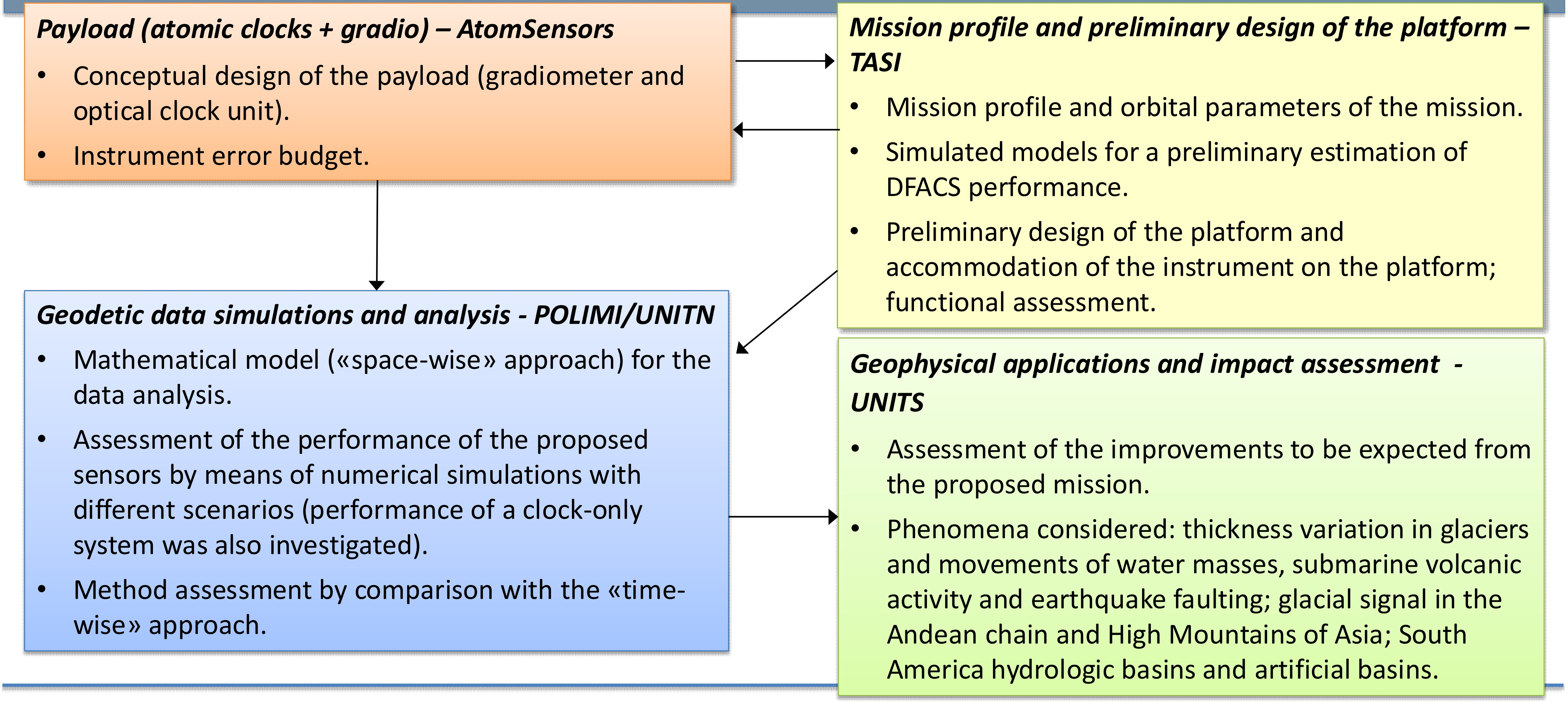
Update from Italy: June 2022

- **Study on QSG mission proposal "MOCAST+" completed (February 2022)**
  QSG mission in formation flying (Bender constellation, with two or three satellites per orbit) with an **"enhanced" quantum payload** consisting of **Cold Atom Interferometers** (^{88}Sr atoms) and **Atomic clocks** (^{87}Sr atoms).

- The study was funded by the Italian Space Agency (ASI) and lasted two years
  Teams:
  - Politecnico di Milano – DICA, Italy (Prime contractor),
  - AtomSensors Srl, Italy,
  - Thales Alenia Space Italia,
  - Università di Trieste – DMG, Italy,
  - Università di Trento – DICAM, Italy.

- Results presented at EGU and LPS, one paper submitted to Surveys in Geophysics (under review), another paper to be submitted within June to Quantum Science and Technology Special Issue on Cold Atoms in Space.

Overview of the MOCAST+ study



Payload (atomic clocks + gradio) – AtomSensors

- Conceptual design of the payload (gradiometer and optical clock unit).
- Instrument error budget.

Mission profile and preliminary design of the platform – TASI

- Mission profile and orbital parameters of the mission.
- Simulated models for a preliminary estimation of DFACS performance.
- Preliminary design of the platform and accommodation of the instrument on the platform; functional assessment.

