WGHM) in order to refine spatial correlations.

The unconstraint regional solution estimates can then be obtained by the solutions of a linear equation system in which the daily contributions (n=1:4) are being superimposed:

$$\text{[illegible]} = [\, H^T_{n=1:4}\, Q_V\, H_{n=1:4}\,]^{-1}\, [H_{n=1:4}{}^T\, Q_V\ \text{[illegible]bs[illegible]}_{n=1:4}\,\text{[illegible]}$$

With the corresponding error covariance estimate

$$\text{[illegible]} = [\, H^T_{n=1:4}\, Q_V\, H_{n=1:4}\,]^{-1}$$

In Fig. 7, re-use of the daily output for the purpose of a refined output after 4-5 accumulated days is outlined.

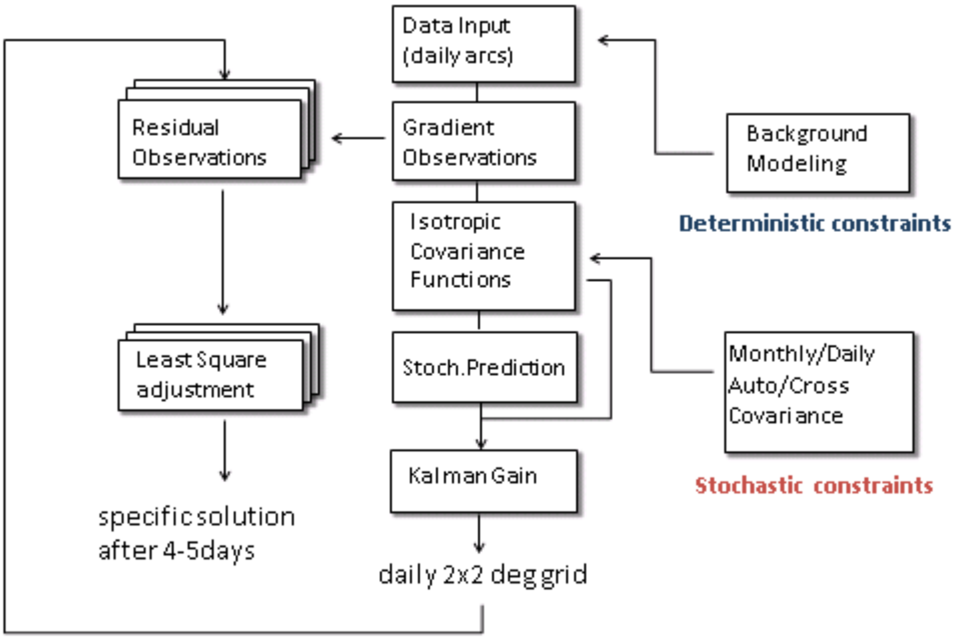


Figure 7: GFZ processing loop for an enhanced solution in defined basins.

3.4 Data scheduling and retrieval

In addition to the daily product output, for selected basins an accumulation stream is realized that leads to enhanced products every 4-5 days.

