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ABSTRACT:
Executive Summary of ESA study *Assessment of Satellite Constellations for Monitoring the Variations in Earth's Gravity Field "SC4GMV"*

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Assessment of Satellite Constellations for Monitoring the Variations in Earth Gravity Field "SC4MGV"

Executive Summary

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Objective and strategy

The overall objective of this study is to assess constellations of two pairs of satellites for the retrieval of time-variable gravity field information for best quality scientific monitoring of mass distribution and transport in the Earth system. Before embarking on this study the geodetic community and space agencies have come to realize that weaknesses in current single-pair gravimetric satellite missions such as GRACE or GRACE-FO (to be launched in 2017) would significantly be alleviated by having a second GRACE-type pair in space simultaneously. In particular the so-called "Bender-constellation" with one polar pair and one pair on an inclined orbit, has tentatively been investigated in the geodetic literature.

The secondary objectives of this study all circle around the phenomenon of *aliasing* as one of the key limitations for future gravity field satellite missions:

- To assess temporal and spatial aliasing in the constellations' observations and the impact on standard retrievals for periods of a few days to a month in support of constellation optimization and of more sophisticated retrievals.
- To explore methods that reduce temporal and spatial aliasing in the process of retrieving time-variable gravity field model.
- To explore post-processing methods that reduce anisotropic model errors under special consideration of Bender-type constellations.

Aliasing is due to undersampling of the time-variable Earth gravity field from orbit. Thus, short-period mass variations such as those driven by tides (or rather: tidal model errors) and atmospheric circulation will map into the longer-period gravity field recoveries. Fundamentally, aliasing must be tackled by improved sampling. Indeed, multiple-pair satellite constellations are required to make a quantum leap in progress on aliasing reduction beyond the current single-pair satellite missions such as GRACE or GRACE-FO. It has been recognized that without such constellations the inherent precision of future measurement technology, e.g. laser interferometry, will not be able to achieve its full potential.

This study's strategy to reduce aliasing is implemented as a three-staged approach:

1. Optimization of double-pair satellite constellations
2. Development of a dealiasing gravity field retrieval method
3. Post-processing

Each of these three stages contributes to the goal of aliasing reduction, as explained in the individual sections below.

Optimization of double-pair satellite constellations

Initial analyses showed that adding a second satellite pair to a single-pair constellation delivers the greatest improvement in terms of dealiasing potential and recovery performance. The impact of adding further pairs, although non-negligible, is decidedly smaller than the quantum step from one to two pairs. The initial preferences about the SC4MGV constellation have been formulated in the Statement of Work of the study, though some were fine-tuned in the course of the study:

- The mission shall feature two pairs of spacecraft flying inline in a "Bender-type" constellation. One pair occupies a near-polar orbit with an inclination range of [88°–92°], whereas the second pair's orbit is inclined with potential inclinations in the prograde range [65°–75°] or retrograde [105°–115°].
- The orbit altitude is restricted to be between 340 km (to guarantee the expected mission lifetime keeping reasonable propellant mass budgets) and 500 km (to guarantee enough gravity field strength for measurement purposes). The lower and upper limits of the orbits are taken from the technical part of the study.
- The orbits should have a repeat cycle between 7 days (minimum) and 32 days (maximum) with shorter sub-cycles that allow shorter solutions.

The genetic algorithm approach of this study made use of a parameter search space as defined above for optimization of the constellation parameters. Moreover, the relative node $\Delta\Omega$ and the relative location in the orbital plane ΔM were free parameters. Inter-satellite range was between 75 and 100 km as the trade-off between sensor noise level of the satellite tracking system and the accuracy of the retrieved models. The non-linear optimization within this search space makes use of a "reduced-scale" tool that can efficiently simulate large amounts of mission scenarios, each of which stands for a 10-day gravity field recovery with a maximum spherical harmonic degree of 100. A genetic algorithm that minimizes global RMS as a cost function was used for optimizing the constellation parameters.