Geodetic data simulations and analysis - POLIMI/UNITN

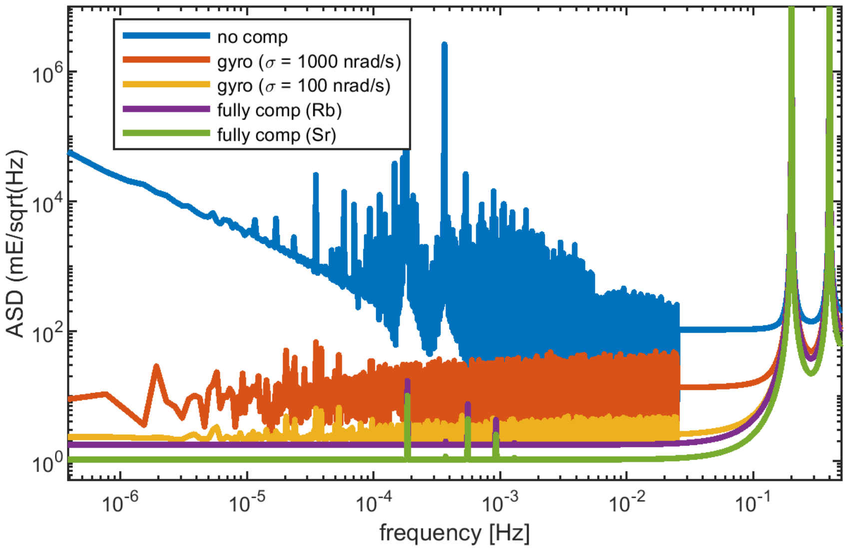
- Mathematical model («space-wise» approach) for the data analysis.
- Assessment of the performance of the proposed sensors by means of numerical simulations with different scenarios (performance of a clock-only system was also investigated).
- Method assessment by comparison with the «time-wise» approach.

Geophysical applications and impact assessment - UNITS

- Assessment of the improvements to be expected from the proposed mission.
- Phenomena considered: thickness variation in glaciers and movements of water masses, submarine volcanic activity and earthquake faulting; glacial signal in the Andean chain and High Mountains of Asia; South America hydrologic basins and artificial basins.

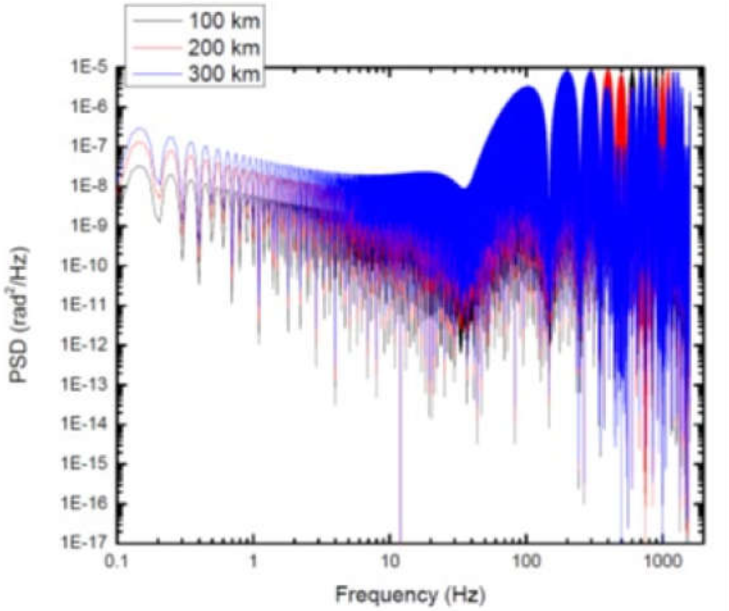
MOCAST+ payload: gradio and clock

- 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.

