EGSIEM
European Gravity Service for Improved Emergency Management

HORIZON 2020

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Deliverable 5.2
NRT SERVICE PRODUCT REPORT

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1. Change Record

Name	Author(s)	Date	Document ID
Release 1	Kvas, Gruber, Flechtner	31.3.2017	

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2. Terms

This document provides the product report of the Near Real-Time and Regional 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.

3. NRT and 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 within EGSIEM.

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. Further details are described in D5.1 (Concept of NRT Service).

The products of the NRT service, independently derived by TUG and GFZ, will be used to observe and monitor European (and global) water resources and ensures wide access to high level, easy to use products. The Hydrological Service at GFZ (WP6) will develop indicators 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 (Rapid mapping concept).

'Off-line' performance tests, i.e. post-processing of available data, have been performed 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 will be performed in cooperation with DLR/ZKI for half a year starting on 1st April 2017. Unfortunately, the status of the GRACE satellite mission at the beginning of this operational test cannot be longer described as ´nominal´, as the accelerometer on GRACE-2 had to be switched off already on 3 September 2016 and the K-band satellite-to-satellite tracking system is only providing data within sunlight. Both degradations are related to unfavorable battery status due to aging after more than 15 years of satellite operation. The impact on the ITG and GFZ solutions is discussed below.

Near-Real-Time & 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 and Documents to be provided by the Service

The milestones and documents to be provided by the NRT Service are described in Table 1.

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	M27
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 TUG and ITG data product provided to the Hydrological Service and quality assurance measures is described. In chapter 5 first results of the NRT operational test are depicted. The document is completed by a summary, references, and a glossary.

4. NRT 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), individually 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 meta data that describes the GRACE contribution and overall quality of the solution. Data exchange is realized through FTP server infrastructure at GFZ, TUG, AIUB (Q/L input data) and JPL (for Q/L L1B data).

Each daily grid file contains a quality flag based on the GRACE contribution to the given epoch. Quality level "A" describes a nominal Kalman update with GRACE contribution, level "B" represents a predicted solution only, level "C" is assigned when no successful Kalman update was performed in the last four days. This means the solution mainly reflects only the variations, i.e. secular and annual, of the long term background (average) models. Fig 4-1 shows the ensemble of Kalman update, static and long term average background models. Thus after 4 days of no ranging measurements the quality level reflects the deterioration of results from level A to C. This also holds reversely, which means that level A will be reached again after 3 days of prediction and update in level B.

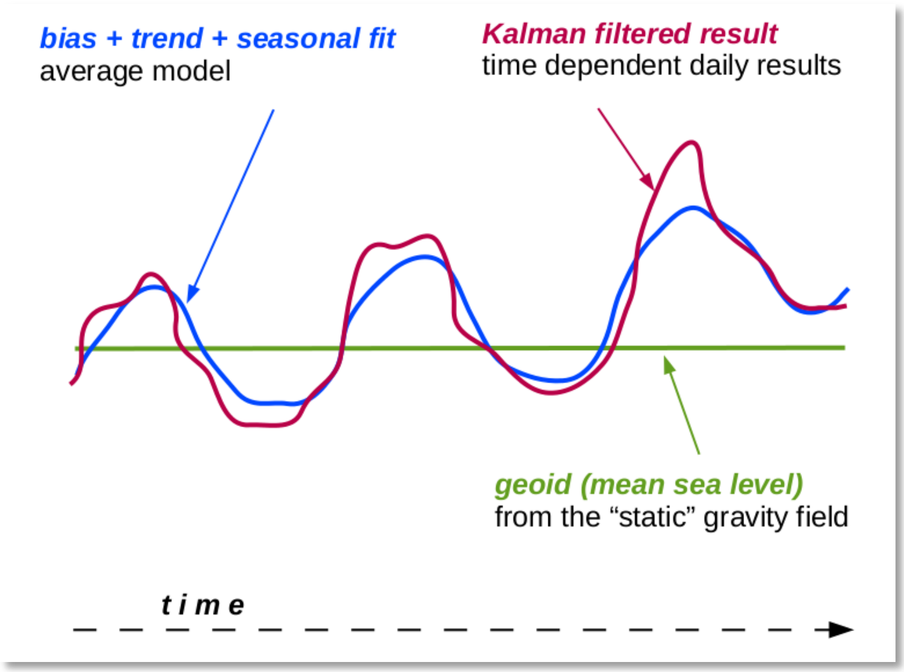

Figure 4-1: General considerations about the Kalman processing to derive for each day a time-dependent gravity field solution.

4.1 NRT Processing at TUG

4.1.1 Method Description

The NRT gravity field solutions computed at TUG are based on the Kalman filter approach introduced by Kurtenbach et. al 2012. We use a *fixed process model* based on stochastic information derived from hydrological and ocean models which is used to describe the spatio-temporal variations of Earth's gravity field between two consecutive epochs. Currently, WGHM (Döll et al. 2003) model output of the years 1979 to 2002 and the error estimates contained in the ESA ESM (Dobslaw et al. 2015) in the years 1995 to 2002 is used to estimate auto- and cross covariance. The end date of 2002 was chosen so that no overlap with the GRACE time series occurs.

The GRACE data processing closely follows the post-processing chain employed for the ITSG-Grace2016 gravity field release (Mayer-Gürr et al. 2016) and is outlined in deliverable D2.1 as well as D5.1.

4.1.2 Required Input Data and Acquisition Strategy

Table 2 outlines the required input data for the NRT processing at TUG.

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

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.

4.1.3 Daily processing schedule

A similar approach to the data acquisition procedure was implemented for the data processing.
A file watcher is started concurrently with the download job, which periodically checks if all the required input data files for a specific epoch were downloaded successfully. If not all files are

available at the end of the time threshold of five days, only the Kalman prediction step is performed and the predicted solution represents the gravity field solution for this epoch. In the nominal case where all files are available, the data processing is started after the prediction. The daily processing schedule follows the concept of D5.1 and is briefly outlined in figure 4.1.3-1 and figure 4. .

