ESA RFP/3-17035/20/NL/FF/tfd

NGGM/MAGIC – Science Support Study during Phase A – Executive Summary

In November 2020 it was decided at ESA's Ministerial Conference to investigate a European next-generation gravity mission (NGGM) in Phase A as first Mission of Opportunity in the FutureEO Programme. The Mass-change And Geoscience International Constellation (acronym: MAGIC) is a joint investigation with NASA's MCDO study resulting in a jointly accorded Mission Requirements Document (MRD) responding to global user community needs. On NASA side, a pre-Phase A study to address these needs started in summer 2021. On ESA side, the MAGIC concept is currently being investigated in two parallel industry Phase A studies, and was complemented by this "NGGM/MAGIC – Science Support Study during Phase A". Further information on this project can be found at the website: https://www.asg.ed.tum.de/iapg/magic/.

1) Evaluation of various constellations and detail studies on specific subjects

In the frame of this science study, several potential mission constellations were investigated and numerically simulated in great depth, in order to narrow down the trade space of a potential MAGIC constellation, to provide feedback to parallel system Phase A industry studies, and to identify an optimum constellation set-up regarding science return, technical feasibility, and costs.

In order to study the impact of different values for the period of a repeat orbit or (sub)cycle and the impact of a change of height, several scenarios were defined for Bender-type constellations consisting of one pair flying in a (near-)polar orbit and one pair in an inclined orbit (Table 1). In addition, a few sun-synchronous orbital (SSO) and pendulum missions were defined. The nominal baseline length is equal to 220 km for all satellite pairs and scenarios. For the scenarios 3d_H and 5d_LL also pendulum pairs with angles of 15^0, 30^0, and 45^0 were defined.

Table 1: Orbits sets for inclined and polar pairs. The ID shows the number of sub-cycle days for which the set is optimized and an additional information about the altitudes: (M)id, (H)igh. Note that the semi-major axis is reduced by 6378 km for highlighting differences in altitude. The other columns provide information about the homogeneity of the ground track patterns).

ID	Sats 1 (IP)		Sats 2 (PP)		h_{l1} [-]	h_{l2} [-]	Δ(Lon)$_1$ [deg]	Δ(Lon)$_2$ [deg]	Sub-cycles [days]
	Alt. [km]	Incl. [deg]	Alt. [km]	Incl. [deg]					
3d_M	409	70	440	89	1.368	1.383	2.308	2.384	2, 3, 8, 11, 30
3d_H	432	70	463	89	1.451	1.449	-3.076	-3.067	3, 7, 31
5d_Ma	396	65	434	89	1.397	1.383	-1.499	-1.458	2, 3, 5, 13, 18, 31
5d_Mb	397	70	425	87	1.168	1.167	0.736	0.733	2, 5, 27, 32
5d_H	465	75	488	89	1.185	1.190	0.762	0.781	4, 5, 29
7d_M	389	70	417	87	1.238	1.253	0.743	0.786	2, 7, 30
7d_H	432	70	463	89	1.218	1.226	0.672	0.692	3, 7, 31
SSO for 3d_H	477	97	463	89	1.454	1.449	-3.097	-3.067	3, 7, 31
SSO for 7d_H	477	97	463	89	1.201	1.226	0.622	0.692	3, 7, 31
5d_LL	344	70	376	89	1.423	1.410	-1.671	-1.628	1, 2, 5, 12, 29
5d_LH	344	71.5	492	89	1.169	1.172	-0.732	-0.790	5, (32-31)

Figure 1 shows an overview of the performance of various constellation designs.

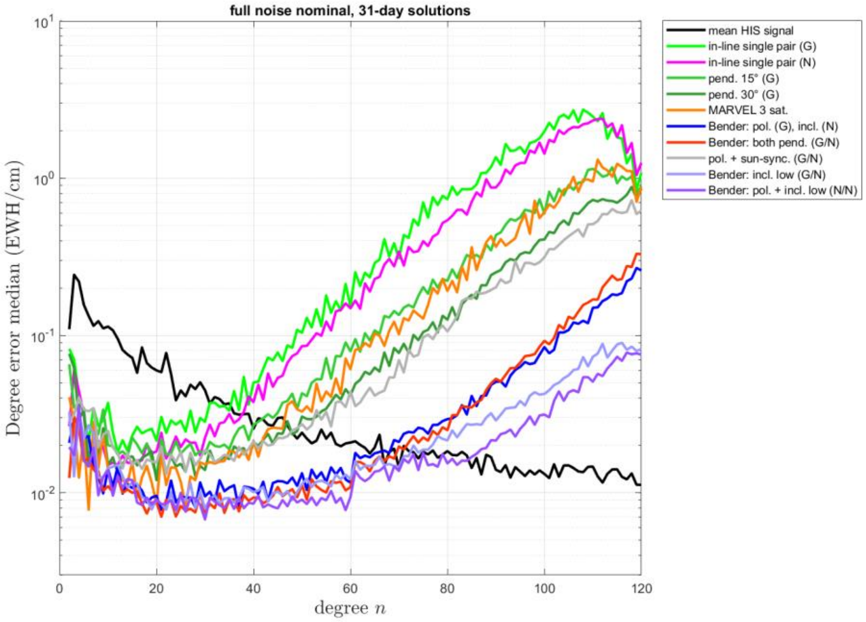


Figure 1: Degree error medians of various mission constellations. G means “SuperStar”, N “MicroStar” accelerometer performance.

These results, which are mainly based on the 3d_H scenario including realistic error models for the key instruments and tidal and non-tidal background errors, clearly demonstrate the superior performance of Bender double-pair mission concepts over all other potential constellations, such as single-pair inline or pendulum missions. There is no added value by flying a pendulum pair as part of a Bender-type constellation. Also the concept of a chronometric 3-satellite pendulum mission was ruled out by these results. In general, temporal aliasing errors are the dominant error source. However, an improved accelerometer (~10^{-11} m/s^2/√Hz) has relatively higher impact in double pair constellations (due to improved de-aliasing capabilities).

Among others, detailed numerical studies were also performed regarding the following aspects:

a) Dependence of performance on the altitude of the satellites/satellite pairs

It could be confirmed that the altitude is the main performance driver. Since in a Bender double-pair scenario the relative contribution of the inclined pair to the total performance is more than 90% in the areas covered with measurements, a low altitude together with a high-performance instrumentation of the inclined pair is essential.

b) Optimum inter-satellite distance

The choice of the inter-satellite distance is a compromise between sensitivity (which improves with distance) and spatial resolution (which degrades with distance). As optimum an inter-satellite distance of 200-250 km is recommended.

c) Double-pair: sensitivity w.r.t. inclination of inclined pair

A rather low inclination of second pair (≤70°) is paramount for the de-aliasing capability of the constellation. Raw (unfiltered) 70° solutions are more stripy (about 50%) than 65° solutions in the covered areas, due to worse estimates of (near-)sectorials, but are better (by about 50%) in the polar areas, due to smaller polar gaps and better estimates of the polar wedge. Post-processed (filtered) 65° solutions are on global average up to 10% better than 70° solutions. This holds for both covered and polar regions. However, this percentage numbers vary with the choice of the filter. An obvious severe disadvantage of 65° inclined orbit is that it results into a larger unobserved region near the poles as stand-alone mission. Therefore, a more conservative 70° inclination of the inclined pair is recommended.

d) Impact of ground track sampling on gravity performance and heterogeneity

Figure 2 shows the simulation set-up for a 3-day solution using polar and inclined orbits with 3-day and/or 5-day sub-cycles polar and inclined orbit (mixture of orbits of the scenarios given in Table 1), leading to homogeneous coverage (3d_H), spatial gaps of the polar tracks (U3d5d_H) or gaps in both pairs (U5d_H). Evidently, a non-homogeneous ground track pattern of the polar pair (blue curve in Figure 3) is acceptable, but leads to slightly larger errors in higher spherical harmonic (SH) degrees compared to the homogeneous ground track sampling of both pairs (red curve). However, combining a polar pair having a non-homogeneous ground track pattern with an inclined pair also having a non-homogeneous ground track pattern with coinciding gaps in the 3-day ground tracks of both pairs results in a severe degradation over the whole spectral range, and thus hampers significantly the homogenous quality especially of short-term (NRT) solutions required for operational service applications.

