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Deliverable 5.1
CONCEPT OF NRT SERVICE

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1. Change Record

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2. General

This document provides the preliminary design of the Near-Real Time and Regional Service of EGSIEM (Work Package 5). Until final installation of the service amendments and improvements are foreseen in the course of project progress.

3. 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 towards the accuracy level of the monthly fields. 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. The product of the NRT service will be used to observe and monitor European (and global) water resources and ensures wide access to high level, easy to use products. GFZ 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.

'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 will be performed in cooperation with DLR/ZKI for half a year.

Near-Real-Time & Regional Service Timeline

NRT and Regional software and output products will be developed based on individual approaches at GFZ and TUG within M04-M27. The concepts and strategies will be refined / converged and improved until M27 leading also to updates of this document, if necessary. Consequently, the service installation is divided into an Implementation Phase (M04-M27) and an Operational Phase **(**M28-M33).

<u>Current status</u>

The outlined processing strategy has already been successfully applied in post-processing of GRACE data, resulting in the daily gravity field solutions included in the ITSG-Grace2014 gravity field model. An updated time-series from GFZ will be made public as soon as it becomes available.

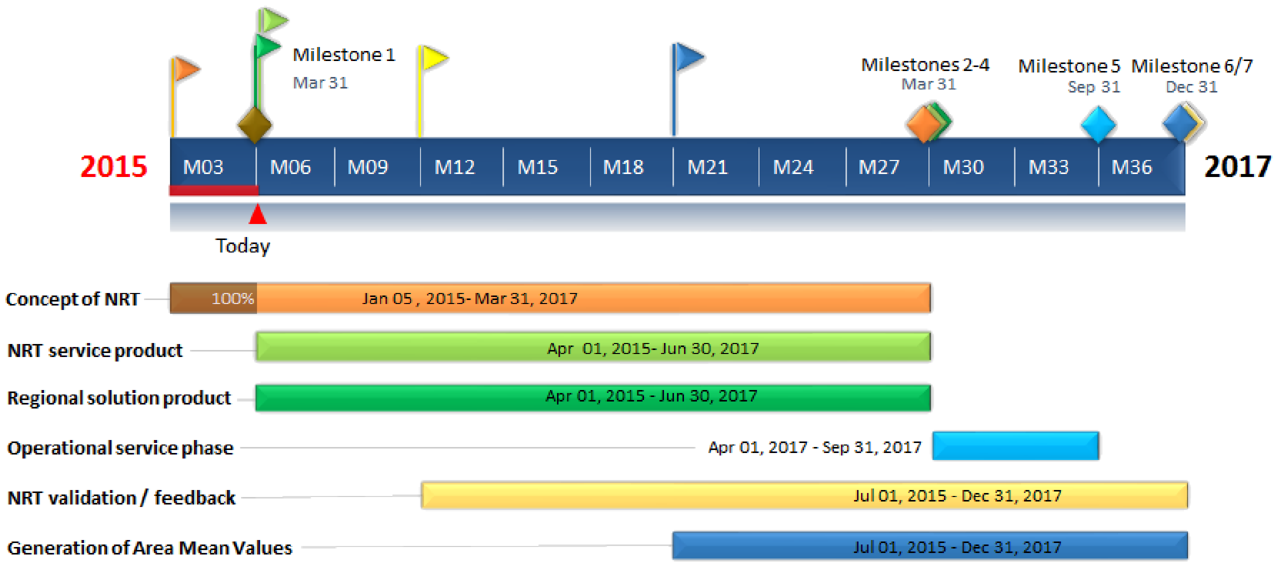

Figure 1: Milestones, Documents and Reports to be provided by the Service

5.1 Draft Concept of NRT Service	(M03)	Milestone 1
5.1 Final Concept of NRT Service	(M27)	Milestone 2
5.2 NRT Service product report	(M27)	Milestone 3
5.3 Operational NRT Service product report	(M33)	Milestone 5
5.4 Regional solution product report	(M27)	Milestone 4
5.5 Generation of Area Mean Values	(M36)	Milestone 6
5.6 NRT validation report	(M36)	Milestone 7

Document overview

This document, in chapters 4 and 5, provides an overview of the processing methods, required input data, necessary adaptions to real-time applications and other issues both for TUG and GFZ, respectively. Chapter 6 discusses the adaption to GNSS orbits and clocks from UBERN. Chapter 7 describes the approach to validate the service results before being used by other project partners or external users. The delivered products are summarized in Chapter 8 followed by the necessary hardware and infrastructure requirements in Chapter 9. The service product time-line and deliverables are summarized in Chapter 10. The document is completed by references, and a glossary.

