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Next Generation Gravity Mission as a Mass-change And Geosciences International Constellation (MAGIC)

A joint ESA/NASA double-pair mission based on NASA's MCDO and ESA's NGGM studies

Mission Requirements Document

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1 INTRODUCTION

Evolution and continuity of gravity missions to observe mass change is foreseen by the end of 2020s to meet priority user needs not addressed by the existing and planned satellite infrastructure. In order to accomplish this objective a new mission to reinforce services by monitoring hydrology, cryosphere, oceanography, solid Earth and climate change is needed. This evolution will provide continuity of science and services with respect to predecessor missions like GRACE, GOCE and GRACE Follow-On and will be complementary to other Earth Observation, ESA Earth Explorer programme and Copernicus missions.

The Mission Requirements Document (MRD) reviews and formulates scientific/user and mission requirements for the Next Generation Gravity Mission (NGGM) elaborated as a Mass-change And Geosciences International Constellation concept. This includes the needs for NASA's Mass Change Designated Observable (MCDO).

International cooperation between ESA and NASA to prepare the next steps for developing a joint constellation for mass change and gravity monitoring has been carried out for several years. For NASA the current framework is that of the MCDO of the 2017 US Decadal Survey on Earth Science and Applications; for ESA it is that of the Next Generation Gravity Mission (NGGM), the first Mission of Opportunity as defined in the FutureEO Programme, following a.o. a successful series of missions in this domain, such as GOCE, the first Earth Explorer. Following interactions in the ESA-NASA Joint Programme Planning Group (JPPG), and leading to letters of intent for joint feasibility studies, Phase A activities for NGGM have been proposed, which will nominally lead to a proposal for implementing a joint ESA-NASA mission to be tabled at Space22+.

This document defines unambiguous and traceable requirements for preparing and developing the Mass-change And Geosciences International Constellation ('the mission' or 'MAGIC' in the text that follows). This constellation is a jointly designed ESA/NASA homogeneous double-pair mission answering global user community requirements.

The specified requirements are based upon the user requirements expressed by the International Union of Geodesy and Geophysics (IUGG), the NASA/ESA Interagency Gravity Science Working Group (IGSWG), the National Academies of Sciences, Engineering and Medicine (NASEM) Decadal Survey (DS) from 2017 [RD3] and additional requirements from recent literature not captured in the afore mentioned documents.

The scope of the MRD includes the end-to-end Earth observation system including user/scientific requirements, mission operations, data product development and processing, data distribution and data archiving.

The intention of the document is also to accommodate results from the Mass Change Designated Observable (MCDO) study from NASA [RD4][RD5] and previous ESA and national studies on the Next Generation Mass Change concepts [RD6][RD18][RD23][RD24][RD25][RD45][RD46][RD50].

The aim of MAGIC is to obtain high-resolution measurements in space and time and include the capability to determine the variations in gravity field due to mass change in hydrology, cryosphere, oceanography, solid Earth and climate change signals so as to serve science and operational products including emergency services.

It should be noted that this document is considered a living document, which will be updated after consultancy with experts and according to new requirement insights, and reissued at various milestones throughout the mission concept lifecycle.

The MAGIC Mission Requirements Document provides guidance and serves as an input to the European Space Agency (ESA) for the Phase-A/B1 initiated in 2020. The initial draft of this MRD was developed by the Ad-hoc Joint Science Study Team (AJSST). The version will be managed by the MAGIC JMCMEG (Joint Mass Change Mission Experts Group) coordinated by ESA and NASA headquarters in line with the ESA Quality Management System (QMS) procedure for Mission Requirements Management (QMS-PR-MMAN-2050-EOP) and Mission Implementation and Operations (ESA-EOP-QMS-PR-2100).

1.1 Document and Requirement Conventions

1.1.1 *Terms*

The term "**To Be Confirmed**" (**TBC**) will be used in combination with the numerical definition of some performance parameters, the final value of which may be changed by the Agency as a result of the Definition Study engineering work.

The term "**To Be Determined**" (**TBD**) will be used for the numerical definition of a parameter at a later stage. Engineering assumptions shall be made in consultation with the Agency for interim numerical definitions.

The terms "**shall**" and "**will**" denote mandatory requirements.

The terms "**should**" and "**may**" denote requirements whose implementation shall be discussed between the Contractor and the Agency.

1.1.2 Requirement Numbering

Within this MRD, requirements are identified by a unique alphanumeric code with the following format:

MRD-DDD

The digits DDD are requirements numbers. The sequence of these numbers may contain gaps and is independent for each combination of MRD-MMM. Some requirements are supported by explanatory comments, which are in a different style.

Requirements marked as "To be Defined" (TBD) or "To be confirmed" (TBC) indicate open issues and will be confirmed by the Mission Advisory Group (MAG) in the course of next phases.

1.2 Requirements and Guidelines

Compliance with all of the requirements specified within this document is necessary for the complete success of the mission. Harmonisation of the definition of these requirements and the technical design of the mission is necessary to ensure that the mission, as eventually implemented, will be capable of full compliance with the requirements.

All of the requirements specified herein shall be verified and traceability provided.

In addition to requirements, this document sometimes contains comments (identified in accordance with the convention defined in Section above) that indicate cases where an extension to the requirement may be desirable, even though a commitment to such performance cannot be confirmed or verified.

Similarly, comments may indicate guidance or limitations.

2 BACKGROUND AND JUSTIFICATION

Earth's mass and climate change play a critical role in gravity field variability. Global climate change and related phenomena such as sea level rise, aridification, have a widespread impact on society and generate alterations of gravity signals. Understanding and quantification of the related mass changes, their magnitude and impact is fundamental to mitigate the challenges ahead.

A long-term programme to monitor Earth's gravity field and its direct impact on hydrology, cryosphere, oceanography and solid Earth including consequences of climate change and extreme weather events is therefore of the utmost interest to both scientific users and national and international organizations. The provided service by MAGIC aims to extend the time series of predecessor and current missions like GRACE, GOCE and GRACE Follow-On enhancing resolution and accuracy. The joint collaboration between ESA and NASA provides a fundamental contribution to achieve a successful mission and enable the possibility to answer multiple scientific and societal questions.

As background to the assessment of the requirements for MAGIC, each of the main factors is addressed, alongside a description of the services the mission will sustain. The main thematic fields which will be investigated by MAGIC are listed in Table 1, further details are available in the following sections.

Table 1. Thematic fields and signals investigated by MAGIC

Thematic field	Signals/Quantities of interest
Hydrology	• Ground-water storage • Soil moisture • Extreme events warning (e.g. drought, flood) • Water balance closure • Global change impact on water cycle
Cryosphere	• Mass balance of ice sheets and glaciers • Contribution to global and regional sea level • Glacial isostatic adjustment (GIA)
Oceanography	• Ocean bottom pressure • Antarctic Circumpolar Current (ACC) and Atlantic Meridional Overturning Circulation (AMOC) variability • Tidal models • Heat and mass observations • Ocean circulation models
Solid Earth	• Geohazards • Deep interior properties and dynamics • Reshaping of Earth surface under external or internal forcing • Natural resources
Climate Change	• Sea-level change • Separation of contributors to the global water cycle
Neutral atmosphere	• Thermospheric neutral density • Thermospheric wind

2.1 User entities

Among the user entities which are playing a crucial role in the definition of the mission requirements it is possible to find the IUGG. The International Union of Geodesy and Geophysics is a non-governmental scientific organization dedicated to advancing, promoting and communicating knowledge of the Earth system, its space environment and the dynamical processes causing change. The IUGG is focused on the promotion and coordination of scientific studies including the shape of the Earth, its gravitational and magnetic fields, the dynamics of the Earth as a whole and of its components parts, the Earth's internal structure, composition and tectonics, earthquakes, volcanism, hydrological cycle, oceans, the atmosphere, magnetosphere and solar-terrestrial couplings. Within this MRD, the document entitled "*Observing Mass Transport to Understand Global Change and to Benefit Society: Science and User Needs*" from 2015 [RD1] was widely used to collect societal and scientific questions and requirements from users.

Another recurring reference based on users and scientific needs is the one from the NASA/ESA Interagency Gravity Science Working Group (IGSWG) [RD2]. The report developed by this group of experts aims at providing inputs for observing mass transport with high accuracy and spatial resolution with temporal scales from daily to monthly. The focus is on global change and to find possible applications to benefit society. The compatibility between user requirements, constellation concepts and expected performance is provided by the IGSWG members and collected in their report together with a roadmap for implementation in the Mass-change And Geosciences International Constellations.

Another main source used within the mission requirements definition is provided by the National Academies of Sciences, Engineering and Medicine with its Decadal Survey [RD3]. The target of this reference is to help shape science priorities and provide guidance for agency investments into the next decade. Main contributions come from scientific community and policy experts.

2.2 Hydrology

The variations in the terrestrial hydrological cycle are mostly due to the influence of natural climate variability, climate change and direct anthropogenic impact. An accurate understanding and monitoring of such variations is going to help hydrological research in the upcoming years and support efforts to safeguard the availability and quality of fresh water, ensure food security, preserve ecosystems and prevent and contain natural hazards. The main challenges include developing sustainable water management strategies, providing early warning for droughts and floods, balancing the needs of ecosystems, agriculture, and other water consumers and understanding and anticipating climate change and direct human impacts on the water cycle. Catchment scale hydrological information and availability and access to groundwater change data are growing demands for future applications.

2.3 Cryosphere

The existence, formation, transformation and dynamics of ice on land and in the ocean are part of the study of the cryosphere. The research of this thematic field is focused on the alteration of ice over global and regional scale and its coupling with climate change and anthropogenic effects. Numerous interactions with oceanography can be found. Indeed, sea ice formation is a large driver of the oceanic circulation, and continental ice mass changes directly induce global and regional sea level change. Due to the large amount of people living in near shore regions, the impact on societal security is of utmost importance. A further connection with hydrology can be detected in the study of glaciers which control regional hydrological systems. Monitoring and studying water retention help the water supply management providing the opportunity to avoid and/or mitigate hazards such as glacially induced flooding. Within this research a great interest is devoted to the ice sheets and large glaciers. In the last 30 years an accelerated decline in mass balance for ice sheets has been observed. This is for a large part due to the polar amplification of global warming and large-scale atmospheric and oceanic circulation patterns. Continuing to observe such trends and refining resolutions and time scales will enable better definition of the involved forcing, and sensitivity of the ice sheets and glaciers to external forcing, which is not sufficiently understood. An enhancement in prediction capabilities for the near-future evolution of ice sheets and sea-level rise poses an important societal and scientific challenge for the coming years.

2.4 Oceanography

The behaviour of the ocean needs constant observation and monitoring to understand and predict oceanographic processes. The mean sea level is presently rising globally at a rate of about 3 mm/yr due to the ocean warming and from mass input from melting ice sheets and glaciers. Sea level is rising faster at several coastal areas close to densely populated areas. Sea-level change is one of the biggest threats which society and scientists need to mitigate in the coming years. This main challenge is posed together with the need to better understand the changes in Earth's global mean surface temperature, the circulation patterns which regulate Earth's climate and the role of the atmosphere in heat fluxes. The accomplishment of all these challenges would allow to improve our ability to make more reliable short-term ocean and weather forecasts. Combining geoid and mean sea surface height from altimetry it is also possible to derive the Mean Dynamic Topography (MDT) of the ocean which is crucial to redistribute heat and thus regulate the Earth's climate.

2.5 Solid Earth

Within the study of the Solid Earth many societal and scientific challenges can be addressed by MAGIC. Monitoring the seismic cycle and all the geohazards associated to earthquakes, tsunamis and volcanoes has a direct influence on human life. With respect to the ground measurements, satellite gravity provides unique information to characterize undersea, deep-underground seismic sources and access areas which are difficult to investigate with ground observations. This includes a unique monitoring of both sides of all major plates boundaries. Tectonic processes leading to such catastrophic phenomena are linked to deep mantle and crustal processes. The next generation mass change mission shall provide insights about Earth's interior structure and dynamics creating a so called 4D Earth model which provides the capability to predict near-surface motion and deformation by the connection with geodynamic processes. Deciphering such processes involved in the creation, evolution and destruction of Earth's crust and their coupling with the climate system is a challenge which can be answered by MAGIC. Gravity can also help to separate present day water mass variations from past deglaciation effects (e.g. GIA), and more generally from all solid Earth deformation processes. This would support cryosphere, sea-level variations and ice loss monitoring and research, which are fundamental for climate science. A highly practical application of solid Earth can be found in the exploitation of natural resources such as minerals, hydrocarbons and water. The new generation mission will also enhance the capabilities to monitor underground fluid movements related to exploitation processes. The improved geology information would help to identify regions with natural resources deposits [RD56]. As highlighted for the previous thematic fields, a combination with other ground or remote sensing observations is crucial to improve current studies. The tectonic plate movements can indeed be observed by GNSS and Synthetic Aperture Radar (SAR) Interferometry (InSAR) measurements. However, these techniques cannot provide a global homogeneous spatial coverage and the same sensitivity to the interior mass displacement (over land and undersea) as satellite gravity.

2.6 Climate change

Estimating climate system trends and anthropogenic changes is intrinsically connected to a deeper understanding of the previous thematic fields. A step forward in this research can be accomplished with the new generation mass change and gravity mission with enhanced resolutions in space and time. The accomplishment of all the previously cited challenges would allow improvement in our ability to make more accurate predictions of the state of the climate system. One of the great targets of climate science is to move from climate projections to high-fidelity climate forecasts. This enhancement would provide a fundamental help to policy members to steer social and economic decisions in the right direction. Among the single signals, the rising sea level is one of the most serious threats due to the consequences of climate change. The water cycle directly responds to climate change. Understanding the impact of irrigation, land-use and storage components as groundwater, permafrost and glaciers is fundamental to cover current lack of information. However, their induced variations in the gravity field can help in determining and separating each of these different signals. To analyse long-term effects and make a clear distinction from anthropogenic effects, the most important objective is to generate continuous and longer time series (at least 30 years). This should be done in combination with higher spatial resolutions.
A deeper knowledge on the state of ice masses and the evolution of ice sheets and glaciers is also key for understanding the climate system and its driving forcing. However, climate change is also coupled with solid Earth deformations. Calculations of deformations due to the past deglaciation and the separation of multiple effects associated to ice or ocean mass variations are indeed crucial to improve our understanding of the climate system. A great contribution to make this possible comes from proper model initialization. At the initial state of the prediction the starting condition should describe reality as close as possible. In order to achieve such high accuracy, more refined resolutions, shorter time scales and combination with multiple observations need to be adopted to separate natural from human-made climate change effects and improve the current state of the art in climate sciences.
The global access of important water cycle components on and under land, ice, oceans and in the atmosphere is unique and helps explaining changes in sea level as a consequence of changes over land [RD10].