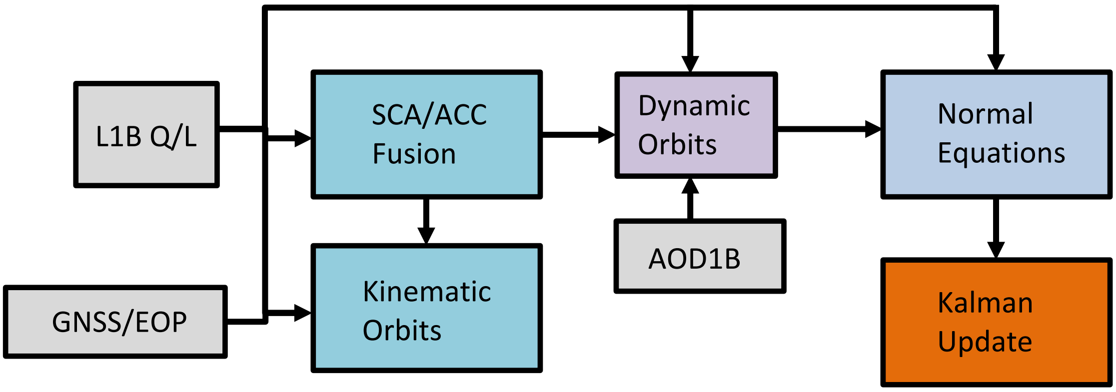

Figure 4.1.3-1: Data dependencies and processing flow chart for each daily solution.

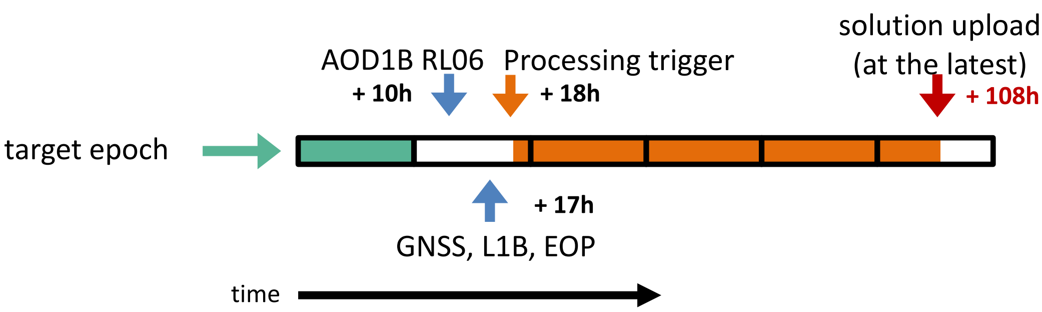

Figure 4.1.3-2: Schematic representation of the processing schedule for each daily gravity field solution.

4.1.4 Impact of Satellite Health on NRT Solutions

Due to the degrading health of the batteries on GRACE-B, the ability to collect science data has been severely limited. From late 2016, the accelerometer on GRACE-B has been turned off and the K-Band ranging instrument has only been active when the satellites are in sunlight.

To investigate the impact of the limited data coverage, a simulation study based on historical data from 2008 was set up. In course of the simulation, three time series were computed. During the first reprocessing, only measurements in full sunlight were considered, otherwise the data has not been altered. In the second time series, all measurements were considered, but the accelerometer data of GRACE-B has been switched with an in-house accelerometer transplant product. In the third time series both effects, sunlight measurements only and accelerometer transplant have been combined. The results of these three scenarios have then be compared to the ITSG-

Grace2016 daily solutions which serve as reference. Being only able to record data during full sunlight means that in time spans where the orbital plane of the satellites is aligned with the Earth – Sun vector the number of observations decreased by 40% (see figure 4.1.4-1).

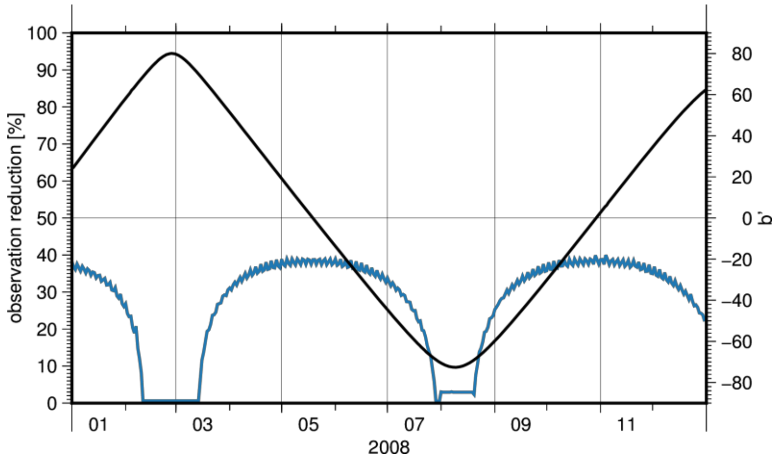

Figure 4.1.4-1: Observation number reduction when only measuring in sunlight compared to the actual observation set.

Moreover, due to the systematic distribution of the data gaps, the length of continuous data segments also decreases significantly. This primarily has an impact on the estimation of the instrument noise, because the length of the data segment determines the spectral resolution of the estimated noise power spectral density, which is depicted in figure 4.1.4-2.

