Towards the selection of optimal gravity satellite missions:

Orbit configuration and technical constraints

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Search Strategy to optimal Mission Scenarios Identification

Main considerations

- Mission performance in retrieving the geophysical signals
  - sensitivity
  - sampling
  - resonance avoidance

- Technical and stability constraints connected with the missions
  - drag compensation and propellant consumption
  - relative velocities / Doppler effect

Previous studies, mostly on orbital aspects

- Orbit optimization
  (Sharifi et al., Bender et al., Wiese et al., Elsaka et al., Reubelt et al., Iran Pour et al., Ellmer, …)

- Repeat orbits, sampling & signal aliasing
  (Visser et al., Weigelt et al., …)

Mission performance in retrieving the geophysical signals

Sampling theorems

- Heisenberg-like principle in satellite geodesy
  (trade-off spatial vs. temporal resolution)

- Colombo-Nyquist rule / modified Colombo-Nyquist rule
  (spatial resolution restriction)

Mission performance in retrieving the geophysical signals

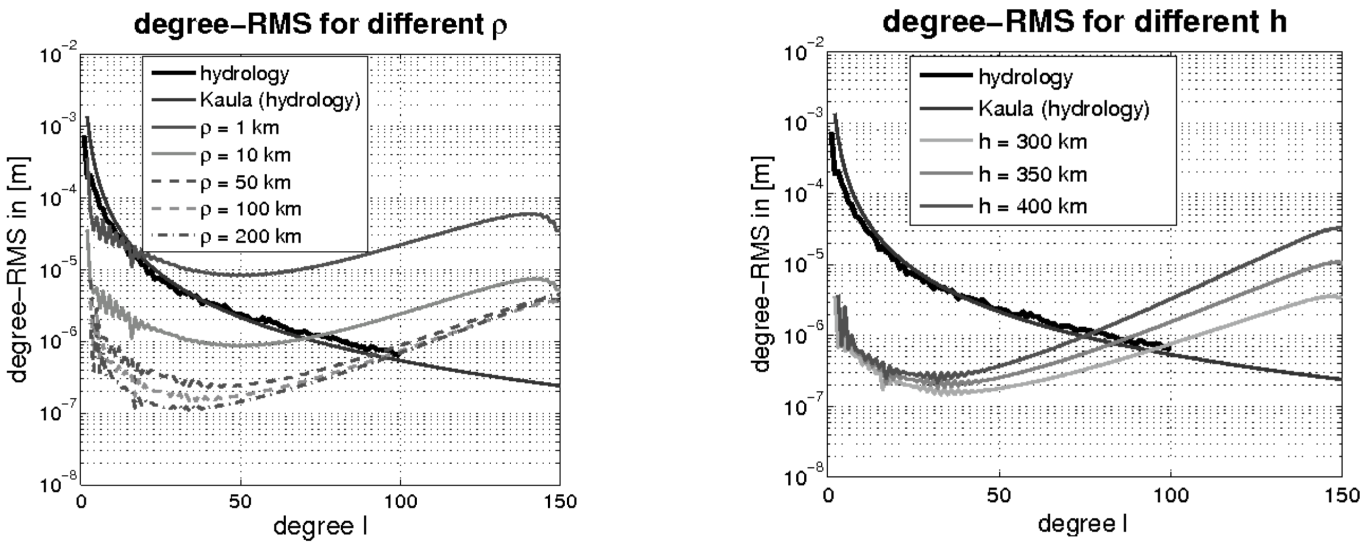
Influence of orbital parameters

- ground-track pattern distribution and gap evolution
- mission altitude
- mission inclination
- inter-satellite distance
- …

Mission performance in retrieving the geophysical signals

Influence of inter-satellite distance and mission altitude

e.g.



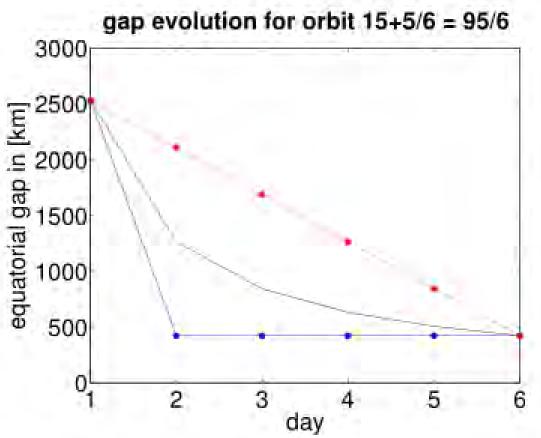
Impact of different SST distances and orbit heights on the accuracy of the gravity field recovery (Reubelt, et al., 2014)