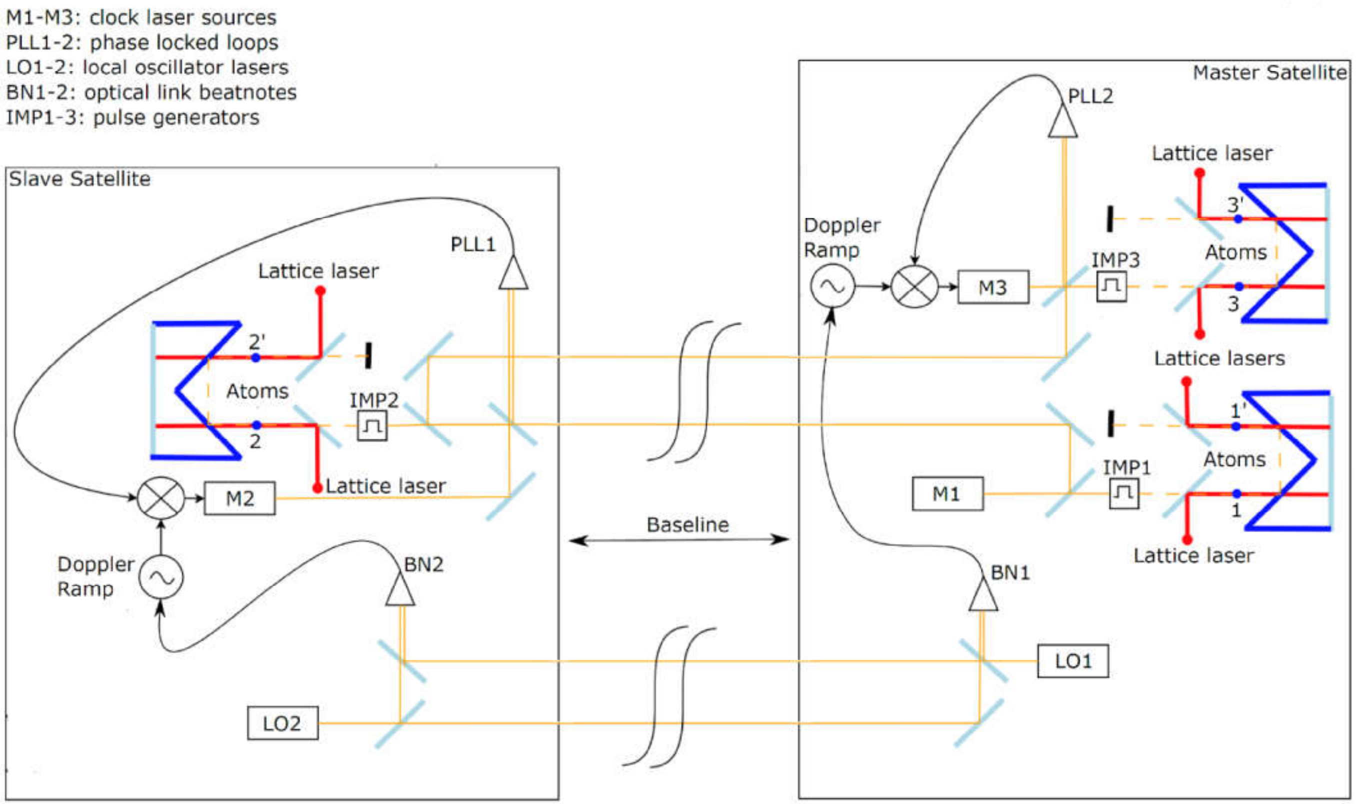


- Clock sensitivity: noise in terms of potential 0.2 m^2s^{-2}/sqrt(Hz).
  - Noise in principle independent from the baseline length;
  - baseline fluctuations affect the measurements: an optical link between satellites is added to correct fast fluctuations (third clock on the "master" satellite to encode 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



The MOCAST+ clock measurement scheme

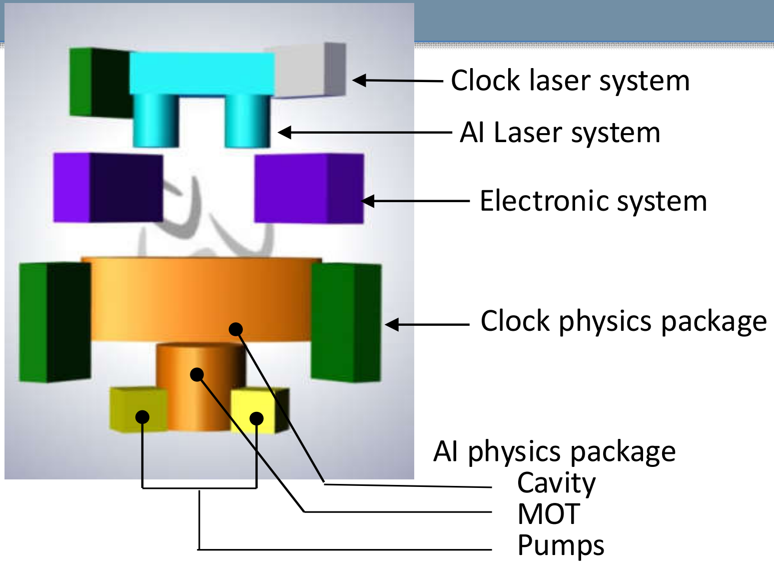


M1-M3: clock laser sources
PLL1-2: phase locked loops
LO1-2: local oscillator lasers
BN1-2: optical link beatnotes
IMP1-3: pulse generators

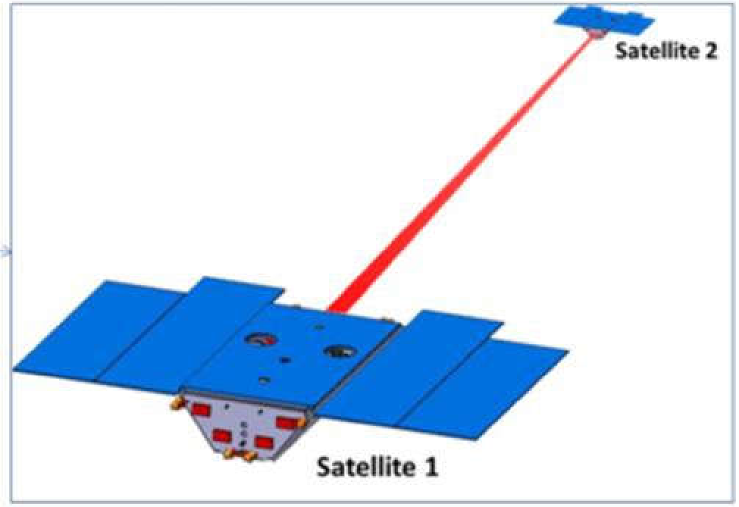
The first clock laser on the Master satellite (M1), while performing the clock interrogation sequence given by a pulse generator (IMP1), is sent towards the Slave satellite. In order to common-mode suppress the M1 phase noise, a phase lock loop (PLL1) with the clock laser on the Slave satellite (M2) is realized, while a second pulse generator (IMP2), synchronized with the previous one, generates the clock interrogation sequence.