4. NRT Processing at TUG

4.1 Method Description

To obtain reliable estimates of Earth's gravity field from one day of GRACE data, additional information is required. In the current approach this a-priori knowledge is represented by the fact that the gravity field does not change arbitrarily over time, but the temporal variations are driven by geophysical processes. The dynamics of the underlying processes and the resulting state-transition matrix are derived from the stochastic properties of geophysical models. This is achieved by computing the temporal auto- and cross-covariance matrix from daily realizations in a time span of 25 years preceding the GRACE mission. This stochastic information allows the prediction from one epoch to the next in a least squares sense (LSC, Moritz 1980).

It is important to note that this approach avoids biases towards the used model values since only stochastic information is used.

The GRACE observations are combined with the process model using the Kalman filter approach introduced in Kurtenbach et al. (2012). The processing of the GRACE L1B data follows the short-arc approach at TUG, which means that the processing methods and standards defined in D2.1 can be applied. The described processing strategy has already been successfully applied in post-processing of GRACE data resulting in the daily solutions included in the ITSG-Grace2014 gravity field model (Mayer-Gürr et al. 2014).

The current concept of the NRT processing strategy at TUG can be found in **Figure 2**.

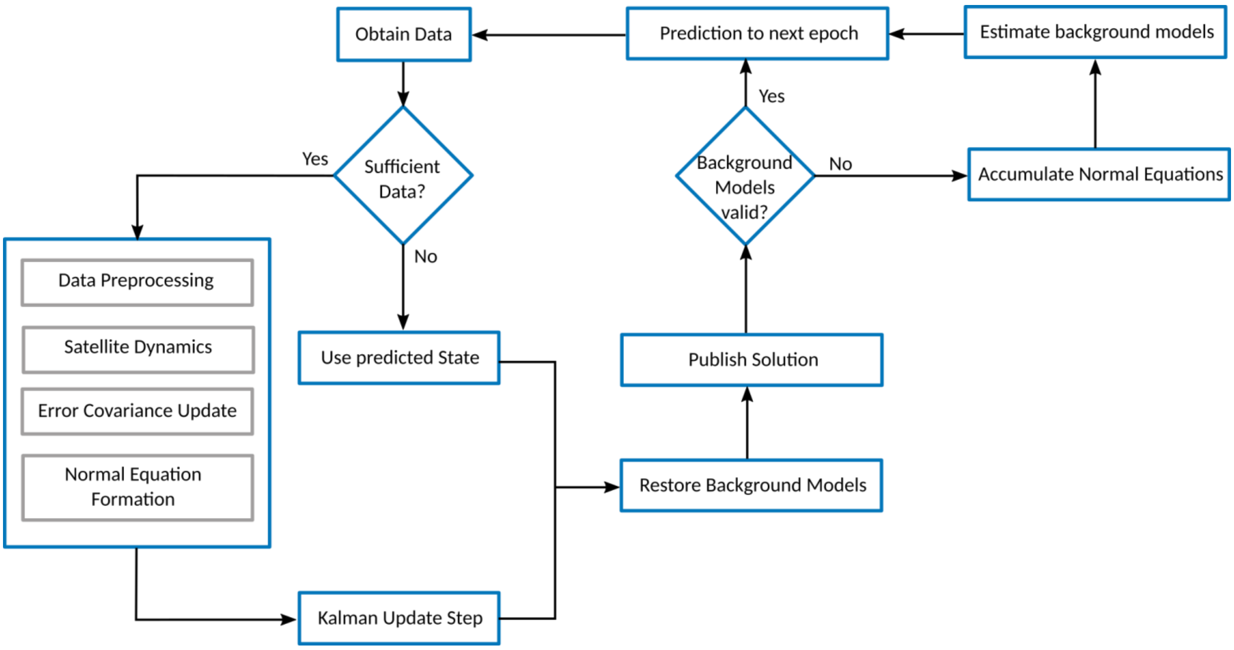

Figure 2: Process flow for the generation of a single daily gravity field solution.

