

Simulated L2 and L3 products for impact studies of the NGGM and MAGIC gravity missions

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Marius Schlaak¹, Julia Pfeffer², Roland Pail³

1. *Université de Toulouse, LEGOS (CNES, CNRS, IRD, UT), 31400 Toulouse, France*
2. *Magellium, 31520, Ramonville Saint-Agne, France*
3. *Institute for Astronomical and Physical Geodesy, Technical University of Munich, Munich, Germany*

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2. Citation

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Table of contents

1. Licence	1
2. Citation	1
3. Data Description	1
3.1. Simulation approach and input assumptions.....	2
3.2. Data processing	2
4. File description	3
4.1. File inventory	4
4.2. File naming convention	4
4.3. Description of data tables	4
4.3.1. Spherical Harmonic Data (L2)	4
4.3.2. Gridded data (L2P, L3)	5

3. Data Description

Since 2002, time-lapse satellite gravimetry missions have successfully observed global time-variable mass transport. The GRACE (Gravity Recovery And Climate Experiment; Tapley et al., 2004, 2019) mission and its successor, GRACE-FO (GRACE-Follow On; Chen et al., 2022; Landerer et al., 2020), have almost continuously delivered monthly observations of the gravity field for more than two decades. As GRACE-FO approaches the end of its lifetime, new satellite gravity missions are planned for launch. For the continuation of the record, GRACE-C (GRACE-Continuity by NASA and the German Space Agency at DLR with support from GFZ, BMWK, BMFB, HGF and MPG) is planned to be launched in 2028 in a near-polar orbit at an altitude of ~500 km. GRACE-C will be followed by the Next Generation Gravity Mission (NGGM) launched by the European Space Agency (ESA) in 2032 in an inclined orbit of 65–70

degrees at an altitude of ~400 km. In their overlapping period, these two satellite pairs form the Mass-change And Geoscience International Constellation (MAGIC).

In the frame of the ESA SING (Studying the Impact of the NGGM and MAGIC Gravity missions) project (SING project website, 2026), extensive simulations have been performed to evaluate the added value of extended gravity field measurements in time with enhanced spatial and temporal resolution, and, reduced latency in data availability. Synthetic observations within this ESA-SING dataset have been generated at Levels 2 and 3 for GRACE-C-like, NGGM and MAGIC satellite configurations using a closed-loop numerical simulator integrating instrument noise, background model errors, and realistic satellite orbits. The simulations utilize target Earth signals from the ESA Earth System Model ESM 2.0 (Dobslaw et al., 2015), including hydrology, ice, and solid Earth components. Two parameterisation strategies used in this study yield simulated gravity solutions of mean fields at 5-day and 30-day resolutions. The other two strategies result in direct estimation of the trend and annual signal (*trendannual*) and direct estimation of the long-term trend (*trendonly*). For each parameterisation strategy, the data products are separated into three levels (*L2*, *L2P*, and *L3*). *L2* are Stokes coefficients of the simulated Earth's potential provided separately for each mission scenario and expressed in the spherical harmonic basis in ICGEM format. *L2P* and *L3* synthetic data represent simulated surface mass anomalies provided separately for each mission scenario and expressed in equivalent water heights over regular $1^\circ \times 1^\circ$ grids in NetCDF format. The *L3* data were corrected for Glacial Isostatic Adjustment (GIA), while the *L2P* data were not. The full description of the data and methods is provided in the data description publication (Schlaak et al. [in prep.](#)), and the file structure of this data set is fully described in the file inventory.

The resolution of all data products (*L2a*, *L2b*, *L2P*, *L3*) for each mission scenario (GRACE-C-like, NGGM, MAGIC) depends on the simulation type described in Schlaak et al. ([in prep.](#)). For 5-daily solutions, the spatial resolution corresponds to ca. 285 km (d/o 70). For monthly solutions, the temporal resolution is 30 days, with a spatial resolution of ca. 166 km (d/o 120). Trend and annual signals (trend-and-annual solutions) have been estimated simultaneously over a period of 12 years (with 1-year increments) and a spatial resolution of ca. 150 km (d/o 130). For trend-only solutions, the spatial resolution is increased to 125 km, with trend estimates over 5 and 12 years.

Additionally, empirical Variance-Covariance Matrices (VCMs) are provided for *L2a* and *L2b* data for the 5-daily and monthly simulation types, computed from Monte Carlo simulations (Schlaak et al., [in prep.](#)).

3.1. Simulation approach and input assumptions

The simulation approach follows the acceleration approach, and the parameterisation of the time variable gravity field is described in more detail in Schlaak and Pail (2025). The orbits for GRACE-C-like, NGGM and MAGIC constellations follow the MRD specifications (Daras et al., [in prep.](#)). The simulations are based on the acceleration approach (Rummel et al. 1976; Hauk 2020; Schlaak 2025), and comprise four parameterisation strategies for three mission scenarios over the 12-year period of ESA's Earth System Model (ESM) 2.0 (Dobslaw et al. 2015). To allow for realistic noise assumptions, tidal (in the form of ocean tide model differences and non-tidal background model errors (Dobslaw et al. 2016) have been considered in addition to instrument noise assumptions for the key payloads (Laser Ranging interferometer (LRI), accelerometers (ACC)) (Daras et al. [in prep.](#)), and tone errors (Pfaffenzeller et al. 2025).

