Results of the MOCAST+ study on a quantum gravimetry mission

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The MOCAST+ QSG mission proposal

A QSG mission in formation flying (Bender constellation, with two or three satellites per orbit) with an **"enhanced" quantum payload** consisting of:

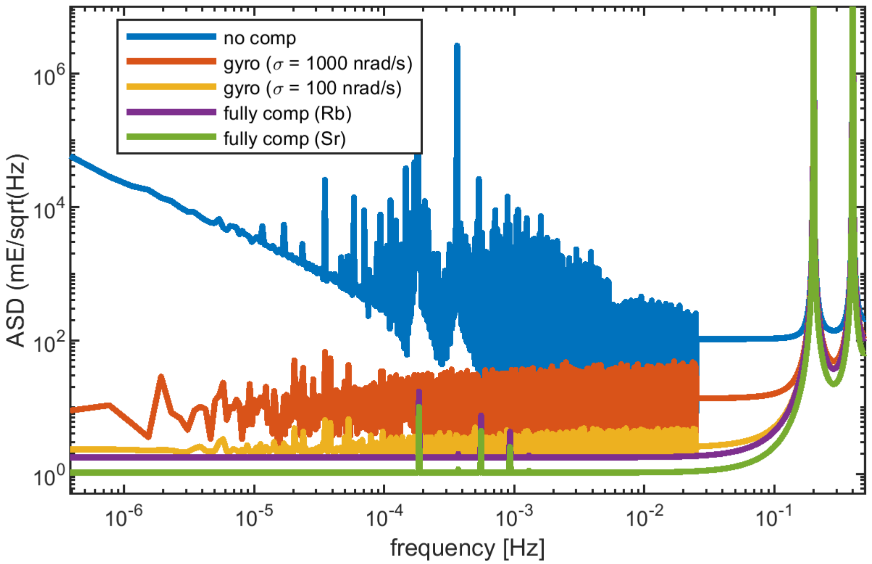
- **Cold Atom Interferometer** (^{88}Sr atoms), providing observations of gravitational gradients (low sensitivity to magnetic fields, high isotopic abundance),
- **Atomic clock** (^{87}Sr atoms) for optical frequency measurements using an ultra-stable laser providing time observations, hence observations of differences of the gravitational potential.

(it is possible to share laser sources but the physics packages are independent).

Goal: to assess the level of accuracy which can be expected from the "enhanced" payload and the level of accuracy which is needed to detect and monitor phenomena identified in the Scientific Challenges of the ESA Living Planet Program (e.g., in Cryosphere, Ocean and Solid Earth).

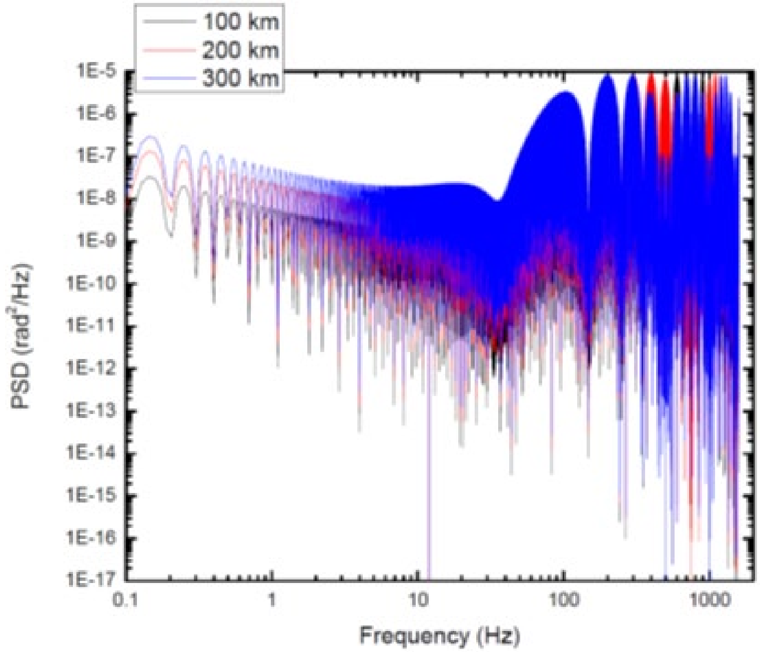
MOCAST+ payload: gradio and clock sensitivity

- Gradio sensitivity: angular rotations, through the centrifugal term, put a serious limitation to the measurement of the gravity gradient in the orbital plane.
  - Rotation compensation of the residual angular rotations around the out-of-plane direction is needed.
  - When the residual angular rotations are not fully compensated, the ASD is independent from the atomic species, because this effect dominates the noise.