4.2 Adaptions to NRT Application

The GRACE data processing at TUG has been briefly summarized in D2.1 and will be applied for the NRT application accordingly, except for the temporal error covariance and observation weight estimation.

For a reliable estimation of the covariance function of instrumental noise (kinematic orbits and range rates), a larger data volume than one day of GRACE observations is required. Therefore the last seven days of GRACE data are analyzed and the instrumental noise is assumed to be stationary in this time span. For long data gaps where no suitable observations are available, the last reliably obtained stochastic model will be used.

4.3 Required Input Data

Lists the required input data for the short arc approach at TUG. Details concerning the GPS orbits, clocks and EOPs from UBERN can be found in D2.1. The last line holds for GFZ’s regional solution in such cases where tailored covariances can be applied. The computational effort to derive the daily gravity field solutions is small, therefore the latency of the NRT gravity field solutions will be largely determined by the input data latency.

Product	Source	Current Latency (IP)	Required Latency (OP)
EOP	IERS/UBERN	IERS: 1-3 days, UBERN: 14 days	IERS: 1-3days, UBERN: 17 hours
GPS Orbits/Clocks	UBERN (T3.4)	14 days	17 hours
GRACE L1B Data	JPL, Backup: GFZ	11 days	1 day
Dealiasing Product (AOD1B)	GFZ	7 days	3-4 days
Specific hydrological basin (upon request)	WP3/6	Not available	1 day

Table 1: Required data for gravity field recovery and respective latencies for the implementation phase (IP) and operational phase (OP)

4.4 Handling of Data Gaps

If no GRACE data is available at a certain epoch, the update step in the Kalman filter approach (see figure 1) is skipped, and the predicted state is seen as gravity field solution for this point in time. The information gain in these prediction-only gravity field solutions compared to raw model output decreases with the length of the data gap. Therefore meta-data in the form of observation counts are provided with the computed solution. This gives the user the ability to decide whether the information provided by the gravity field is usable at the given epoch.

4.5 Update of Reference Models

To obtain a satisfactory approximation for the sake of linearization, static, annual and secular a-priori gravity field models are reduced from the input data. These models are, however, strictly valid only in the time span of data they are based on. A regular update of the time variable reference models (secular and annual variations) is therefore necessary and will be performed using the normal equations computed in the Kalman filter update step. The optimal frequency of these updates will be determined during the implementation phase (T5.2).

4.6 Kalman Smoothing

If data latency during the operational phase is sufficiently smaller than the nominal five days delay, a backward filtering (smoothing) of the computed solutions is possible. This is done by applying the Kalman filter front to back and forming a weighted average of the forward and backward filtered states. The effect on the estimated gravity field models of this procedure will be evaluated during the implementation phase (T5.2).

5. GFZ's NRT approach

5.1 Method description

GFZ follows the acceleration approach of GRACE. Briefly, differential inertial spacecraft velocities between the GRACE-A and -B satellites are combined with inter-satellite K-Band range (KBR), range-rate (KBRR) and range-accelerations (KBRA) to in-situ observations. Globally and regionally defined integration grids serve as source points to provide functions of gradient differences for the unknown time variable potential field at orbital altitude. Radial basis functions (RBF) provide the integral equations via the Poisson Kernel (Novák 2007). Least squares inversion connects the unknown values with the integrated in-situ observations in daily batches, processed through a Kalman filter. Covariance information for the observations is obtained from time averaged auto-correlations of the observations and enters the Kalman filter as observation weight matrix. Covariance information of hydrology (Döll et al. 2003), non-tidal atmosphere and ocean variability (Flechtner et al. 2014) and glacial isostatic adjustment (Peltier 2004) will constrain the derived NRT solutions. Necessary predicted states are obtained by Least Squares Collocation (LSC) from the previous day. Causal daily results and error covariance updates are subsequently provided by the Kalman filter update (cf. Gruber et al. 2014). Fig. 2 depicts the processing loop at GFZ for the generation of daily solutions.