The scheme is repeated for the second optical clock on the Master satellite. In parallel, an optical link between local oscillators (LO1 and LO2) is employed to provide Doppler compensation and to monitor short term baseline fluctuations

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



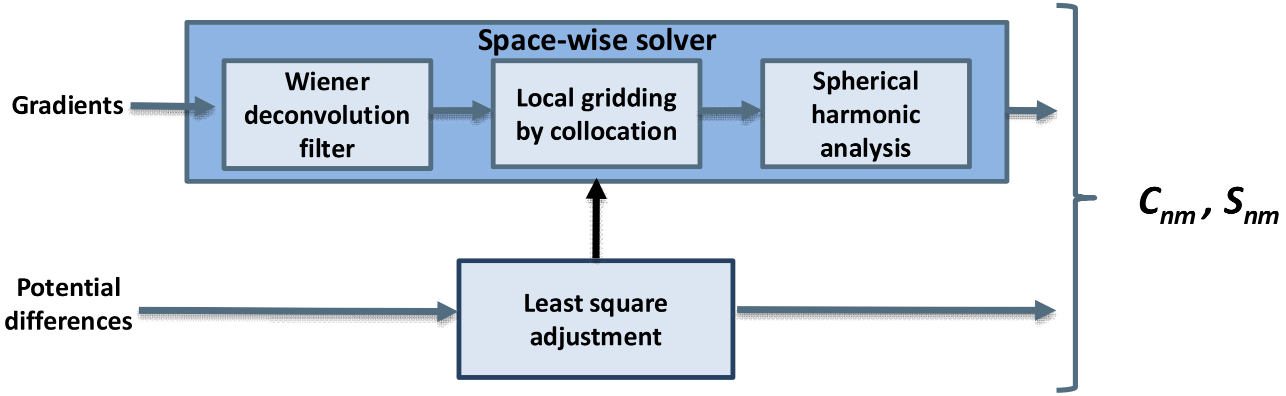
Solar panels to be optimized based on the orientation of the measurement axis wrt the satellite axes, the payload consumptions and the duration of the eclipses.

MOCAST+: mission profile and data simulation

- 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).
  - EGM2008 error degree variances for generating Monte Carlo samples,
  - Non-tidal mass variations in AOHIS: 3-hourly ESA Earth System Model (10% of the signal introduced into the observations).

MOCAST+: data analysis by the space-wise approach

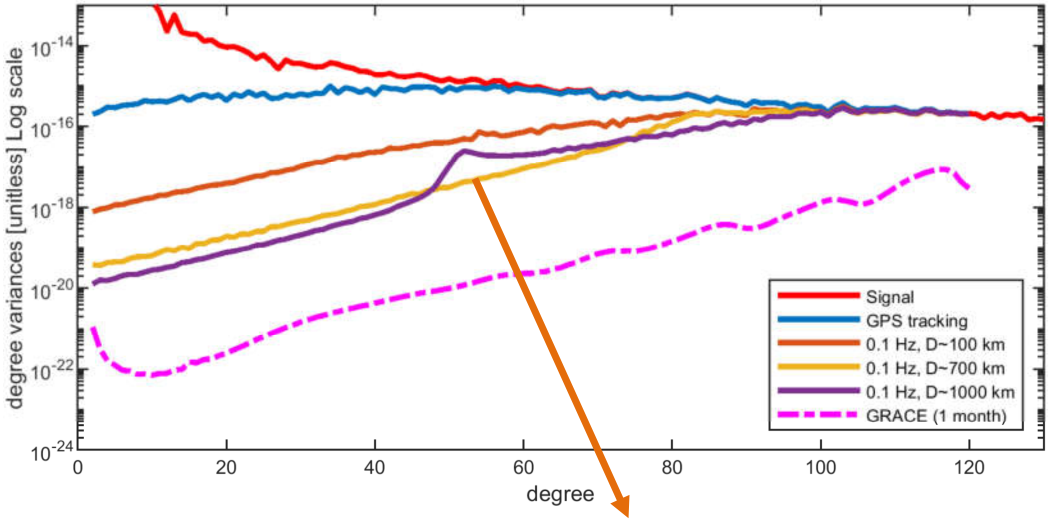


Clock only simulations

(Koç et al., EGU2022)