3.2. Data processing

Data processing is evaluated and described in more detail in Schlaak et al. ([in prep.](#)). From the acceleration approach, spherical harmonics are computed from degree 2 to the maximum degree of the simulation depending on the temporal sampling considered (50 for 5-day, 120 for 30-day, 130 for

a parametric estimation of the trend and annual cycle, 160 for a parametric estimation of the trend only). The C00, C10, C11, S11 coefficients are estimated using the target signal (i.e. the HIS layers of ESA ESM2.0). These coefficients constitute the L2a datasets, provided separately for each mission configuration and each simulation type (5-day, 30-day, trend-and-annual, trend only).

L2b are generated from VADER-filtered L2a coefficients, taking the formal Variance-Covariance information and the scaled signal variance into account in the VADER filter. These filtered datasets are provided for monthly and 5-daily simulation types, always denoted by the letter 'b'.

L2P data convert L2a and L2b simulated geopotential anomalies into surface mass anomalies projected into a 1° equivalent water height grid in millimetres. Before the transformation, the C20 coefficient is replaced with the target signal value (C20 of HIS layers in ESA ESM2.0), assuming SLR accuracy (a white noise component is added with a mean and standard deviation typical of SLR noise). The transformation from L2P to L3 is realised by removing the GIA signal from the products using the linear trend in the S-component of the ESA ESM 2.0.

4. File description

L2a and L2b products, including Stokes coefficients, are in ICGEM format. L2P and L3 products, including equivalent water height grids, are in NetCDF format.

For ICGEM files, a file description is included in the header, describing the input assumptions, mission scenario, simulation type, and start, end, and middle epoch of the simulated gravity field. The maximum spatial resolution is described by the maximal degree and order in the header. Following the header, the columns include the spherical harmonic degree/order (L/M) of the cosine and sine coefficients of the simulation results (C & S), as well as the residuals (ΔC & ΔS) representing the coefficient differences between the simulation results and the reference HIS.

The empirical Variance-Covariance Matrices (VCM) are provided in MATLAB (.mat) format and contain two matrices. C ($C_{filtered}$, in case of L2b) corresponds to the VCM matrix, which is a square matrix with dimension length (d) dependent on the maximum degree and order of the product (l_{max}). Additionally, the variable (lmc) is provided to clarify the order of the coefficients in the VCM matrix. The first column indicates the SH degree, the second column the SH order. The third column indicates the coefficient type (0 for cos-coefficients, 1 for sin-coefficients).

The variables of the NetCDF files are listed in Table 3. The grids are provided in a regular one-degree EWH grid in millimetres. For the simulation types of trend-only and trend-and-annual, there are additional attributes for trend and annual signal amplitudes (Sim_trend, Sim_Sann, Sim_Cann) and residuals (Sim_trend, Sim_Sann, Sim_Cann). The reference grids are provided at the same spatial resolution as the simulation's maximum resolution. Additionally, a mission-independent omission error grid is provided that represents the signal between the maximum degree and order of the reference and the ESM up to d/o 180.

4.1. File inventory

The dataset is sorted by product level, as shown in Figure 1. For L2 data, the ICGEM files are stored with the following structure:

L2/<MissionScenario>/<SimulationType>/<ProductLevel>/

For high-frequency and monthly solutions, the products are subdivided for the respective year:

L2/<MissionScenario>/<SimulationType>/<ProductLevel>/timeseries/<year>/

The respective empirical VCMs and their diagonal values are provided in:

L2/<MissionScenario>/<SimulationType>/<ProductLevel>/empricalVCM/

For the higher product levels (L2P and L3), the mission constellations are summarised in each netCDF file; therefore, the grids are sorted in the archive following the following logic:

L3/<SimulationType>/

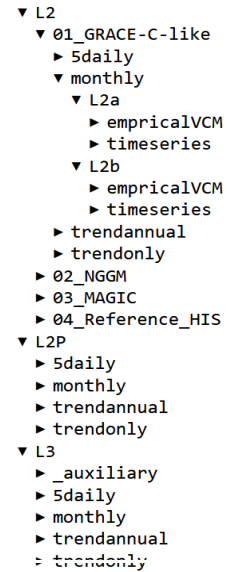


Figure 1: File tree overview of the dataset

4.2. File naming convention

The naming-convention of the ICGEM follows the structure:

shc_<Productlevel>_<Simulationtype>_<MissionScenario>_<StartDate>_<EndDate>_<lmax>.gfc

The naming-convention of NetCDF files follows the structure:

<Productlevel>_<Simulationtype>_<Period>.nc

4.3. Description of data tables

4.3.1. Spherical Harmonic Data (L2)

L2-data contains Stokes coefficients to the maximum degree and order resolution for the given simulation type, mission constellation, and temporal coverage. The beginning of the files contains comments with a brief description of the simulation environment and input assumptions, as well as generating institute and contact details. Following this description starts a header (Table 1), following the ICGEM standard (Förste et al. 2023), with the exception of the represented errors (Table 2). The errors in the ICGEM files of this data set are residuals representing the difference between the simulated observations and the target signal introduced into the simulations. After the header section of the file, the data section continues in tabular format (Table 2).