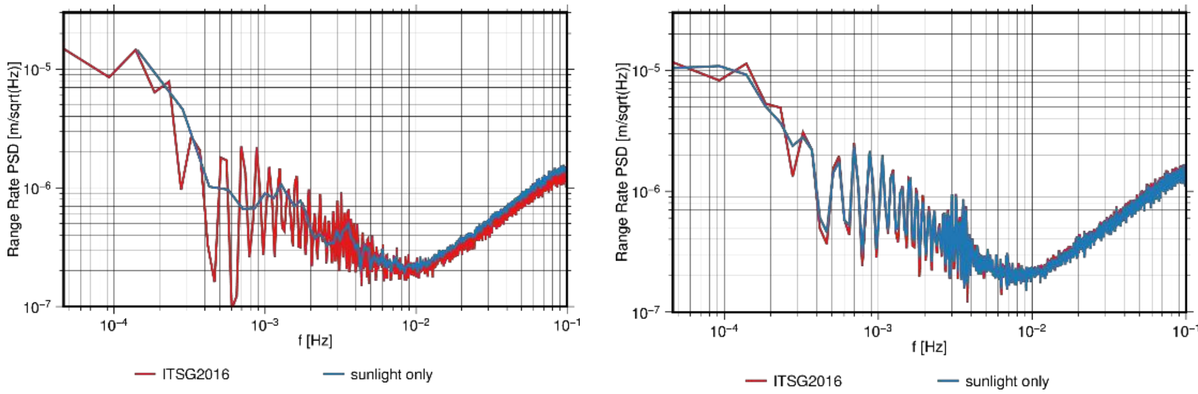

Figure 4.1.4-2: Estimated K-Band range-rate PSD for May (left) and February (right).

The impact of discarding observation in Earth's shadow on the daily solutions is depicted in figure 4.1.4-3 in terms of correlation with the reference time series. As can be seen, the correlation for all three scenarios remains in the high positives. This suggests that the expected reduction in K-Band ranging data as well as the missing accelerometer measurement does not deteriorate the daily gravity field solutions.

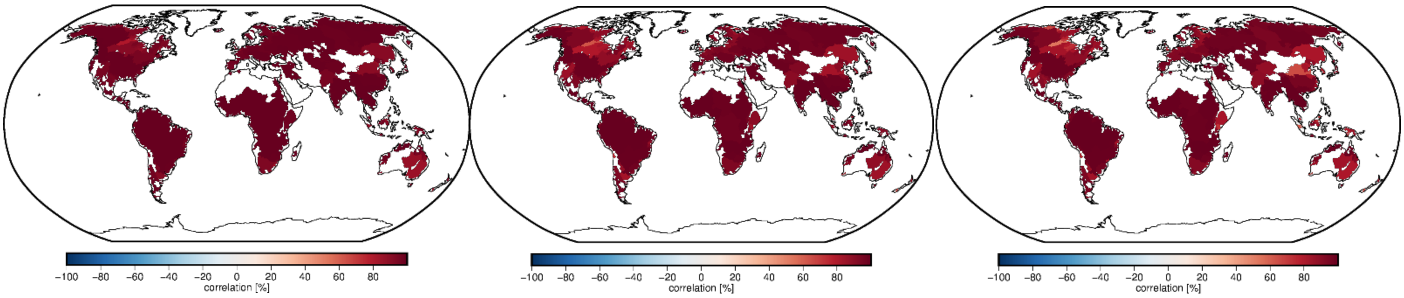

Figure 4.1.4-3: Correlation coefficient between ITSG-Grace2016 and simulation scenario 1 (observations in sunlight only, left) simulation scenario 2 (accelerometer transplant, center) and simulation scenario 3 (combination of both effect, right).

Similar conclusions can be drawn when looking at high-pass filtered area mean values of Ganges and Danube (very high correlation with reference) and the Yellow River (decreased correlation with the reference) shown in figure 4.1.4-4, suggesting that even under the harshest conditions - missing accelerometer and measurements only in sunlight - the high frequency content of the hydrological signal can be picked up very well. This leaves us optimistic that the NRT solutions can provide added value to flood and drought prediction, even with the given decreased observation coverage.

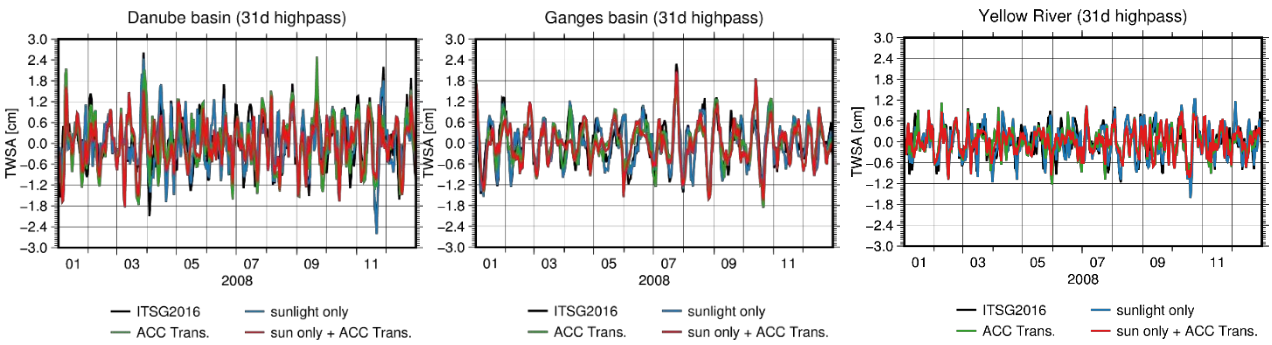

Figure 4.1.4-4: 31 day high pass filtered area mean values of the Danube (left), Ganges (center) and Yellow River (right) basins, showing the comparison of all three simulation scenarios.

4.1.5 NRT Solutions in Fast Forward Mode

GRACE L1B Q/L data starting from February 2016 was made available to TUG in November 2016. The NRT software was run in fast forward mode (i.e. sequential processing without wait times) to compute solutions from February to December, which allowed to evaluate the NRT solution performance by comparison with the ITSG-Grace2016 post-processing time series (forward sweep) in the months February to July, where both time series overlap. This overlap comparison shows very good results which suggests that the L1B Q/L and rapid GNSS data do have comparable quality to the final products and that the necessary approximations made in the NRT processing chain do not have a very high impact on the solution. In figure 4.1.5-1, the global difference RMS between both time series and the time series of an arbitrary point is shown. The differences between the time series is generally below 1 cm of equivalent water height on the continents, with some ocean basins exceeding 2 cm. This follows the spatio-temporal constraint, since in the ocean a higher temporal variability is expected.