A group of 10 constellations of high genetic fitness, i.e. well-performing missions, was selected for more careful study. From these we identified the following constellation as the best performer:

	polar pair	**inclined pair**
inclination	92°	115°
orbit height	361.9 km	342.5 km
repeat rate	172 revolutions in 11 nodal days	460 revolutions in 29 nodal days
sub-cycle	3 days	7 days

A difference in inclination gives rise to a differential nodal drift of the orbital planes, which, in turn, produces a slight but noticeable modulation in gravity recovery quality. As a consequence the concept of a single best constellation should be abandoned, as signals and recovery quality are fundamentally time-variable. Instead, one should see the above optimal constellation as one among several with comparable quality.

The simulations suggested that the importance of sub-cycles is small. However, this is a point that requires further investigation. The ground track fill-in pattern of the repeat orbit appeared to be not decisive for the recovery quality, unless an unfortunate fill-in pattern like the so-called drifting fill-in is employed.

Thus, the Bender constellation design has successfully been corroborated in this study. Although the above-mentioned constellation showed the overall best performance, the class of high-performers consisted of many more constellations. Note that the second pair's orbit was restricted to be inclined; constellations of polar-pairs were not part of this study.

Development of a dealiasing gravity field retrieval method

Although other approaches for reducing aliasing behaviour exist in the literature, early on in this study the so-called "Wiese approach" was identified as the most versatile method. In this methodology temporal aliasing is absorbed by means of co-parameterizing low-degree spherical harmonics of gravity field solutions at shorter time intervals together with the full solution. The Wiese approach has successfully been implemented in this study in two independent ways by the Delft and Munich groups. Fundamental decisions regarding the embedded parameters, such as the duration of the short-period solutions (e.g. half-daily, daily, 3-daily), the maximum spherical harmonic degree (and order) of short-period solutions (e.g. 10, 15, 20), the duration of the long-period solutions (e.g. 10-day solutions), and their maximum degree were required.

Two different strategies are employed for the de-aliasing method by "Wiese" parameterization. One solves for the full time-variable gravity field caused by mass transport in the atmosphere (A), the oceans (O), the terrestrial hydrosphere (H), the cryosphere (I) and the solid Earth (S). The other strategy solves only for the time-variable gravity field caused by mass transport in the terrestrial hydrosphere (H), the cryosphere (I) and the solid Earth (S) while correcting for mass transport in the atmosphere and the oceans by using models. By solving for the full "AOHIS" signal we could investigate the potential of the optimized Bender constellation to treat the full geophysical mass variations as an integrated system and to deliver the full signal, which contains also the atmospheric and oceanic components. The arguments that support solving for the full "AOHIS" signal, given the chosen constellation and the dealiasing method applied, were that the "Wiese" parameterization was more effective in minimizing temporal aliasing in that case. A contribution analysis of the individual components to the temporal aliasing error budget has demonstrated that the atmosphere is one of the major contributors to the total aliasing error of the full solution. Since most of the high frequency processes in the atmosphere have periods around a day, those signals are captured by the daily parameterization to a large extent and are correctly assigned to the mean "Wiese" solution. Consequently, the full "AOHIS" signal contains more power in daily periods than the "HIS" signal, and in that case the "Wiese" parameterization reduces temporal aliasing more effectively.

As a general result of all testing and methodological fine-tuning this study corroborated the power of the Wiese approach to mitigate aliasing behaviour. By testing different short-period solution intervals, the best de-aliasing skill was obtained with a 1-day parametrization. A 3-day parametrization, equal to the sub-cycle of the polar satellite pair, did not provide any advantages. Neither did half-day solutions, which would be closer to the semidiurnal aliasing signals.

After experimenting with several values of maximum degree and, independently, maximum order, the one-day solutions were resolved up to degree and order 20. A slight deterioration was identified due to interference with the first resonance band around order 16, but this was deemed acceptable. We find that the combination of daily parameterization and degree 20 solutions provides the best compromise between the largest possible amount of signal to be captured and the shortest time period in which it changes.