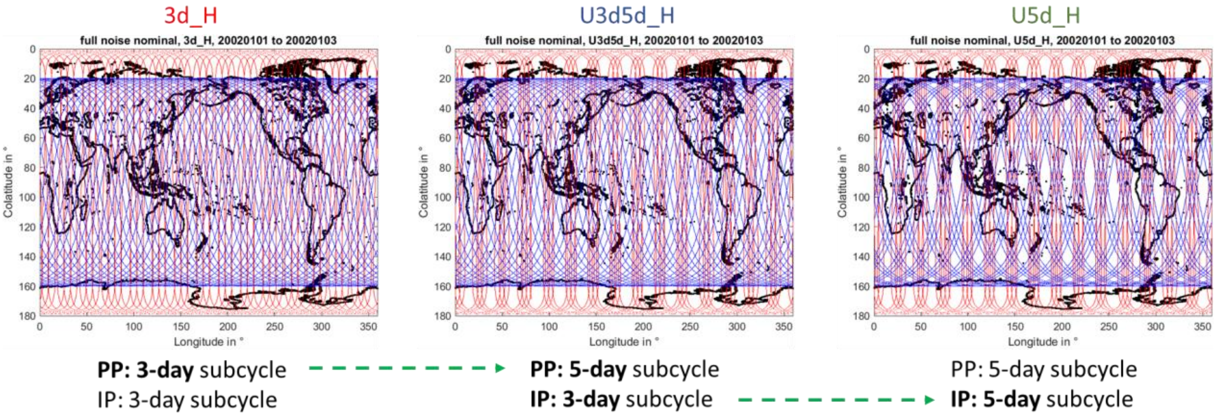


Figure 2: Ground track patterns of simulation set-ups with varying ground track homogeneity.

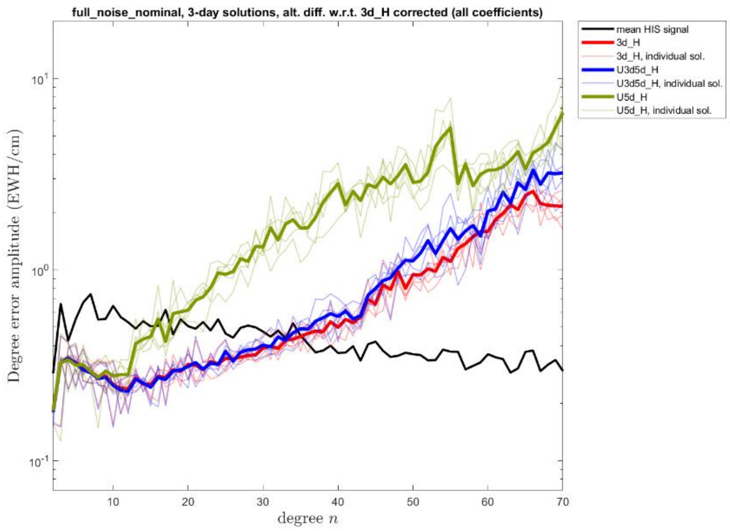


Figure 3: Degree error RMS of gravity field retrievals related to the scenarios shown in Figure 2.

e) Impact on drag-free conditions and accelerometer performance

Various scenarios representing a combination of the MicroSTAR instrument performance combined with different levels of imperfect drag compensation for the inclined satellite pair in regard to different atmospheric conditions ranging from a “best-case” full 3D (blue curve in Figure 4) to a “worst-case” 1D drag compensation in along-track direction and with maximum atmospheric conditions (red curve), have been analyzed. In all cases, the same assumption on the polar pair of a SuperSTAR ACC is applied. Figure 5 a shows, that in the product-noise only case, a degradation of varying extent of all scenarios compared to the reference scenario (black curve) is visible, with the maximum impact up to degree/order 30. It should be emphasized, that a stochastic stochastic modelling of the tone error peaks at multiples of the orbital frequency (cf. Figure 4) as part of the gravity adjustment process is indispensable to avoid significant degradation of the retrieval performance.. In case of the full-noise simulation scenario (Figure 5 b) where de-aliasing is applied for the AO and OT components with the HIS component as target signal, the differences between the investigated scenarios are much smaller, because most of the impact of the drag compensation is covered by the temporal aliasing.

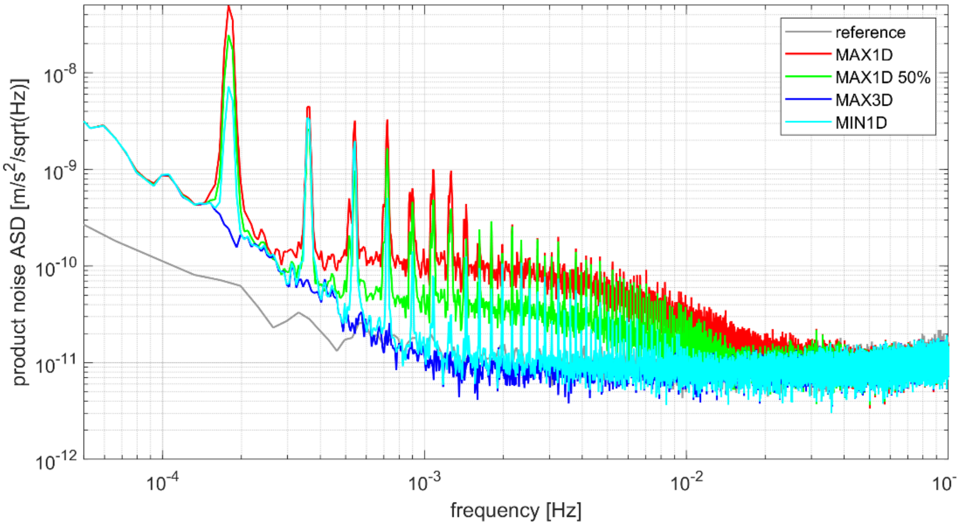


Figure 4: Product noise amplitude spectral densities (ASD) for various set-ups of ACC performance and drag-free conditions. The terms “MAX” and “MIN” denote a maximal or minimal atmospheric activity, respectively, while the terms “1D” and “3D” denote whether drag compensation is applied exclusively in along-track or in all three spatial directions. The “reference” scenario denotes in essence the performance of a MicroSTAR-type accelerometer and differs from the “MAX3D” scenario only by its lower low-frequency noise increase (1/f instead of 1/f²).