Mission performance in retrieving the geophysical signals

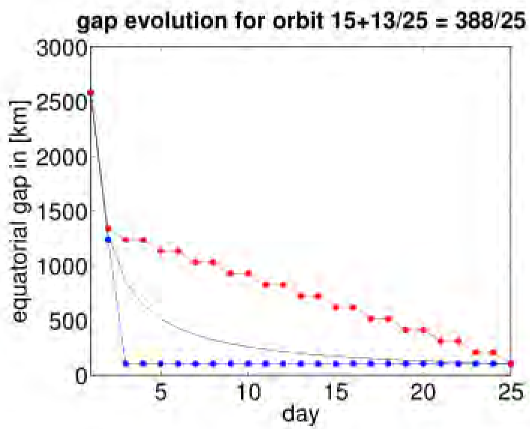
Ground-track pattern distribution and gap evolution

e.g.

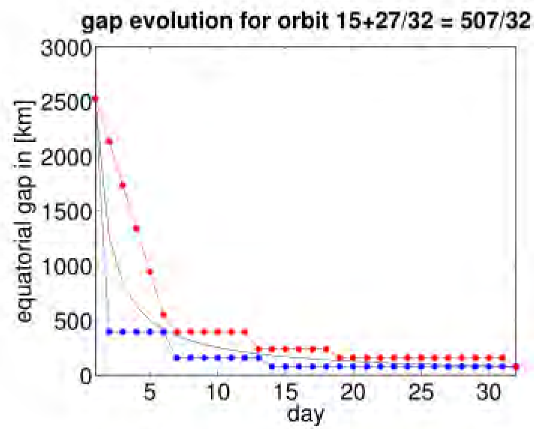
at equator



drifting orbit



slow skipping orbit



fast skipping orbit

Mission performance in retrieving the geophysical signals

Trade-off between Pendulum and Bender Configuration

Why alternative formations?

- problems with anisotropic gravity field recovery error (striping effects) due to the inline satellite-to-satellite tracking (SST) measurement (along-track direction only)!

Why pendulum formation, in particular?

- relative technological simplicity (esp. when opening angle small) compared to the other advanced formations like Cartwheel, LISA, …

Mission performance in retrieving the geophysical signals

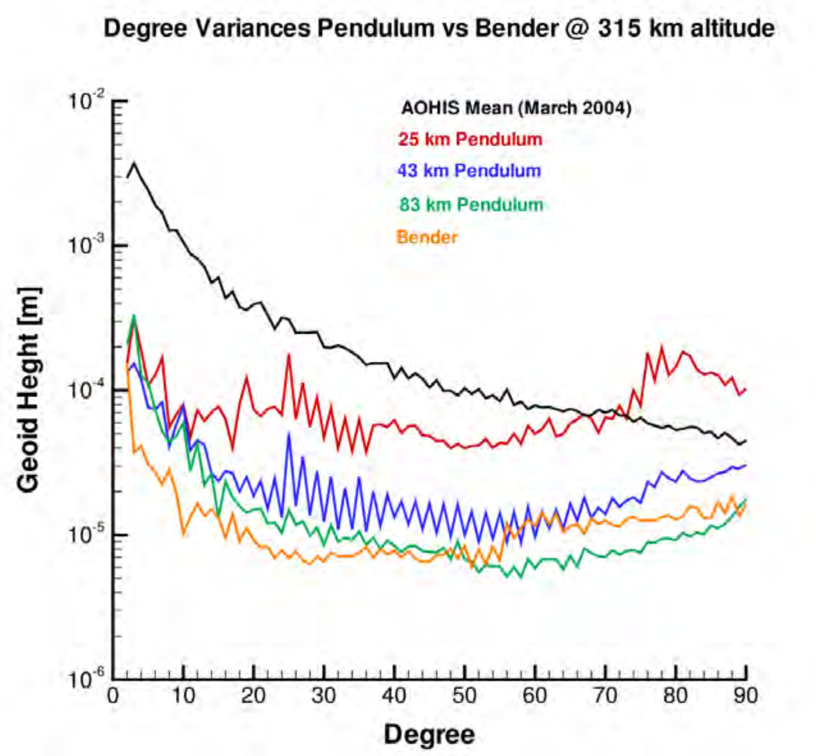
Trade-off between Pendulum and Bender Configuration

And so why Bender (dual inline mission)?