2.7 Atmosphere

As shown by the past gravity missions like CHAMP, GRACE and GOCE, the on-board instrumentation can be exploited for the derivation of neutral density and wind data. Reconstructing the satellite aerodynamics and using the accelerometer-derived accelerations, it is indeed possible to derive information on the neutral component of the atmosphere. The observed accelerations can provide high-resolution information about density variations in proximity of specific regions (e.g. polar caps) and events (e.g. geomagnetic storms) [RD38][RD39][RD40]. Extending the current measurements of thermospheric density and wind is crucial to fully characterize the neutral thermosphere and the coupling with ionosphere and magnetosphere. Additional data would also benefit studies on seasonal, local solar time, longitudinal and solar activity variations [RD1]. Longer time series would cover multiple solar cycles providing important inputs for studies on gas-surface interactions (GSI) and solar radiation pressure modelling, which play crucial roles in the density and wind estimation [RD41]. Simultaneous multiple observations from different platforms would allow for a wider description of the thermosphere providing also the opportunity for further data calibration/validation and additional scientific investigations on GSI modelling [RD41], transient phenomena in the upper atmosphere, and a better separation of local time and seasonal variations [RD1]. Beyond the use of on-board accelerometers, studies on the neutral density can also be performed using the GPS-derived accelerations as already demonstrated by the Swarm mission [RD42]. MAGIC will also help to improve the calibration of thermospheric density and wind models, and thereby enhancing the multi-decadal data record.

Atmospheric short-period mass variations can be better estimated with higher temporal resolution and accuracy. This would allow to derive new atmospheric parameters, which can be used to improve models quality and separate atmospheric signals from the sum of all mass variations [RD1].

2.8 Current gravity missions limitations

An enhancement of current capabilities is required to improve current gravity missions. This is especially required if regional and near-real time applications are needed. Achieving accurate purely satellite-based solutions on daily to weekly time scales was not possible with the previous generation of gravity missions. Indeed, currently this is only achievable in combination with models [RD57]. MAGIC aims at introducing this new objective to help current models and in particular to mitigate and introduce the capability to forecast extreme events.

The GRACE mission provided global observations of large-scale water storage variations. With this mission, basins and catchments were investigated over seasonal, inter-annual and long-term variations providing a precious input for hydrology research. However, the current limitations in such domain are still related to spatial sensitivity, accuracy and the length of time series. The typical size of basins is below the GRACE and GRACE-FO resolution. Indeed, depending on the signal strength, time scale and geographic location satellite gravity is currently limited to 200-500 km scales [RD1]. Even on larger scales, high accuracies with respect to such missions are also necessary to mitigate leakage effects in the storage changes estimations. The average latency for currently operational GRACE-FO is ~50 days. This needs to be reduced in the next missions. Near-real time analysis of gravity data with a reduced latency between few days and weeks is necessary for monitoring and forecasting hydrological extreme events. For all these reasons, for MAGIC higher resolutions and shorter latency for the release of new monthly (and/or sub-monthly) gravity fields are strongly recommended together with the fundamental requirement of continuous and extended time series [RD1]. Further improvements will be reached in the validation and calibration of precipitation data sets, land surface – atmosphere feedback, land use management and, in general, a better closure of the water cycle budget will be possible.

Similar considerations can be drawn for the cryosphere and oceanography research fields which also require long time series, higher spatial and time resolutions beside a better separation of different superimposed processes of mass redistribution.

Solid Earth signals from previous missions like GRACE provided great information about GIA, earthquake deformation and hydrologic signals. However, a mission targeting signals one order of magnitude smaller than currently possible enables a leap forward [RD1]. MAGIC could provide information on the accumulation of mass along active tectonic zones, separation of fault plane models and monitoring of locked seismic zones. The higher accuracy would benefit the combination with altimetry to separate GIA effects from cryosphere mass changes at low spatial scales, enhancing the capability to detect superimposed hydrological sources.

Using a double pair of satellites as proposed in the Bender concept [RD20] reduces the reliance on the de-aliasing models and the full signal (including the high frequency contents) can be observed reducing the significance of post-processing.

To characterize the main gravity and mass change signals under each of the previous thematic fields, further specifications on magnitudes, temporal scales and required accuracies are described in the next sections. The final requirements are provided in the list of mission requirement entries in Chapter 4.

3 MISSION PRIORITIES, AIMS AND OBJECTIVES

In this chapter, the observational priorities of the 'Mass-change And Geosciences International Constellation' are described. These priorities are then used to frame the overall mission aim, and to define the mission objectives.

3.1 User Priorities

The driving user requirements for the mission are set out in the following list:

1. Continuous and longer time series (at least 30 years) together with past and existing missions;
2. Higher spatial resolution at various time scales (daily to weekly, monthly to seasonal, long-term);
3. Shorter time scales (daily to weekly) for near-real time observations and monitoring of extreme events;
4. Reduced latency (from a few months to a few days and weeks).

The mass change signals are expected to enable the investigation on:

- Ground-water storage change;
- Soil moisture;
- Extreme events warning (e.g. drought, flood);
- Water balance closure;
- Global change impact on water cycle;
- Mass balance of ice sheets and glaciers;
- Global and regional sea level change;
- Global Isostatic Adjustment (GIA);
- Ocean bottom pressure;
- ACC and AMOC variability;
- Tidal models;
- Heat and mass observations for ocean;
- Ocean circulation models;
- Geohazards;
- Deep interior properties and dynamics;
- Reshaping of Earth surface under external or internal forcing;
- Natural resources;
- Water cycle separation of contributions.

3.2 Science/societal Questions and Objectives

Based on the user requirements and priorities outlined above, a set of high-priority science and societal questions and objectives are provided. The AJSST members collected the following science questions and user needs which can be answered by MAGIC. The questions are labelled with the first capital letter of the thematic field name followed by a numeric ID (e.g. *H1*). The necessary objectives to answer each question are listed just after adding an extra alphabetic ID (e.g. *H1-a*). The *Climate Change* thematic field is abbreviated with *CL*.
At the end of each thematic field it is possible to find a table summarizing spatial resolutions and accuracies. In the rest of this document, the spatial resolution is expressed as one side of a cell with

equal dimensions. For each sub-thematic field (or signal), the connection with the societal and science questions and objectives are also shown in a separate table. In ANNEX-A: TRACEABILITY MATRIX this link together with a full traceability of the requirements is included with a comparison with other gravity and mass change missions like GRACE, GRACE-FO and MCDO. All this information is provided by the Science Traceability Matrix (STM). In order to answer the questions and achieve the objectives listed in this section, the observations need to accommodate the user requirements available in the tables at the end of each of the next sub-sections. In order to generate these requirements, two main references were used: the IUGG report (Table 2) and the e.motion2 ESA proposal's bubble plot (Figure 1). Spatial resolutions are obtained from the e.motion2 study for each thematic field looking at the intersections of the mission's threshold curve with the signal bubbles, while the accuracies are generated interpolating the values from Table 2 and using as input the spatial resolution obtained from the e.motion2 proposal. The threshold requirements are defined by the community as the baseline desired to be achieved. Whereas the targets are more ambitious goals to be achieved.

Table 2. IUGG mission scenarios and performances (Table 1-1 from [RD1]). Scenario 1 and 3 are the IUGG threshold requirements and Scenario 2 and 4 are the target requirements.

Mission	Temp. res.	Performance				
		Spat. res.	Equivalent Water Height (EWH)	Geoid	Gravity anomaly	Gravity Gradient
GRACE	1 month	800 km (d/o 25)	7.5 mm / 0.75 mm/yr	0.15 mm / 0.015 mm/yr	0.25 μGal / 0.025 μGal/yr	10 μE / 1 μE/yr
		400 km (d/o 50)	25 mm / 2.5 mm/yr	0.25 mm / 0.025 mm/yr	1 μGal / 0.1 μGal/yr	0.1 mE / 0.01 mE/yr
		200 km (d/o 100)	0.5 m / 5 cm/yr	2.5 mm / 0.25 mm/yr	25 μGal / 2.5 μGal/yr	5 mE / 0.5 mE/yr
Scen. 1	1 month	800 km (d/o 25)	1.5 mm / 0.15 mm/yr	0.03 mm / 3 μm/yr	0.05 μGal / 5 nGal/yr	2 μE / 0.2 μE/yr
		400 km (d/o 50)	5 mm / 0.5 mm/yr	50 μm / 5 μm/yr	0.2 μGal / 0.02 μGal/yr	20 μE / 2 μE/yr
		200 km (d/o 100)	10 cm / 1 cm/yr	0.5 mm / 0.05 mm/yr	5 μGal / 0.5 μGal/yr	1 mE / 0.1 mE/yr
		150 km (d/o 133)	50 cm / 5 cm/yr	1 mm / 0.1 mm/yr	10 μGal / 1 μGal/yr	5 mE / 0.5 mE/yr
		100 km (d/o 200)	5 m / 0.5 m/yr	10 mm / 1 mm/yr	200 μGal / 20 μGal/yr	50 mE / 5 mE/yr
Scen. 2	1 month	800 km (d/o 25)	0.15 mm / 0.015 mm/yr	3 μm / 0.3 μm/yr	5 nGal / 0.5 nGal/yr	0.2 μE / 0.02 μE/yr
		400 km (d/o 50)	0.5 mm / 0.05 mm/yr	5 μm / 0.5 μm/yr	0.02 μGal / 0.002 μGal/yr	2 μE / 0.2 μE/yr
		200 km (d/o 100)	1 cm / 0.1 cm/yr	0.05 mm / 0.005 mm/yr	0.5 μGal / 0.05 μGal/yr	0.1 mE / 0.01 mE/yr
		150 km (d/o 133)	5 cm / 0.5 cm/yr	0.1 mm / 0.01 mm/yr	1 μGal / 0.1 μGal/yr	0.5 mE / 0.05 mE/yr
		100 km (d/o 200)	0.5 m / 0.05 m/yr	1 mm / 0.1 mm/yr	20 μGal / 2 μGal/yr	5 mE / 0.5 mE/yr
Scen. 3	1 day	800 km (d/o 25)	15 mm	0.3 mm	0.5 μGal	20 μE
		400 km (d/o 50)	50 mm	0.5 mm	2 μGal	200 μE
Scen. 4	1 day	800 km (d/o 25)	1.5 mm	0.03 mm	0.05 μGal	2 μE
		400 km (d/o 50)	5 mm	0.05 mm	0.2 μGal	20 μE

Multiple thresholds and targets (Threshold-a, Threshold-b, etc.) are introduced in the next sections in order to cover most of the useful resolutions ranges for different applications. The different threshold and target requirements are interpolated from the IUGG requirements in Table 2 in combination with the signal boundaries and extent provided in Figure 1 (See also ANNEX-A: TRACEABILITY MATRIX). Long-term trend requirements are also expressed and are valid for the nominal 7-year mission lifetime.

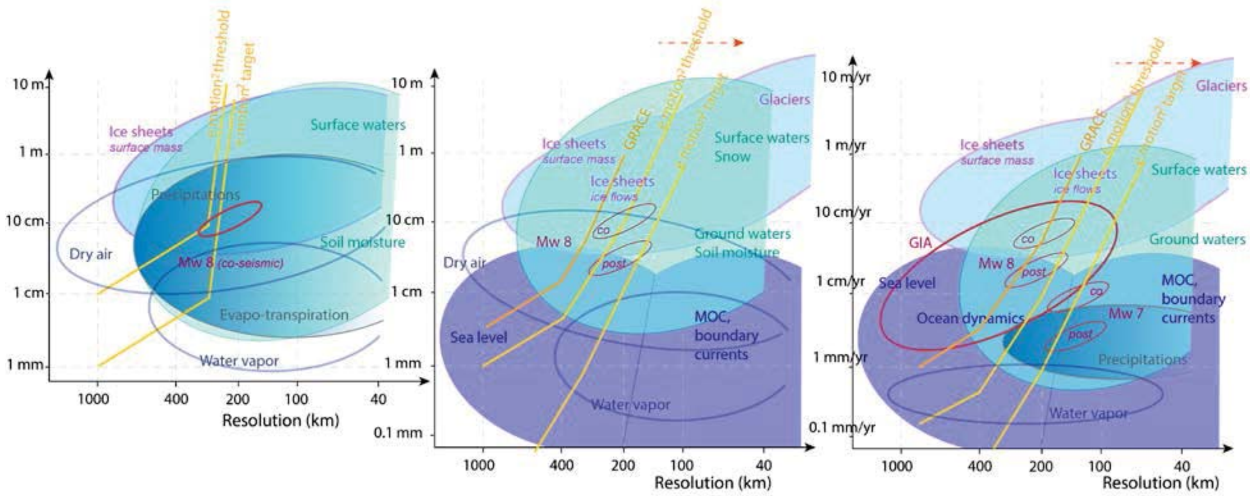


Figure 1. Signal amplitudes of mass variations in EWH as a function of spatial resolution, together with GRACE accuracy and resolution, and e.motion2 expected threshold and target requirements (Figure 1-8 from [RD6]). Three different time scales are shown: on the left the daily to weekly, in the middle the monthly to seasonal and on the right the long-term trend.

3.2.1 Hydrology

Within the "Hydrology" thematic field, the following societal and science questions and objectives need to be answered and achieved by MAGIC with complementary information:

H1: How is the **water cycle** changing? How are these changes expressed in frequency and magnitude of extremes events such as droughts and floods? Is it possible to close the **water budget** on various spatial and temporal scales?

- **H1-a**. Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins (confined to scales larger or equal than 150x150 km^2). Provide constraints of the net fluxes.
- **H1-b**. Quantify rates of snow accumulation, snowmelt and ice melt at regional scales.
- **H1-c**. Estimate water storage change in small river basins and separate medium-scale drainage basins.

H2: How do **anthropogenic changes** in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences? Is it possible to identify the **climate change signature** on the hydrological cycle?

- **H2-a**. Quantify the magnitude of anthropogenic processes that cause changes in snowmelt, and ice melt, as they alter downstream water quantity (See CL2).

- **H2-b**. Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management, affect water storage and especially groundwater recharge, threatening sustainability of future water supplies.
- **H2-c**. Drive and constrain predictive hydrological models with gravity data. Quantify individual natural and human-driven influences on the water cycle, as well as the separation of the different effects in a joint effort of combining modelling approaches and observations.

H3: How do changes in the water cycle **impact local and regional** freshwater availability-and the services these provide?

- **H-3a**. Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages in and between all reservoirs (atmosphere, rivers, lakes, groundwater, and glaciers) and the response to extreme events as a basis for developing sustainable water resource management strategies.

H4: How does the water cycle interact with other Earth system processes to change the predictability and impacts of hazardous events and hazard chains (e.g. floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related **extreme events**? How can we improve seasonal climate forecasts and the predictions of such extreme scenarios?

- **H4-a**. Improve drought and flood monitoring to forecast short-term impacts more accurately and to assess potential mitigations based on near real-time observations. Include gravity data into operational forecasting of drought and flood events (from long- to short-term).

The previous science and societal questions and objectives are connected to the specific signals in the following Table 3. The user requirements are collected in Table 4.

Table 3. Societal and science questions and objectives link to specific hydrology signals.

Thematic field	Signal	Scientific/societal Questions & Objectives
Hydrology	Ground-water storage	Q: H1, H2, H3, CL2; O: H-1a, H-1c; H2-b, H2-c; H-3a; H4-a; CL-2a
	Soil moisture	Q: H1, H2, H3, CL2; O: H-1a, H1-c; H2-b, H2-c; H-3a; H4-a; CL-2a
	Extreme events warning (e.g. drought, flood)	Q: H1, H3, H4; O: H-1a; H-2c; H-3a; H4-a
	Water balance closure	Q: H1, H2, H3, CL2; O: H-1a, H-1c; H-2b, H-2c; H-3a; CL2-a
	Global change impact on water cycle	Q: H1, H2, H3, CL2; O: H-1a, H-1c; H2-b, H2-c; H-3a; CL-2a

Table 4. MAGIC user requirements for Hydrology (Ground-water storage, Soil moisture, Extreme events warning, Water balance closure, Global change impact on water cycle). Values are obtained from IUGG user requirements [RD1] and the e.motion2 proposal [RD6]. At the bottom of the table a few additional requirements are obtained from specific references which are available in the STM table at the end of the document (Annex-A).