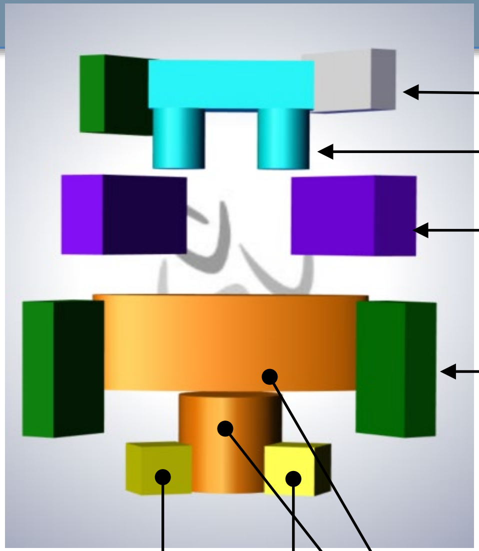


- Clock sensitivity: noise in terms of potential 0.14 m^2s^{-2}/sqrt(Hz).
  - Noise in principle independent from the baseline length;
  - baseline fluctuations affect the measurements: an optical link between satellites is added to correct fast fluctuations (third clock on the "master" satellite to encode the phase shift due to the optical path variations during the clock interrogation time).

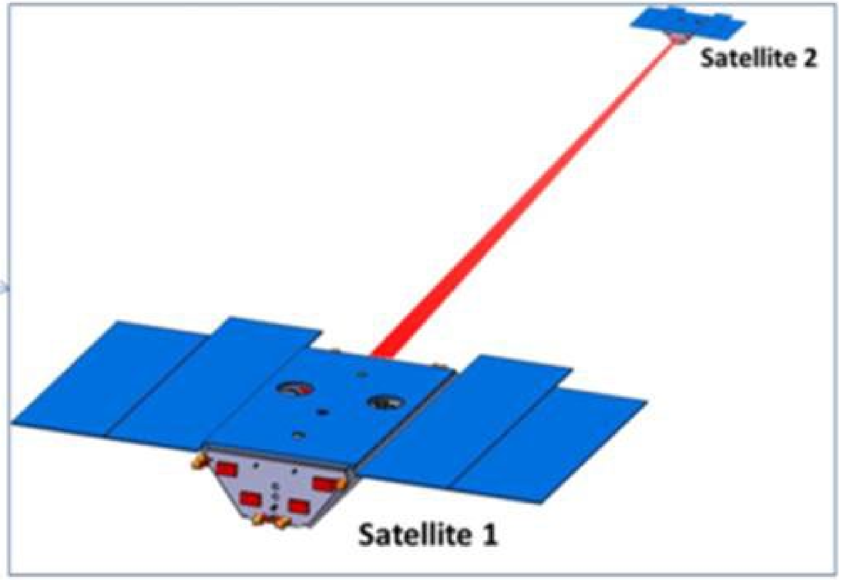
PSD of the residual phase noise due to clock laser drifts for different baseline lengths