- less technical complexity, better sampling, better performance

Mission performance in retrieving the geophysical signals

Trade-off between Pendulum and Bender Configuration



Mission performance in retrieving the geophysical signals

Bender: Selection of optimal Inclination (QLT for sensitivity analysis)

inclination of 2nd pair I [°]	geoid error [mm] (L = 130)	geoid error [mm] (L = 50)	ice region geoid error [mm]	equator region geoid error [mm]	geoid variation (normalized)	average correlation
55	0.0987	0.00079	0.1131	0.1022	0.1324	0.9908
60	0.0974	0.00076	0.1000	0.1043	0.1199	0.9882
65	0.0975	0.00080	0.0828	0.1066	0.1294	0.9805
70	0.0988	0.00092	0.0722	0.1093	0.1469	0.9641
75	0.1016	0.00121	0.0677	0.1134	0.1655	0.9160
80	0.1102	0.00218	0.0675	0.1256	0.1979	0.7244

Evaluation of Bender pairs with different inclinations of the 2nd pair w.r.t. different performance criteria.
Best mission's values are in red and tolerances within 22.5% are in blue.
The best constellation (I = 70°/ 89.5°) fulfilling all tolerances is marked in the red box.

Mission performance in retrieving the geophysical signals

Optimal orbits regarding temporal aliasing:
Spherical harmonic resonance orders

Depending on two main observing frequencies of a satellite orbit:

- the rate of the argument of latitude $\dot{u}$,
- the rate of the longitude of the ascending node $\dot{\Lambda}$,

The largest effects of temporal aliasing occur at specific SH order bands. These order bands are found around integer multiples of the number of revolutions per day (LEO:): $m = k(\beta/\alpha) \approx 15\text{–}16$.

Mission performance in retrieving the geophysical signals

Optimal orbits regarding temporal aliasing:

Spherical harmonic resonance orders

The strength of the resonance effect depends on $\dot{u}$ and $\dot{\Lambda}$.
The SH orders m and k are mapped on the along-orbit frequency ω :

$$\omega(m) = k\dot{u} + m\dot{\Lambda} \qquad \text{with } -l_{max} \leq k \leq l_{max} \text{ and } 0 \leq m \leq l_{max}$$

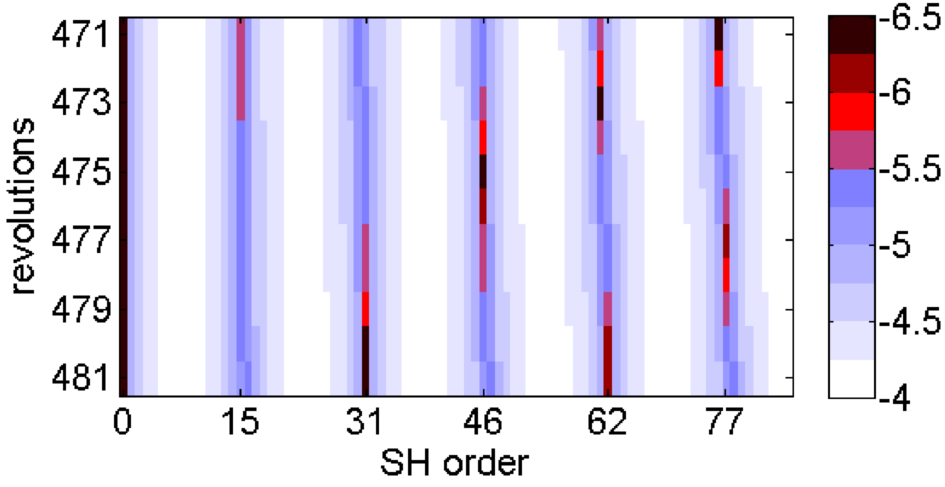
The largest effects occur for frequencies $\omega \cong 0$.

In the case of equally weighted double pairs on different altitudes, the resonances of both orbits occur in the combined solution.