5.2 GRACE Orbits

GFZ is using differential dynamic satellite velocities that are currently best estimates derived from existing background models and GRACE-derived time-variable potential fields. Since these velocity estimates are of low noise ratio this works well for the prediction of in-situ gravity observations - but this approach bears the risk of 'self-tuning' results as background and observations are merged (this in fact happens in the Kalman filter again, but it is controlled with full stochastic modelling). Further research is necessary to properly address the problem of self-augmentation. Ongoing development during T5.2 will investigate the following issues:

a) Tests on optimal velocity prediction for in-situ gravity observations
   - tests on convergence are conducted by an iterative scheme where the output of the Kalman-filter is re-used for the LEO orbit determination.
   - post-orbit corrections will be applied after the LSC prediction of daily gravity fields.
   - The orbit (correction) itself will be subject to LSC.

b) It needs to be investigated whether kinematic orbits (rapid kinematic) may be used for the velocity estimation needed for the objectives of the NRT service (global/regional) in the RBF approach.

c) The question whether in-situ gravity observations can be processed without GNSS velocity differences will be investigated.

The current features for iterative orbit computation and parameter estimation from the GFZ (EPOS-OC program package) are used for determination of GRACE-A and -B trajectories and background forces.

a. arc-wise initial orbital elements / empirical scales and biases for accelerometry
b. epoch-wise background forces computation for dynamic orbit integration (3rd bodies, 6-hourly AOD, static gravity field, tides).
c. receiver clock computation and phase center variations.
d. step-wise increasing emphasis on KBR inter-satellite observations as side constraints for ambiguity fixing and outlier detection.

The processing standards apply according to Deliverable 2.1.