In-line configuration: Polar orbit only

Case: inter-satellite distance and clock error

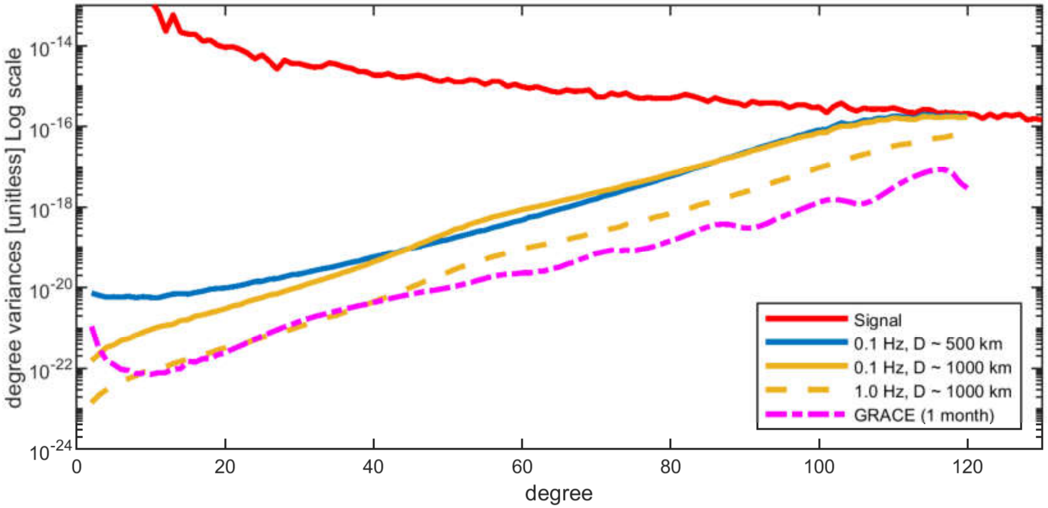


The reason behind jump in the error curve around d/o 85 (sc. 700 km distance) and d/o 55 (sc. 1000 km distance) is the ill-posed estimation of some coefficients due to the term $Y_{lm}(\vartheta_i, \lambda_i) - Y_{lm}(\vartheta_j, \lambda_j)$ in design matrix

the clock observation noise standard of $0.2\ {}^{m^2 s^{-2}}/_{\sqrt{Hz}}$, referred to the potential difference observations, was degraded to $1.35\ {}^{m^2 s^{-2}}/_{\sqrt{Hz}}$ for GOCE-like scenario

Bender configuration

Case: Bender configuration with three satellites



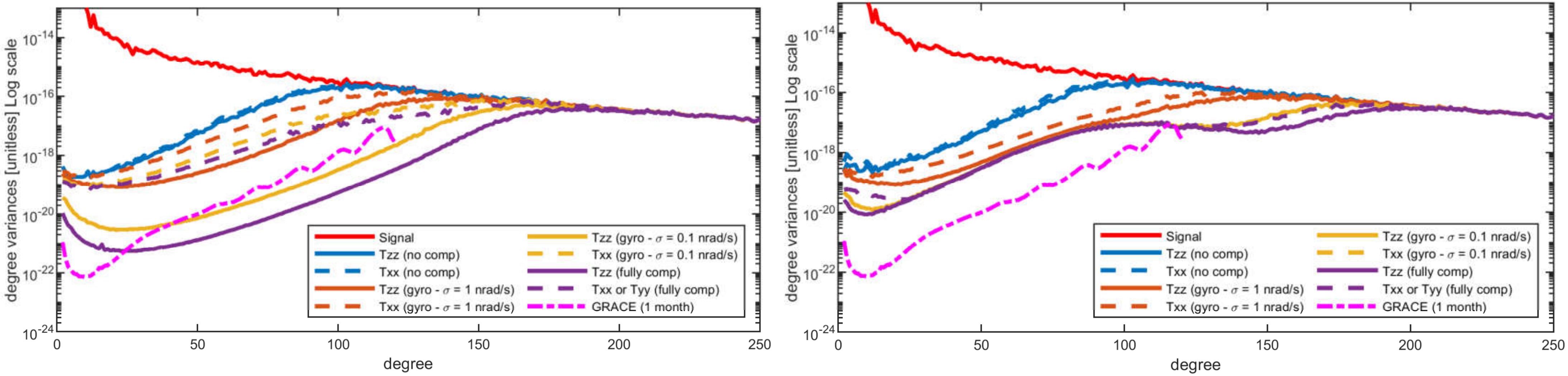
(i) adding the third satellite on an intermediate location between the leader follower satellites, e.g. an inter-satellite distance of 500 km between each pair (leader-middle, middle-follower)

(ii) adding the third satellite behind the follower satellite with a distance about 1000 km, thus having an inter-satellite distance of about 1000 km between each pair of satellites

Clock + CAI gradiometer simulations

Single-satellite single-arm gradiometer

The effect of noise degradation on the polar and inclined orbits:



(a) Polar orbit

(b) Inclined orbit

*Colors represents possible noise PSDs.

The best solution: gradiometer arm directed along the radial direction (drag-free and compensation at the level of 0.1 nrad/s)

↓

BUT the current technologies cannot provide such an accuracy for attitude control system yet.