MOCAST+: payload accommodation and preliminary spacecraft configuration



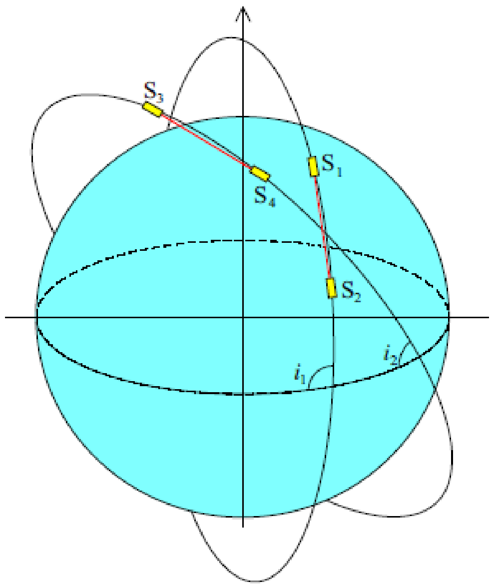
	Mass (kg)	Power (W)	Volume (l)
AI physics package	35	35	350
Clock physics package	25	40	120
AI Laser system	20	15	50
Clock laser system	25	15	30
Optical interfaces	10	-	20
Electronic system	45	350	70
Total	160	455	640



Solar panels to be optimized based on the orientation of the measurement axis wrt the satellite axes, the payload consumptions and the duration of the eclipses.

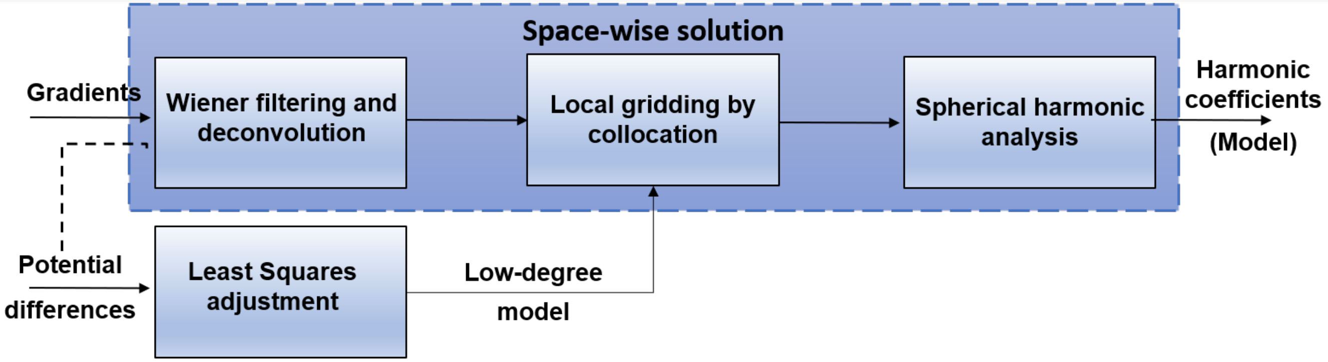
MOCAST+: mission profile and data simulation and analysis

- Orbital data simulation:
  - Formation flying (Bender constellation) with 2 or 3 satellites per orbit:
    h = 371 km, I = 88° (polar orbit)
    h = 347 km, I = 66° (inclined orbit)
  - Intersatellite distance 100 km (baseline), increased to 400 km, 700 km, and 1000 km
  - 95 days of science simulation steady state + 20 days of formation settling time
  - EGM2008 gravitational model to degree/order 200
  - Moderate solar activity
  - Realistic thruster equipment layout for drag compensation along flight direction
- Simulated observations:
  - Gradients: T_{xx}, T_{yy} and T_{zz} (functionals to be estimated after gridding: T, T_{rr}, $T_{\lambda\lambda}$).
  - Potential differences (clock observations).
- Models:
  - EGM2008 error degree variances for generating Monte Carlo samples,
  - 3-hourly ESA Earth System Model (10% of this signal was introduced into the observations).