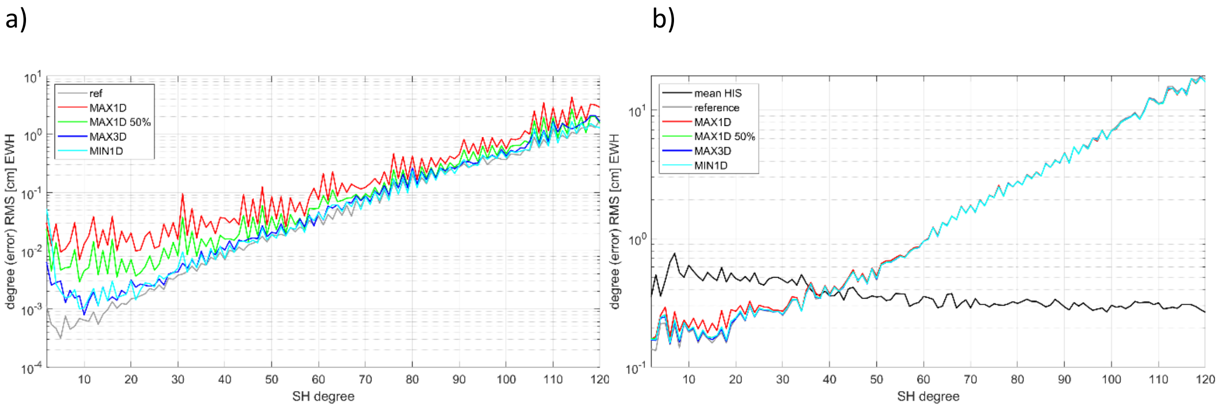


Figure 5: Degree error RMS of gravity field retrievals related to the scenarios shown in Figure 4, left: product-noise only case, right: full noise case.

f) Scaling of performance with retrieval period

As to be expected, in the product-noise only case the performance can be scaled linearly with the number of observations (= retrieval period). We found out that this linear scaling can also be roughly applied to the full-noise solutions (including background model errors) down to about 3 days. In contrast, co-estimated as well as stand-alone daily solutions perform even better than predicted by linear scaling.

g) Capabilities of short-term (near-real time) retrieval

Short-term daily co-estimates (proposed by Wiese et al. 2011) are possible up to SH degree 15 to 20 for double-pair scenarios. In specific cases this parameterization causes “bumps” in the degree variance plots at higher degrees. This happens whenever the inclined pair has a very high weighting compared to the polar pair, for example if it has a significantly lower altitude or a much better instrument (accelerometer) performance. In this case, alternatives to the classical "Wiese parameterization" will have to be applied, such as the DMD method (cf. section 4 c).

h) Raw vs. post-processed (filtered) solutions, effect of filtering

Depending on the post-processing strategy, a wide range of results can be achieved in comparison to the MRD/IUGG requirements. It is recommended to use the raw (unfiltered) solution as the baseline strategy for the evaluation of mission performances, keeping in mind that this composes the "worst case" compared to the IUGG requirements, which assumed a certain degree of post-processing.

i) Effect of tone errors

The effect of tone errors is clearly visible in product-only cases, where mainly the low-degree zonal SH coefficients are affected. An adequate stochastic modelling of tone errors is paramount to avoid significant degradation of higher-degree coefficients. Increasing the amplitude of tone errors by a factor of 10 w.r.t. the original SRD specifications, their impact reaches the error level of the full-noise solution, where the effect of tone errors is partly mixing with other error sources. Based on these results, it was recommended to relax the SRD requirements regarding tone error amplitudes by a factor of 10.

2) Second software implementation

In order to validate the TUM numerical simulation results and to prove that these results are reliable, a second implementation of the simulator was done at GFZ based on the EPOS software package. The inter-comparison was performed not only on the final result, but also selected intermediate products, such as orbits, background models and corrections. After some software adaption on both sides, a very good agreement both for product-only and full-noise scenarios could be achieved, even though these two packages are based on different evaluation methods (short-arc approach at TUM vs. numerical integration approach at GFZ). As an example, Figure 6 shows the TUM and GFZ results for a 3d_H double pair scenario. In general, the RMS deviation between the two solutions is less than 5% of the resulting error level of the simulation. Also co-estimated daily ("Wiese") parameters show a very similar performance.

With this, two very comparable software systems are available for further simulation studies.

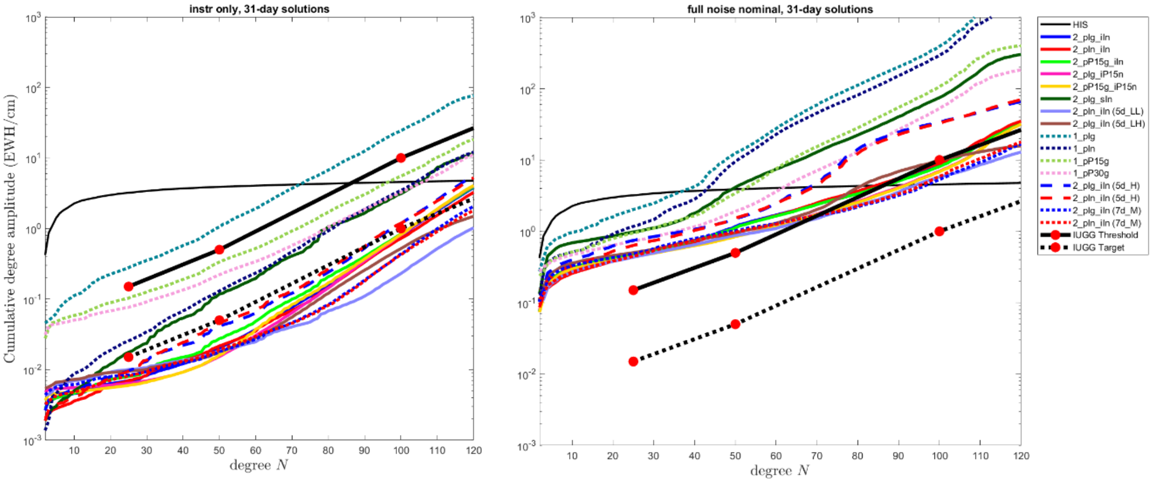
Figure 6: Full noise solutions of the 3d_H Bender scenario simulated by GFZ (red and magenta) and TUM (blue and green) in terms of SH degree error amplitudes. The monthly averaged HIS signal is displayed in black.

3) Match against MRD requirements

All simulation scenarios performed in this study were evaluated in terms of cumulative EHW errors, and the results were compared against the MRD requirements, which are largely based on the IUGG user requirements (Pail et al., 2015).

Figure 7 a shows the cumulative EWH errors of various scenarios in the product-only noise case for a monthly (31 day) retrieval period. Evidently, in the absence of background model errors and related temporal aliasing the results come very close to fulfil even the very ambitious target requirements

Figure 7 b shows the same quantities for the full-noise scenarios. Here, the threshold requirements can largely be reached, with the exception of the low degrees. This significant reduction of performance for the full-noise case compared to the product-only noise case again demonstrates the dominant role of background model errors in the total error budget. However, it should be emphasized that the simulations are based on very conservative assumptions of the background model errors. Additionally, the cumulative error curves are based on the raw solutions, i.e. without any a-posteriori filtering, while the IUGG requirements assumed some degree of post-processing. It is expected that in the near future, the overall performance of the mission, which is currently not limited by the key payload and system design, will be improved by improvements of geophysical background models, going hand in hand with further improvements in processing methodology to reduce the impact of temporal aliasing.



a) b)

Figure 7: Cumulative RMS curves for a 31-day d/o 120 a) product-only noise, and b) full-noise simulation results, compared to the IUGG threshold and target requirements. For each individual scenario, the mean curve of the cumulative RMS curves of two subsequent 31-day solutions is shown.