Mission performance in retrieving the geophysical signals

Optimal orbits regarding temporal aliasing:
Spherical harmonic resonance orders

Single inline satellite pair (LEO): $m = k(\beta/\alpha) \approx 15\text{–}16$

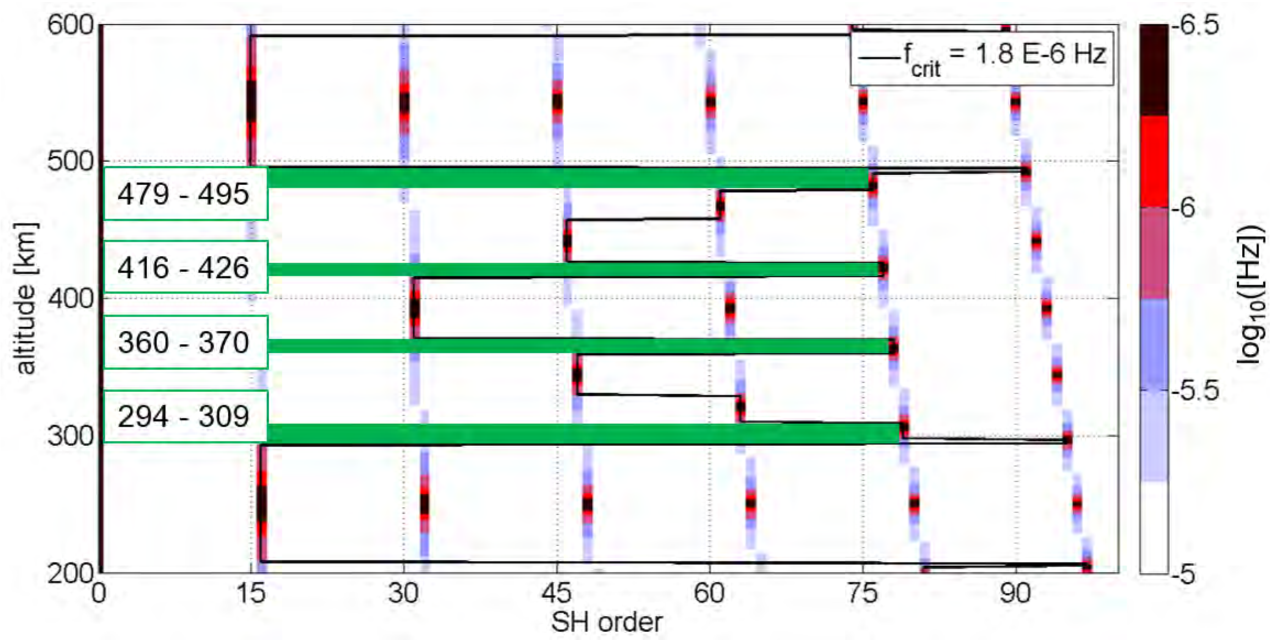


Absolute minimum frequencies for the eleven GRACE-like 31 day repeat orbits in $\log_{10}(|f\ [Hz]|)$
(Murböck, Pail, Daras, & Gruber, 2014)

Mission performance in retrieving the geophysical signals

Optimal altitude bands

Resonance avoidance



Technical Constraints for Orbit Configuration

Goal

- to evaluate the feasibility of the suggested scenarios concerning the drag-compensation and the involved propellant/power demand

- further constraints concerning the orbit configuration as e.g. the relative velocity and the inter-satellite pointing

Technical Constraints for Orbit Configuration

Selected Scenario to investigate

Bender configuration, Scenario 1:

h ~ 460 km, β/α = 107/7, I = 89.5°, ρ_x = 100, Ω = 0°
h ~ 450 km, β/α = 471/31, I = 63°, ρ_x = 100, Ω = 180°

Bender configuration, Scenario 2:

h ~ 360 km, β/α = 125/8, I = 89.5°, ρ_x = 100, Ω = 0°
h ~ 372 km, β/α = 484/31, I = 72°, ρ_x = 100, Ω = 180°