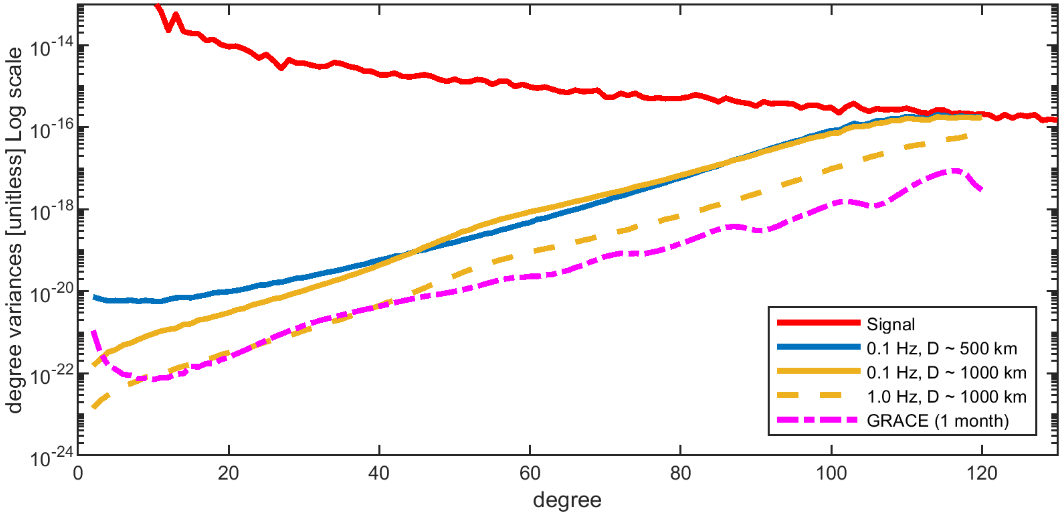


Bender constellation

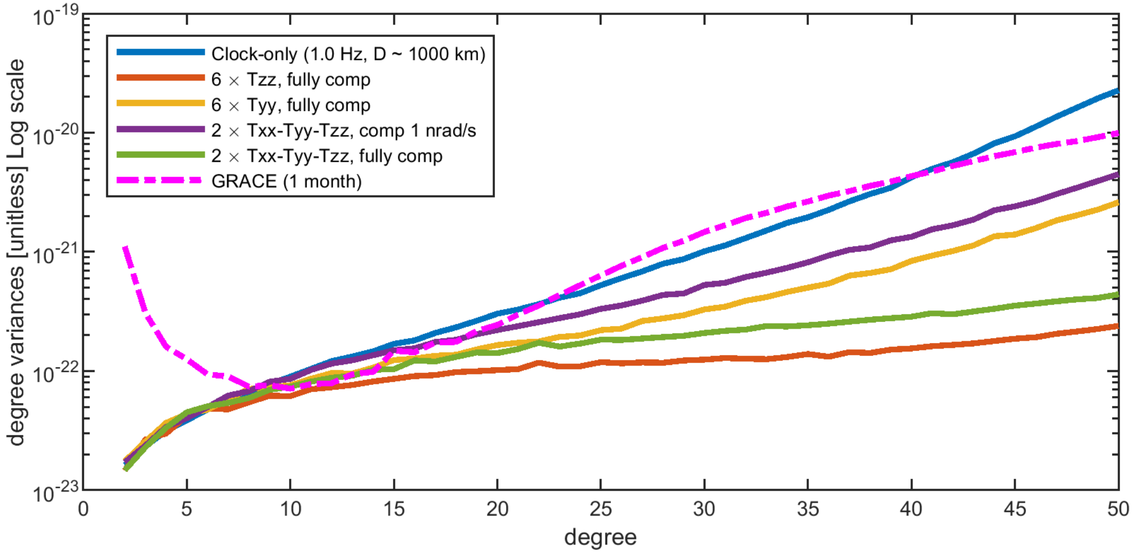
MOCAST+: data analysis by the space-wise approach and best case scenarios



Clock-only, Bender formation, three satellites per orbit, different inter-satellite distances