Also the match for sub-monthly periods was analyzed. As an example, Figure 8 visualizes cumulative errors of simulations using a 3 day retrieval period (up to SH degree 100). The monthly MRD threshold and target requirements were scaled to a 3-day period (cf. 1f) by multiplying with a factor of sqrt(31/3). Similar conclusions as for the monthly retrieval period also hold for the sub-monthly period.

a) b)

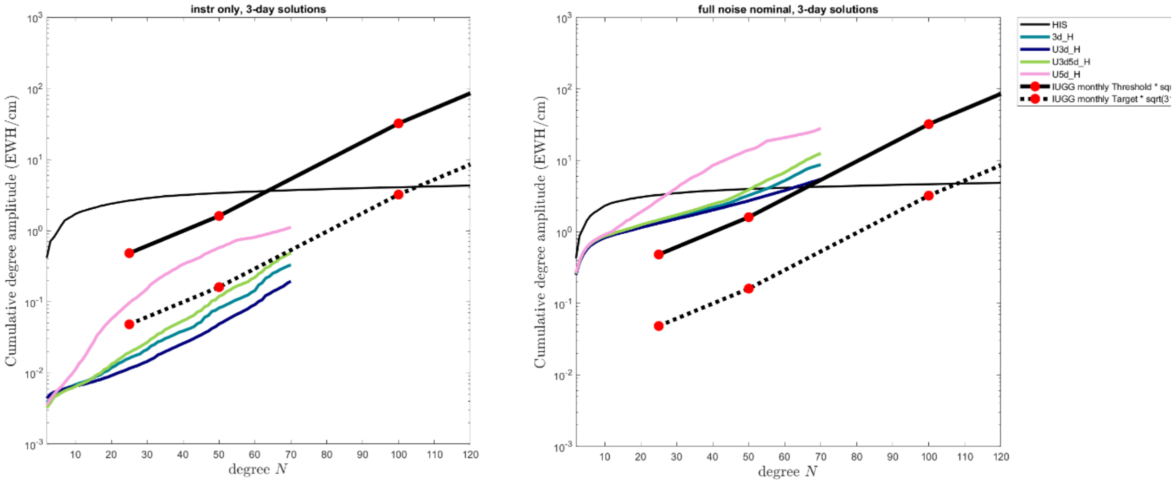


Figure 8: Cumulative RMS curves for a 3-day d/o 100 a) product-only noise, and b) full-noise simulation results, compared to the MRD threshold and target requirements (monthly req. scaled by sqrt(31/3)). For each individual scenario, the mean curve of the cumulative RMS curves of 20 subsequent 3-day solutions is shown.

4) Development of improved processing methods

In the frame of this project, improved processing strategies have been developed, implemented, numerically analyzed and compared to the performance of the baseline strategy.

a) Optimal application of de-aliasing models

In order to investigate the impact of temporal aliasing errors in more detail, tidal and non-tidal aliasing errors were assessed individually, by excluding either the one or the other error signal from the simulation, but keeping the same product-error assumptions for all simulations. Results demonstrate that the orbit altitude is the main performance driver, either omitting ocean tide errors or omitting errors due to non-tidal aliasing. If non-tidal AO signals are included in the simulation, lower orbit altitudes lead to significantly reduced temporal aliasing errors, even in the longer wavelength spectrum, as temporal aliasing errors due to AO error is the dominating error contributor. In this context, it is to mention that the altitude of the inclined pair is crucial since an altitude, which is much lower (e.g. below 400 km) than the one of the polar pair, results into smaller retrieval errors, also in the high frequency spectrum. If no AO signals are included in the simulation and tidal aliasing errors are dominating, the performances of gravity field solutions of double pair formations having different altitudes show similar behavior at the low-to-mid degree spectrum. In that case, the role of orbit altitude becomes more important for the performance at the mid-to-high frequency spectrum. For sub-monthly retrievals, the length of the respective retrieval period plays an important role as well, next to the altitude. This is especially true if non-tidal AO signals are included.

b) Treatment of ocean tides in NRT analysis and post-processing

It could be shown by Hauk and Pail (2018) that the co-estimation of ocean tide parameters is possible and reduces temporal aliasing errors. However, this method requires long observation time series and is therefore not applicable in near-real time (NRT) analysis. Therefore, an alternative method was developed and applied to Bender double-pair constellations. It is based on the idea to introduce ocean tide background model errors as additional stochastic model into the parameter adjustment, and to propagate it through the whole process to the parameter estimates. Details of the method and a detailed analysis for single- and double pair scenarios can be found in Abrykosov et al. (2021).

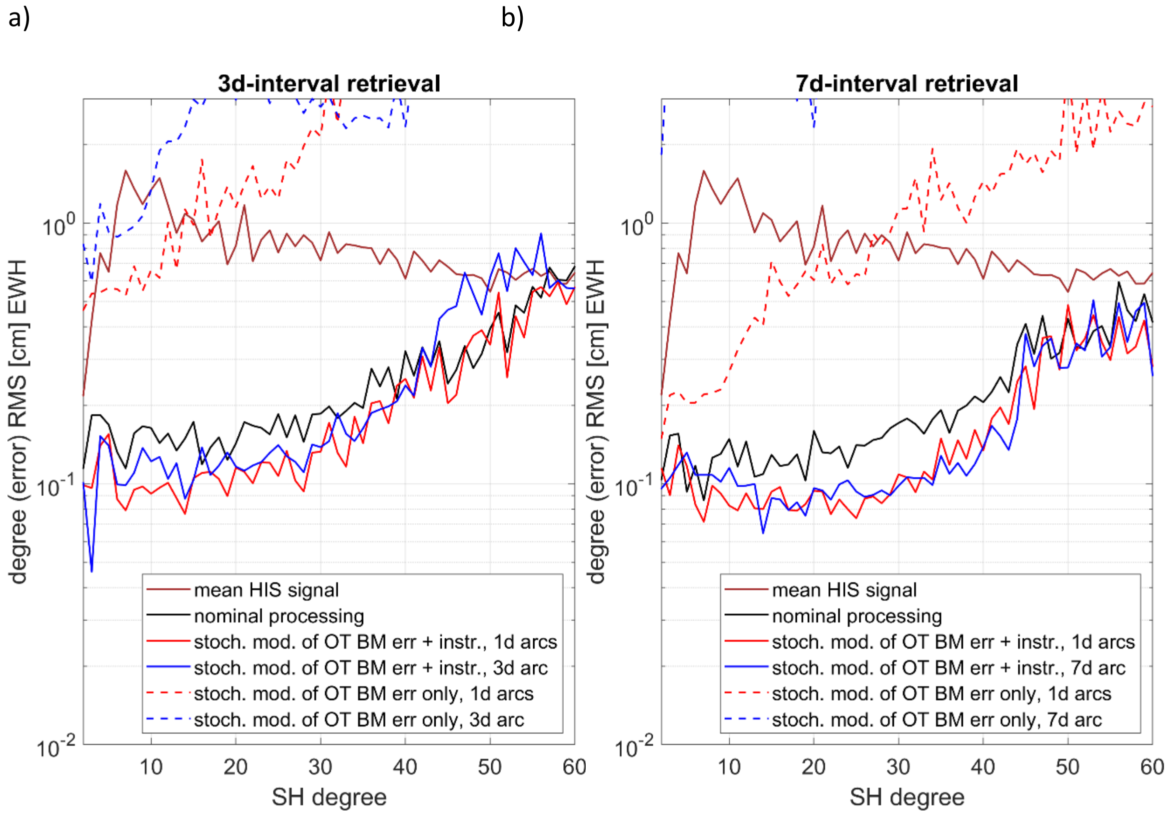


Figure 9: Retrieval performance of scenarios including tidal and non-tidal gravity signal as well as instrument noise when stochastic modelling is applied for OT BM errors only, OT BM errors and instrument noise or no stochastic modelling of OT is applied at all. Retrieval period is a) 3 days (left), and b) 7 days.