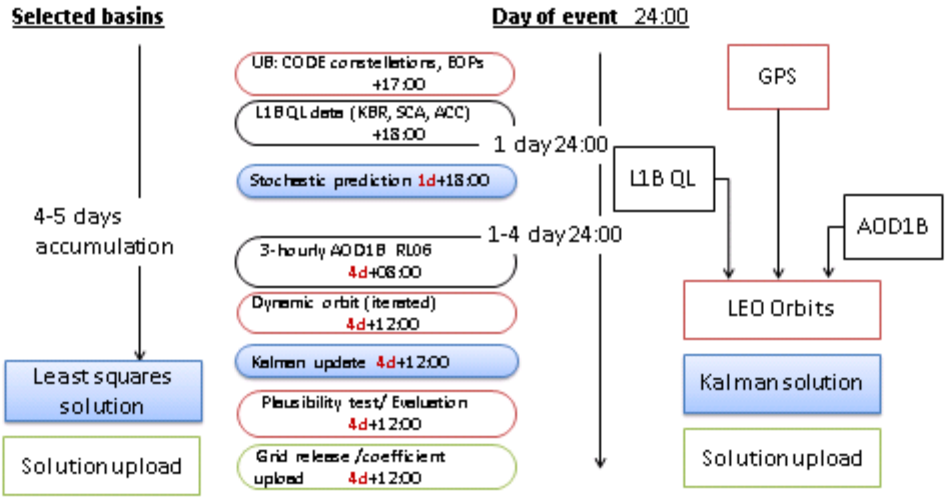
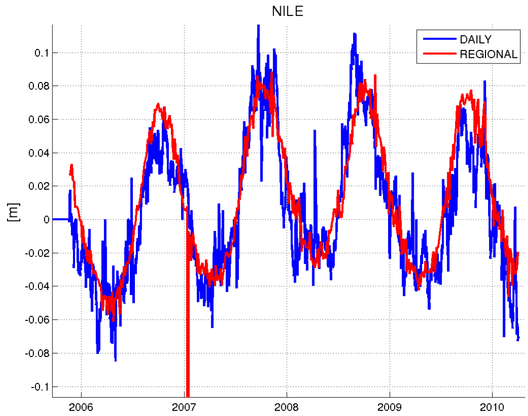
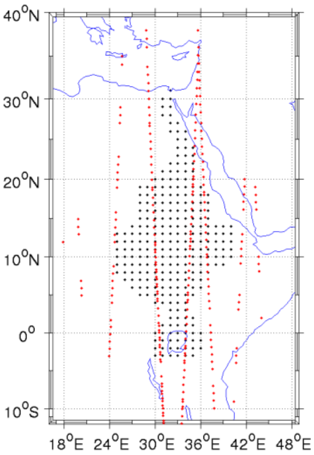


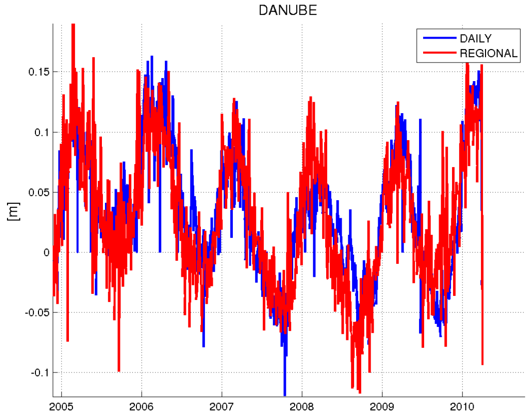
Figure 8: Outline of the GFZ daily gravity solutions in Near-Real-Time. The time-stamp for solution delivery is defined conservative to 4d+12:00. Additionally, every 4-5 days of data stream are accumulated for selected basins.

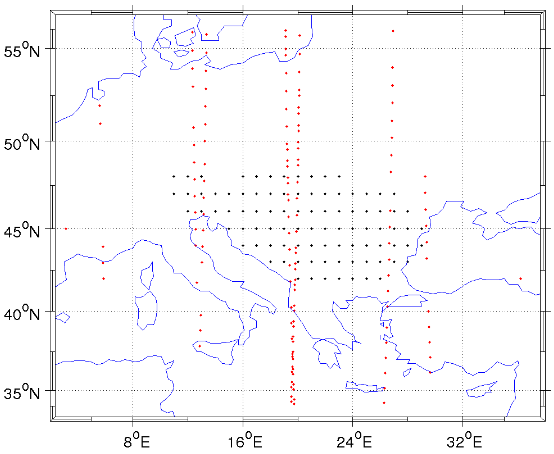
4. Results of the regional service

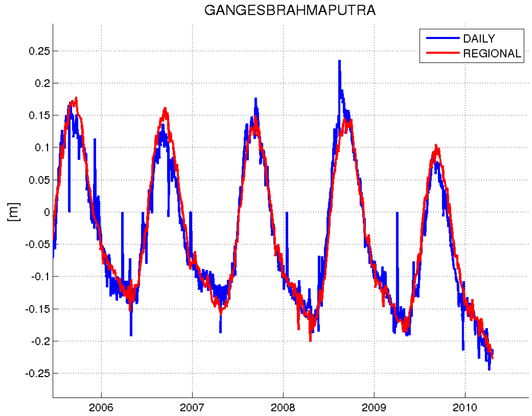
The following plots compare the global daily Kalman filtered results and regional solutions over selected basins. The spatial distribution of the observation data has been exemplified over a period of 4-5 days in the right-hand side plots that are subject to changes in ground track coverage over time. The solutions for the selected basins match quite well, and exhibit as previously described, generally smaller dynamic.