Table 1: Header section of the ICGEM files of the dataset

Row Header	Unit	Description
begin_of_head		The position of this keyword indicates the begin of the header section. All preceding lines are comment
Signal components		Description of Simulation input and reference signal
product_type		Field expressed in spherical harmonic coefficients e.g. 'gravity_field'
modelname		Name of the simulated model
earth_gravity_constant	m ³ s ⁻²	gravitational constant times mass of the earth
radius	m	reference radius of the spherical harmonic development

max_degree		maximum degree of the spherical harmonic development
errors		Errors that have been included. As the simulation allows a comparison with the ground truth the errors are 'residuals'
norm		either "fully_normalized" (=default) or "unnormalized"
end_of_head		The position of this keyword defines the end of the header

Table 2: header of each column of the data file.

Column Header	Description
key	Keywords (gfc, gfct,trnd,acos,asin)
L	Spherical harmonic degree
M	Spherical harmonic order
C	Cosine coefficient of Ddegree L and order M
S	Sine coefficient of Ddegree L and order M
ΔC	Residual errors of cosine coefficient
ΔC	Residual errors if sine coefficient
t0 [yyyymmdd] period [y]	Reference date (in case of 'gcf'), period in years (in case of asin and acos)

4.3.2. Gridded data (L2P, L3)

L2P and L3 data are NetCDF file formats that follow the structure of Table 3 for monthly and 5-daily products and the structure of Table 4 for trendannual and trendonly products. Each file contains grids of signals for each mission constellation, as well as a reference grid containing the target signal at the same spatial resolution. The grids are stored in latitude times longitude dimensions, with a temporal sampling along the third dimension.

Table 3: Variables of in the NetCDF files of the monthly and 5-daily products.

Name	Long Name	Unit	Dimension (5daily)	Dimension (monthly)
time	reference epoch	days (mjd)	876	146
lat	latitude	Degree north	180	180
lon	longitude	Degree east	360	360
	Reference	EWH mm	180*360*876	180*360*146
	'L3a_GRACE_C_Like_unfiltered'	EWH mm	180*360*876	180*360*146
	'L3a_NGGM_unfiltered'	EWH mm	180*360*876	180*360*146
	'L3a_MAGIC_unfiltered'	EWH mm	180*360*876	180*360*146
	'L3b_GRACE_C_Like_VADER_filtered'	EWH mm	180*360*876	180*360*146
	'L3b_NGGM_VADER_filtered'	EWH mm	180*360*876	180*360*146
	'L3b_MAGIC_VADER_filtered'	EWH mm	180*360*876	180*360*146
	'Omission_error'	EWH mm	180*360*876	180*360*146

Table 4: Overview of the variable of trend-only and trend-annual products for L2P, as an example, the same structure holds for L3 data of this simulation type.

Name	Long Name	Unit	Dimension (trendannual)	Dimension (trendonly)
time	Reference epoch	days (mjd)	1	1
lat	latitude	Degree north	180	180
lon	longitude	Degree east	360	360
sd	Start date	date	13	13
ed	End date	date	13	13
	'L2Pa_GRACE_C_Like_unfiltered_offset'	EWH mm	180*360*13	180*360*3
	'L2Pa_GRACE_C_Like_unfiltered_trend'	EWH mm/yr	180*360*13	180*360*3
	'L2Pa_GRACE_C_Like_unfiltered_acos'	EWH mm	180*360*13	
	'L2Pa_GRACE_C_Like_unfiltered_asin'	EWH mm	180*360*13	
	'L2Pa_NGGM_unfiltered_offset'	EWH mm	180*360*13	180*360*3
	'L2Pa_NGGM_unfiltered_trend'	EWH mm/yr	180*360*13	180*360*3
	'L2Pa_NGGM_unfiltered_acos'	EWH mm	180*360*13	
	'L2Pa_NGGM_unfiltered_asin'	EWH mm	180*360*13	

	'L2Pa_MAGIC_unfiltered_offset'	EWB mm	180*360*13	180*360*3
	'L2Pa_MAGIC_unfiltered_trend'	EWB mm/yr	180*360*13	180*360*3
	'L2Pa_MAGIC_unfiltered_acos'	EWB mm	180*360*13	
	'L2Pa_MAGIC_unfiltered_asin'	EWB mm	180*360*13	
	'Reference_offset'	EWB mm	180*360*13	180*360*3
	'Reference_trend'	EWB mm/yr	180*360*13	180*360*3
	'Reference_acos'	EWB mm	180*360*13	
	'Reference_asin'	EWB mm	180*360*13	
	'Omission_error_offset'	EWB mm	180*360*13	180*360*3
	'Omission_error_trend'	EWB mm/yr	180*360*13	180*360*3
	'Omission_error_acos'	EWB mm	180*360*13	
	'Omission_error_asin'	EWB mm	180*360*13	

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