Thematic field	**Time scale** **D**: Daily to weekly; **M**: Monthly; **L**: Long-term trend	**Threshold: Resolution & Accuracy [EWH]**	**Target: Resolution & Accuracy [EWH]**
Hydrology	**D**	Threshold-a: 600 km @ 3.2 cm; Threshold-b: 300 km @ 5.9 cm; Threshold-c: 280 km @ 6.0 cm	Target-a: 600 km @ 0.3 cm; Target-b: 300 km @ 0.6 cm; Target-c: 280 km @ 0.6 cm
	M	Threshold-a: 400 km @ 0.5 cm; Threshold-b: 260 km @ 4.8 cm	Target-a: 400 km @ 0.05 cm; Target-b: 260 km @ 0.48 cm
	L	Threshold-a: 350 km @ 0.1 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 350 km @ 0.01 cm/yr; Target-b: 150 km @ 0.5 cm/yr
Thematic sub-field			
Ground-water storage	**L**	See Hydrology	Target: 200 km @ 0.1 cm/yr
Water balance closure	**M**	See Hydrology	Target: 200 km @ 1 cm
Global change impact on water cycle	**L**	See Hydrology	Target: 200km @ 0.1 cm/yr

3.2.2 Cryosphere

Within the "Cryosphere" thematic field, the following societal and science questions and objectives need to be answered and achieved by MAGIC with complementary information:

C1: How much will ice sheets contribute to sea level change, globally and regionally, over the next decade and beyond? How can we determine the changes of ice sheets?

- **C1-a**. Determine the contribution of the ice sheets and mountain glaciers to global mean sea-level change to within 0.1 mm/yr over the course of a decade (assuming 15 Gt/yr [See C2-b]).
- **C1-b**. Improve the knowledge on the dynamic response of ice flow to changing oceanic and atmospheric boundary conditions, including interactions with intra- and sub-glacial hydrology [See C2].
- **C1-c**. Determine the contribution of ice sheets and mountain glaciers to regional patterns of sea-level change to within 0.05 mm/yr over the course of a decade.

C2: What will be the consequences of climate change on mass changes of ice sheets and glaciers?

- **C2-a**. Reduce current uncertainties related to mountain glaciers and ice caps relative to the “eustatic” contribution to sea level rise.
- **C2-b**. Determine the changes in surface mass balance and glacier ice discharge and uncertainties within the 15 Gton/yr accuracy over the entire ice sheets, continuously, for decades to come. Disentangle the superimposed processes from a combination of geodetic observations and modelling approaches (See Solid Earth).
- **C2-c**. Improve modelling capabilities to fully understand ice sheet and glacier changes and provide enhanced robust predictions. Enhance number and accuracy of observations. Validate model developments, provide boundary conditions and allow model initialization. Understand the processes revealed by observations for further developing models with the aim of reaching predicting capabilities for emergency applications like meltwater flooding.
- **C2-d**. Separating ice sheet changes from coastal ocean changes. This task includes the account for the gravitationally consistent ocean changes induced by the ice mass changes themselves, as well as changes due to ocean dynamics.
- **C2-e**. Cryosphere mass balance at monthly to decadal time scales to understand climate forcing on ice sheets and glaciers.

C3: : How can we improve the description of **geodynamic processes, induced by continental ice mass changes,** which act globally? How can we better interpret Glacial Isostatic Adjustment (GIA) and distinct spatial “fingerprints” of global oceanic mass redistributions?

- **C3-a**. Improve the information on glacial history and solid Earth rheology, as well as consistency in the observing systems, and therefore embrace a large range of geoscience disciplines. Gravity has a key role due to its integrative nature and its direct relationship to conditions of mass conservation between changes in the cryosphere, the oceans and continental hydrology.

The previous science and societal questions and objectives are connected to the specific signals in the following Table 5. The user requirements are collected in Table 6.

Table 5. Societal and science questions and objectives link to specific cryosphere signals.

Thematic field	Signal	Scientific/societal Questions & Objectives
Cryosphere	Cryosphere mass balance	Q: C1, C2, C3, CL2; O: C-1b; C-2a, C-2b, C-2d, C-2e; C3-a; CL-2a, CL-2b
	Global and regional sea level	Q: C1, C2, CL1, CL2; O: C-1a, C-1c; C-2a; CL-1a, CL-1b; CL-2a
	GIA	Q: C1, C2, CL2; O: C-1a, C-1c; C-2a; CL-2a, CL-2b
	Mass changes of ice sheet and glaciers	Q: C1, C2, CL2; O: C-1b; C-2a, C-2b, C-2c, C-2d, C-2e; CL-2a, CL-2b

Table 6. MAGIC user requirements for Cryosphere (Cryosphere mass balance, Global and regional sea level, GIA, Mass changes of ice sheet and glaciers). Values are obtained from IUGG user requirements [RD1] and the e.motion2 proposal [RD6]. At the bottom of the table a few additional requirements are obtained from specific references which are available in the STM table at the end of the document (Annex-A).

Thematic field	Time scale D: Daily to weekly; M: Monthly; L: Long-term trend	Threshold: Resolution & Accuracy [EWH]	Target: Resolution & Accuracy [EWH]
Cryosphere	**D**	Threshold-a: 400 km @ 5.0 cm; Threshold-b: 300 km @ 5.9 cm; Threshold-c: 250 km @ 6.3 cm	Target-a: 400 km @ 0.5 cm; Target-b: 300 km @ 0.6 cm; Target-c: 250 km @ 0.6 cm
	M	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm
	L	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr
Thematic sub-field			
GIA	**M**	See Cryosphere	Target: 200 km @ 1.0 cm
	L	See Cryosphere	Target: 150 km @ 0.2 cm/yr
Mass changes of ice sheet and glaciers	**L**	See Cryosphere	Target: 200 km @ 0.1 cm/yr

3.2.3 Oceanography

Within the "Oceanography" thematic field, the following societal and science questions and objectives need to be answered and achieved by MAGIC with complementary information:

O1: How are decadal-scale global ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?

- **O1-a**. Quantify the changes in the oceanic circulation patterns, reducing the uncertainty by a factor of 2.
- **O1-b**. Quantify the linkage between natural and anthropogenic forcing and oscillations in the climate system and the one between the dynamical and thermodynamic state of the ocean on decadal time scales. For both, reduce the uncertainty by a factor of 2.
- **O1-c**. Quantify the linkage between global climate sensitivity and circulation change on regional scales, including the occurrence of extremes and abrupt changes. Quantify the changes in the strength of AMOC to within 5% per decade; changes in ENSO spatial patterns, amplitude, and phase.

- **O1-d**. Provide observational verification of models used for climate projections. Enhanced simulations on evolution of the large-scale patterns in the ocean circulation and tides are necessary. Improving descriptions nearby coasts and current de-aliasing is crucial. Improved tidal models by co-estimation of ocean tide parameters requires long time series as well as increased accuracy compared to the current state.
- **O1-e**. The ocean bottom pressure variations and the time mean dynamic topography can be provided by satellite gravity missions which are a powerful tool for investigating the ocean's internal dynamics. It mainly requires an improvement in spatial resolution. Combination with altimetry needs further improvement.

The previous science and societal questions and objectives are connected to the specific signals in the following Table 7. The user requirements are collected in Table 8.

Table 7. Societal and science questions and objectives link to specific oceanography signals.

Thematic field	Signal	Scientific/societal Questions & Objectives
Oceanography	Sea-level change	Q: O1, CL1, CL2; O: O-1a, O-1b; O-1c, O-1d, O-1d; CL1-a; CL-2a, CL-2b
	Ocean bottom pressure	Q: O1; O: O-1c, O-1e
	ACC and AMOC variability	Q: O1; O: O-1a, O-1c, O-1d
	Tidal models	Q: O1; O: O-1d
	Heat and mass observations	Q: O1, CL1, CL2; O: O-1a, O-1b, O-1c, O-1d, O-1d, O-1e; CL-1b; CL-2a, CL-2b
	Ocean circulation models	Q: O1; O: O-1a, O-1b, O-1c, O-1d, O-1e

Table 8. MAGIC user requirements for Oceanography (Sea-level change, Ocean bottom pressure, ACC and AMOC variability, Tidal models, Heat and mass observations, Ocean circulation models). Values are obtained from IUGG user requirements [RD1] and the e.motion2 proposal [RD6]. At the bottom of the table a few additional requirements are obtained from specific references which are available in the STM table at the end of the document (Annex-A).

Thematic field	Time scale **D**: Daily to weekly; **M**: Monthly; **L**: Long-term trend	Threshold: Resolution & Accuracy [EWH]	Target: Resolution & Accuracy [EWH]
Oceanography	**D**	N.A.	N.A.
	M	Threshold-a: 1000 km @ 0.2 cm; Threshold-b: 400 km @ 0.5 cm; Threshold-c: 250 km @ 5.5 cm.	Target-a: 1000 km @ 0.02 cm; Target-b: 400 km @ 0.05 cm; Target-c: 250 km @ 0.55 cm.
	L	Threshold-a: 800 km @ 0.015 cm/yr; Threshold-b: 400 km @ 0.05 cm/yr; Threshold-c: 180 km @ 1.8 cm/yr.	Target-a: 800 km @ 0.0015 cm/yr; Target-b: 400 km @ 0.005 cm/yr; Target-c: 180 km @ 0.18 cm/yr.
Thematic sub-field			
ACC and AMOC variability	**M**	See Oceanography	Target: 200 km @ 1.5 cm
Tidal models	**D**	Threshold: 400 km @ 5.0 cm	Target: 400 km @ 0.5 cm
Heat and mass observations	**D**	Threshold: 400 km @ 5.0 cm	Target: 400 km @ 0.5 cm
	M	See Oceanography	Target: 200 km @ 1.0 cm

3.2.4 Solid Earth

Within the “Solid Earth” thematic field, the following societal and science questions and objectives need to be answered and achieved by MAGIC with complementary information:

S1. How can large-scale geological hazards be accurately forecast in a socially relevant time frame? How do geological disasters directly impact the Earth system and society following an event? How can we monitor geohazards associated with earthquakes, tsunamis and volcanoes?

- **S1-a**. Measure and forecast inter-seismic, pre-seismic, co-seismic, and post-seismic activity over tectonically active areas on time scales ranging from hours to decades to distinguish the instant effects from long-term movements. Detect tectonic, aseismic creep events equivalent to magnitude >7.
  Rapid capture of the transient processes following disasters is needed for improved predictive modelling, as well as response and mitigation through optimal re-tasking and analysis of

space data. A spatial resolution of 200 km with an accuracy of 0.5 μGal is needed. Monthly resolution is required, acquisition of daily to weekly data with low latency is vital for specific short-term monitoring.
- **S1-b**. Forecast, model, and measure tsunami generation, propagation, and run-up for major tsunamigenic events.

S2. How does energy flow from the core to Earth's surface? Can we better quantify the physical properties in the deep interior and their relationship to deep and shallow geodynamic processes?

- **S2-a**. Determine the effects of convection within Earth's interior, specifically the dynamics of Earth's core and its changing magnetic field and the interaction between mantle convection and plate motions.
  If high accuracy (signals amplitude: 0.5-1 mm EWH in 10 years) can be reached at long wavelengths (thousands km) and decadal timescales, on-going deep Earth dynamics may become observable: geostrophic flows near the top of the core that change pressures at the CMB [RD15], on-going large-scale convective mantle flow [RD13].
  Time-integrated body tides perturbations from the heterogeneous mantle mass distribution are 10 times larger than the above deep Earth dynamics signals, reaching 0.5-1 mm EWH in one year [RD14]. Observe gravimetric perturbations caused by tidal forcing of convection-induced mantle heterogeneity.

S3. How can we jointly quantify and improve separation of the ongoing solid Earth deformation in response to surface loads, as the last deglaciation (i.e., the post-glacial rebound (GIA) signal), or resulting from the internal dynamics, together with the present-day ice sheet loss and water mass variations [RD1][RD16]?

- **S3-a**. Identification of long-term effects and the separation from annual to inter-annual climatic factors which affect surface deformation of the crust: time series length in combination with past and existing missions of at least 30 years is required. A long time series characterized by a trend accuracy of 0.05 μGal/yr on scales of 200 km will be critical to provide regional-scale estimates of ongoing crustal deformation across the topographic land surface, ocean bottom and lower crustal boundary.
- **S3-b**. Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface due to surface processes, tectonics, and societal activity.
- **S3-c**. Distinguish the creeping portions of subduction zones from the locked portion, which is crucial for hazard estimation of the inter-seismic interval of large earthquakes, or to observe regional tectonic processes as mountain building. By constraining Earth's low viscosity layers, it will enable characterization of the coupling between the plates and the mantle in active and oceanic areas.
- **S3-d**. As long-term processes are involved, the most important aspect is a continuous time series in combination with an increased spatial resolution. The minimum required time series for this mission is 6 years. Monthly resolution is adequate.

S4. How much water is traveling deep underground and how does it affect geological processes over the long term and short term (earthquakes) and water supplies (e.g. water management)? How do we improve discovery and management of energy, mineral, and soil resources? How can we achieve sustainable exploitation of natural resources?

- **S4-a**. Improve spatial resolution for imaging of the 3D structure of the crust and mantle using the static gravity field. This is needed in order to locate and monitor changes in key resources.

- **S4-b**. Monitor underground anthropogenic driven mass variations. Monthly resolution is adequate, weekly resolution is desirable.

- **S4-c**. Measure all significant fluxes in and out of the groundwater system across the recharge area. Determine the transport and storage properties in situ within a factor of 3 for shallow aquifers and an order of magnitude for deeper systems. Assess the impact of these water redistributions on earthquakes.

The previous science and societal questions and objectives are connected to the specific signals in the following Table 9. The user requirements are collected in Table 10.

Table 9. Societal and science questions and objectives link to specific solid Earth signals.

Thematic field	Signal	Scientific/societal Questions & Objectives
Solid Earth	Geohazards	Q: S1, S3, S4; O: S-1a, S-1b; S-3c; S-4c
	Evolution of Earth's crust under external or internal forcing	Q: S2, S3, S4; O: S-2a; S-3a, S-3b, S-3c, S-3d; S-4a
	Natural resources exploitation	Q: S4; O: S-4a, S-4b, S-4c
	Deep interior properties and dynamics	Q: S2, S3; O: S-2a; S-3a, S-3b, S-3c, S-3d

Table 10. MAGIC user requirements for Solid Earth (Geohazards, Evolution of Earth's crust under external or internal forcing, Natural resources exploitation, Deep interior properties and dynamics). Values are obtained from IUGG user requirements [RD1] and the e.motion2 proposal [RD6]. At the bottom of the table a few additional requirements are obtained from specific references which are available in the STM table at the end of the document (Annex-A).