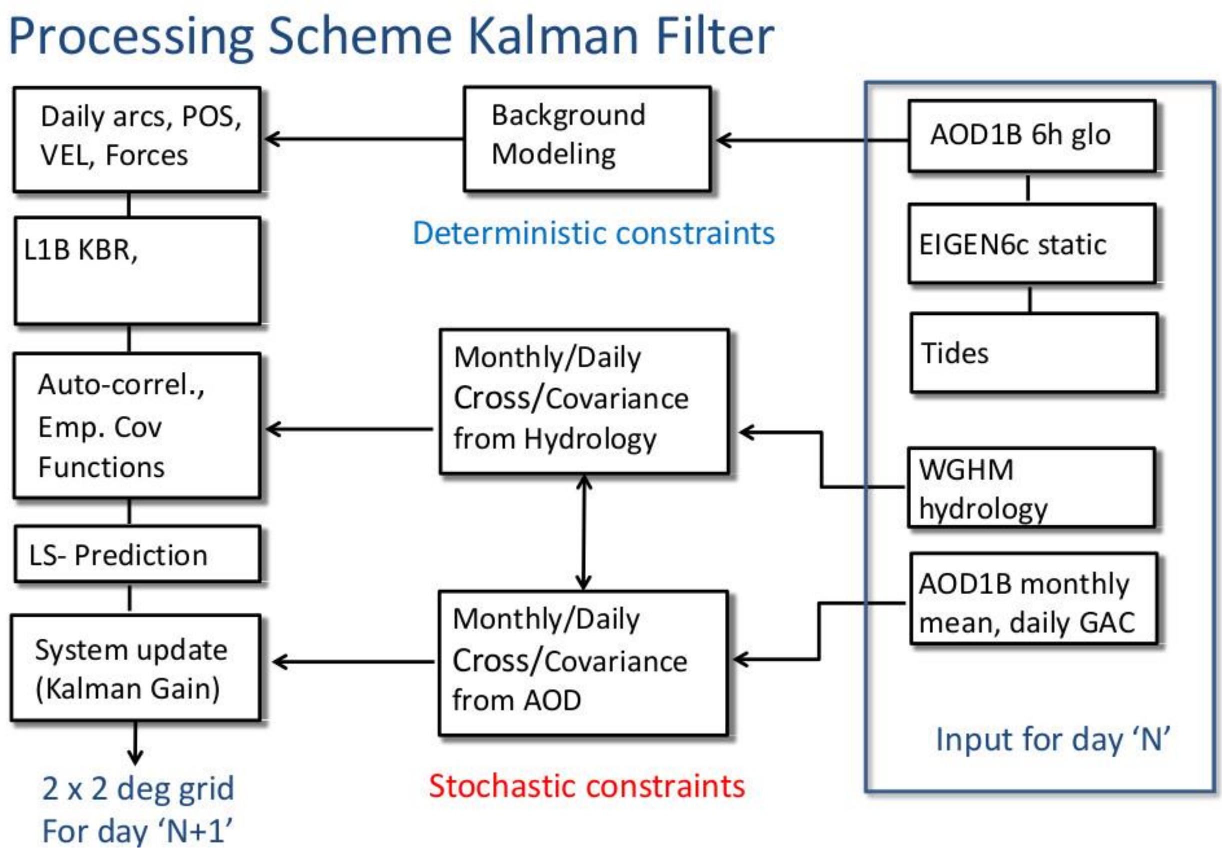

Figure 3: Process flow for the generation of a single day global 2x2 degrees solution. Regional basins similar.

5.3 Adaption to NRT processing

The required GNSS constellations for the NRT solutions of the EGSIEM project (operational phase) will be based on CODE GPS orbits/ clocks (see chapter 6).

Until the products with required latency come online (see **Table 2**), i.e. during the implementation phase, GFZ will additionally apply and compute (from predicted, EOP):

- N-R-T GNSS solutions (30min latency) with 10 cm accuracy and
- rapid GNSS solutions (14hour latency) with 3-4 cm accuracy.

AOD1B latency will be reduced to 3-4 days, operationally. Faster solutions (48hours) will be discussed and tested experimentally.

5.4 Required Input Data

Table 1 lists the required input data for the RBF method at GFZ. Additional hydrological basin information can be included upon request.

5.5 Update of Reference Models

For the stochastic prediction (LSC) of daily gravity field variations static, annual, semi-annual and secular a-priori gravity field models are reduced from the input data. A regular update of the time variable reference models is necessary and will be obtained consistently from the Kalman solutions. Furthermore, the reference models will be also deduced from consolidated solutions (D4.2) taking into account all available variance/covariance information of the solutions. This reference model is introduced in the dynamic orbit determination in chapter 5.2. Finally, the reference solutions will serve as FAR-Zone contribution that is reduced from observations for the purpose of regional refinement.

6. Using CODE GPS Orbits/Clocks

The task of the Center for Orbit Determination in Europe (CODE) for EGSIEM NRT is the provision of the reference frame. There are two IGS processing lines available:

- "Final" with latency of 2 weeks
- "Rapid" available after 17 hours

The regular rapid product meets the requirements of the NRT service of the EGSIEM project.
Phase based GNSS clock interpolates with 30-sec.

6.1 Interface issues

Necessary adaptions to standard exchange formats such as SP3 and RINEX are handled by each processing center individually.

7. Integration / Validation of Results

The NRT service requires frequent inter-change and discussion of results and progress. This will be performed by regular meetings and correspondence by email, e.g. on a ~ bi-monthly basis. In formal reports we will keep track of these activities.

An informal (during Implementation Phase) and NRT (during Operational Phase) validation feed-back loop from UL will be established based on hydrological analysis and GNSS site displacements.

Validation will be conducted directly from gridded values (in Equivalent Water Heights, cf. Wahr et al. 1998) and in spherical harmonic coefficients. An FTP server will be installed that is regularly scanned and processed according to anticipated requests off-line or in NRT (during Operational Phase). The input format will be the gridded data in the provided resolution (and if applicable SH coefficients). Additionally, the NRT station coordinates provided by UBERN in T3.4 will be used. Other sources for GNSS site displacements will be tested. Interfaces and output formats will be defined by UL during the implementation phase and based on the requirements of the consortium members and users. Hydrological data can be currently examined in post-processing; the comparison with actual data will be established in cooperation with DLR/ZKI during the second half of the project.