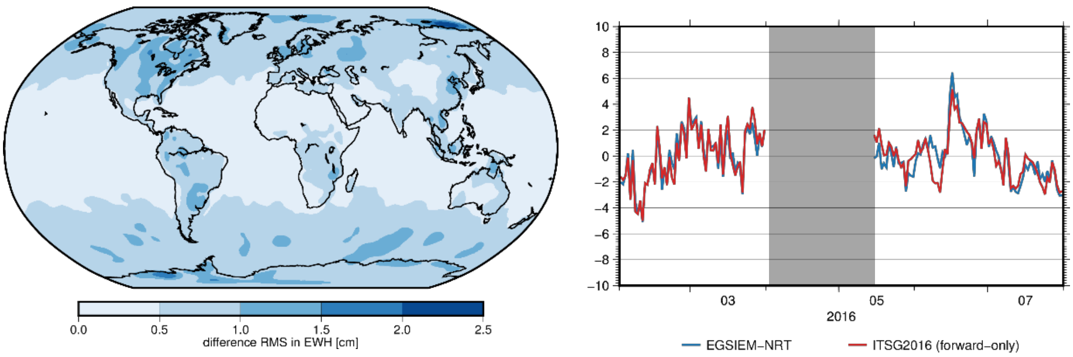

Figure 4.1.5-1: Comparison of NRT solution and ITSG-Grace2016 post processing solution (forward sweep).

4.1.6 NRT Estimation of Geocenter Motion

To provide water storage anomalies in center of figure, the displacement between center of mass frame and the center of figure frame – here referred to as geocenter motion – is required. Since data sets of techniques providing this offset, such as SLR, are not available in NRT, the algorithm introduced by Swenson et al. (2009) and extended by Bergmann et al. (2014) has been included in the NRT processing chain. This approach, while being an approximation procedure, has the advantage that only data already contained in the GRACE L1B data stream is necessary to compute the geocenter motion. Comparisons with independent techniques (see figure 4.1.6-1) show that this approach delivers promising results.

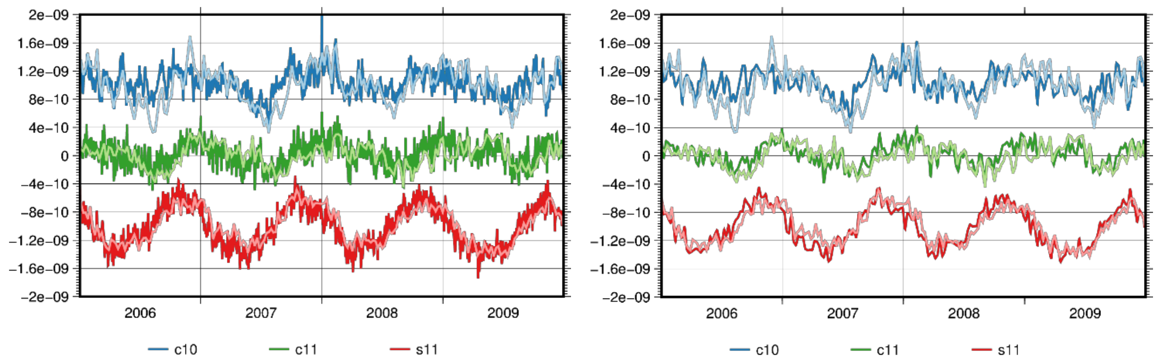

Figure 4.1.6-1: Comparison of degree one coefficients computed from daily Kalman solutions (dark colors) and a GNSS loading based solution by Rietbroek et al. 2011 (light colors) in daily (left) and weekly (right) temporal resolution.

4.2 NRT Processing at GFZ

4.2.1 Processing details

The main program flow is outlined in Fig. 4.2.1-1. After data deployment the Kalman filtered results are being produced according to Fig. 4.2.1-2. :

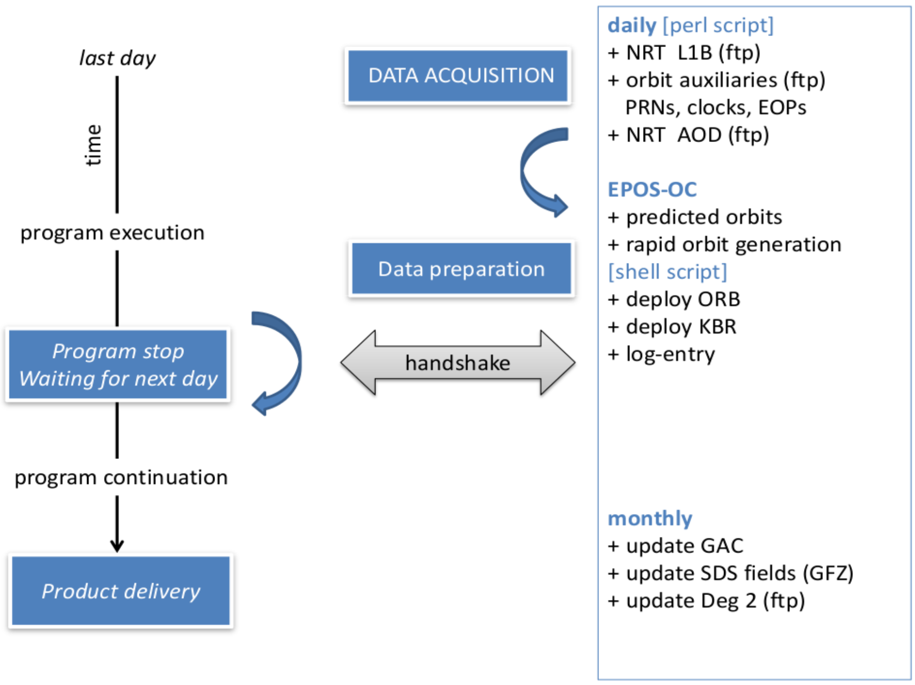

Fig. 4.2.1-1 Near-Real-Time program realization for daily Kalman results until product delivery.

The Kalman filtered solutions are derived from a differential acceleration approach and surface integral equations that are used to map the gravitational signal from the satellites to ground level. The required input data is as TU Graz (see above).