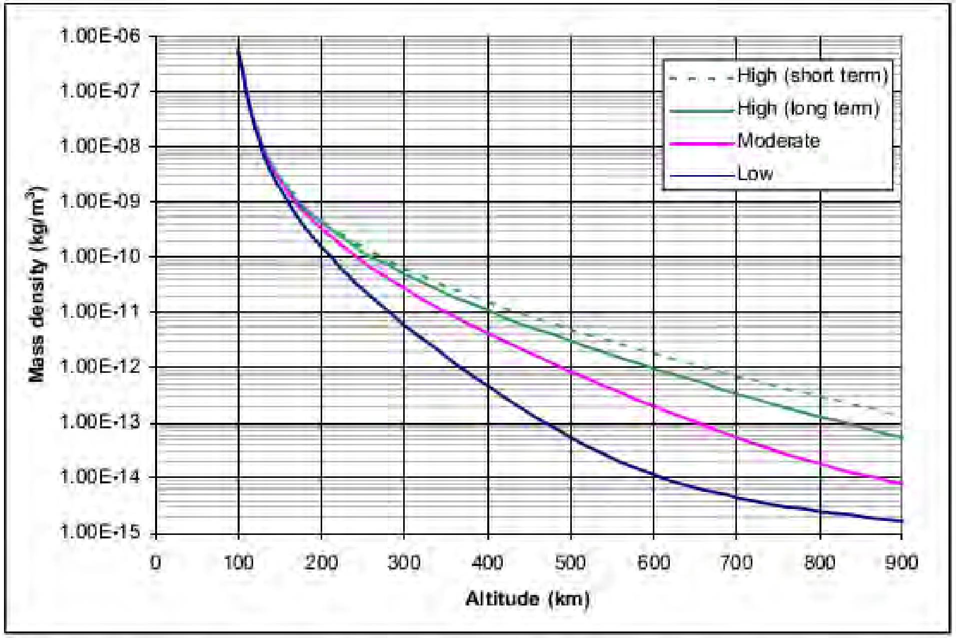
Technical Constraints for Orbit Configuration

Computation of the Air Drag - Assumptions

- Drag forces and resulting moments using the atmosphere JB2006 model
- Earth's gravitation model
- Gravitational forces of sun and moon
- Solar radiation pressure and resulting moment
- Gravity gradient moment
- Magnetic disturbing moment generated by Earth's magnetic field

Technical Constraints for Orbit Configuration

Computation of the Air Drag - Assumptions



Low, moderate, high long term and high short term solar and geomagenetic activities have the following meanings:
low ($F10.7 = F10.7_{avg} = 65$, $S10.7 = S10.7_{avg} = 60$, $M10.7 = M10.7_{avg} = 60$, $A_p = 0$)
moderate ($F10.7 = F10.7_{avg} = 140$, $S10.7 = S10.7_{avg} = 125$, $M10.7 = M10.7_{avg} = 125$, $A_p = 15$)
high long term ($F10.7 = F10.7_{avg} = 250$, $S10.7 = S10.7_{avg} = 220$, $M10.7 = M10.7_{avg} = 220$, $A_p = 45$)
high short term ($F10.7 = 300$, $F10.7_{avg} = 250$, $S10.7 = 235$, $S10.7_{avg} = 220$, $M10.7 = 240$, $M10.7_{avg} = 220$, $A_p = 240$)

Variations of the mean air density (Jacchia-Bowmann model 2006) dependent on orbit height and different solar and geomagnetic activities (from ECSS-E-ST-10-04C)

Mission Scenario I

	Bender configuration
orbit parameters	satellite pair 1: h = 460 km, I = 89.5°; satellite pair 2: h = 450 km, I = 63°
feasibility	yes
propulsion system	cold gas propulsion system
propellant demand	approx. 43 kg (N_2) for drag compensation approx. 14 kg (N_2) for attitude control
mission duration [years]	11
launcher	Dnepr

Mission Scenario II

	Bender configuration
orbit parameters	satellite pair 1: h = 360 km, I = 89.5°; satellite pair 2: h = 372 km, I = 72°
feasibility	yes
propulsion system	cold gas/electric propulsion μRITs* for drag compensation, cold gas for attitude control
propellant demand	approx. 8 kg (Xenon) for drag compensation approx. 14 kg (N_2) for attitude control
mission duration [years]	11
launcher	Dnepr

Important Concerns and Recommendations

- Employing modified Colombo-Nyquist rule for single & dual pair missions
- Considering good sampling pattern and gap evolution (fast skipping orbits)
- Superiority of Bender mission to pendulum formations (geodetic performance & technical constraints)
- Avoid low mission altitude (less than 340 km)
- Intersatellite distance around 100 km (compromise between geodetic sensitivity and technological feasibility)
- Inclination of second (inclined) pair around 70°
- Avoid orbit heights with large resonances
- Use cold gas propulsion system for the Bender scenario of high orbit altitude and a combined propulsion system for scenario with lower altitude, using µRITs for drag compensation and cold gas for attitude control