Thematic field	Time scale **D**: Daily to weekly; **M**: Monthly; **L**: Long-term trend	Threshold: Resolution & Accuracy [EWH]	Target: Resolution & Accuracy [EWH]
Solid Earth	**D**	Threshold: 300 km @ 6.0 cm	Target: 300 km @ 0.6 cm
	M	Threshold-a: 350 km @ 1.0 cm; Threshold-b: 180 km @ 18 cm.	Target-a: 350 km @ 0.1 cm; Target-b: 180 km @ 1.8 cm.
	L	Threshold-a: 250 km @ 0.5 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 250 km @ 0.05 cm/yr; Target-b: 150 km @ 0.5 cm/yr
Thematic sub-field			
Geohazards	**D**	Threshold: 300 km @ <10.0 cm (Mw 8 earthquakes)	Target: <250 km @ 10.0-1.0 cm
	M	Threshold: 300 km @ 1-2 cm (Mw 8 earthquakes)	Target: 200 km @ 1.0 cm (Mw > 7 earthquakes)
	L	Threshold: 200 km @ 1 cm/yr	Target: 100 km @ 1.0 cm/yr
Evolution of Earth's crust under external or internal forcing	**L**	See Solid Earth	Target-2c: <100 km @ 10 cm/yr
Natural resources exploitation	**D**	Threshold: 300 km @ 10.0 cm	Target: <250 km @ 10.0-1.0 cm
Deep interior properties and dynamics	**D**	See Solid Earth	Target: 6000 km @ 0.15 mm (Body tides)
	L	See Solid Earth	Target-a: 2000-6000 km @ 0.05-0.1 mm in 10 yr; Target-b: 230-330 km @ 1 mm in 10 yr

3.2.5 Climate change

Within the "Climate Change" thematic field, the following societal and science questions and objectives need to be answered and achieved by MAGIC with complementary information:

CL1: How much will sea level change, globally and regionally, and along coastlines over the next decade and beyond, and what will be the role of ocean heat storage?

- **CL1-a**. Quantify the rates of sea-level change and its driving processes at global and regional scales.
- **CL1-b**. Determining how and where heat is being taken up by the ocean, estimating how much is being stored in the deep ocean, and understanding the processes that control this are all important to understand sea level rise and improve the predictive skill of climate models.

CL2: Is it possible to separate the effects of natural climate variability, long-term climate change and direct anthropogenic impacts on the water cycle?

- **CL2-a**. Evaluate seasonal to decadal climate predictions and assess long-term climate model projections [RD11] [RD10].
- **CL2-b**. Ensure the continuation of current mass transport observations to provide multi-decadal time series [RD21] [RD22].

3.3 Mission Objectives

The aim is reached by implementing objectives that address specific scientific and technical aspects. Mission requirements of MAGIC are then derived from Mission Objectives. The complete list of objectives can be also obtained in the Science Traceability Matrix (STM) table delivered by the AJSST members. The details are available in Section 3.2 and ANNEX-A: TRACEABILITY MATRIX. Each signal has a connection with at least one of the scientific/societal questions introduced in the previous chapter. Short, medium and long-term mass changes are analysed for each thematic field creating a detailed view on the high spatial resolution observations over different time scales.

The **objectives** of the mission for the time scales daily to weekly, monthly to seasonal and long-term are:

- **OBJ-1.** to measure and monitor the mass change and improve current estimations of ground-water storage, soil moisture, water balance closure, global change impacts on water cycle, providing the capability to raise extreme events warning (e.g. drought, flood).
- **OBJ-2.** to measure and monitor the cryosphere mass balance, the global and regional sea level, the Glacial Isostatic Adjustment (GIA), including the estimation of mass changes for ice sheet and glaciers.
- **OBJ-3.** to provide mass and sea level change and heat estimates for oceanography to improve tidal and ocean circulation models. Such information will also serve as critical input to operational oceanography and marine forecasting services as well as sea ice monitoring in the polar oceans.
- **OBJ-4.** to measure and monitor the mass change on Earth's deep interior properties and dynamics, Earth's crust under internal or external forcing, including observations for improvements in natural resources exploitation and assessment of effects of geohazards (e.g. earthquakes, tsunamis and volcanic activities).
- **OBJ-5.** to measure and monitor the mass change and its trends for climate change applications.
- **OBJ-6.** to provide measurements of mass change for ground-water storage and global change impact on water cycle applications for extreme events warnings and soil moisture.
- **OBJ-7.** to provide measurements of mass change for estimations of cryosphere mass changes including ice sheet and glaciers.
- **OBJ-8.** to support monitoring applications of geo-hazards (including Mw 8 earthquakes and Mw 7 as target) over few hundred kilometres areas and deep interior properties and dynamics over large spatial scales (e.g. 6.000 km) for estimating Body tides at millimetre accuracy.
- **OBJ-9.** to provide measurements of thermosphere neutral density and wind.
- **OBJ-10.** to provide new atmospheric parameters to separate atmospheric signals from the mass variation measurements.

4 MISSION REQUIREMENTS

This Chapter provides a quantitative description and justification of the Level-2 geophysical requirements that would enable fulfilling the mission objectives and of the associated Level-1 observation requirements, including the level of priority, the rationale for their derivation, either explicitly or by reference to previous studies, experiences or publications, in such a way that each observation requirement is traceable to the geophysical requirements and that the consequence of a possible partial compliance of the observing system with the observation requirement can be assessed.

Complementary to the mission requirements, auxiliary indicative Level-2 performance levels of MAGIC are provided based on full-scale simulations performed in the frames of ESA projects [RD45] and related publications [RD25]. The results in terms of cumulative EWH errors per SH degree of expansion are provided in ANNEX-B: Auxiliary simulations for the relevant temporal scales (i.e. daily-to-weekly, monthly, long-term). The assumptions taken on the instrument noise levels as well as the background models used in the processing (e.g. Ocean Tide model errors) are rather pessimistic. This results to a significant performance margin included with respect to the expected performance levels.

4.1 Constellation Requirements

4.1.1 Lifetime

MRD-010	The operational lifetime of the mission shall be at least 7 years.
	Note 1: The operational lifetime is 7 years assuming a nominal commissioning of 6 months. The lifetime is for each single satellite. *Note 2: A long-term programme is required to monitor hydrology, oceanography and solid Earth and to detect longer-term trends at high spatial resolution. Extend programme of record to achieve climate series beyond 30 years.*

4.1.2 Constellation Observation Requirements

The so-called Bender constellation consisting of two pairs of satellites flying at two different orbit inclinations was identified as the most promising concept and is recommended for MAGIC. This constellation type is favoured over other formations due to its good performance for gravity field retrieval and technical feasibility. The latter, stemming from the fact that the satellites are flying in inline formation, imposes less constraints on the satellites' design compared to other more complex formations. In [RD27], the Bender-type constellation is investigated in detail with the aim to optimize the gravity retrieval. Since aliasing of fast atmospheric and oceanic mass variations is considered to be a major limitation, [RD27] also reviewed methods for reducing this effect. The Wiese method [RD28] was selected, further developed [RD35] and used throughout [RD27] for a deep analysis of 10 well-performing Bender-type constellations. Beyond the Bender concept previously introduced, further studies about Pendulum with a single or double pair were also performed and are available in the literature [RD46][RD43][RD44][RD48][RD49]. For gravity field measurements, there are three essential needs: flying as low as possible in order to maximize the signal strength, keeping the retrieval period as short as possible to maximize the time resolution of the gravity field solutions, and to ensure that the ground track coverage is dense enough within the retrieval period for maximizing spatial resolution. The following observation requirements aim at satisfying all these points and the previous studies.

MRD-020 The mission shall deliver global observations. Optimally observations between +90 deg and -90 deg latitude shall be delivered.

Note 1: In case specific requirements on satellite operations apply, a small deviation down to 89 deg latitude can be accepted.

MRD-030 The constellation shall consist of two pairs. The first one in near-polar orbit (89-90 deg) and the second one with an orbit inclination between 65-70 deg.

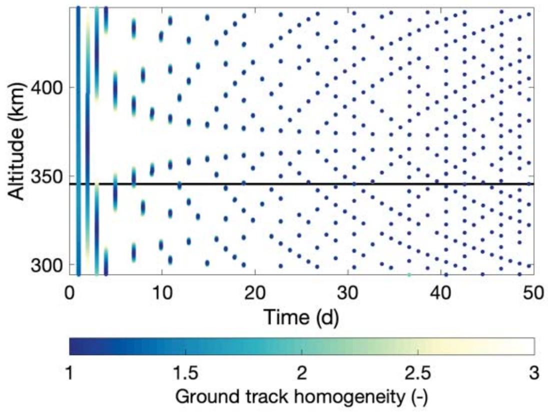
Note 1: It is assumed that the satellite pairs are inline or pendulum formations.

MRD-040 The mission shall provide a near-homogeneous sampling over a sub-cycle of 5-7 days.

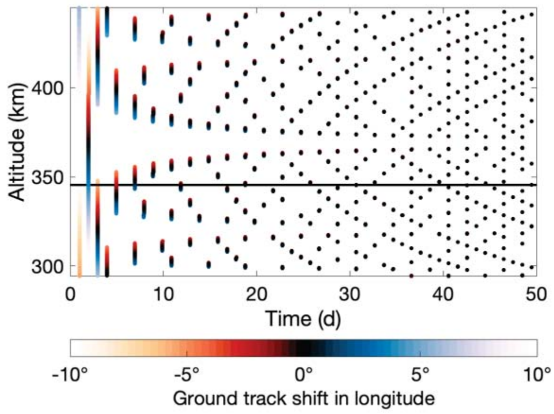
Note 1: To quantify the density of the spatial sampling at a predefined number of orbital revolutions, it is necessary to define the ground track homogeneity. The ground track homogeneity (h_l) is defined as the ratio of the largest and the smallest difference between adjacent ascending equator crossings, denoted by $\Delta\lambda_{max}$ and $\Delta\lambda_{min}$, respectively, where l is the number of orbital revolutions.

$$h_l = \frac{\Delta\lambda_{max,l}}{\Delta\lambda_{min,l}}$$

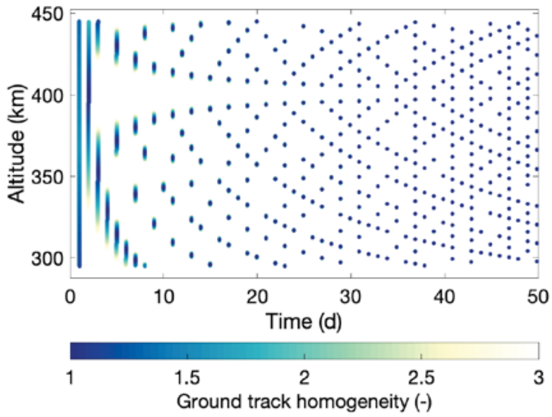
Figure 2 presents all homogeneity values h_l<3 for the possible altitude range within a time span of 1–50 days. This graph is particularly useful for selecting the altitude of the individual satellite pairs of the constellation. In order to do so, it is necessary to draw a horizontal line into the graph to identify whether an altitude provides small homogeneity values, i.e. a dense spatial sampling, for the desired time spans. For shorter time spans small homogeneity values stretch over much larger altitude ranges than for longer time spans. Figure 3 shows the ground track shift in longitude for the homogeneity values h_l<3, which are illustrated in Figure 2. For homogeneity values equal to one, which correspond to repeat orbits, the ground track shift is obviously zero. Generally, small homogeneity values result in small ground track shifts. In order to select the optimal orbit it is necessary to search for the altitudes that offer small homogeneity values for a sequence of periods, which is related to the desired temporal resolutions, and fulfil the constraint that the ground track shift of the shortest period longer than one day is the same for both satellite pairs. Thus, the combination of the two plots illustrated below enables us to optimize the sampling of the individual satellites as well as the constellation. It is noted that the choice of near-homogeneous sampling results in flying at constant mean altitude over mission life. In principle, the polar pair has the same pattern but it is slightly shifted (up or down) depending on the choice of inclination and altitude.



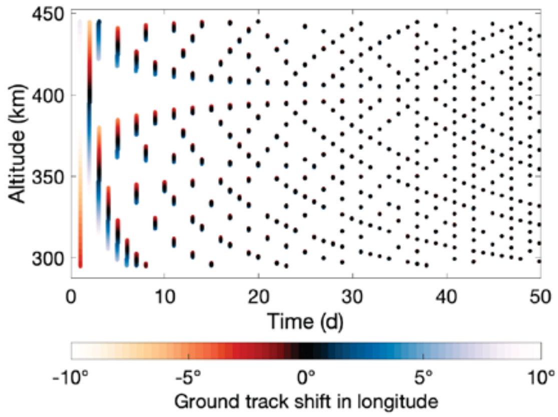
(a)



(a)



(b)



(b)

Figure 2. Ground track analysis graphs for circular orbits with an inclination of 70° (a) and 89° (b): Ground track homogeneity

Figure 3. Ground track analysis graphs for circular orbits with an inclination of 70° (a) and 89° (b): Ground track shift in longitude per sub-cycle period.

MRD-050 The altitude and inclination orbital parameters of the two satellites shall be chosen such as to provide a common drift of the interleaved ground track pattern of 0.5-3 degrees per day.

Note 1: From *Figure 2* and *Figure 3* the mission orbit altitude of 350 km is shown as an example; an orbit altitude close to 400 km can provide similar sampling patterns. The choice of the orbits needs to guarantee enough sensitivity to mass change signals, optimal near-homogeneity and sub-cycles. In these illustrations the altitude is computed as the difference between the mean semi-major axis and the Earth radius (6378 km). Examples of polar and inclined orbit choices approximately between 350-400 km used in extensive simulations are shown in [RD18].

MRD-060 The mission shall maintain the selected near-homogeneity and drift rate over mission lifetime.

Note 1: The chosen orbits take into account a common drift of the ground track pattern for both pairs, since an exact repeat orbit is not desirable due to fact that the associated ground track spacing would not allow for a high-degree gravity field recovery even if longer periods of data are used according to the Nyquist-Colombo sampling rule for space-borne Gravimetry [RD54].

MRD-070 For co-estimating ocean tides based on a long-term data set, the phasing of the orbits shall be chosen such that constituents can be decoupled (by taking into account aliasing periods).

Note 1: The expected limiting source of error is due to under-sampling of high-frequency geophysical signals like ocean tides, non-tidal atmosphere and ocean variability, which alias into the gravity solution [RD29].

MRD-080 Inter-satellite separation shall be chosen such as to achieve optimal gravity field solutions.

Note 1: The effect of the inter-satellite distance was investigated by [RD26], which found that a distance of 100 km is optimal at low altitude.
Note 2: The baseline lengths beyond 100 km do not provide any benefit in terms of gravity field recovery at low altitude. The performance for inter-satellite distances in the range 70-100 km is relatively constant [RD47].

MRD-090 The measurement system requirements comprise the performance requirements of a Level-2 geophysical product that results solely from instrument inaccuracies and their coupling effects at constellation level excluding all other effects (e.g. aliasing errors).

MRD-100 The measurement system shall perform at least better than the threshold and aim reaching the target requirements provided in Table 11.

Note 1: The threshold requirements result from simulations presented in ANNEX-B: Auxiliary simulations which include a considerable safety margin taking into account that state-of-the-art accelerometer noise levels are expected to perform at higher accuracy levels.

Table 11. Measurement system requirements extracted from Figure 10 of ANNEX-B: Auxiliary simulations (monthly solutions).

	Measurement System Requirements – DegRMS EWH (mm)	
SH (deg)	**Threshold**	**Target**
2	0.25 (TBC)	0.025 (TBC)
10	0.14 (TBC)	0.014 (TBC)
70	0.9 (TBC)	0.09 (TBC)

4.1.3 Timeliness Requirement and availability

MRD-110 The mission shall be capable to deliver products in near-real time or longer latency periods (a few days) as required by the relevant application together with the right quality and availability of auxiliary/ancillary data needed to generate the products.

