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Networks of CubeSats and their potential for gravity field retrieval in the frame of the CubeGrav Project

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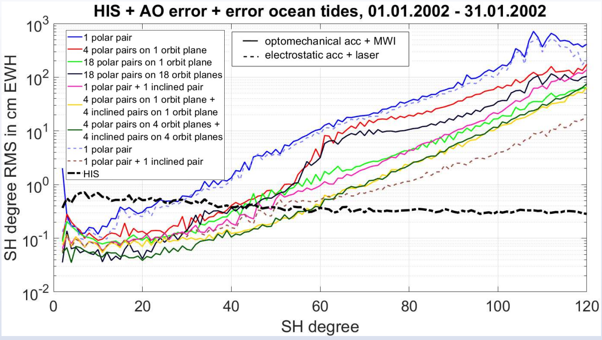
1. Introduction

Based on the success of the satellite missions CHAMP, GRACE, GOCE and GRACE-FO new concepts for next generation gravity missions (NGGMs) are investigated in order to:

- Increase the spatio-temporal resolution
- Reduce the under-sampling of the aliasing temporal gravity field
- Reducing the cost for realization of the NGGM

In the frame of the CubeGrav project, funded by the German Research Foundation (DFG), these aspects are considered and the main objective is to derive for the first time optimized satellite networks of inter-linked CubeSats for Earth's gravity field recovery. In this contribution we want to present a preliminary mission concept.

3.1 Monthly Gravity Field Solution

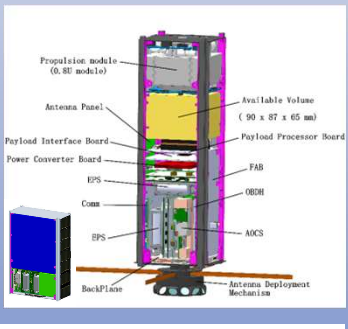


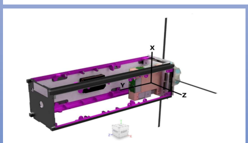
In the Gravity Field Processing tidal constituents (errors from ocean tides) and non-tidal constituents (signal from Hydrology, Ice and Solid Earth (HIS) and errors from Atmosphere and Ocean (AO error)) are taken into account. Impact of Satellite Constellations on monthly gravity field retrieval:

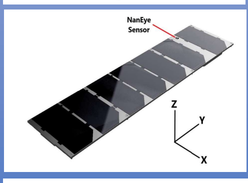
- Increasing the number of polar satellite pairs improves performance and simultaneously decreases the added value from additional observations
- Benefit of inclined satellite pairs is higher than the distribution of polar satellite pairs on one or more orbit planes

3.3 Platform Design

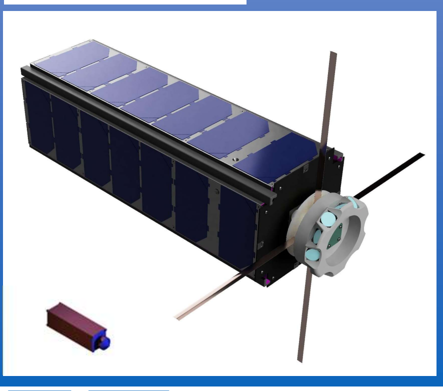
The baseline satellite solution is a 3U-6U CubeSat platform and is an evolution of an existing product line. The key mission requirements to be satisfied by the candidate payload are power, volume, thermal management and data transmission as well as orbit maintenance and degradation protection while complying to risk mitigation and redundancy concepts.







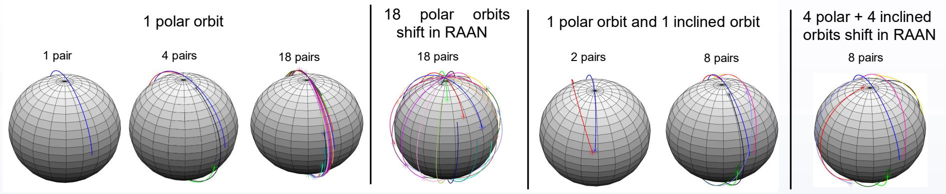
The platform subsystems have flight heritage from ZfT's NetSat mission and can be to a high extend re-purposed and re-used. Subsystems future modularity composed with the UNISEC standardization of electrical and software interfaces. The satellite system is defined and dimensioned based on experience and results of the UWE and NetSat satellite missions with future iterations soon in-orbit in the upcoming CloudCT and TOM missions.

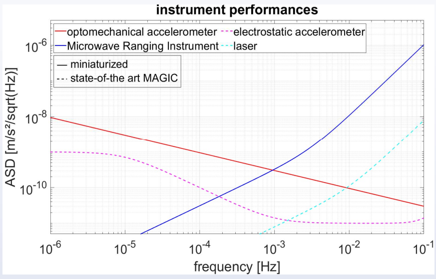


2. Simulation Setup

In numerical closed loop simulations, the impact of satellite formations and constellations on retrieving temporal gravity fields to different resolutions will be analyzed. The orbital parameters used in the Mass-change And Geoscience International Constellation (MAGIC) study are taken as basis for generating the satellite orbits. Six different configurations of satellite pairs are considered for this study:

Type	Altitude [km]	Incl. [°]
Polar	463	89
Inclined	432	70





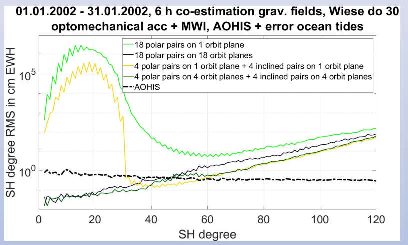
A prerequisite for the realization of a CubeSat gravity mission is the miniaturization of the key payload which is the accelerometer for measuring the non-gravitational forces and the high-precision inter-satellite link (ISL) ranging instrument.