The results of Figure 9, which are based on a 3d_H Bender-type double-pair scenario, demonstrate that stochastic modelling of OT background errors has the potential to significantly improve the retrieval performance. This method can be applied not only to the retrieval of long-term, e.g. monthly, solutions, but also short-interval fields. It thus poses a valid processing strategy for estimating NRT-type gravity field solutions. The main limiting factor are non-tidal (AOD) background model errors. In future research, it is planned to develop a similar strategy for stochastic modelling of non-tidal background model errors, and apply it together with the OT method discussed here.

c) Optimal signal parametrization with respect to space and time

An alternative method for the co-estimation of daily long-wavelength gravity fields together with coefficients of higher SH degrees ("Wiese approach"), the data-driven multi-step self-de-aliasing (DMD) method, has been developed (Abrykosov et al. 2022a), originally for the "self-dealiasing" of the single-pair missions GRACE and GRACE-FO. In the course of this, a detailed analysis of the space-time pattern of temporal gravity signals was performed, showing that also long-term signals create high-frequency spatial structures. Therefore, the standard concept proposed by Wiese et al. (2011) is not able to fully capture these signals. It was demonstrated that especially in this case of a single-pair scenario long-wavelength, high-amplitude signal components are mapped into other spectral bands, thus degrading the retrieval performance. Therefore, the decoupling of daily low-degree and multi-daily higher-degree estimates, as done in DMD, is of great benefit especially for single-pair scenarios, because the effect of aliasing reduction by means of daily estimates is larger than the spectral leakage due to decoupling of low and higher degrees.

In the frame of this project, the DMD concept was transferred to double-pair constellations. Here, compared to single-pair constellations the behavior of DMD is somewhat different, because of the intrinsic aliasing reduction of the double-pair constellation due to the additional inclined pair, leading to a lower gain of additional de-aliasing relative to the spectral leakage effect. The DMD performance depends on the amplitude of the signal (being a potential source of aliasing) and the resolution of the gravity field product (defining the relative contribution of spectral leakage errors). Figures 10 a and 10 b show the results when using only AO or the full AOHIS signal as an input, respectively. Evidently, the classical Wiese parameterization performs slightly better for the present simulation set-up including the full AOHIS signal up to degree/order 50. However, both classical Wiese and DMD perform generally better than the nominal processing without additional parametrization.

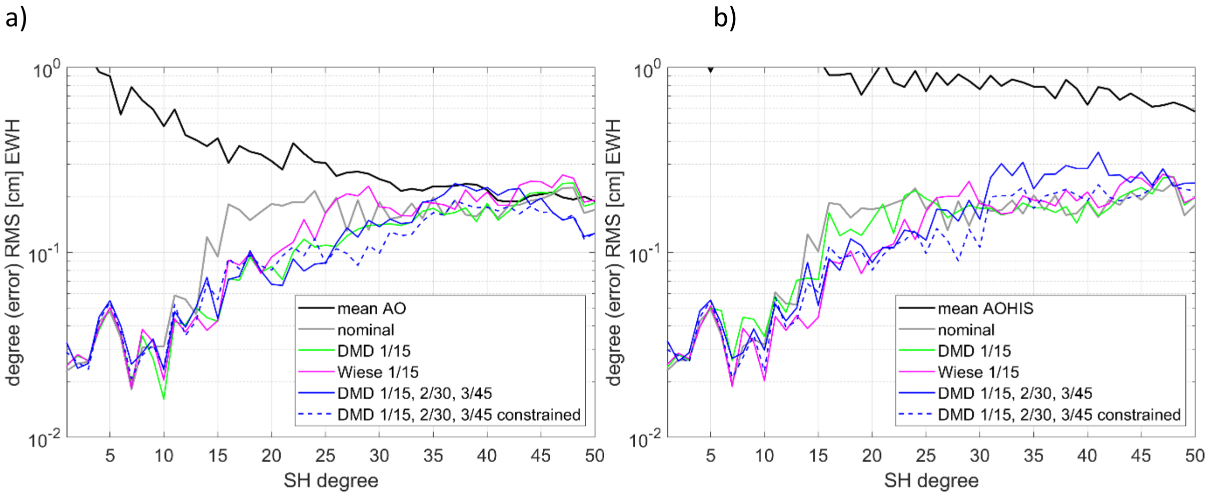


Figure 10: Degree error RMS of gravity field retrievals related to various parameterization schemes.

In addition, expanding the classic “Wiese approach” with additional intermediate steps in terms of successively longer periods increases the processing complexity, but has not shown any improvements in achievable gravity performance. In contrast, as shown in Figure 10, a DMD multi-step approach has some potential to further improve the results.

d) Analysis of need for long-term trend estimation

Linear trend parameters have been co-estimated together with monthly temporal gravity fields for a 10-year period in the frame of a joint adjustment. Comparing the monthly solutions with and without co-estimation, there is no indication of a benefit when the long-term trend is co-estimated.

e) Analysis of need for post-processing

An optimal filter technique for post-processing of Bender-type gravity field solutions was developed. Methods based on non-isotropic smoothing by approximate decorrelation and regularization (DDK), and time variable decorrelation (VADER/VDK filters) were investigated. The VDK filter usually outperforms the DDK filter. Exemplarily, Figure 11 shows the results of a raw and a VDK-filtered solution of the Bender-pair scenario 3d_H. Comparing single and double-pair solutions, a much lower filter strength has to be applied to reduce the residual striping of double-pair missions.

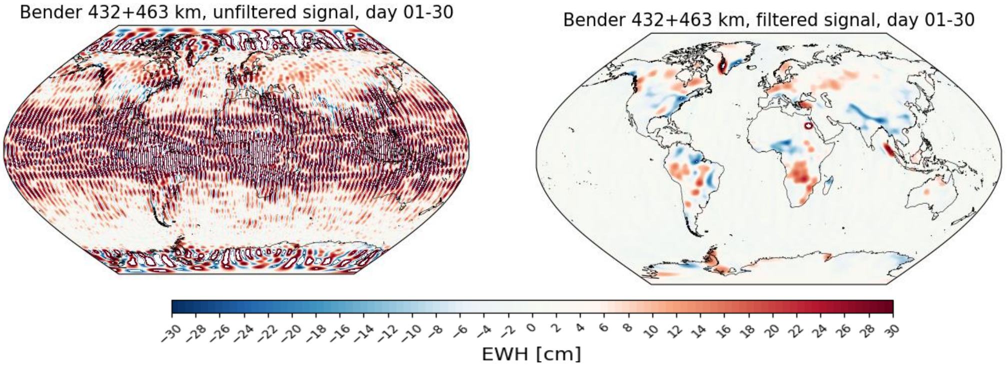


Figure 11: Spatial comparison of filtered and unfiltered monthly retrieval periods for Bender double-pair scenario 3dH.