4.2 Satellite-related observation requirements

The payload-related product requirements are supported by previous studies and technology developments performed by ESA and NASA in recent years, and take into account proven technological feasibility.

MRD-120 The Laser Tracking Instrument (LTI) shall perform at the level of the state of art, allowing continuity of quality of inter-satellite ranging products (TBC).

Note 1: The continuity of quality shall be at the level of the experimental tracking system of GRACE-FO. The inter-satellite ranges and range-rates have to be observed with very high accuracy in order to observe relative orbit perturbations caused by small mass variation signals.
Note 2: The range rate product used in most recent simulations [RD25] is shown in ANNEX-B: Auxiliary simulations.

MRD-130 The accelerations originating from non-gravitational forces have to be observed with high-sensitivity accelerometers at least at the level of GOCE tailored to the actual environmental condition for producing the non-gravitational acceleration product.

Note 1: The non-gravitational acceleration product includes calibration errors, GNSS errors and projection errors as a consequence of the attitude control and/or knowledge.
Note 2: The satellite system shall guarantee relevant projections of the accelerations for calibration purposes.
Note 3: The resolution is tailored to the requested dynamic range.
Note 4: The ASD of the non-gravitational acceleration product used in most recent simulations [RD25] is shown in ANNEX-B: Auxiliary simulations.
Note 5: The accelerometer design should target exploitation of the full science measurement bandwidth (1-100 mHz, TBC) and possibly to improve (with respect to the state of art, e.g. GRACE, GRACE-FO, GOCE) the performance at low frequency, given an improved system design.

MRD-140 The precise orbit and geo-location of the satellites shall be determined by GNSS system at the state-of-the-art level of LEO POD.

Note 1: The GNSS space receiver needs enough channels (state of the art better than the cm level for GOCE) to provide ultimate accuracy. For MAGIC it is foreseen to fly a space receiver capable to track satellites of all GNSS systems available at the time the mission will be in orbit.
Note 2. As a minimum the receiver shall be capable to track the U.S. GPS system as well as the European Galileo system with a minimum of at least 12 channels each.

MRD-150	The attitude of the satellites has to be observed and reconstructed with very high accuracy improving the current state-of-the-art performances.
	Note 1: In order to maintain the laser tracking between the satellite pair both payloads have to be oriented with high accuracy against each other enabling high precision inter-satellite range measurements. Attitude information from inter-satellite ranging system is expected to support the attitude science product. *Note 2: Using at least 3 different star cameras oriented in different directions ensures that also in case of sun or moon blinding always enough information is available to determine attitude based on at least 2 star camera readings [RD30][RD31].*

4.3 Mass Change Products Requirements

The main input for generating geophysical data products, i.e. Level-2 and higher, is the Level-1b data product (calibrated and geo-located including required auxiliary data). A traceability matrix is provided in ANNEX-A: TRACEABILITY MATRIX, linking user requirements to previous and the MAGIC mission requirements. The IUGG and IGSWG reports and further references describe the status and current observational gaps in measuring mass change for the selected applications. For a complete traceability of the references it is recommended to look at the STM table available in ANNEX-A: TRACEABILITY MATRIX.

Compared to single pair missions, the MAGIC constellation is expected to deliver mass change products with significantly lower error levels by reducing temporal aliasing effects.. Moreover, its enhanced spatio-temporal sampling and error isotropy enables a different approach than traditional de-aliasing methods used so far for the GRACE, GRACE-FO missions, when it comes to further reducing temporal aliasing effects. It has been extensively demonstrated by simulations that a “self-de-aliasing” approach [RD28], [RD35], [RD25] leads to a successful mitigation of temporal aliasing effects while at the same time it preserves the full spectrum of Earth’s non-tidal geophysical processes that are retrievable by the constellation which is directly provided by the mission. The mass change products are therefore unbiased from synthetic de-aliasing mismodelling errors which might be beneficial for specific applications (e.g. oceanography). However, each de-aliasing approach results in different signal content and error levels that might vary the product suitability depending on the application. Therefore, it is expected that MAGIC mission will provide both types of mass change products.

The mission requirements can be translated as follows:

MRD-160	The mission shall provide two types of Level-2 global gravity field products depending on their signal content: Type 1: Excluding non-tidal high-frequency atmospheric and ocean signals. Type 2: Including all non-tidal geophysical processes retrievable by the constellation.
	Note 1: Type-1 product is generated with the traditional GRACE, GRACE-FO de-aliasing approach where the effect of these signals is subtracted during the Level-2 gravity field processing with the use of de-aliasing models [RD36]. A further mitigation of temporal aliasing effects by use of self-de-aliasing approaches [RD28], [RD35], [RD25] is also possible. *Note 2: Type-2 product is generated by use of self-de-aliasing approaches during the Level-2 gravity field processing where short-term low-resolution gravity field solutions are co-estimated with the average target solution [RD28], [RD35], [RD25].*

MRD-170	The mission shall provide Level-2 near-real time global gravity field products.
	Note 1: The near-real time necessary products (e.g. POD, tides, AOD models) should be available in line with the processing chain [RD37].

MRD-180	The mission shall aim to retrieve mass change products according to the IUGG threshold user requirements listed in the Table 12 for daily to weekly, monthly to seasonal and long-term time scales as a minimum and try to reach target requirements.
	Note 1: Thresholds and targets differ by one order of magnitude in accuracy. *Note 2: The requirements are compared with simulation results based on the previous work from [RD25] in ANNEX-B: Auxiliary simulations.*

Table 12. MAGIC thresholds and targets for long-term trend, monthly to seasonal and daily to weekly time scales.

IUGG Scenario	Time scale	Spatial Resolution	Accuracy (EWH)
Scenario #1	Monthly to seasonal (MAGIC Threshold)	800 km (d/o 25)	1.5 mm
		400 km (d/o 50)	5 mm
		200 km (d/o 100)	10 cm
		150 km (d/o 133)	50 cm
		100 km (d/o 200)	5 m
Scenario #1	Long-term trend (MAGIC Threshold)	800 km (d/o 25)	0.15 mm/yr
		400 km (d/o 50)	0.5 mm/yr
		200 km (d/o 100)	1 cm/yr
		150 km (d/o 133)	5 cm/yr
		100 km (d/o 200)	0.5 m/yr
Scenario #2	Monthly to seasonal (MAGIC Target)	800 km (d/o 25)	0.15 mm
		400 km (d/o 50)	0.5 mm
		200 km (d/o 100)	1 cm
		150 km (d/o 133)	5 cm
		100 km (d/o 200)	0.5 m
Scenario #2	Long-term trend (MAGIC Target)	800 km (d/o 25)	0.015 mm/yr
		400 km (d/o 50)	0.05 mm/yr
		200 km (d/o 100)	0.1 cm/yr
		150 km (d/o 133)	0.5 cm/yr
		100 km (d/o 200)	0.05 m/yr
Scenario #3	Daily to weekly (MAGIC Threshold)	800 km (d/o 25)	15 mm
		400 km (d/o 50)	50 mm
Scenario #4	Daily to weekly (MAGIC Target)	800 km (d/o 25)	1.5 mm
		400 km (d/o 50)	5 mm

4.4 Calibration and Validation Requirements

Calibration and validation will, principally, be carried out during the commissioning and verification phases. The objectives of calibration and validation are:

- To establish the values of parameters needed in the generation of Level 1b and level 2 products;
- To establish the values of any relative offsets (biases) between in situ reference measurements;
- To determine, if possible, any drift error within the Mission measurements;
- To characterise the uncertainties in the measurements provided in the Mission data products (sometimes simplified to the term *error budget*).
- Due to the launch date in the late 2020s, there might be a period of overlapping measurements between MAGIC and GRACE-FO. This overlap will allow for an improved

understanding of data validation, further calibration and transition of the time series and improve the long-term historical data record.

Calibration addresses aspects of the measurement system, which need to be addressed in the generation of the level 1b data products. Since they are concerned with the conversion from the instruments' measurement quantities into standard physical units, they may be addressed by many techniques. Validation is a term used in the context of the conversion of these instrument measurements into the geophysical quantities. Validation is exclusively concerned with the characterisation of uncertainty in the level 2 parameters. Commonly, this is achieved by suitable analysis of the level 2 data themselves, often in combination with Fiducial Reference Measurements. In order to validate the products, a Calibration and Validation Plan shall be established that describes how all measurements and techniques identified as necessary in the Calibration and Validation Concept will be implemented.

MRD-190 Data products shall be validated throughout the mission lifetime.

Note 1: Actual status of verification for each requirement shall be reported in the Verification Database (TBC).

5 PRELIMINARY SYSTEM CONCEPT

In the same way as the GRACE and GRACE-FO missions, MAGIC observes mass change through measuring tiny changes in the time-variable gravity field. For that purpose, two satellites are flying in the same orbit in an in-line formation, separated by a distance of approximately 100 km. Due to the spatial separation, the satellites are subject to slightly different gravitational accelerations, which causes changes in the distance between the two satellites that are measured extremely precisely by laser interferometry. The effect of non-gravitational accelerations on the satellites is measured by accelerometers, noting that both the laser ranging and accelerometer measurements must reference to the satellite's center of mass. GNSS receivers for positioning, star sensors for attitude determination, and an angle-lateral metrology for ensuring the inter-satellite pointing, required by the laser interferometer, complement the measurement system illustrated in Figure 4. In order to compensate non-gravitational forces and torques, the satellites are equipped with an attitude and orbit control system (AOCS) that may use ion thrusters for both attitude and orbit control.

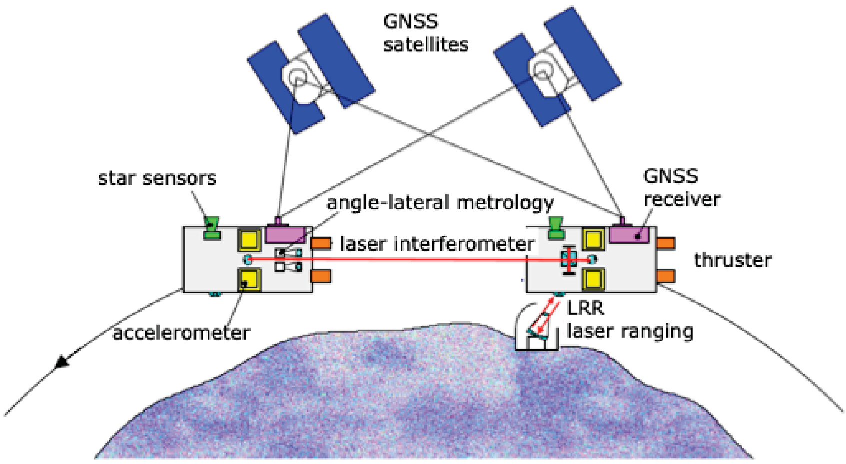


Figure 4.Illustration of the measurement principle. Figure reproduced from [RD51]

One of the limitations of present-day time-variable gravity field models is related to fast mass change in the atmosphere and oceans, which is typically reduced from the ranging observations using atmosphere and ocean models. Though these models were significantly improved in the past decade, they are still regarded as one of the largest error sources for time-variable gravity models [RD52]. In addition, the measurement system is inherently sensitive in the direction of the laser axis, which for a single pair of satellites flying in an in-line formation in a polar orbit, as illustrated in Figure 4 and Figure 5 (left), results in sensitivity in the North-South direction for a large part of the globe, whereas the sensitivity in the East-West direction is significantly lower.

In order to overcome these limitations, [RD20] proposed the constellation shown in Figure 5 that consists of two satellite pairs flying in an in-line formation, one in a polar orbit and the other in an orbit with an inclination of approximately 67°. This has the advantages of doubling the space-time sampling and adding a significantly improved East-West sensitivity of the measurements in the latitude range covered by the satellite pair flying in the inclined orbit. As a result, the time-variable gravity field model errors are much more isotropic than those based on a single polar satellite pair, which reduces the need for sophisticated post-processing. More importantly, it is possible to use the approach described by [RD28] for retrieving the effect of non-tidal mass change in the atmosphere and oceans directly from the measurements instead of relying on models for reducing the effect. For tidal mass change in the oceans, [RD29] and [RD55] demonstrated that imperfections in the ocean tide models could be compensated by co-estimating their effect in the time-variable gravity field, provided that the observation period is sufficiently long (multiple years). Further information about the orbit and linked mission requirements are listed in Chapter 4 and in particular in Section 4.1.2.

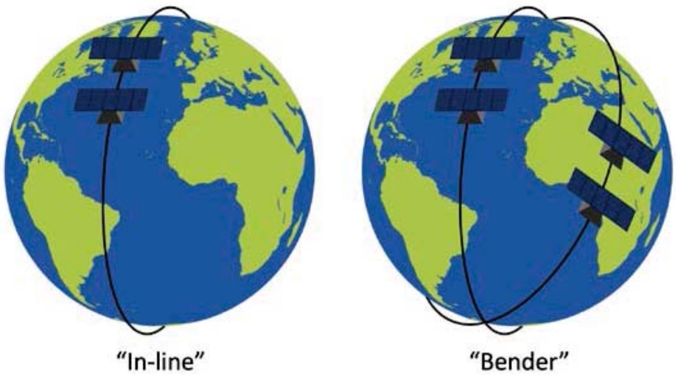


Figure 5. Illustration of In-line formation (left) and Bender constellation (right) [RD18].

In order to fulfil the scientific objectives of the mission, the space segment shall be equipped with a laser interferometer measuring the inter-satellite distance variation with the resolution of few nanometers, accelerometers, GNSS receivers and retro-reflectors for laser ranging from the ground. Auxiliary optical metrology has been devised to achieve the required laser beam pointing starting from initial random conditions and avoiding long and critical searching procedures. Each satellite shall be equipped with a suitable Drag-compensation, Formation flying, Attitude and Orbit Control System (DFAOCS), in order to guarantee the control of the attitude and the environmental disturbing accelerations, the loose formation flying of each satellite pair, and maintain the altitude/inclination combinations all over the mission lifetime. The spacecraft propulsion enacting the DFAOCS and orbit control functions is the main challenge of the spacecraft design: the thrust range and modulation capability imposed by the mission, coupled with the lifetime requirement, need to be taken care of [RD50].

6 DATA PRODUCTS AND USAGE

This chapter includes a qualitative description of the data products at Level-0, Level-1 and Level-2, the operational data processing requirements and accompanying requirements.
MAGIC shall deliver at least Level-1 and Level-2 products to the science user community as summarized in the table below. The summarised information in this section is in line with the e.motion2 Earth Explorer proposal which is also using a double pair for mass change observations [RD6].