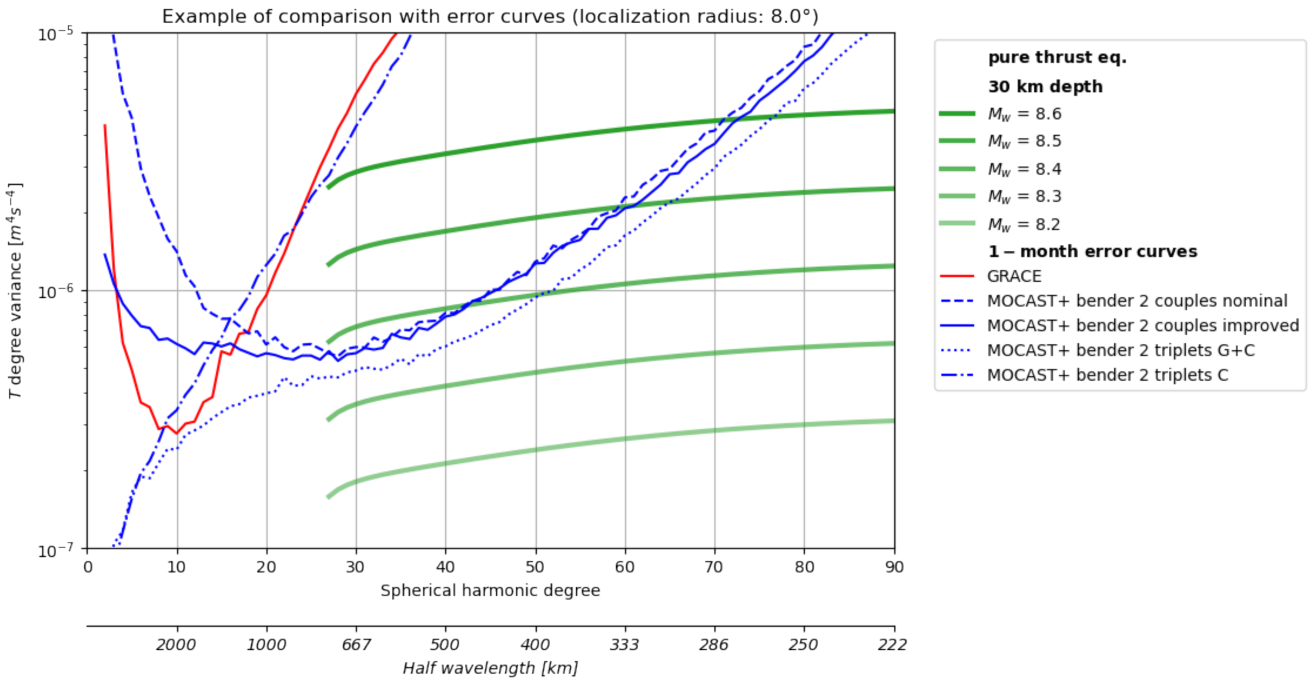
Bender, three satellites per orbit in optimal and degraded gradiometer noise PSD scenarios, different orientations of the gradiometer arm on the satellites



MOCAST+: geophysical applications and impact assessment

Improvements in the identification and monitoring of geophysical phenomena by exploiting MOCAST+ observations (investigation by localized spectral analysis of the signals to be expected from mass variation rates):

- detectability of **earthquakes** of smaller magnitude than GRACE, down to M 8.4;
- sensitivity to **deglaciation** processes with improved minimum observable rate: e.g., for Patagonia glaciers minimum observable rate 5 Gt/yr (for GRACE, 10 Gt/yr);
- long term monitoring of **hydrologic basins and lakes** with improved spatial and temporal resolution: e.g., Tibetan lakes: MOCAST+ after 1 year resolves the variation which GRACE resolves after two years;
- monitoring of seasonal components of **reservoirs** (study areas Tibet and South America), **lakes and glaciers** with areas > 8000 km^2 and seasonal mass variations of 10 Gt.



Degree variance spectra of 1-month gravity change (expressed as potential T) for the same earthquake focal mechanism, at different moment magnitudes.

Conclusions

- MOCAST+ could improve the current knowledge of the Earth gravity field and its time variation, provided that a quite complex mission configuration is implemented: 1 Hz clock observations, long inter-satellite distances ($\sim$ 1000 km) and Bender formation with three satellites per orbit .

- By properly designing the satellite configuration and payload, atomic clocks can give a contribution to improve the knowledge of the Earth gravity field and its variations (direct observation of the gravitational potential by atomic clocks).

- Optimization of payload on the platforms is definitely relevant in reducing differences and minimize non-recurrent costs (e.g., gradiometers only on the two central satellites of the in-line formation can reduce costs and increase spacecraft constellation symmetry).

- The intrinsic stability of the quantum sensors and its valuable performance at the very low degrees, make this concept interesting also for geodetic applications to other Solar system bodies (e.g., Mars), where low harmonic orders mapping can provide significant scientific results for planetary exploration.