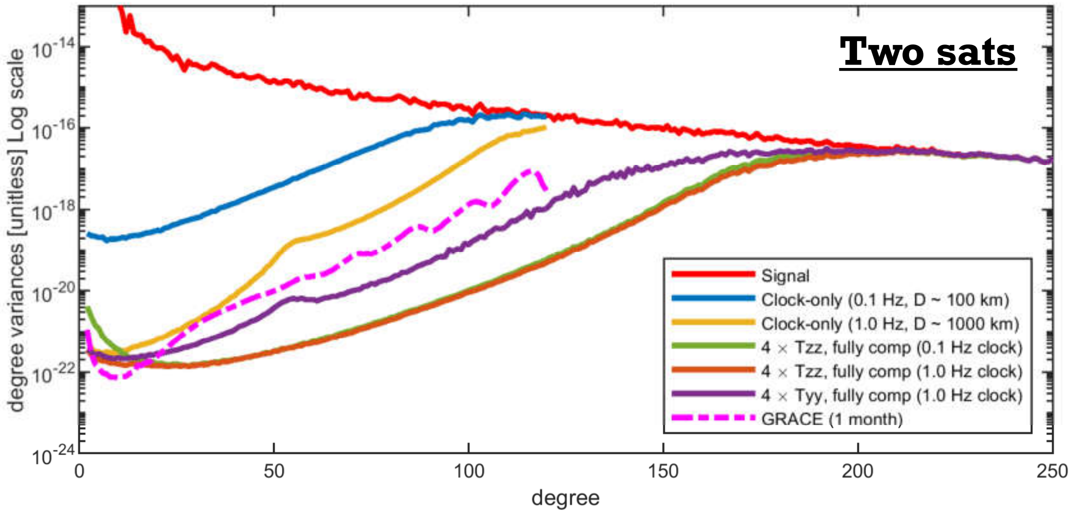
↓

The most realistic scenario: orienting the gradiometer arm along the out of plane axis (y)

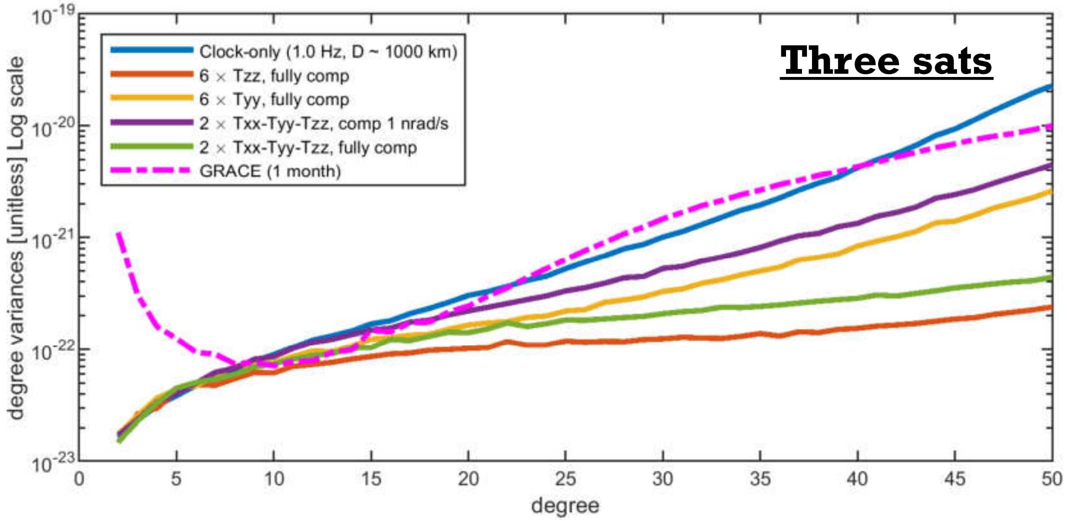
Clock + CAI gradiometer simulations

Bender configuration with two and three satellites

The effect of different gradiometer noise PSD and gradiometer orientation:



(a) different inter-satellite distances and optimal gradiometer noise PSD scenarios



(b) the optimal and degraded gradiometer noise PSD + different orientations of the gradiometer arm on board the satellites