Table 13. Overview of Level-1 and Level-2 products for MAGIC

Level-1 data products	Parameters
Low-low satellite-to-satellite tracking (LL-SST) ranging (for each pair)	Biased range, Range rates, Range accelerations
Non-gravitational accelerations (for each satellite)	Linear & angular accelerations
Kinematic positions and velocities (for each satellite)	Code & phase
Attitude information (for each satellite)	Inertial attitude quaternions, inter-satellite orientation from low-low satellite-to-satellite tracking
Other data	Temperature, satellite geometry model, surface characteristics, thrust, control and alignment information
Level-1b de-aliasing products	SH coefficients of the anomalous external gravity field of the Earth caused by the non-tidal short term mass variability of atmosphere, ocean and solid Earth predicted by numerical models
Level-1b tidal corrections	Ocean tides constituents

Level-2 data products	Parameters
Gravity field	Estimate (incl. full error variance-covariance information) of monthly SH coefficients up to degree and order 150 (TBD)
	Estimate (incl. full error variance-covariance information) of daily SH coefficients up to degree and order 20 (TBD) (depending on the constellation)
Level-2 de-aliasing products	SH coefficients of the anomalous external gravity field of the Earth caused by the non-tidal short term mass variability of atmosphere and ocean predicted by numerical models, averaged over the time span of the Level-2 Gravity Field products
Precise science orbits	3D inertial positions & velocities

Apart from these a selected set of Level-3 products (mass transport estimates for different areas and applications) shall be identified. The processing of these products shall be under the responsibility of science groups, but made available as mission products to all possible users. This last category of products can be subjected to a significant post-processing.
The concept for MAGIC is based on the Satellite-to-Satellite tracking (SST) between low Earth orbiters. This design is successfully operated in the GRACE mission and GRACE-FO mission. Therefore, most of the Level-1, Level-2, and Level-3 processing algorithms and data products are well established and have a high scientific readiness level.

6.1 Level-0 data products

Level-0 products are computer-readable data directly representing the output of the on-board instrument in its native data structure and in engineering units (e.g. clock cycle counts), after extraction from the downlinked data stream. Data are chronologically ordered and any overlapping (duplicate) data have been removed. Quality flags related to the reception and decoding process may be appended. The Level-0 data products are defined as the result of telemetry data reception, collection and de-commutation of the raw data. Telemetry data from each down-link pass is separated into the science instrument and satellite housekeeping data streams and placed in an archive.

6.2 Level-1 data products

Level-1a products are time-ordered unpacked Level-0 packets, geo-located and converted from engineering to SI units. Instrument effects and calibration terms / corrections shall be provided. Level-1a data products are defined as the result of non-destructive processing applied to the Level-0 data. Binary encoded measurements will be converted to engineering units. When required, time tag integer second ambiguity will be resolved and data time tagged to the respective satellite receiver clock time. Quality control flags are added and data is reformatted for further processing. Level-1a data should be reversible to Level-0.

Level-1b products are fully calibrated and geo-located without corrections for geophysical effects. The Level-1b data products will be the result of a possibly irreversible processing applied to the Level-1a data. Data will be correctly time-tagged and data sample rate may be reduced from former higher rates.

The sampling of all Level-1 data shall be not larger than 1 s. The Level-1 data products consist of some key observations, which are provided by the inter-satellite laser ranging interferometer (LRI) and the accelerometers. The Level-1 data products of the accelerometers are 3D accelerations observed in the accelerometer reference frame (usually approximately in along-track, cross-track and radial direction). The processing algorithms have been successfully applied in previous and current gravity missions (e.g. CHAMP, GRACE, GOCE) and are mature. Further Level-1 products come from the GNSS receiver (code and phase measurements), the star cameras (inertial attitude quaternions) and the temperature sensor. Additional products for de-aliasing and tidal corrections are also necessary within the Level-1 data products.

6.3 Level-2 data products

The measurement data are converted into geophysical quantities for each satellite pair, and combined with auxiliary input data from other sources to yield geophysical parameters for the constellation. The Level-2 data products comprise all gravity field model and mass transport products as well as related data products derived from the application of the Level-2 processing to

the previous level data products. The verification of Level-2 data products can be performed through selected independent gravity field computations.
The main Level-2 products are global gravity field models with different spatial and temporal resolutions. Applying the orbit perturbation [RD32], Mascon [RD33] or other approaches one can estimate a global monthly gravity field with high spatial resolution (down to 150 km). In addition, daily global gravity fields can be estimated with reduced spatial resolution corresponding to a maximum SH degree and order between 10 and 20, depending on the constellation [RD28], [RD35].
Two types of Level-2 global gravity field products shall be provided:

- Type 1: Excluding non-tidal high-frequency atmospheric and ocean signals. This product is generated with the traditional GRACE, GRACE-FO de-aliasing approach where the effect of these signals is subtracted during the Level-2 gravity field processing with the use of de-aliasing models [RD36]. A further mitigation of temporal aliasing effects by use of self-de-aliasing approaches [RD28], [RD35], [RD25] is also possible.
- Type 2: Including all non-tidal geophysical processes retrievable by the constellation. This product is generated by use of self-de-aliasing approaches during the Level-2 gravity field processing where short-term low-resolution gravity field solutions are co-estimated with the average target solution [RD28], [RD35], [RD25]

The mission shall provide Level-2 near-real time global gravity field products and the processing chain should be in line with the availability of these products. Furthermore, as Level-2 data products also precise science satellite orbits with 3D inertial positions and velocities are delivered.

Level-2 products include also synthetic global geophysical products of the de-aliasing models used in the Type-1 Level-2 processing which are averaged over the same time span as the Type-1 Level-2 global gravity field solutions. The synthetic products comprise of the non-tidal short term variations in the atmosphere and ocean in various combinations and averaging options [RD36] depending on the intended application.

6.4 Level-3 data products

Level-3 products contain geophysical parameters that have been spatially and/or temporally resampled. This may include averaging over multiple measurements and additional post-processing. Based on the Level-2 data products of MAGIC the users have the opportunity to select different spatial and temporal resolution products. But, as the satellites observe integrated mass distributions for different applications, signal separation is one of the most important and challenging tasks for the users. Furthermore different post-processing strategies are available in order to improve the signal to noise ratio for specific wavelengths. An overview of the most important aspects in this context with application examples in different fields is given in [RD34]. Within the Level-3 products also a separation of effects can be performed with the aim of estimating the different components from the full observed signal.

7 SYNERGIES AND INTERNATIONAL CONTEXT

The mission draws from the experience of several in-orbit missions and from the ongoing GRACE Follow-On programme. Many collaborations and/or applications with the European Union (EU) Copernicus programme, planned altimetry missions and other projects can be found.

7.1 Copernicus

A joint mission contribution to Copernicus services can be provided by MAGIC. Satellite gravity should be integrated in existing products for soil moisture, surface waters and glaciers. This would also include early warning systems for droughts and floods like the ones from the European Flood Awareness System (EFAS), the Global Flood Awareness Systems (GloFAS) and the Drought Observatory for Europe (EDO). New Copernicus products can be developed based on satellite gravity. Within this group of products it is possible to highlight the global gravity-based groundwater product - G3P and the Total Water Storage (TWS). The first one is currently developed as new product within the Copernicus Climate Change Service (C3S). At the same time, the TWS is currently under revision to become an Essential Climate Variable (ECV) by the Terrestrial Observation Panel for Climate (TOPC) within the Global Climate Observing System (GCOS). The possibility to establish a future Copernicus TWS service can be also examined according to MAGIC observations.
Further collaborations can be achieved on water availability forecasting and additional assimilation into operational weather forecast systems and/or atmospheric re-analyses (e.g. providing constrain on net fluxes). In order to accomplish such tasks, reliable data delivery, stable data quality and short latency are the main requirements to satisfy.
Among these initiatives a great synergy can also be achieved with Sentinel-1 hydrological observations. Indeed, the derived products for soil moisture (e.g. Surface Soil Moisture - SSM) can be compared with the mass-change observations. This would allow further insights in local and regional precipitation impacts and soil conditions.

7.2 Other current and planned missions and ground campaigns

A useful contribution from other missions can be provided for topography through current and planned altimetry and SAR missions. Solid Earth can exploit SAR measurements to determine small-scale deformations. This can be done in collaboration with GNSS measurements as well. From altimetry and complementary remote sensing missions insights about regional representation, filtering, error models, separation of signal components and mass balance can be obtained in combination with gravity observations. Using multiple missions, it is indeed possible to further enhance the understanding of multi-disciplinary environments including a better description of mantle and crustal dynamics, oceanic transport, continental hydrology, ice mass balance and sea level changes. A new generation of remote sensing satellites and altimetry ice missions will allow us to measure surface geometry of land and sea ice and variations thereof with unprecedented accuracy. Ocean surfaces at cm-precision and height variations of water surfaces on land (e.g. lakes, rivers, wetlands) are, and will be, observed by altimeter missions and would allow a direct comparison with gravity observations enhancing the detection and separation of multiple mass signal components (e.g. thermal expansion and mass surplus in the oceans).
Furthermore, it is possible to combine satellite gravimetric data with weather-station observations and output from meteorological models to improve the determination of mass transport in the atmosphere and atmospheric pressure at the ~100–500 km spatial scale. If the air pressure signal can be directly derived from satellite gravity data (by first subtracting other mass transport signals from hydrology, cryosphere and solid-earth), there is the intriguing possibility of using the long-term (inter-annual) variations in this signal to provide novel information on climate variability and change [RD2]. In addition to mass change observations, the instrumentation and orbital characteristics of the past gravity missions have proven to be well suited for the derivation of neutral density and wind

data sets in the upper atmosphere. The processed data are derived from an aerodynamic analysis of the satellite accelerations observed by high-precision accelerometers [RD2][RD39][RD40]. Therefore, all the planned and future missions with an on-board accelerometer will provide great synergy with MAGIC.

Additional sources for possible synergies can be found in the Decadal Survey for Earth Observation from Space [RD3], which presents a multi-disciplinary overview of possible collaborations and different mission/data exploitation.

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LIST OF ACRONYMS

ACC	Antarctic Circumpolar Current
AJSST	Ad-hoc Joint Science Study Team
AMOC	Atlantic Meridional Overturning Circulation
AOCS	Attitude and orbit control system
ASD	Amplitude spectral density
C3S	Copernicus Climate Change Service
CEOS	Committee on Earth Observation Satellites
CHAMP	Challenging Minisatellite Payload
CMB	Core–mantle boundary
DS	Decadal Survey
ECV	Essential Climate Variable
EDO	Drought Observatory for Europe
EFAS	European Flood Awareness System
ENSO	El Niño–Southern Oscillation
ESA	European Space Agency
EU	European Union
EWH	Equivalent Water Height
G3P	Global gravity-based groundwater product
GCOS	Global Climate Observing System
GIA	Glacial Isostatic Adjustment
GloFAS	Global Flood Awareness Systems
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment – Follow On
GSI	Gas-Surface interactions
HIS	Hydrology, Ice and Solid Earth
IGSWG	NASA/ESA Interagency Gravity Science Working Group
InSAR	Interferometric synthetic-aperture radar
IUGG	International Union of Geodesy and Geophysics
JMCMEG	Joint Mass Change Mission Experts Group
LEO	Low Earth Orbit
LL-SST	Low-low satellite-to-satellite tracking
LRI	Laser ranging interferometer
LTI	Laser Tracking Instrument
MAG	Mission Advisory Group
MAGIC	Mass-change And Geosciences International Constellation
MCDO	Mass Change Designated Observable
MDT	Mean Dynamic Topography
MRD	Mission Requirements Document
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering and Medicine
NGGM	Next Generation Gravity Mission
NRT	Near-real Time
POD	Precise Orbit Determination
QMS	Quality Management System
RMS	Root mean square
SAR	Synthetic-aperture radar

SATM	Science and Application Traceability Matrix
SH	Spherical harmonic
SSM	Surface Soil Moisture
SST	Satellite-to-satellite tracking
STM	Science Traceability Matrix
TBC	To Be Confirmed
TBD	To Be Determined
TOPC	Terrestrial Observation Panel for Climate
TWS	Total Water Storage

ANNEX-A: TRACEABILITY MATRIX

User Requirements are crucial to steer and to adjust the future evolution of the gravity missions.
To prepare this evolution, the AJSST members from ESA and NASA have undertaken the collection of user requirements that should best fulfil users' requirements and services.
The following table provides a full overview of the spatial and time resolutions which can be achieved by MAGIC. A complete comparison with previous and current studies is provided as well. Multiple thresholds and targets (Threshold-a, Threshold-b, etc.) are shown in the table in order to cover most of the user community specified resolutions for different applications. The different threshold and target requirements are interpolated from the IUGG requirements in Table 2 in combination with the signal boundaries and extent provided in Figure 1, multiple thresholds and targets aim to cover the signal range of each thematic field.

Spatial resolutions and temporal scales associated to gravity changes Science and Applications Traceability Matrix (SATM) Current status Vs. MCDO Vs. Joint constellation (MAGIC)					References: **IUGG-interpolated**, **IUGG specific requirement**, **DS+MCDO**, **IGSWG**, **Grav. Seismo.**; **Wiese et al. 2016**, **Metivier & Conrad, 2008;** **Marquart et al.,2005 + Dumberry, 2010** **N.A.** = Not Applicable/Not Available (e.g. due to lack of measurements/capabilities)		
Thematic field	**Signal**	**Time scale** (**D**: Daily to weekly; **M**: Monthly (Seasonal to inter-annual); **L**: Long-term trend)	**Current state of the art (e.g. GRACE, GRACE-FO)**	**MCDO**	**Joint constellation (MAGIC)**		
			Resolution & Accuracy	**Resolution & Accuracy**	**Resolution & Accuracy**		**Scientific/societal <u>Q</u>uestions & <u>O</u>bjectives**
					Threshold	**Target**	
Hydrology	Ground-water storage	**D**	N.A.	N.A.	Threshold-a: 600 km @ 3.2 cm; Threshold-b: 300 km @ 5.9 cm; Threshold-c: 280 km @ 6.0 cm	Target-a: 600 km @ 0.3 cm; Target-b: 300 km @ 0.6 cm; Target-c: 280 km @ 0.6 cm	Q: H1, H2, H3, CL2; O: H-1a, H-

		M	450 km @ 2.5 cm	Baseline: 450 km @ 2.5 cm; Goal: 50 km @ 1.0 cm	Threshold-a: 400 km @ 0.5 cm; Threshold-b: 260 km @ 4.8 cm	Target-a: 400 km @ 0.05 cm; Target-b: 260 km @ 0.48 cm	1c; H2-b, H2-c; H-3a; H4-a; CL-2a
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 350 km @ 0.1 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 350 km @ 0.01 cm/yr; Target-b: 150 km @ 0.5 cm/yr; Target-c: 200km @ 0.1 cm/yr	
	Soil moisture	D	N.A.	N.A.	N.A.	N.A.	Q: H1, H2, H3, CL2; O: H-1a, H1-c; H2-b, H2-c; H-3a; H4-a; CL-2a
		M	450 km @ 2.5 cm	Baseline: 450 km @ 2.5 cm; Goal: 200 km @ 2.5 cm	Threshold-a: 400 km @ 0.5 cm; Threshold-b: 260 km @ 4.8 cm	Target-a: 400 km @ 0.05 cm; Target-b: 260 km @ 0.48 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 350 km @ 0.1 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 350 km @ 0.01 cm/yr; Target-b: 150 km @ 0.5 cm/yr	
	Extreme events warning (e.g. drought, flood)	D	N.A.	Goal: 50 km @ 1.5 mm	Threshold-a: 600 km @ 3.2 cm; Threshold-b: 300 km @ 5.9 cm; Threshold-c: 280 km @ 6.0 cm	Target-a: 600 km @ 0.3 cm; Target-b: 300 km @ 0.6 cm; Target-c: 280 km @ 0.6 cm	Q: H1, H3, H4; O: H-1a; H-2c; H-3a; H4-a
		M	450 km @ 2.5 cm	Baseline: 450 km @ 2.5 cm;	Threshold-a: 400 km @ 0.5 cm; Threshold-b: 260 km @ 4.8 cm	Target-a: 400 km @ 0.05 cm; Target-b: 260 km @ 0.48 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 350 km @ 0.1 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 350 km @ 0.01 cm/yr; Target-b: 150 km @ 0.5 cm/yr	
	Water balance closure	D	N.A.	N.A.	N.A.	N.A.	Q: H1, H2, H3, CL2; O: H-1a, H-1c; H-2b, H-2c; H-3a; CL2-a
		M	1000 km @ 1.0 cm	Baseline: 1000 km @ 1.0 cm; Goal: 3 km @ 1.0 cm	Threshold-a: 400 km @ 0.5 cm; Threshold-b: 260 km @ 4.8 cm	Target-a: 400 km @ 0.05 cm; Target-b: 260 km @ 0.48 cm; Target-c: 200 km @ 1 cm	
		L	1000 km @ 1.0 mm/yr	TBD	Threshold-a: 350 km @ 0.1 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 350 km @ 0.01 cm/yr; Target-b: 150 km @ 0.5 cm/yr	
	Global change impact on water cycle	D	N.A.	N.A.	N.A.	N.A.	Q: H1, H2, H3, CL2; O: H-1a, H-1c; H2-b,
		M	1000 km @ 1.0 cm	Baseline: 1000 km @ 1.0 cm;	Threshold-a: 400 km @ 0.5 cm; Threshold-b: 260 km @ 4.8 cm	Target-a: 400 km @ 0.05 cm; Target-b: 260 km @ 0.48 cm	