Dedicated post-processing methods

In spite of optimal constellations and optimal de-aliasing retrieval methods, it is clear that user communities will always attempt to further improve gravity field products by applying tailored filtering strategies. Thus, post-processing was an integral part of this study. Indeed, further filtering improved the gravity field products to a certain extent.

No literature on filtering multiple-pair recoveries exists yet. Nevertheless, the familiar classes of filters (deterministic, stochastic, data-driven) used to extract signal from the GRACE gravity fields are applicable. The reason is the fundamental property of longitude-invariance of orbit geometries, which is equally valid for single and for double pairs.

The first observation from the post-processing analysis is the fact that the double-pair retrievals, unlike GRACE-solutions, already demonstrate good isotropic error behaviour. Hence, relatively little filtering is needed. Second, it is obvious that a large part of the spatial error variance will be concentrated at the latitudes just beyond the min/max latitudes that are defined by the inclined pair's inclination. This behaviour is peculiar to the Bender constellation.

The main filters that were studied included the empirical destriping filter, the EOF-based filter (with KS-testing), and the stochastic or regularization filter. Although the stochastic regularization filter should be optimal from a statistical viewpoint, better results were obtained with the deterministic destriping filter (using tuned parameters). From the validation of all filtered solutions the analysis concludes, however, that the added benefit of such filtering is small relative to a simple isotropic Gaussian filter. This result may appear disappointing, but in fact demonstrates again the efficiency of the Wiese approach in combination with a double-pair satellite constellation.

The figure below illustrates the error spectrum in terms of geoid height RMS. It exemplifies the effectiveness of each of the 3 aforementioned stages. The retrieval error of a single near-polar pair (from the optimal scenario 5) and the geophysical input model signals (AOHIS) are also shown for reference. In order to avoid the Gibbs effect due to spectral truncation, note that input models were also smoothed by a Gaussian filter of radius 167 km for the post-processing error curve.

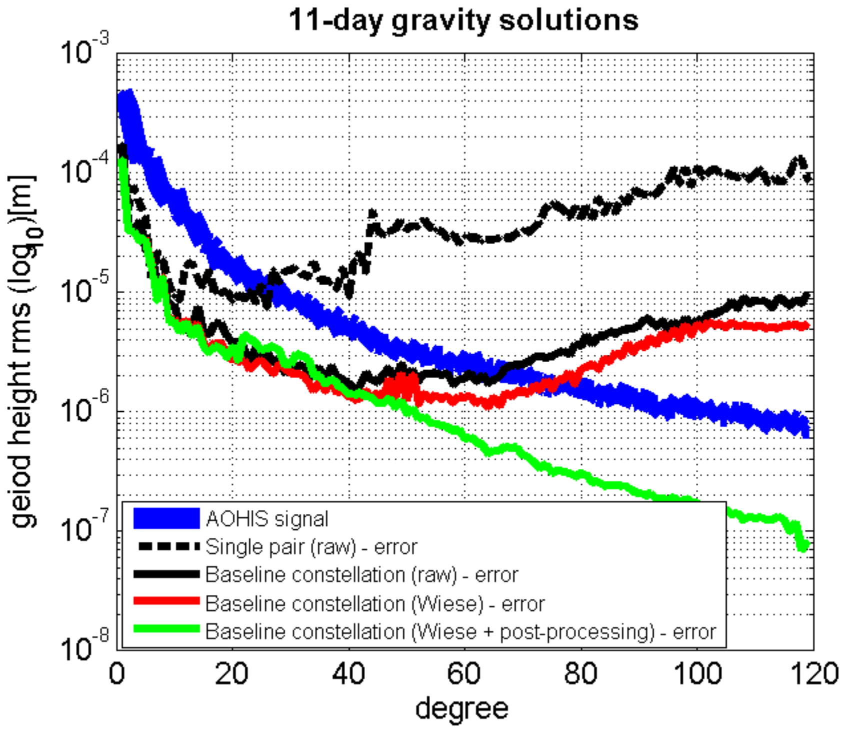

Figure: Error spectra (geoid height RMS) of the 3 stages for the best-performing constellation (Bender-type scenario 5). The error of a single near-polar pair (also from scenario 5) and the AOHIS signal (as model input) are shown for reference.