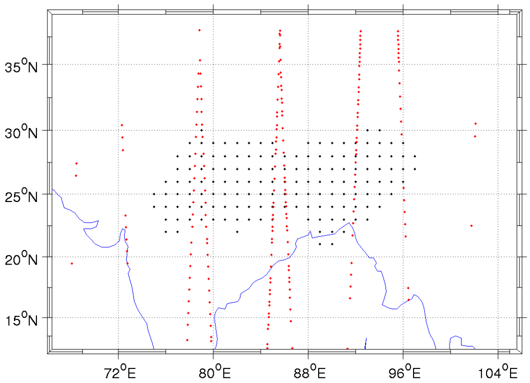


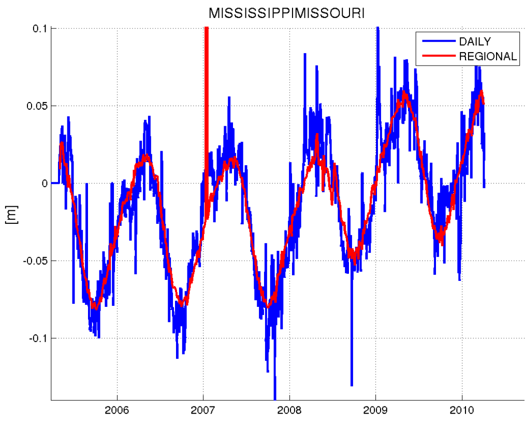


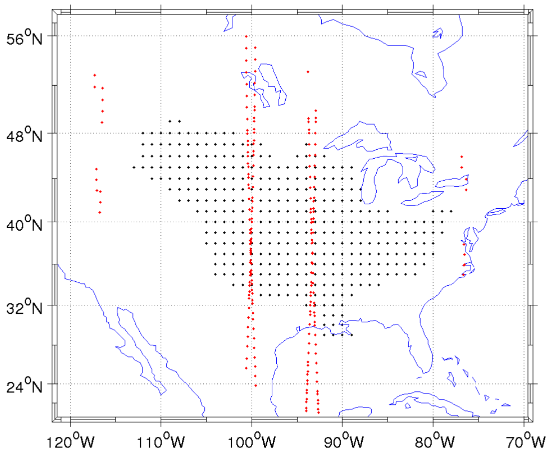


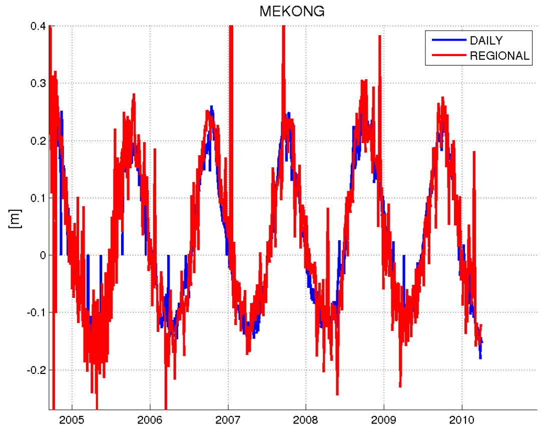


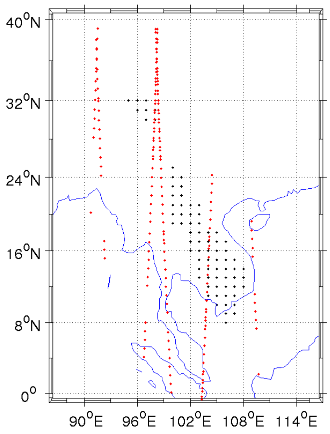












Summary

Both processing centers have implemented and tested regional approaches for the evaluation of GRACE data. In a first test-run for the selected basins Nile, Danube, Ganges Brahmaputra, Mississippi-Missouri and Mekong the comparison to the global Kalman results shows good correspondence and will serve as a starting point for further development.

This could be a mutual combination of the daily Kalman-filtered results with the 4-5 day independent basin estimates. In view of the required external process modeling for the Kalman filter, where only the long-term averaged variability of hydrological events can be captured, some valuable additional signal from singular events (earthquakes) or of other extremes such as natural hazards can possibly be captured better and introduced as side-constraint to enhance the global daily solutions. This needs, however some further detailed investigation.

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