				Goal: 3 km @ 1.0 cm			H2-c; H-3a; CL-2a
		L	1000 km @ 1.0 mm/yr	TBD	Threshold-a: 350 km @ 0.1 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 350 km @ 0.01 cm/yr; Target-b: 150 km @ 0.5 cm/yr; Target-c: 200 km @ 0.1 cm/yr	
Cryosphere	Cryosphere mass balance	D	N.A.	N.A.	N.A.	N.A.	Q: C1, C2, C3, CL2; O: C-1b; C-2a, C-2b, C-2d, C-2e; C3-a; CL-2a, CL-2b
		M	200-500 km @ 4.0-5.0 cm	Baseline: 300 km @ 4.0 cm; Goal: 100 km @ 1.0 cm	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr	
	Global and regional sea level	D	N.A.	N.A.	N.A.	N.A.	Q: C1, C2, CL1, CL2; O: C-1a, C-1c; C-2a; CL-1a, CL-1b; CL-2a
		M	300 km @ 1.5 cm	Baseline: 300 km @ 1.5 cm; Goal: 100 km @ 1.5 cm	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr	
	GIA	D	N.A.	N.A.	N.A.	N.A.	Q: C1, C2, CL2; O: C-1a, C-1c; C-2a; CL-2a, CL-2b
		M	300 km @ 2.5 cm	Baseline: 300 km @ 2.5 cm; Goal: 200 km @ 1.0 cm	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm; Target-c: 200 km @ 1.0 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr; Target-c: 150 km @ 0.2 cm/yr	
		D	N.A.	N.A.	N.A.	N.A.	

	Mass changes of ice sheet and glaciers	M	200-500 km @ 4.0-5.0 cm	Baseline: 300 km @ 4.0 cm; Goal: 100 km @ 1.0 cm	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm	Q: C1, C2, CL2; O: C-1b; C-2a, C-2b, C-2c, C-2d, C-2e; CL-2a, CL-2b
		L	200 km @ 10 cm/yr	TBD	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr; Target-c: 200 km @ 0.1 cm/yr	
Oceanography	Sea-level change	D	N.A.	N.A.	N.A.	N.A.	Q: O1, CL1, CL2; O: O-1a, O-1b; O-1c, O-1d, O-1d; CL1-a; CL-2a, CL-2b
		M	300-500 km @ 1.5 cm	Baseline: 300 km @ 1.5 cm; Goal: 100 km @ 1.5 cm	Threshold-a: 1000 km @ 0.2 cm; Threshold-b: 400 km @ 0.5 cm; Threshold-c: 250 km @ 5.5 cm.	Target-a: 1000 km @ 0.02 cm; Target-b: 400 km @ 0.05 cm; Target-c: 250 km @ 0.55 cm.	
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 800 km @ 0.015 cm/yr; Threshold-b: 400 km @ 0.05 cm/yr; Threshold-c: 180 km @ 1.8 cm/yr.	Target-a: 800 km @ 0.0015 cm/yr; Target-b: 400 km @ 0.005 cm/yr; Target-c: 180 km @ 0.18 cm/yr.	
	Ocean bottom pressure	D	N.A.	N.A.	N.A.	N.A.	Q: O1; O: O-1c, O-1e
		M	300-500 km @1.5 cm	Baseline: 300 km @ 1.5 cm; Goal: 50 km @ 1.0 cm	Threshold-a: 1000 km @ 0.2 cm; Threshold-b: 400 km @ 0.5 cm; Threshold-c: 250 km @ 5.5 cm.	Target-a: 1000 km @ 0.02 cm; Target-b: 400 km @ 0.05 cm; Target-c: 250 km @ 0.55 cm.	
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 800 km @ 0.015 cm/yr; Threshold-b: 400 km @ 0.05 cm/yr; Threshold-c: 180 km @ 1.8 cm/yr.	Target-a: 800 km @ 0.0015 cm/yr; Target-b: 400 km @ 0.005 cm/yr; Target-c: 180 km @ 0.18 cm/yr.	
	ACC and AMOC variability	D	N.A.	N.A.	N.A.	N.A.	Q: O1; O: O-1a, O-1c, O-1d
		M	300-500 km/N.A. @ 1.5 cm	Baseline: 300 km @ 1.5 cm; Goal: 50 km @ 1.0 cm	Threshold-a: 1000 km @ 0.2 cm; Threshold-b: 400 km @ 0.5 cm; Threshold-c: 250 km @ 5.5 cm.	Target-a: 1000 km @ 0.02 cm; Target-b: 400 km @ 0.05 cm; Target-c: 250 km @ 0.55 cm.; Target-d: 200 km @ 1.5 cm	

		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 800 km @ 0.015 cm/yr; Threshold-b: 400 km @ 0.05 cm/yr; Threshold-c: 180 km @ 1.8 cm/yr.	Target-a: 800 km @ 0.0015 cm/yr; Target-b: 400 km @ 0.005 cm/yr; Target-c: 180 km @ 0.18 cm/yr.	
	Tidal models	D	N.A.	N.A.	Threshold: 400 km @ 5 cm	Target: 400 km @ 0.5 cm	Q: O1; O: O-1d
		M	300-500 km@ 1.0-2.5 cm	Baseline: 300 km @ 1.5 cm; Goal: 50 km @ 1.0 cm	Threshold-a: 1000 km @ 0.2 cm; Threshold-b: 400 km @ 0.5 cm; Threshold-c: 250 km @ 5.5 cm.	Target-a: 1000 km @ 0.02 cm; Target-b: 400 km @ 0.05 cm; Target-c: 250 km @ 0.55 cm.	
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 800 km @ 0.015 cm/yr; Threshold-b: 400 km @ 0.05 cm/yr; Threshold-c: 180 km @ 1.8 cm/yr.	Target-a: 800 km @ 0.0015 cm/yr; Target-b: 400 km @ 0.005 cm/yr; Target-c: 180 km @ 0.18 cm/yr.	
	Heat and mass observations	D	N.A.	Goal: 100 km @ 1.5 cm	Threshold: 400 km @ 5 cm	Target: 400 km @ 0.5 cm	Q: O1, CL1, CL2; O: O-1a, O-1b, O-1c, O-1d, O-1d, O-1e; CL-1b; CL-2a, CL-2b
		M	300-500 km @ 1.5 cm	Baseline: 300 km @ 1.5 cm	Threshold-a: 1000 km @ 0.2 cm; Threshold-b: 400 km @ 0.5 cm; Threshold-c: 250 km @ 5.5 cm.	Target-a: 1000 km @ 0.02 cm; Target-b: 400 km @ 0.05 cm; Target-c: 250 km @ 0.55 cm; Target-d: 200 km @ 1.0 cm	
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 800 km @ 0.015 cm/yr; Threshold-b: 400 km @ 0.05 cm/yr; Threshold-c: 180 km @ 1.8 cm/yr.	Target-a: 800 km @ 0.0015 cm/yr; Target-b: 400 km @ 0.005 cm/yr; Target-c: 180 km @ 0.18 cm/yr.	
	Ocean circulation models	D	N.A.	N.A.	N.A.	N.A.	Q: O1; O: O-1a, O-1b, O-1c, O-1d, O-1e
		M	300-500 km @ 1.5 cm	Baseline: 300 km @ 1.5 cm; Goal: 50 km @ 1.0 cm	Threshold-a: 1000 km @ 0.2 cm; Threshold-b: 400 km @ 0.5 cm; Threshold-c: 250 km @ 5.5 cm.	Target-a: 1000 km @ 0.02 cm; Target-b: 400 km @ 0.05 cm; Target-c: 250 km @ 0.55 cm.	

		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 800 km @ 0.015 cm/yr; Threshold-b: 400 km @ 0.05 cm/yr; Threshold-c: 180 km @ 1.8 cm/yr.	Target-a: 800 km @ 0.0015 cm/yr; Target-b: 400 km @ 0.005 cm/yr; Target-c: 180 km @ 0.18 cm/yr.	
Solid Earth	Natural hazards	D	N.A.	N.A.	Threshold-a: 300 km @ 6.0 cm; Threshold-b: 300 km @ <10.0 cm (Mw 8 earthquakes);	Target-a: 300 km @ 0.6 cm; Target-b: <250 km @ 10.0-1.0 cm	Q: S1, S3, S4; O: S-1a, S-1b; S-3c; S-4c
		M	300 km @ 2.5 cm	Baseline: 300 km @ 2.5 cm; Goal: 200 km @ 1.2 cm	Threshold-a: 350 km @ 1.0 cm; Threshold-b: 180 km @ 18 cm; Threshold-c: 300 km @ 1-2 cm (Mw 8 earthquakes);	Target-a: 350 km @ 0.1 cm; Target-b: 180 km @ 1.8 cm; Target-c: 200 km @ 1.0 cm (Mw 7 earthquakes)	
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 250 km @ 0.5 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr; Threshold-c: 200 km @ 1 cm/yr	Target-a: 250 km @ 0.05 cm/yr; Target-b: 150 km @ 0.5 cm/yr; Target-c: 100 km @ 1.0 cm/yr	
	Evolution of Earth's crust under external or internal forcing	D	N.A.	N.A.	N.A.	N.A.	Q: S2, S3, S4; O: S-2a; S-3a, S-3b, S-3c, S-3d; S-4a
		M	300 km @ 2.5 cm	Baseline: 300 km @ 2.5 cm; Goal: 200 km @ 1.0 cm	Threshold-a: 350 km @ 1.0 cm; Threshold-b: 180 km @ 18 cm.	Target-a: 350 km @ 0.1 cm; Target-b: 180 km @ 1.8 cm.	
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 250 km @ 0.5 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 250 km @ 0.05 cm/yr; Target-b: 150 km @ 0.5 cm/yr; Target-c: <100 km @ 10 cm/yr	
	Natural resources exploitation	D	N.A.	N.A.	Threshold-a: 300 km @ 6.0 cm; Threshold-b: 300 km @ 10.0 cm	Target-a: 300 km @ 0.6 cm; Target-b: <250 km @ 10.0-1.0 cm	Q: S4; O: S-4a, S-4b, S-4c
		M	300-450 km @ 2.5 cm	Baseline: 450 km @ 2.5 cm; Goal: 100	Threshold-a: 350 km @ 1.0 cm; Threshold-b: 180 km @ 18 cm.	Target-a: 350 km @ 0.1 cm; Target-b: 180 km @ 1.8 cm.	

				km @ 1.0 cm			
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 250 km @ 0.5 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 250 km @ 0.05 cm/yr; Target-b: 150 km @ 0.5 cm/yr	
	Deep interior properties and dynamics	D	N.A.	N.A.	N.A.	Target: 6000 km @ 0.15 mm (Body tides)	Q: S2, S3; O: S-2a; S-3a, S-3b, S-3c, S-3d
		M	300 km @ 2.5 cm	Baseline: 300 km @ 2.5 cm; Goal: 200 km @ 1.2 cm	Threshold-a: 350 km @ 1.0 cm; Threshold-b: 180 km @ 18 cm.	Target-a: 350 km @ 0.1 cm; Target-b: 180 km @ 1.8 cm.	
		L	300 km @ 1.5 cm/yr	TBD	Threshold-a: 250 km @ 0.5 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 250 km @ 0.05 cm/yr; Target-b: 150 km @ 0.5 cm/yr; Target-c: 2000-6000 km @ 0.05-0.1 mm in 10 yr; Target-d: 230-330 km @ 1 mm in 10 yr	

ANNEX-B: AUXILIARY SIMULATIONS

This chapter provides plots of cumulative EWH errors per SH degree of expansion which depict the gravity field retrieval error of full-scale simulations [RD45][RD25] against user requirements [RD1][RD2]. The simulations include a dual-pair scenario at 350km geodetic altitude and 100km inter-satellite distance separation. For more details on the simulations please refer to [RD25].

The assumptions taken on the LRI and accelerometer noise levels propagated with satellite system noise in the ranging and non-gravitational acceleration product used in simulations are shown in Figure 6. It shall be stressed out that the assumptions on the accelerometer product noise are rather pessimistic compared to state-of-the-art accelerometer performances and potential improvements expected from technological pre-developments. For the noise, the principal measurement unit is observed by the laser interferometry instrument. Its product noise can be described in terms of double-sided amplitude spectral density (ASD) range-rates by:

$$d_{range\ rates} = 4 \cdot a \cdot 2\pi f \sqrt{\left(\frac{10^{-2}Hz}{f}\right)^2 + 1}\,\frac{m}{s\sqrt{Hz}}\ ,$$

where α has being set to 10^{-8}. The Laser interferometer range product performance is visualized in green, in Figure 6 in terms of ranging accelerations (first order derivatives of range rates) in order to be comparable with the accelerometer product errors. The non-gravitational acceleration product includes calibration errors, GNSS errors and projection errors as a consequence of the attitude control and/or knowledge, this contribution is expressed by double-sided ASD:

$$d_{acc.x} = d_{acc.z} = 2 \cdot 10^{-11} \sqrt{\left(\frac{10^{-3}Hz}{f}\right)^4 \Big/ \left(\left(\frac{10^{-5}Hz}{f}\right)^4 + 1\right) + 1 + \left(\frac{f}{10^{-1}Hz}\right)^4} \times \frac{m}{s^2\sqrt{Hz}}$$

$$d_{acc.y} = 10 \cdot d_{acc.z}$$

with x being the along-track, y across-track and z the radial component. In Figure 6 the MAGIC product noise is visualized in blue and red (sensitive axes). The two product noise equations (for ACC and LRI) in [RD25] erroneously miss a factor of 2. However, this did not impact the simulations as these were performed with the correct time series corresponding to the curves in Figure 6.

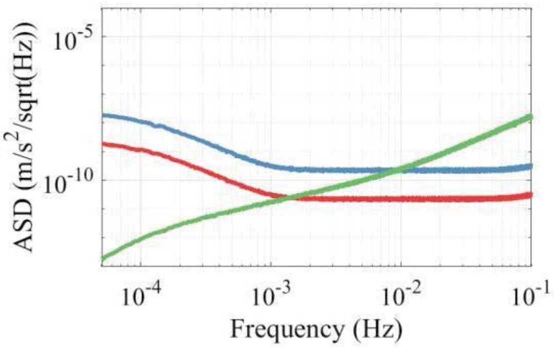


Figure 6. Double-sided amplitude spectral density (ASD) of the MAGIC product noise (Blue: ACC cross track product; Red: ACC along track/radial product; Green: Laser range acceleration product).