GNSS vertical site-displacements reveal a strong secular correlation with GRACE derived ice-mass loss over Greenland (Khan et al. 2010) or seasonal variation in California (Argus et al. 2014) and can be used as a measure of time-correlation. As GNSS observations are available on a daily basis they can be used to investigate daily variation estimates from the NRT process.
Reference criteria of the evaluation will be standard correlations with GNSS site displacement time-series and explained variances for the compared signals. Spatial averages will be used for basins or large–scale GNSS cluster. The procedure will be automated to allow for a prompt (less than 1 hour) validation of the NRT service products.

The validation chain will be established and documented starting from test data of a historical GRACE period (e.g. 2-3 years) and areas of interest (with documented flooding events, T6.1) in a specified format and model resolution and implemented accordingly.

8. Product deliverables

The products of the NRT service will consist of daily spherical harmonic coefficients (TUG), global 2 by 2 degree grids (separate solutions from GFZ and TUG) as well as 1 by 1 degree grids for selected basins where additional stochastic information is available (GFZ).

File formats for data exchange will be adapted to planned GRACE-FO L3 products, thus providing compatibility with planned/existing interfaces. The computed grids will be made available for validation (T5.6) and hydrological service (T6.2) through FTP servers at the respective processing centers.

Based on spatial averages of equivalent water height for selected river basins (T5.5), GFZ will develop indicators as a measure of catchment wetness from gravity-based water storage anomalies and will evaluate their performance for forecasting historical hydrological extreme events (T6.2). The results will provide input to the NRT rapid mapping concept (T6.3). The spatial averages (area mean values, AMV) of equivalent water height for selected river basins (T5.5) will also be used for validation/feedback (T5.6) and visualization (work-package 7). For this purpose hydrological adjusted/optimized river basin masks for the GRACE products will be provided for the areas of interest to compute AMVs.

9. Hardware and Infrastructure for EGSIEM service obligations

In the following **tables 3** and **4** the individual GFZ and TUG hardware/software realizations that are available during the project are summarized. Note that this part so far does not cover the final EGSIEM hardware endowment at UBERN or UL which are described elsewhere.

Product	Hardware	Software
Serversystem	Supermicro X10DRW-i	Matlab/shell scripts
	Dual socket R3 (LGA 2011) supports Intel® Xeon®	Fortran90 source
Processor	E5-2690 v3, 2.60 GHz, 12-Core Socket 2011-3, 30MB Cache	
Memory	256GB (16x 16GB) DDR4 / PC2133 Reg. ECC	
Storage	4x 3TB SATA3 Server-RAID-Festplatte HGST Ultrastar 7K4000 3.5IN 7200RPM, 24*7-certified	

Table 2: Infrastructure at GFZ

Product	Hardware	Software
Server System	Supermicro 2042G-TRF	C++/Python Source
	4x SG34 MB H8QGi-F	
Processor	CPU AMD OPTERON 6176 2.3GHZ 12Core SG34 18MB Cache	
Memory	32 x 8GB DDR3-RAM 1333MHZ	
Storage	SEAGATE HARDDISK 1000GB S-ATA2 7200RPM 32MB ST31000524NS	

Table 3: Infrastructure at TUG

10. Time-line for service products and deliverables

Daily global time variable potential fields (spherical harmonic coefficients) or global 2x2 degree grids in equivalent water heights or other gravity functional will be available via ftp. Additionally, daily 1x1 degree grids for selected basins where additional available stochastic data is applicable (GFZ). In those cases where no observables exist, predicted-only daily gravity field solutions will be provided.

The production flow for the generation of individual single daily global/regional solutions has been summarized in **Figure 4**.

Between the final Kalman update (7) and product release (9) there is a 6 hours time-span for issue resolving if required. This is reserved to handle problems, e.g. the evaluation shows that the data is not trustworthy or the processing chain has malfunctioned because of a problem with a server or the internet is down. In the Implementation Phase this will be done manually while in the Operational Phase an automatic procedure will be implemented.