The filtered gravity fields are then further evaluated against the true reference signal as well as unfiltered fields at the example of river basins and ice sheets. Results demonstrate, that VDK filtering of Bender-type gravity fields can be useful in order to extract the signal of interest by reducing temporal aliasing effects significantly. Depending on the region to be investigated, it is advisable to look at the error distribution of the 'raw' retrieval on a spatial scale first and then decide which type of gravity field (filtered or unfiltered) to be used.

5) Science impact analysis

The science impact analyses for the fields of hydrology, cryosphere, oceanography and solid Earth revealed significant added value of MAGIC constellations for unravelling and understanding mass transport and mass change processes in the Earth system. For hydrological applications, the number of hydrological units, e.g. river basins, that can be analyzed for water storage variations within the limits of MRD requirements will markedly increase compared to a GRACE-like mission. At a comparatively high spatial resolution, the threshold accuracy (10.1 cm at N=77) can be fulfilled by MAGIC for more than 90% of the river basins worldwide (compared to 2.5% with GRACE-type missions), and even higher accuracies that may be required for several hydrological applications can be met in a large number of basins (Figure 12). In contrast, the current MRD requirement at the lower spatial resolution of 400 km cannot be met by MAGIC for any river basin. However, relaxing this threshold accuracy to 2.5 cm or 3.5 cm, which can be expected to be still acceptable for many hydrological applications, will allow for resolving TWS variations in 67% and 90% (0.5% and 2.5% for GRACE-type missions) of the river basins, respectively. For the optimally filtered solutions, the improvement of MAGIC relative to GRACE in terms of RMSD errors of basin-average water storage variations worldwide amounts to a factor of 1.5 to 5, where the largest improvements occur for basin in low-latitude regions, which are hampered most by temporal aliasing errors.

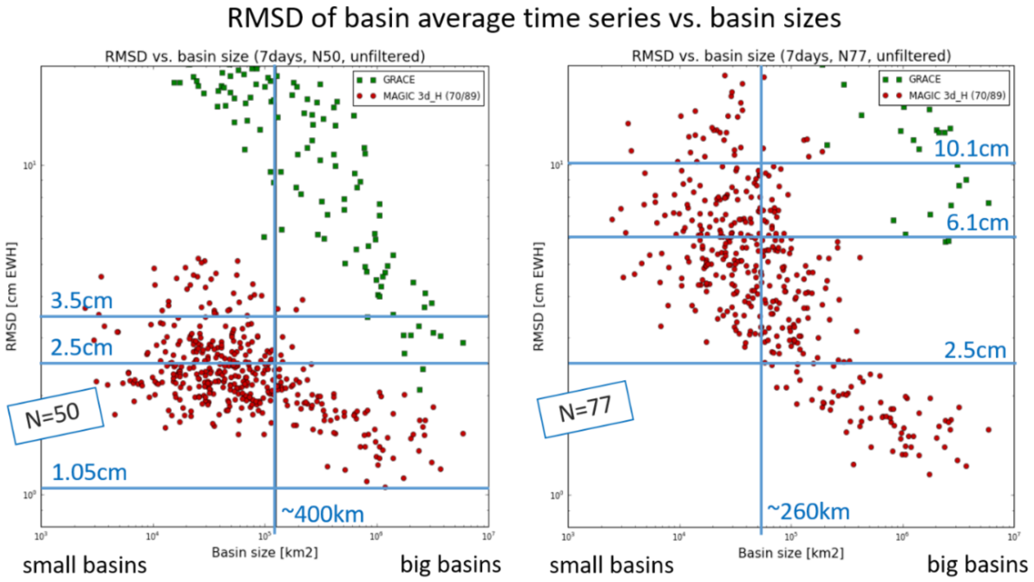


Figure 12: Root-mean square deviations of weekly basin-average water storage variations for GRDC river basins worldwide, truncated at N= 50 (left) and N=77 (right), for the MAGIC 3d_H and a GRACE-like configuration. Different accuracy requirements are given by blue horizontal lines. The vertical blue lines represent the spatial extent of spherical caps with 400km and 260km diameter, respectively.

Climate change impacts on the global water cycle such as its intensification will be markedly better be observed by a MAGIC double pair mission than by a GRACE-like mission. While, according to our simulations, a GRACE-like mission can only detect the projected changes of the annual amplitude of continental water storage in 36% of the land area after 30 years of observation, MAGIC-like missions would be able to identify such changes in 64% of the land area (Figure 13). Similarly, the projected 30-years phase change of water storage can be detected by the single-pair scenario in 30% of the land area while a significant increase of this portion (56% of land area) can be achieved with the MAGIC constellation.

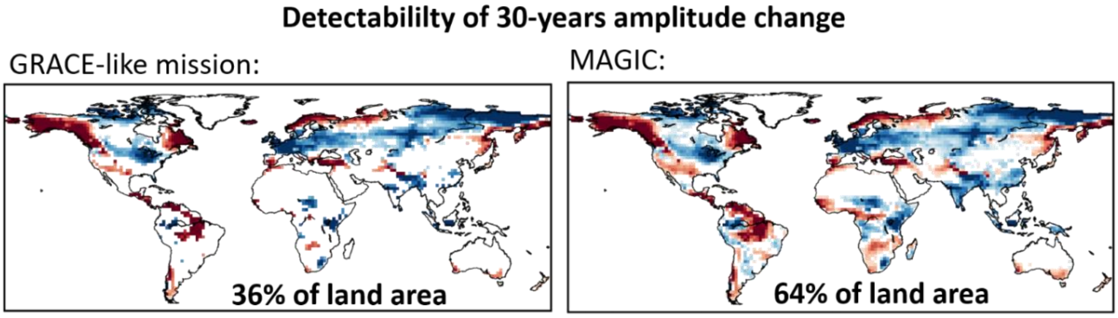


Figure 13: Detectability of the projected climate-change induced annual amplitude change of terrestrial water storage after 30 years of satellite gravimetry observations: coloured pixels denote where projected amplitude change exceeds the magnitude of the GRACE or MAGIC accuracy.

For cryosphere applications, our analysis shows that the double-pair MAGIC configurations will drastically improve our ability to monitor mass displacements on the ice sheets compared to what is currently possible. It is shown that it should be feasible to separate mass signals in the interior of Greenland or Antarctica from those in the coastal zones (Figure 14), which is of high scientific interest. While for the hydrology, ocean and solid Earth analyses the MAGIC 3d_H, 5d_Ma and 5d_Mb constellations performed very similar, the 5d_Mb configuration shows the best performance for the cryosphere applications, which is related to the lower altitude of the polar pair compared to scenario 3d_H, and the higher inclination of the inclined pair compared to scenario 5d_Ma. Correspondingly, scenario 5d_Mb shows the largest number of basins passing the threshold and target criteria and the lowest RMSE. At a 250 km resolution, the threshold accuracy for monthly time scales (5.5 cm RMSE) is met for 40 out of the 45 basins, and at daily-to-weekly time scales (6.3 cm RMSE) still for 37 basins. For the Antarctic Peninsula as a region of rapid ice loss, the added scientific value of a double-pair mission is far-reaching as the RMSE drops to an order of magnitude lower than what is currently achievable with a single-pair mission.