Each of the following plots includes two types of simulation worlds, namely the "nominal" and "instrument-error-only" cases. The "nominal" case takes into account all possible error sources, including temporal aliasing, ocean tide mismodelling errors and de-aliasing mismodelling errors. The solutions have also been processed by means of co-parameterization in shorter temporal scales (i.e. daily) in order to mitigate the temporal aliasing effects. The "instrument-only-errors" case includes only the effects of the accelerometer and ranging product errors without the presence of aliasing (Purkhauser, 2020 – personal communication).

Along with the gravity field retrieval errors the plots include also the IUGG threshold and target requirements [RD1], as well as selected requirements for geophysical signals of different thematic fields as provided in the STM table of Annex A. The power of the retrieved signal (i.e. Hydrology, Ice and Solid Earth – "HIS") is also plotted over the land regions. The original simulations are provided with a maximum spatial resolution corresponding to a spherical harmonic degree and order expansion of 70 degrees and they are projected in the plots with solid blue and grey curves. However, since the maximum resolvable spatial resolution can take higher values, a projection to finer spatial scales (c.f. dotted curves) is provided by means of common logarithm extrapolation.

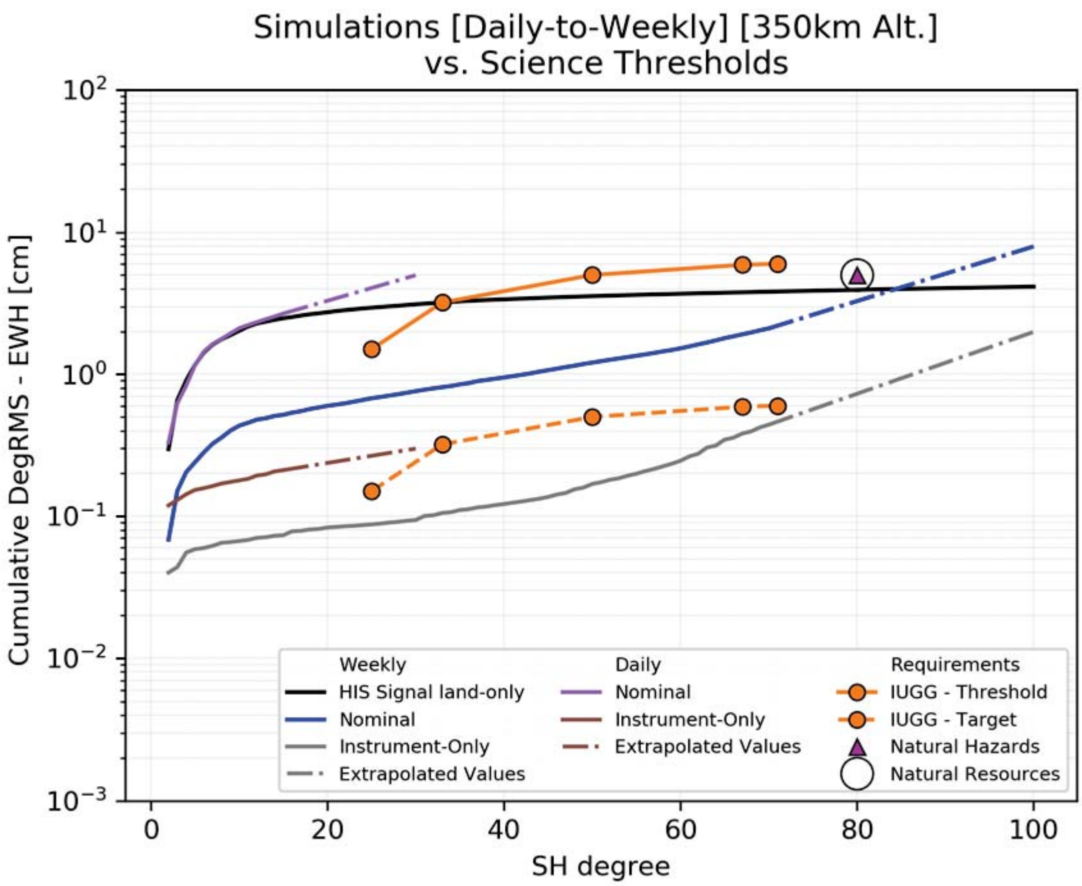
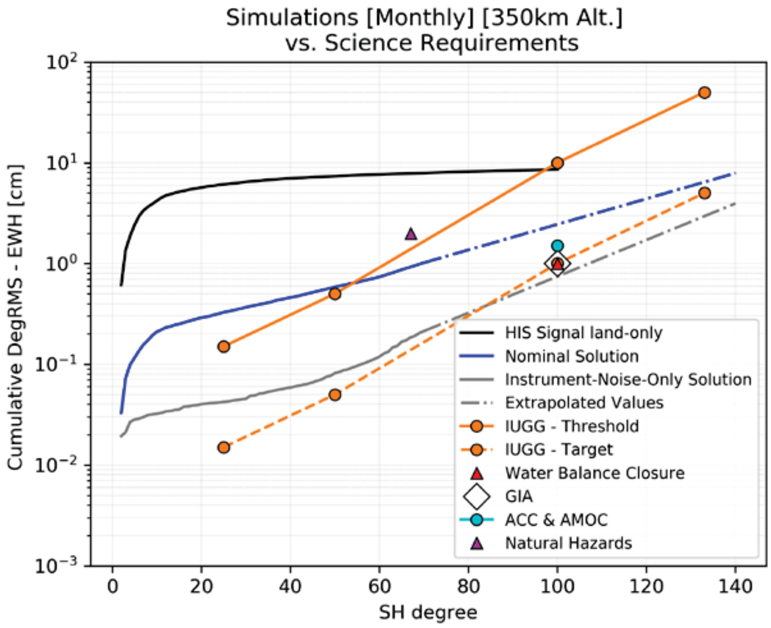
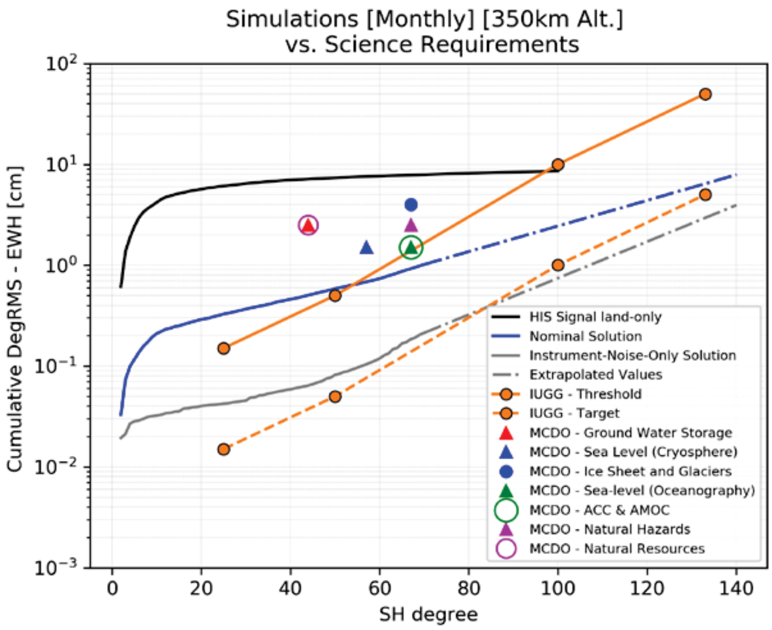


Figure 7. Cumulative errors of gravity field simulation vs. user and mission requirements expressed in EWH for daily-to-weekly time scales. The markers indicate specific target requirements.



(a)



(b)

Figure 8. Cumulative errors of gravity field simulation vs. user and mission requirements expressed in EWH for monthly time scales. All markers refer to specific target requirements except natural hazards (threshold) (a). NASA's MCDO baseline requirements are shown in the same representation in the figure below (b).

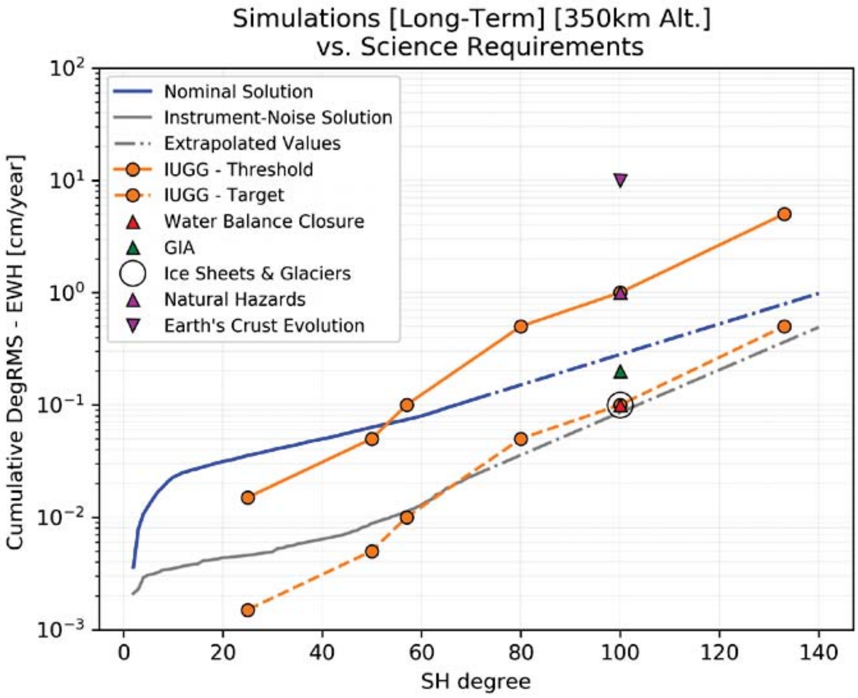


Figure 9 – Cumulative errors of gravity field simulation errors vs. user and mission requirements expressed in EWH for long-term (trend) scales. The nominal and instrument-noise solutions have been obtained as a trend for 7-year period. All markers refer to specific target requirements.

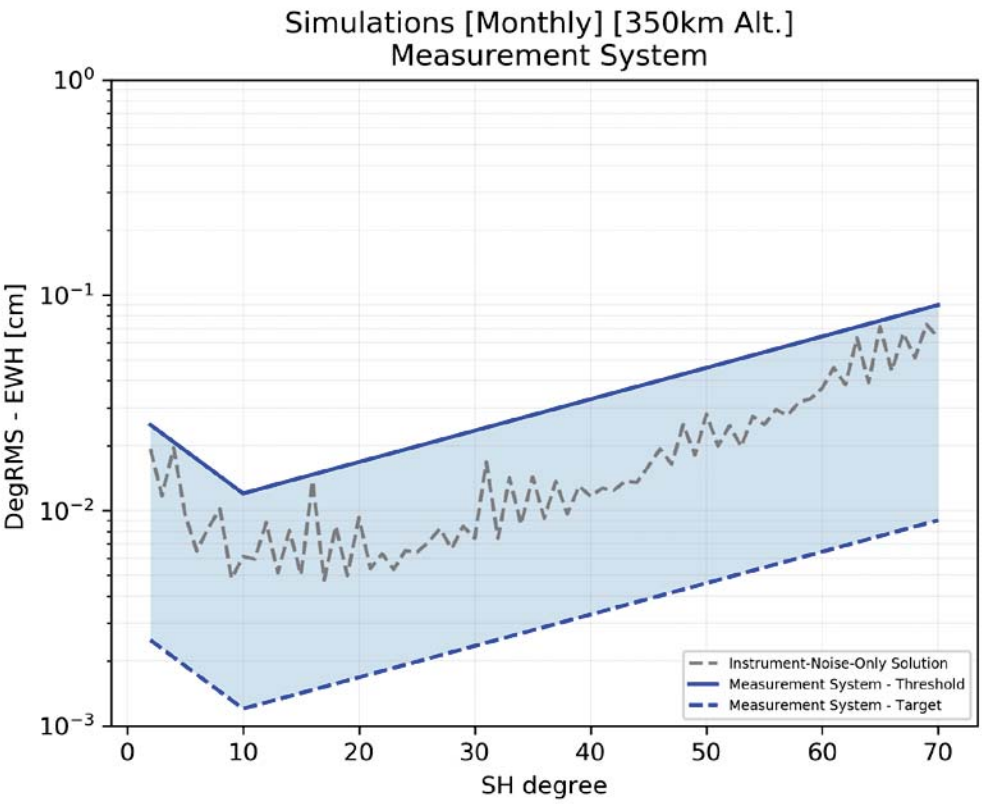


Figure 10 – Degree RMS of instrument-noise-only gravity field simulation and observation system accuracy envelope expressed in EWH for monthly time scales.

DEFINITION TERMS

Along track direction:
Direction parallel to the projection of the spacecraft velocity on the tangent plane to the Earth at the geodetic sub-satellite position.

Altitude:
The distance of the satellite centre of mass above the reference ellipsoid.

Ancillary Data:
Data acquired on-board in support of the observation data, both for the instrument and the platform, such as calibration and timing data.

Auxiliary Data:
Supporting data sets provided outside the Space Segment data stream used to apply corrections to the Space Segment sensor data.

Calibration Mode:
Mode of operation defined to support the in-flight characterisation of the payload.

Data Latency:
The latency is the time interval from data acquisition by the instrument to delivery as Level 1B data product at the user segment interface.

Glacier:
A mass of ice predominantly of atmospheric origin, usually moving from higher to lower ground. A seaward margin of a glacier that is aground, the rock basement being at or below sea-level, is termed an ice wall. The projecting seaward extension of a glacier, which is usually afloat, is termed a glacier tongue. In the Antarctic, glacier tongues may extend over many tens of kilometres.

Height:
The elevation of the actual surface observed above the reference ellipsoid.

Near Real-Time (NRT):
Product delivered in 1-3 days (TBC) to the point of user pickup after data acquisition by the satellite.

Orbit sub-cycle:
Orbital sub-cycles are defined as a period of near-repeat for Earth remote-sensing satellites, see Rees (1990).

Product level:
The concept of product levels, and the definitions thereof, have been codified by CEOS (Committee on Earth Observation Satellites). The CEOS definitions are the basis for the product levels defined in these requirements, with appropriate modifications since the original definitions were formulated with imaging sensors in mind.

Data downlinked from the satellite consist of a serial stream of data bits embedded within a framework of transfer frames appropriate for the purpose. This level of data, which may be temporarily archived at the reception station, is not readable by a general-purpose computer and not included in the set of product level definitions.

Level	Description
L0	Unprocessed payload and satellite source packets (ISP).
L1A	L0 data reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and geo-referencing parameters (e.g., platform ephemeris) computed and appended but not applied to the data.
L1B	Level 1A data that have been quality controlled and reformatted but not resampled. Calibration has been applied. Geometric information is computed, appended but not applied. Preliminary pixel classification is included in the product.
L2	Derived geophysical variables at the same resolution and location as Level 1 source data.
L3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.

Signal to Noise Ratio:
Ratio of signal power to the noise power.

Validation:
The process of assessing by independent means the quality of the data products (the results) derived from the system outputs.