GFZ GRACE data processing follows a 2-step processing strategy (Gruber (2014), Gruber (2017, submitted). Fig. 4.2.1-2 outlines the external and GRACE data stream for daily Kalman results:

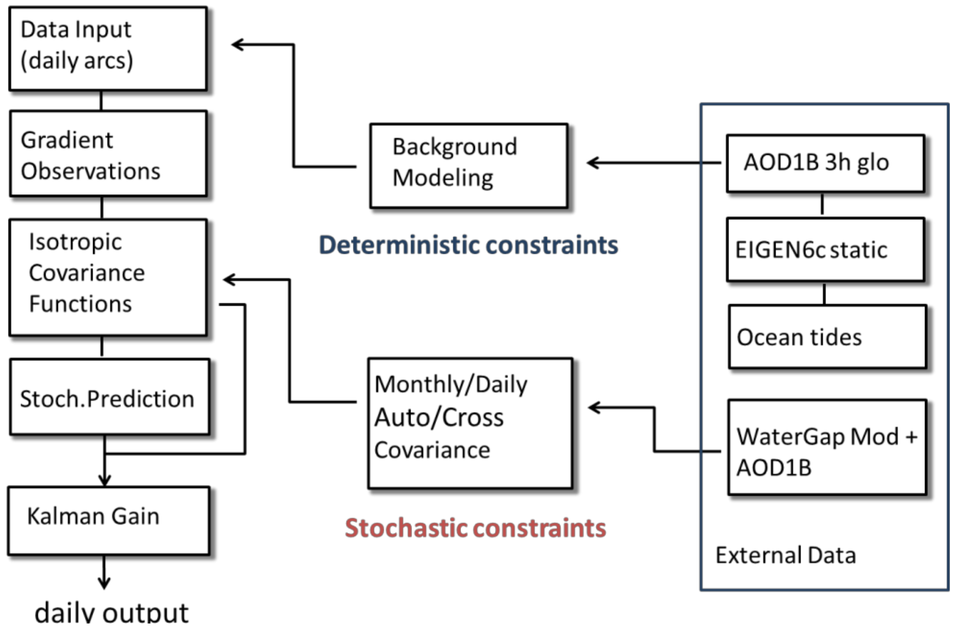

Figure 4.2.1-2: GFZ Kalman processing loop for enhanced observation de-correlation and temporal resolution. GRACE data is processed (left column) and constrained by external data products (right column).

Reduced dynamic LEO orbits (reduction of empirical parameters per revolution) are iteratively constraint to the K-Band ranging data. Then, they are converted to in-situ gradient differences in line-of-sight, directly including the ranging measurements. For the stochastic model derivation a seasonally dependent process model is applied that is based on external hydrology and the atmosphere and ocean de-aliasing product. A time-dependent average seasonal and secular background model (derived from monthly fields) is removed before stochastic prediction and later restored. The Kalman filter is applied to the residual (anomalous) signal on daily batches and maps the gradient differences by surface integral equations onto [2x2] arc degree equal area spherical surface tiles. The surface integral equations use radial basis functions in a tailored reproducing kernel formulation (Poisson's integral, Novak 2007). The L1B data is provided by JPL as quick look product; the AOD1B RL06 is available from GFZ; the GPS constellation is provided from BERN; the Earth Orientation parameters are from IERS, see Table 2 for details about latencies.

4.2.2 Impact of Satellite Health on NRT Solutions

Since the K-band measurements have become available in sun-light regime only the range-rate the total available ranging data has dropped from nominal 17280 (5s sampling) to only 40-45%. Besides that, the PSD and high-frequency instrument error estimates for the purpose of observation de-correlation are more difficult to obtain. Nominally, observation de-correlation is applied in a bandwidth of [0.12 – 100] mHz that corresponds to more than 2 hours. Since ranging data has become available in sun-light only, i.e. for less than 46 min, the lower bandwidth has increased to 0.38 mHz. An investigation on the impact of satellite health on the gravity field solutions was given in chapter 4.1.4 under realistic assumptions.

The global Mean Standard Deviation of the estimated GFZ solutions has increased to 3.9 cm (15 cm^2 MSE) in May 2016 up to 4.7 cm (22 cm^2 MSE) beginning of April 2017 from nominal values around 2.8 cm during healthy satellite conditions in 2008 (see Figure 4.2.2-1). This implies that the Kalman gain from the available data processing has become substantially lower and stochastic prediction (and errors thereof) are more present in the solutions.

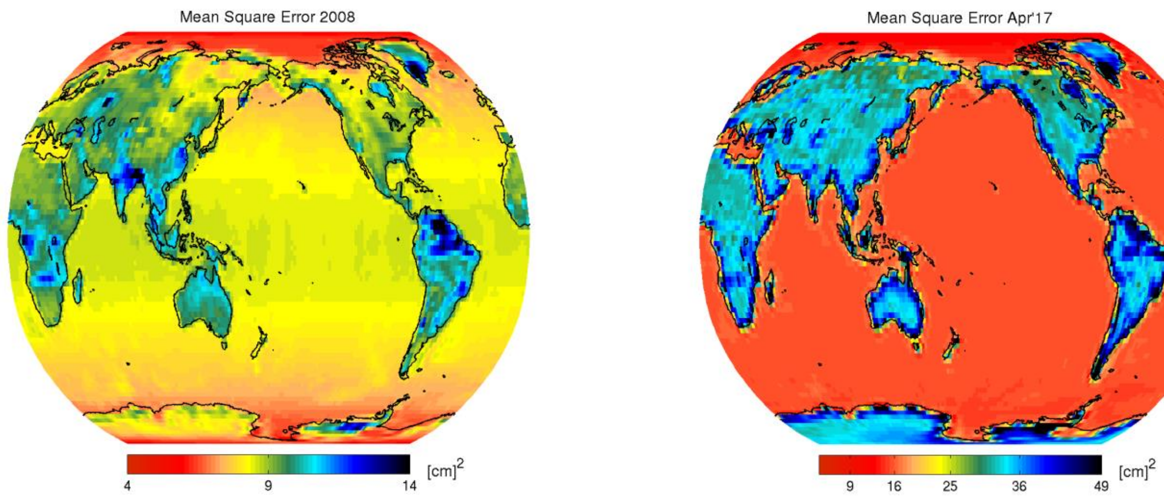

Figure 4.2.2-1: GFZ Mean Square Errors under nominal conditions (2008, left) and in current NRT (Apr 2017, right). Note: the colorbar scale has changed due to the strong increase in Mean Square Errors.