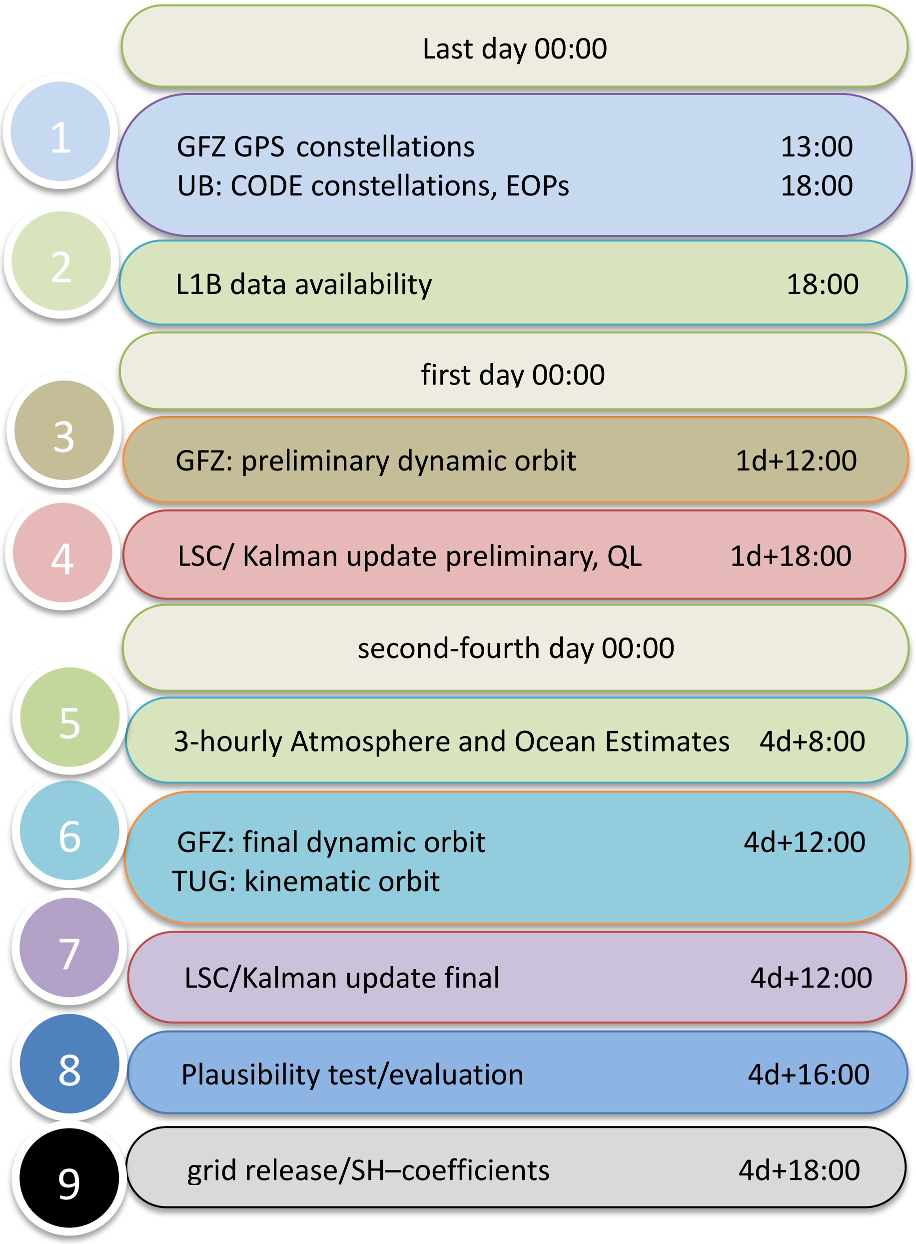

Figure 4: Production flow for the generation of a single day global/regional solution.

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12. Glossary

AMV	Area Mean Values
CODE	Center for Orbit Determination in Europe
DLR/ZKI	German Aerospace Center/ Center for Satellite Based Crisis Information
EOP	Earth Orientation Parameters
FAR-Zone	Background contribution from outer region
GFZ	German GeoForschungsZentrum
GNSS	Global Navigation Satellite System
IERS	International Earth rotation and Reference system Service
IRF	Inertial Reference Frame
KBR	K-Band Range
KBRR	K-Band Range Rate
KBRA	K-Band Range Acceleration
LSC	Least Squares Collocation
NRT	Near Real Time
RBF	Radial Basis Functions
SLR	Satellite Laser Ranging
TUG	Technical University of Graz
UBERN	University of Bern