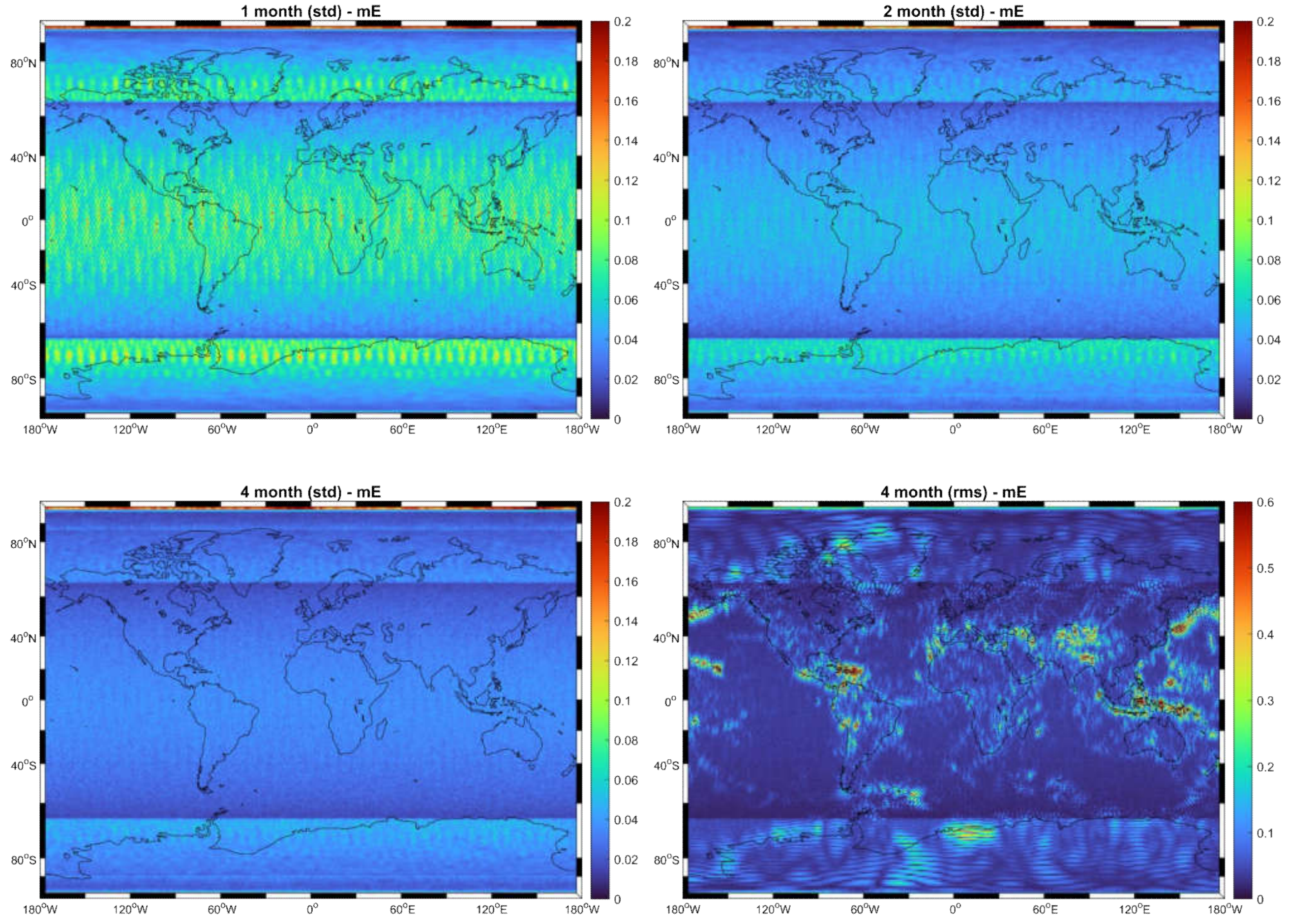
Gradient contribution

middle-high degrees: a better estimation of the spherical harmonic degrees up to about degree 200

low degrees: below degree 10 the solution is dominated by the clock information, while about above degree 30 the gradiometers only are playing a role.

Longer simulation periods and cumulative commission errors

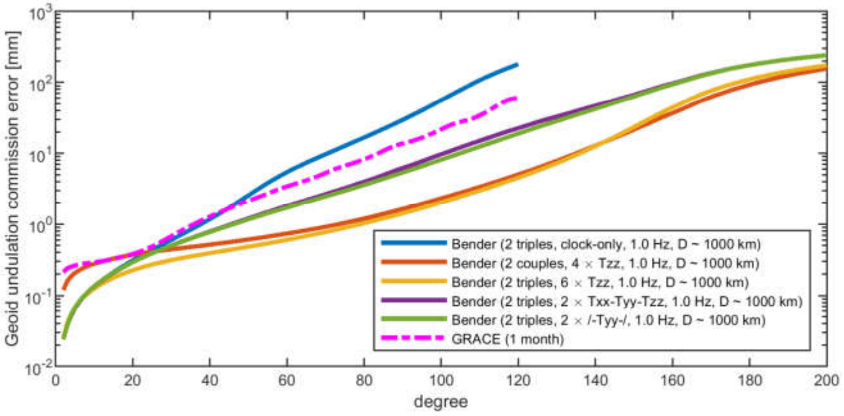
Grid estimation error in terms of standard deviation for different mission life-times:



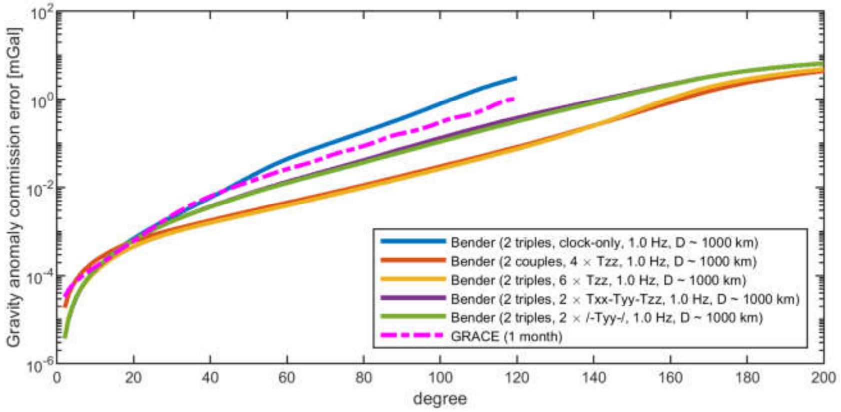
***The root mean square error for the 4-month scenario is given to quantify the omission error**

Cumulative commission errors:

(a) Geoid undulations

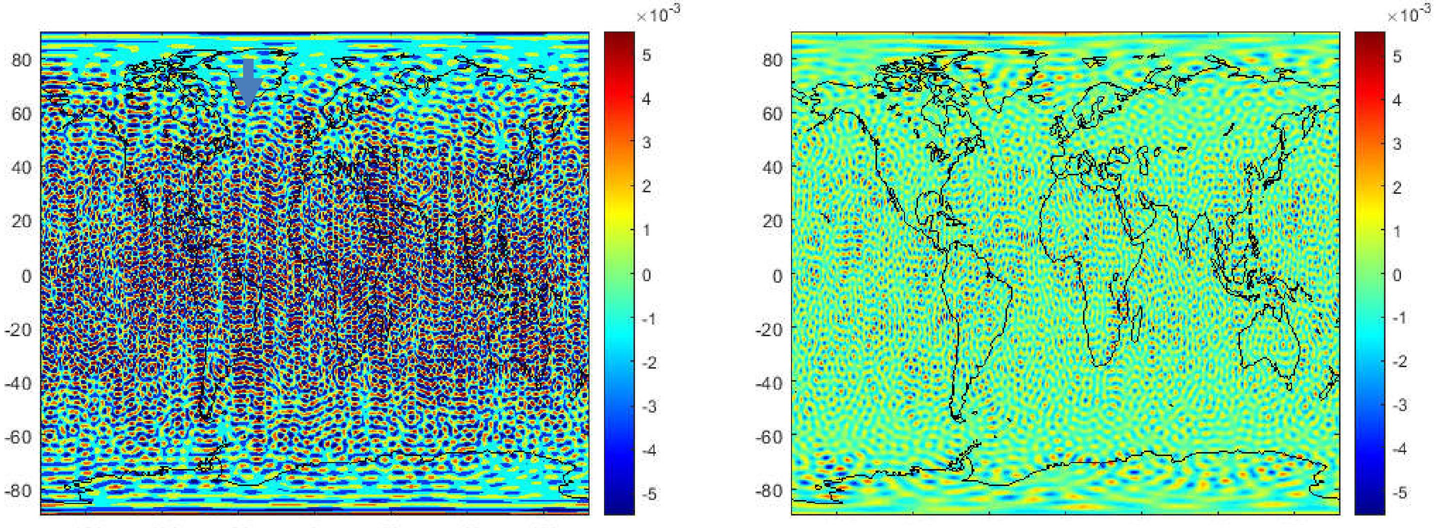


(b) Gravity anomalies



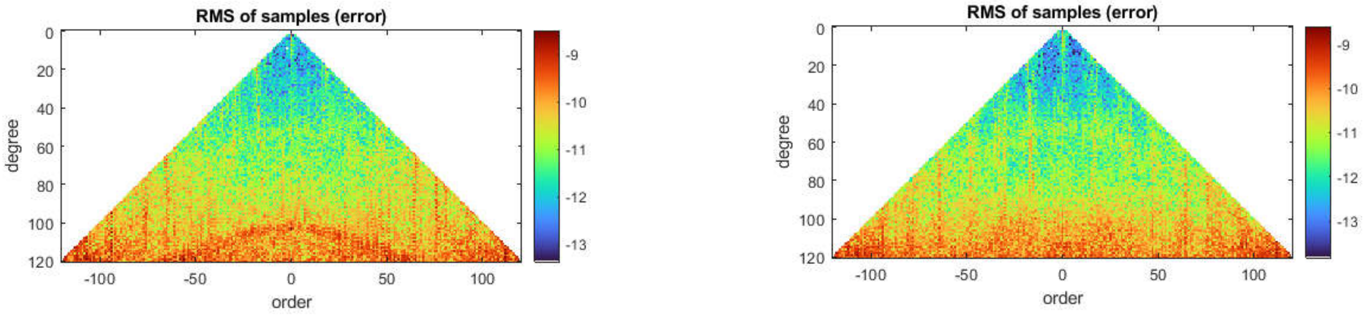
Inclusion of non-tidal mass variations

Aliasing over a geoid undulation grid [unit: m]



(a) Polar orbit only

(b) Bender configuration



Bender configration offers:

increase in the spatial resolution along the East-West direction

an increment in isotropy

Take away:

- The aliasing effect and the longitudinal striping are reduced significantly in the Bender configuration scenario.

- Having a polar pair coupled with an inclined pair provides a better and less degraded gravity field solution

Conclusions on the gravity field recovery

Regarding the data:

- the direct observation of the gravitational potential differences by the atomic clocks can be an asset; the AC transfer function prevents the dampening of the spherical harmonic spectrum at the very low degrees (typical of GRACE).

Regarding the results:

- The mission configuration is more complex than a "simple" GRACE-like scenario. This would imply considering 1 Hz (instead of 0.1 Hz) clock observations, longer inter-satellite distances (about 1000 km instead of 100 km) and a Bender formation with three satellites on each orbit. Without these "complications", the mission profile would not be competitive with GRACE in the retrieval of the gravity field at low-medium degrees.

NOTE: Optimization of payload on the platforms would be relevant in reducing differences and minimizing 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).

MOCAST+: geophysical applications and impact assessment

- 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), with improvements (WRT GRACE) in:
  - detectability of **earthquakes** (down to M 8.4);
  - sensitivity to **deglaciation** processes (e.g., for Patagonia glaciers minimum observable rate 5 Gt/yr; GRACE, 10 Gt/yr);
  - long term monitoring of **hydrologic basins and lakes (**e.g., Tibetan lakes: 1 year of data to resolve variations which GRACE resolves after two years);
  - monitoring of seasonal components of **reservoirs**, **lakes and glaciers** with areas > 8000 km^2 and seasonal mass variations of 10 Gt.

  The impact assessment was investigated by localized spectral analysis of the signals to be expected from mass variation rates of the above phenomena.

- Applications in planetary exploration: 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.