4.2.3 Data scheduling and retrieval

According to the defined grid release latency of 5 days data scheduling is outlined in Fig. 4.2.3-1. In case that there is no data available after 5 days, the Kalman prediction is triggered without the subsequent measurement update. The quality flag is then set accordingly to 'B' or 'C' (see above).

The data collection stream and possible repeat steps are illustrated in Fig. 4.2.3-2. First, the GPS constellations and clocks, processed by CODE at AIUB are downloaded and the quick-look L1B data is acquired from JPL. The AOD1B-RL06 global atmosphere and ocean de-aliasing is obtained from GFZ Potsdam. In case of retrieval failure time-outs are triggered to repeat data retrieval and preprocessing.

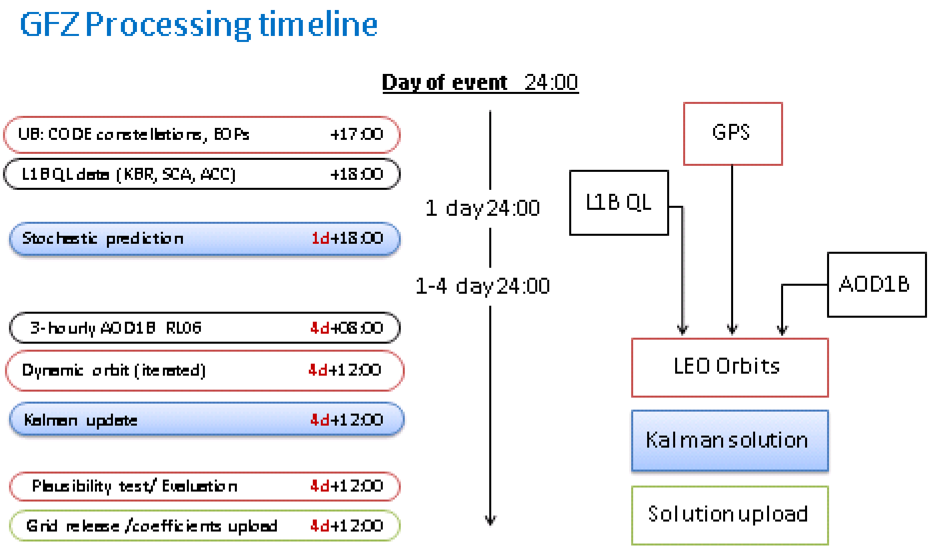

Figure 4.2.3-1: Outline of processing schedule for daily gravity solutions in Near-Real-Time. The time-stamp for solution delivery is defined conservative to 4+ days and was met since start of the service run within just 2+ days.

Together with predicted EOPs the GPS high-low observations are then preprocessed and iteratively fitted by the GFZ orbit integration software EPOS-OC to result in reduced dynamic LEO orbits. The missing accelerometry data from Grace- B has been replaced by ‘transplant’ Grace- A data (provided by JPL). The LEO orbits are then deployed and a software handshake continues the processing loop in Fig. 4.2.3-1. In this main program loop the stochastic prediction and Kalman update for the respective day is computed. The result is further appended by geocenter estimates and reduced for GIA uplift. Finally, daily [1x1] degree grid files are stored in ftp://egsiem@gfzop.gfz-potsdam.de for data retrieval at the Hydrological Service.

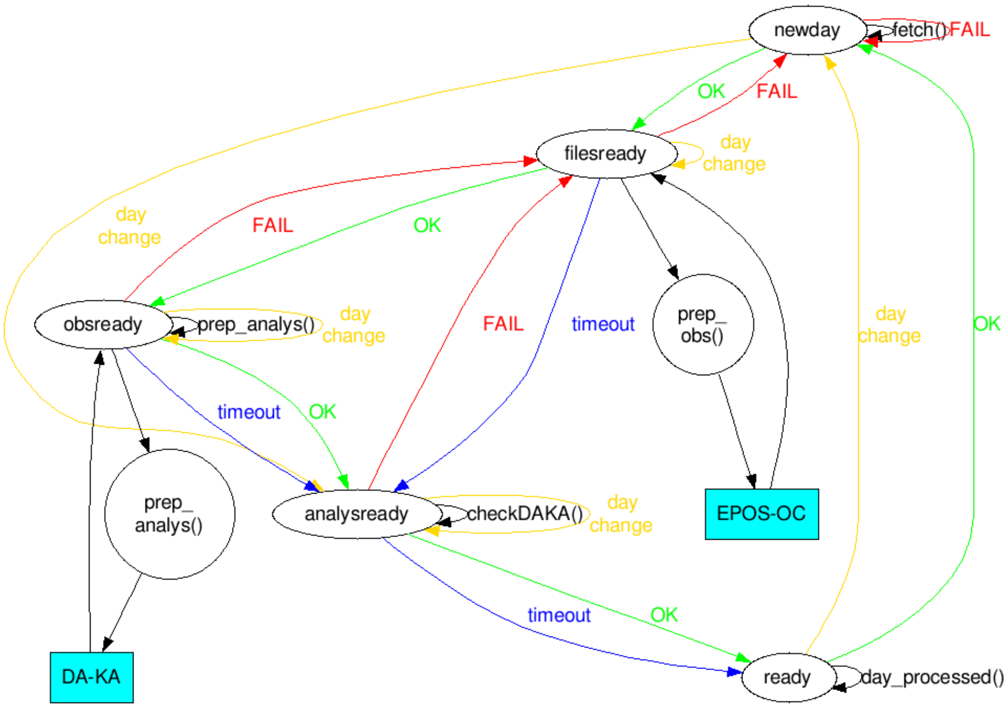

Figure 4.2.3-2: GFZ Near-Real-Time data collection and conversion. After successful data download the processing of background models, LEO orbit (EPOS-OC) and daily Kalman (DA-KA) solutions will commence.