Open issues and recommendations

This study has resulted in the development of a coherent strategy for handling data from an optimized double-pair constellation in the context of dealiasing. Although the corresponding project goals have been achieved, a number of new questions arose. In the following, these open issues are summarized in terms of recommendations to ESA for further study.

1. *Assessment of short period solutions in terms of signal:* The study considered the short period (1-day) solutions in the dealiasing method as a noisy by-product that should be discarded. However, the Wiese approach was successful in absorbing much of the high-frequency aliasing signal. This success prompts the question whether the short period solutions represent meaningful high-frequency signal. A first analysis of the signal content of these solutions was indeed very encouraging. We strongly recommend a deeper analysis into this issue. The short period solutions may well turn out to contain, e.g., significant atmospheric signal, in which case a future gravity mission may have a strong contribution to make to atmospheric science. The study team of such a further study must incorporate expertise from atmospheric science.

2. *Further optimization and extension of Wiese approach:* The study team made deliberate choices for the various parameters that are internal to the Wiese approach (see above). The parameter space is large, though, and further analysis of interaction between parameters may be beneficial.

Extending the parametrization is still an open issue. One obvious candidate for extension is to connect the daily solutions by means of a Kalman-filter type of parametrization.

3. *Co-parametrization of ocean tide (error)*: Ocean tide errors were identified as one of the major contributors to the error budget. Given the regular spectral character of tidal constituents, their aliasing behaviour on repeat orbits is regular, too. We recommend to further investigate the co-parametrization of tides together with constellation optimization for the purpose of reducing this major error source. We must point out, however, that this task is non-trivial given the unexplored but highly correlated interaction between the Wiese parameters and the tidal parameters.

4. *Interaction between constellation optimization and Wiese approach:* Within our study logic the first step was to identify optimal constellations, after which the Wiese approach was then implemented to deal with the dealiasing of simulated observations from such a constellation. The successful dealiasing skill of the Wiese approach raises the question, whether so much effort in constellation optimization is justified or whether a larger class of constellations would suffice. The preliminary answer is that an optimal constellation design remains necessary. However, we recommend more investigation in this direction, leading to deeper understanding of the interaction between constellation optimization and efficiency of the Wiese approach. Such understanding is particularly relevant for potential future multi-agency multiple-pair missions.

5. *Constellation design vs. signals-of-interests from individual user communities*: The constellation optimization was driven by a non-dedicated cost function and, hence, the optimal constellation satisfies a broad range of user communities. Adapting to signals-of-interest from individual geophysical user communities or to newly identified signals-of-opportunity requires further investigation. No concrete recommendations are provided here other than mentioning the ingredients for further analysis:

   - Generation of longer time-series of dealiased gravity retrievals up to a full solar cycle. Certain signals at short spatial scales may be retrievable through their long-period temporal characteristics.
   - Identification of new signals-of-interest from current literature and their spatial-temporal signature. Examples of such signals are, for instance, moving ocean current fronts at short spatial and long temporal scales, seasonal amplitude variations of M2-tide, or atmospheric signals.
   - Constellations with long repeat periods (e.g. 180 days) with drifting homogeneous sub-cycle patterns.

   As a side effect, the generation of longer time-series would be beneficial to filter design in the class of data-driven filters (PCA, copula), since they rely on a training period that should cover the seasonal cycle sufficiently. Hence, a few years of output as a minimum are already necessary for the training.