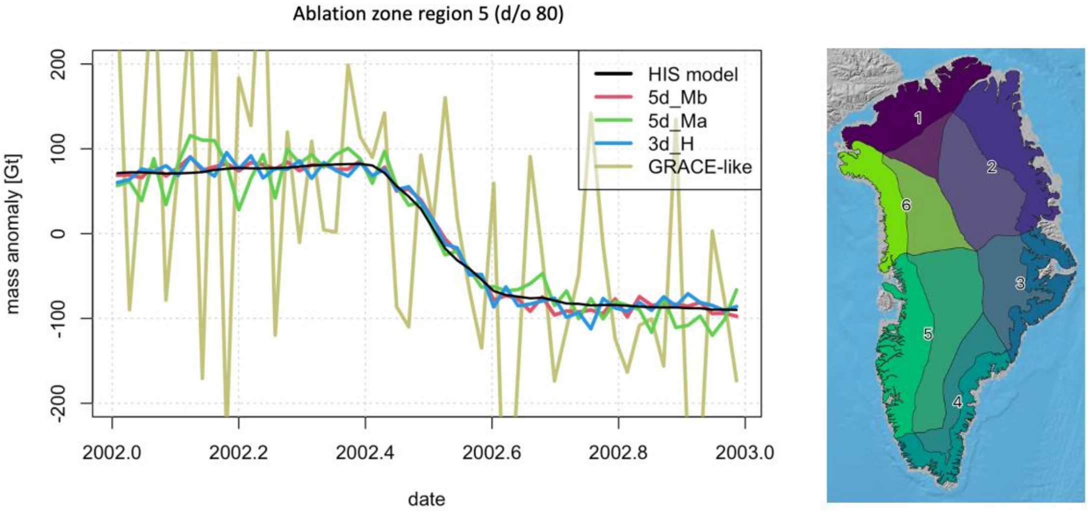


Figure 14: Mass variations in the ablation zone of Greenland basin 5 simulated by the HIS model and retrieved from the 4 mission configurations simulations.

In the field of oceanography, the MAGIC double-pair configurations produce a dramatic improvement in ocean bottom pressure determination over the single pair GRACE-style configuration. While the present state GRACE measurements cover only the large-scale fluctuations over the range of degrees from about 5 to 15-30 which are of little climatic interest, the new configurations extend the valuable information out to degrees up to between degree 50 and 80, depending on the signal. This is a game-changing extension, permitting clear physical interpretation of aspects of the ocean circulation which are of most relevance to the Earth System, including the potential to monitor meridional overturning circulation changes on time scales of years and decades. The Caribbean Sea example shows a change from barely detectable signals (at about 1 cm RMS) to clearly detectable ones, increasing the explained variance from about 50% of the single-pair to 80%-90% with the double-pair configuration (Figure 15).

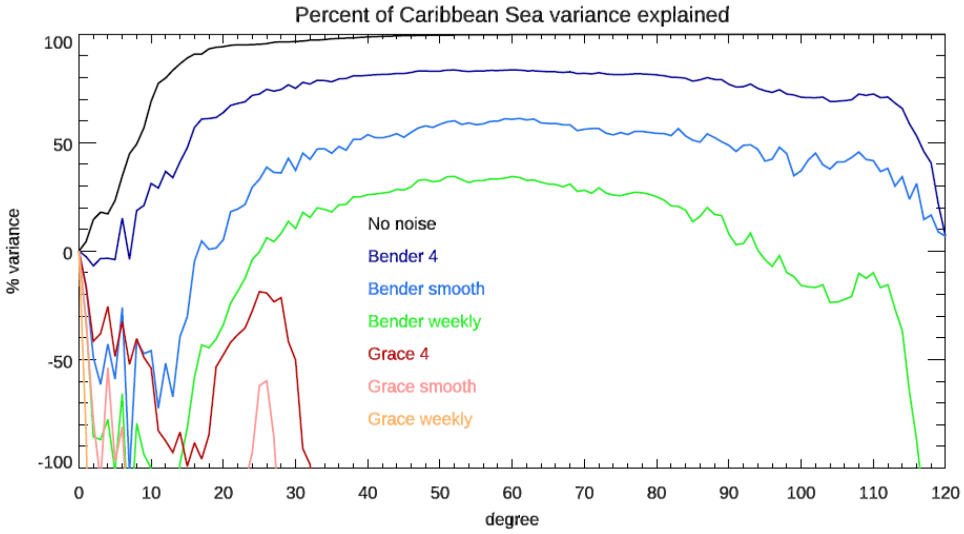


Figure 15: Percentage variance explained, of the Caribbean Sea basin-averaged bottom pressure, by the pressures truncated at different spherical harmonic degrees and with noise of different amplitudes added. "4" means noise has been reduced by a factor of square root of 4 (in order to propagate the weekly values for the noise to 4-weekly (monthly) means). “smooth” means 4-week averages were used instead of weekly data.

Our analysis of the MAGIC performance in detecting a gravity signal generated by an earthquake of a magnitude *M* shows that it will bring a definitive improvement compared to the present observation technologies of a GRACE-like configuration. When comparing single and double pair configurations with weekly solutions, the double pair significantly lowers the detectable moment magnitude from *M*=8.8 to *M*=8.2, and increases the highest observable degree up to about 60 (333 km resolution). Lowering the time resolution to 1 year, the Bender configuration would detect earthquakes with magnitude *M*=7.4 upwards (Figure 16).

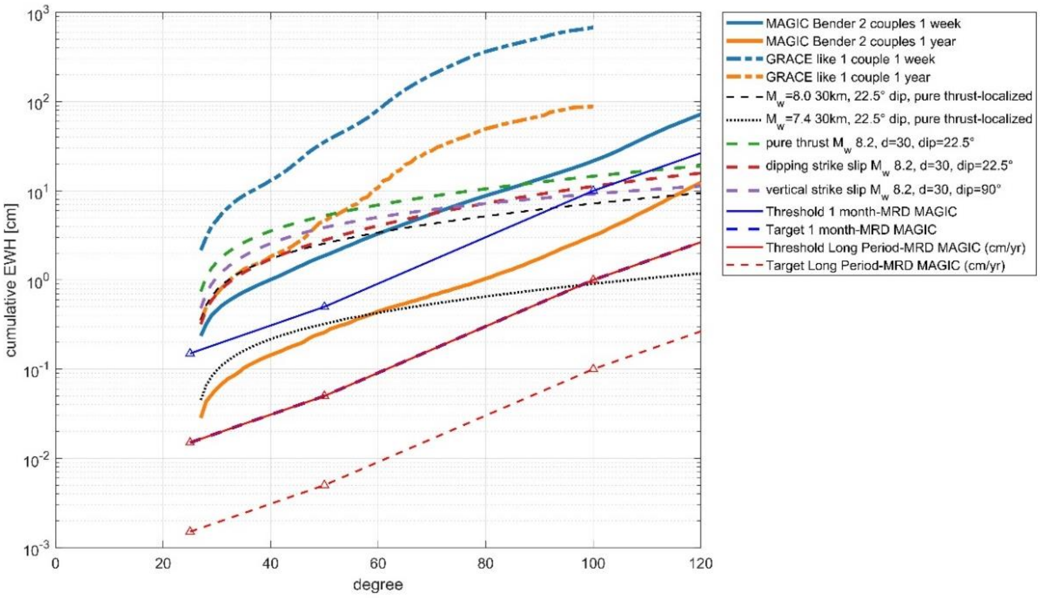


Figure 16: Cumulative noise curves and cumulative spectral signal curves for some selected earthquake mechanisms. EWH amplitude spectra. The blue and red triangles correspond to the MRD threshold and target requirements (Table 12 of MRD-ESA document; threshold requirement monthly:of 0.15 cm EWH@degree 25, 0.5 cm EWH@degree 50, 10 cm EWH@degree 100, and 50 cm EWH@degree 133, 500 cm EWH@degree 200 (month). The monthly target curves are scaled by a factor 10. The long period error curves in cm/yr values correspond to a division by factor 10 of the monthly values.