4.2.4 Impact of NRT on Orbit solution

Due to the necessity to exchange the GPS system constellation and clocks from AIUB (see also product latencies) for the NRT service run as well as using predicted Earth orientation parameters (EOP) from BIH, GFZ's LEO results for the GRACE-A and -B satellites varies by 1-2 centimeters in standard deviation compared to in-house results that are based on post-processed GPS constellations, clocks and final EOPs. These differences are illustrated in Fig. 4.2.4-1 and are on average not very large such that the impact on the gravity field is small, cf. Fig. 4.2.4-2. Comparing the patterns for the individual components in the left and right columns (GRACE-A vs. GRACE-B) they are very similar so that the distance between the satellites (baseline) remains overall consistent.

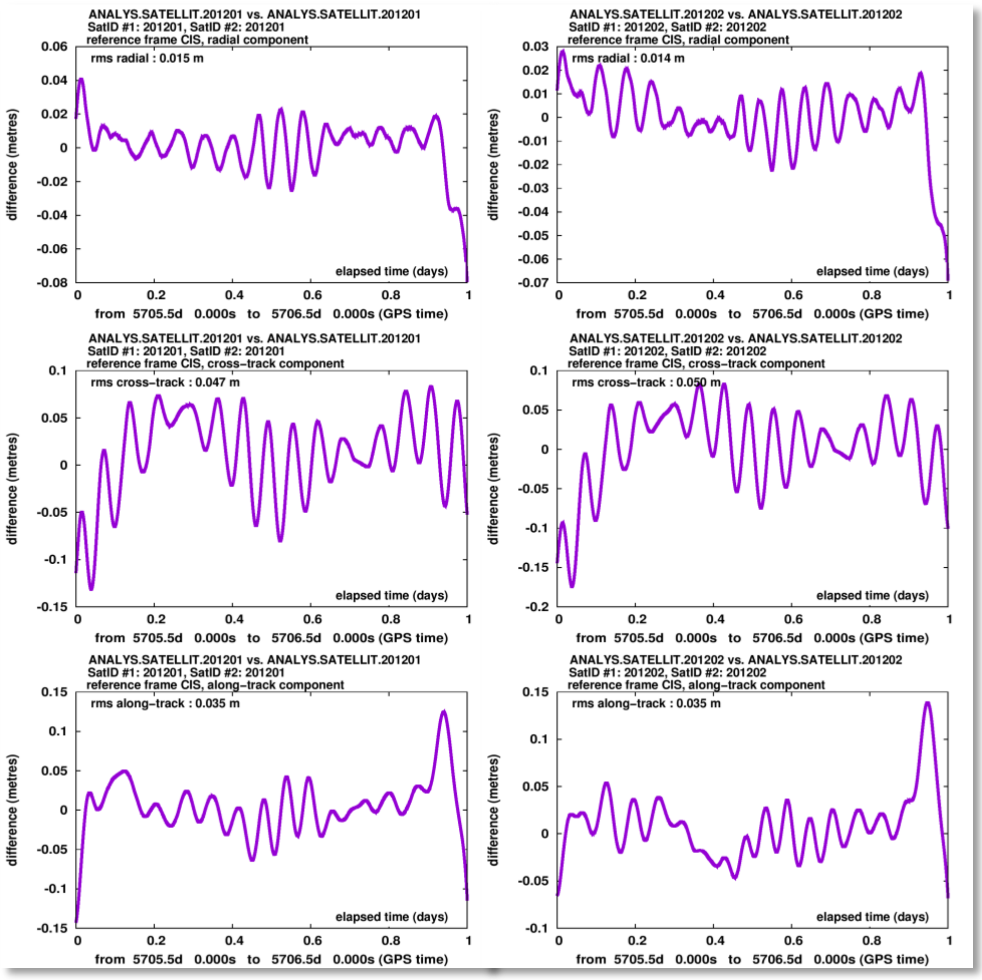

Figure 4.2.4-1: Variation of orbital results for radial, cross-track and along-track both for GRACE A (left) and B (right), respectively. Maximum offsets occur at begin/end of the daily arcs exceeding 10 cm.

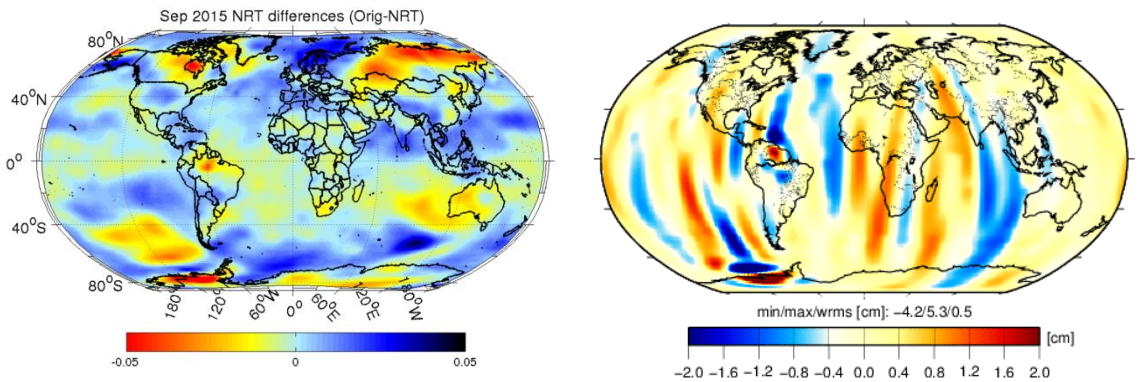

Figure 4.2.4-2: Impact on Sep 2015 solutions in spatial domain based on RBF (left) and standard parameter estimation in frequency domain (right) after exchanging GPS constellation and clocks as well as EOPs. Variations remain globally well below 1cm of equivalent water

5. First results of the NRT service

The normalized Kalman state, i.e. the sum over the most recent updates divided by their standard deviation, represents the anomalous signal w.r.t. the time variable background modeling. It is therefore a good indicator for high and low hydrological conditions and may serve also as a plausibility check before data delivery.