Accelerometer: The optomechanical sensor presented by Hines et al. 2020 is considered as a suitable candidate for the accelerometer (footprint: 48 mm x 92 mm, mass: 26 g).

Ranging: Up-to-date, no space-qualified instrument with the required accuracy of < 1 µm could be identified. Currently, there are developments for ISL on CubeSats, for example, in the CLICK mission (Tomio et al. 2022), which expects an accuracy of 0.5 cm, or in the LISA mission, where a miniaturized mNPRO laser (Numata et al. 2019) is planned as ranging system.

Therefore, we made an assumption of a future miniaturized instrument with the GRACE-FO K-Band Microwave Ranging System (MWI) performance and the following specifications: volume < 3U, weight < 2kg. The instrument accuracies of the MAGIC study are used a reference. All instrument performances are visualized in the Amplitude Spectral Density (ASD).

3.2 Short Temporal Gravity Fields Co-Estimates



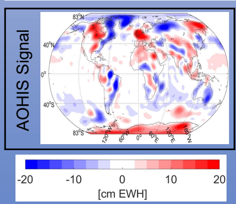
With the increased number of observations, the potential of retrieving gravity fields with higher temporal resolutions is analyzed. Therefore, the gravity field processing approach is adapted according to Wiese et al. 2011 in order to co-estimate short periodic (12 h, 6 h) gravity fields up to d/o 30. As an example a monthly solution with 6 h co-parametrization and the spatial plots of the 12 h residual gravity fields for January 1, 2002 is visualized.

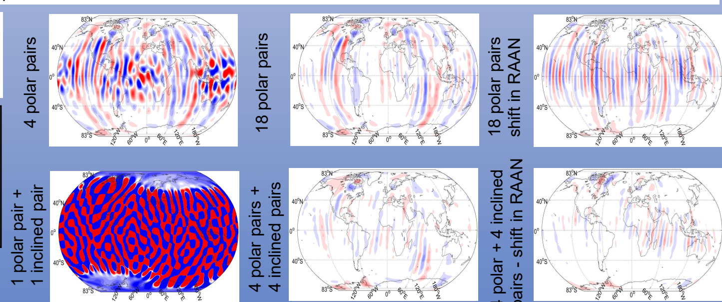
For the monthly solution with 6 hour parametrized gravity field estimates, multi-satellite constellations with satellites pairs distributed on several orbit planes (shift in RAAN) provide sufficient ground track coverage to achieve a stable overall solution.

The retrieval of 12 hours time-varying AOHIS field is only possible with satellite configurations that deliver residuals lower than the signal, depending on the spatial sampling of the multi-satellite constellations. When considering only polar satellite pairs, the highest amount of distributed satellite pairs delivers the best performance but the typical striping pattern as in GRACE-like solutions is still present as only along-track observations are provided. Additional cross-track information by inclined satellite pairs can reduce the residuals.

In general, the resolvability of short-temporal stand-alone gravity fields depends only on sufficient ground track coverage of the Earth within the desired time spans.

Global estimated half-daily Gravity Field Residuals from Simulations compared to AOHIS Signal in Equivalent Water Height (EWH) on 01.01.2002 12:00 h to 24:00 h





References: Hines, Adam; Richardson, Logan; Wisniewski, Hayden; Guzman, Felipe (2020): Optomechanical Inertial Sensors. In: *Appl. Opt.* 59 (22), G167. DOI: 10.1364/AO.393061
Numata, Kenji; Yu, Anthony; Jiao, Hua; Merritt, Scott; Micalizzi, Frankie; Fahey, Molly et al. (2019): Progress and plans for a U.S. laser system for the LISA mission. In: Nikos Karafolas, Zoran Sodnik und Bruno Cugny (Hg.): International Conference on Space Optics — ICSO 2018
Tomio, Hannah; Grenfell, Peter; Kammerer, William; Serra, Paul; Cierny, Ondrej; Lindsay, Charles et al. (2022): Development and Testing of the Laser Transmitter and Pointing, Acquisition, and Tracking System for the CubeSat Laser Infrared CrosslinK (CLICK) B/C Mission. In: 2022 IEEE International Conference on Space Optical Systems and Applications (ICSOS)

3.4 Impact on Mission Design - Very Low Earth Orbit Simulations

In the VLEO altitude baseline, the incident flow of thermospheric particles to the surfaces of an orbiting spacecraft can be characterized as free molecular and hyperthermal. Given the approximately convex and oblong shape of the envisioned CubeSat platform design, the potential to reduce the operational altitude to VLEO is demonstrated resulting in increasing retrieved signal strength. A DSMC (Direct Simulation Montel Carlo) framework has been set up in ZfT to encompass particle interactions on the CAD design of the platform.

Once a particle interacts with the surface it will be either trapped or stick or scatter from it. Thus, incident and reflected velocities of these particles must be calculated to model the exchange of energy and momentum due to impact and re-emission. The process of modelling these interactions is the target of a Gas Surface Interaction Model (GSIM).

A simplex geometry as such of a CubeSat can easily be divided into a finite number of plates. Each of these plates can be characterized as a convex shape, all these plates-surfaces have their own orientation in space and the resulted force applied in each plate is different. Subsequently, the accommodation coefficient of each plate is different. Thus, the overall force coefficient of the body is found by summing up the contribution of every plate and dividing by the reference area (indicated in the drag coefficient definition).

The turbulent torques, erosion depth and propulsion necessary for orbit maintenance in lifetime estimations can therefore be accurately determined in mission analysis considering available solar/geomagnetic prediction databases