6) DORIS-aided orbit and gravity field determination

The impact of embarking DORIS receivers on board of the gravity field satellites was investigated. It will be assessed if DORIS, in addition to precise cm-level kinematic orbit solutions derived from GNSS observations, has the capability to enhance the quality of retrieved temporal gravity field models. The use of satellite tandems allows to form differential DORIS observations, which mitigates some common errors such as tropospheric delay correction errors. Therefore, the gravity field retrieval simulations included solutions based on both absolute and differential DORIS observations. The gravity field retrieval simulations have been conducted for the scenario 3d_H. It was verified that TU Delft and CNES software lead to comparable gravity field retrieval simulation results. The DORIS differential measurement type, even the ideal case tested in the gravity field retrieval simulations, does not provide additional information, i.e. accuracy, to the solution. In reality, the errors in the DORIS differential measurements will be much larger as they will for an important part not cancel out, as was shown with real Sentinel 3A/3B data. The DORIS receiver can therefore only be considered as a back-up instrument for the GNSS receiver in the unlikely event of its failure.

7) Accelerometer calibration

Connected to the studies on the DORIS-aided orbit and gravity field determination (section 6), it was also investigated if such a scenario has the potential to enhance the calibration of accelerometers. Also in this case, the calibration simulations were based on scenario 3d_H and included solutions based on both absolute and differential DORIS observations. The accelerometer calibration assessment was based on having one accelerometer in the center-of-mass with a GRACE-type noise. The biggest contribution for precise accelerometer calibration comes from the kinematic orbit coordinates (GNSS). The addition of DORIS or ll-SST observation hardly improves the accelerometer calibration by POD.

Drag-free flight leaves a very small non-gravitational signal to be observed by the accelerometers, which makes the estimation of accelerometer scale factors less crucial and also very unstable. A proper maneuver scheme allows a very accurate kinematic orbit based calibration of the scale factor of the accelerometers: very accurate values can be obtained for the X and Z axes (accuracy generally better than 0.001), and more reliable estimates for the Y axis scale factors are obtained (better than 0.05). Periods of a few hours with thrust of the order of 50 nm/s^2 might be sufficient. Accurate estimates of scale factors can be obtained as well when not flying drag-free (e.g. during the commissioning phase), especially for the X axis (much better than 0.001 during solar maximum, better than 0.01 during solar minimum). For the Y and Z axes, the performance is an order of magnitude worse, even more so for the Z axis during solar minimum.

A proposed implementation is to have 3 accelerometers on board of each satellite, with 1 accelerometer in the center-of-mass of the satellite and the other two symmetrically located with respect to this center-of-mass. This possibly leads to a √3 noise reduction when for example using a 3-accelerometer common-mode in case of accelerometer calibration by POD. The exact impact of such a possible reduction is yet to be assessed. Heritage from GOCE shows that similar results are obtained for 2-accelerometer and 1-accelerometer calibration by POD, but also that other calibration schemes, e.g. by comparison with star tracker observations, are feasible for at least the accelerometer scale factors.

8) Conclusions

In the frame of this MAGIC/Science project, which was performed in parallel to two industry system studies, the trade space of a wide range of satellite constellations could be narrowed down, leading to a clear recommendation for a Bender-type double pair mission concept. The performance of the constellation is mainly driven by the inclined pair. Therefore, at least the inclined pair has to fly a coordinated orbit with a ground-track pattern forming short sub-cycles, in order to guarantee homogeneous performance of short-term solutions which is an indispensable requirement for operational service applications. All simulation results were compared against the MRD requirements In the full-noise case, which includes very conservative assumptions especially regarding background model errors as the dominant error contributors, the double-pair results can largely meet the threshold requirements for monthly solutions, with the exception of the low degrees. This is also true for short-term solutions of a few days.

The scientific potential was assessed in the main fields of applications continental hydrology, cryosphere, ocean, solid Earth, and climate research. Based on the analysis of single- and double pair simulation scenarios spanning over 1year, the latter could demonstrate significant added value in all analyzed thematic fields. This is reflected, e.g., by a much larger number of hydrological units that can be analyzed for water storage variations within the limits of MRD requirements, an increase in capability to detect the projected climatic changes of the annual amplitude of continental water storage from 36% to 64% of the land area after 30 years of observation, a drastic improvement to monitor mass displacements on the ice sheets including the feasibility to separate mass signals in the interior of Greenland or Antarctica from those in the coastal zones, and the ability to detect earthquakes with magnitude M=7.4 upwards for a time resolution of 1 year. In the field of oceanography, the MAGIC double-pair configuration would be a game changer, permitting clear physical interpretation of aspects of the ocean circulation, including the potential to monitor meridional overturning circulation changes on time scales of years and decades.

During this science study, several interactions with the parallel system Phase A studies existed, leading, e.g. to the identification of the optimum inter-satellite distance, the impact of various accelerometer and drag free scenarios, and a loosening of the requirements for tone errors. The reliability of the simulation results were guaranteed by an independent second implementation of a numerical simulator based on GFZ’s EPOS software, which produces very comparable results to TUM’s numerical simulator for all tested scenarios. In the frame of this projects, also several methodological improvements were developed, implemented and assessed, such as the treatment of ocean tides (OT) in near-real time (NRT) processing based on the stochastic modelling of OT background model errors, Science impact analysis, a data-driven multi-step self-de-aliasing (DMD) method for better treatment of short-term atmosphere and ocean signals and corresponding reduction of temporal aliasing, or the optimal application of de-aliasing models. Additionally, impact of embarking DORIS receivers on board of the gravity field satellites was investigated. In full-scale simulation, it was found out that the DORIS differential measurement type does not provide additional information to GNSS.

In summary, important lessons regarding the optimum set-up of a MAGIC double-pair mission, the tuning of its key parameters, and its optimized processing could be learnt during this project, providing also valuable feedback for the parallel system studies and paving the way for a significantly improved monitoring of mass transport processes from space.

References

Abrykosov P, Murböck M, Hauk M, Pail R, Flechtner F (2022a): Data-driven multi-step self-de-aliasing approach for GRACE and GRACE-FO data processing, Geophysical Journal International, ggac340, doi: https://doi.org/10.1093/gji/ggac340.

Abrykosov P, Sulzbach R, Pail R, Dobslaw H, Thomas M (2022b): Treatment of ocean tide background model errors in the context of GRACE/GRACE-FO data processing. Geophysical Journal International 228 (2022). 1850-1865, doi: https://doi.org/10.1093/gji/ggab421.

Hauk M, Pail R (2018): Treatment of ocean tide aliasing in the context of a next generation gravity field mission. Geophysical Journal International 214, 345-365, doi: https://doi.org/10.1093/gji/ggy145.

Mission Requirements Document, 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 (2020). ESA-EOPSM-FMCC-MRD-3785

Pail R, Bingham R, Braitenberg C, Dobslaw H, Eicker A, Güntner A, Horwath M, Ivins E, Longuevergne L, Panet I, Wouters B (2015): Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society. Surveys in Geophysics, 36(6):743-772, doi: https://doi.org/10.1007/s10712-015-9348-9.

Wiese DN, Visser P, Nerem RS (2011): Estimating low resolution gravity fields at short time itnervals to reduce temporal aliasing errors. Advances in Space Research 48 (2011), 1094-1107, doi: https://doi.org/10.1016/j.asr.2011.05.027.