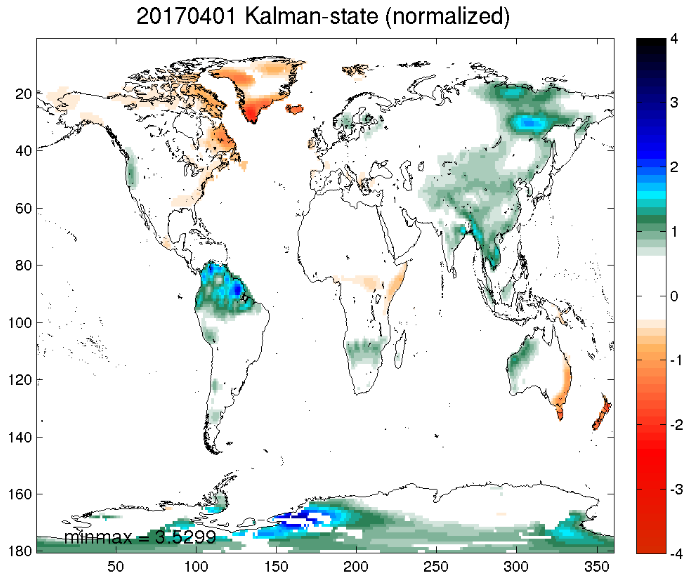

Figure 5-1: First results for normalized Kalman results that represent anomalies w.r.t background models.

In Fig. 5-2 preliminary results for the combined EGSIEM flood-/ drought index are displayed. The value of the most significant signals has to be evaluated throughout the service run test period.

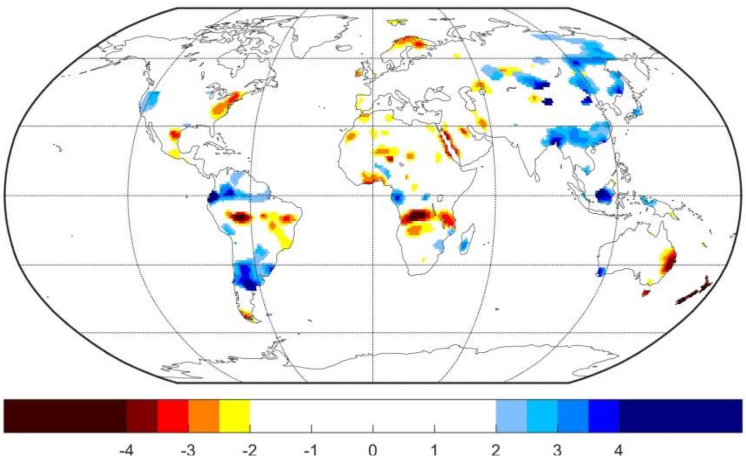

Figure 5-2: First results for the combined EGSIEM flood/drought index for 2017-04-08.

6. Summary

This document outlines the work undertaken during the implementation phase of the NRT Grace gravity service run from M03-M27. Additionally, the document serves as reference for the definition of the NRT gravity field product and the interfaces for data exchange with the Hydrological Service.

Section 4 provides a detailed description of the TUG and GFZ NRT mass grid product provided to the Hydrological Service and the approaches used to categorize the NRT gravity field solutions in terms of quality.

Section 4.1 contains a summary of the implementation and evaluation activities performed at TU Graz. Special attention was given to the quantification of the impact of deteriorating satellite health on the daily gravity field solutions. The simulation study carried out showed that even under the harshest conditions – no K-Band measurements in Earth's shadow and no accelerometer measurements on GRACE-B – the daily solutions still perform very well and pick up high frequency hydrological signals. Furthermore an evaluation of the NRT processing chain in fast-forward mode was carried out by comparison with the ITSG-Grace2016 post-processed time series. Analysis of a five month overlap between the two time series showed that both the rapid input data quality is comparable with the standard data products and that the unavoidable simplifications made in NRT processing chain have very little impact on the solution. Finally, an algorithm to estimate the geocenter motion in NRT was implemented to enable a transformation of the gravity field estimate from center of mass to center of figure.

Section 4.2 contains a summary of the implementation and evaluation activities performed at GFZ. The NRT rapid data has an impact on the orbit solutions while for the gravity fields it is found to be of minor influence. The current impact of missing ranging data outside of sunlight periods (~50% of an orbital revolution) as well as the accelerometer switch-off on GRACE-B resp. the need to use transplant GRACE-A data on the standard deviations of the Kalman results are presently high. Moreover, some major part of the full signal is based on appropriate modeling of the average time-variable background process that has become due to data gaps especially in recent months more and more difficult. This will be further investigated during the operation test run and may lead to an update of this document.

Section 5 shows that the TUG and GFZ NRT solutions provide reasonable input for the Hydrological Service although there are still differences between the two individual daily wetness indices. However, we believe that these differences are - at least partly - rather in spatial extent, while (many) areas of higher and lower water storage are presented in both indices, e.g. increased water storage in Latin America (Columbia/Peru, Argentina) and low water storage in Africa (northern Nigeria/South-Sudan, Angola/Zambia/Mozambique). These are in fact the two flood (Columbia) - and drought (Nigeria/Sudan)-related crises, which have also been reported in the news. Additionally, the differences between the two indices may be regarded as an indication of uncertainty.

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8. Glossary

BIH	Bureau International de l'Heure
BTS	BIH Terrestrial System
CoM	Center of Mass
CODE	Center for Orbit Determination in Europe
ECMWF	European Center for Medium-range Weather Forecast
EOP	Earth Orientation Parameters
GFZ	German GeoforschungsZentrum
IERS	International Earth rotation and Reference system Service
JPL	Jet Propulson Laboratory, Pasadena
KBR	K-Band Range
LSC	Least Squares Collocation
LEO	Low Earth Orbiter
NRT	Near Real Time
OBP	Ocean Bottom Pressure
OMCT	Hamburg Ocean Model for Circulation and Tides
RBF	Radial Basis Functions
TUG	Technical University of Graz