POLITECNICO
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Applying the space-wise approach to concepts of future quantum missions for the Earth gravity field determination

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https://satgeo.dica.polimi.it/

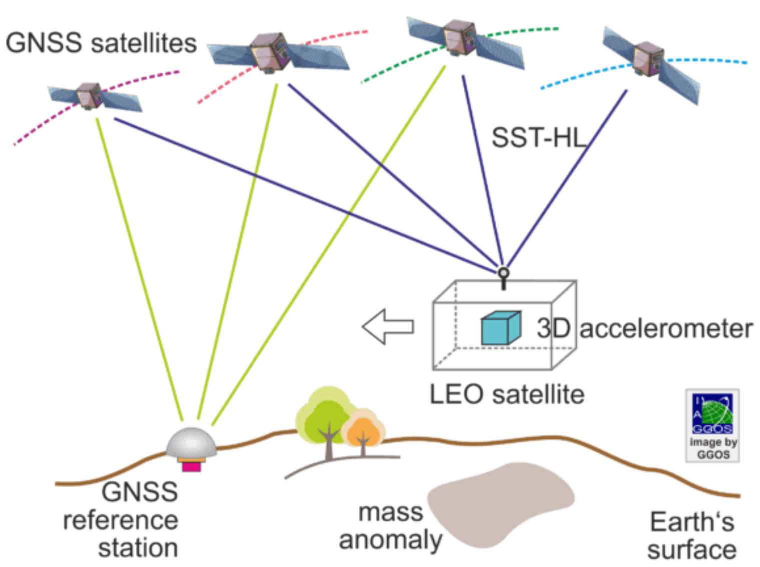
Outline of the presentation

- Observation of the Earth gravity field from space:
  - Satellite geodesy concepts and missions for the Earth gravity field
  - Towards Quantum Space Gravimetry (QSG) for the Earth gravity field observation
- Applying the space-wise approach to observations of future Quantum Satellite Gravity (QSG) missions
- QSG projects at POLIMI

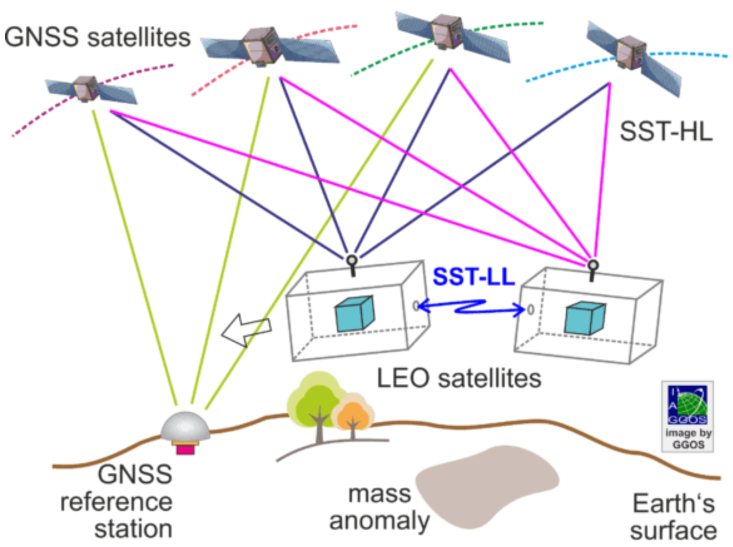
Observations of the Earth gravity field from space

- Observations from satellites provide data to model the static Earth gravity field and to observe and monitor **mass and mass transport** in the Earth system, also contributing to the determination of a number of Essential Climate Variables (ECVs) as defined by GCOS (Global Climate Observing System).

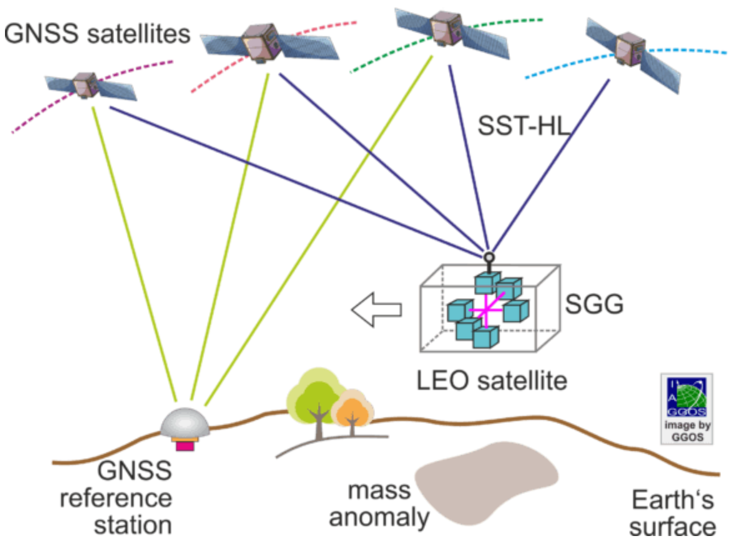
Satellite-to-Satellite tracking in the high-low mode



Satellite-to-Satellite tracking in the low-low mode

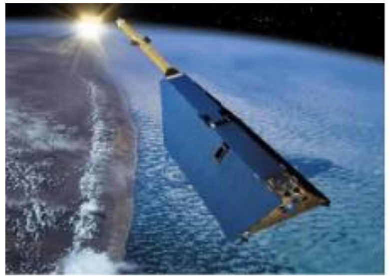
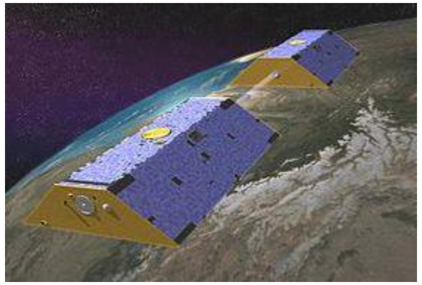
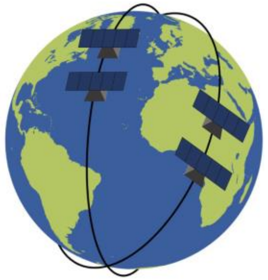


Satellite Gravity Gradiometry plus high-low SST



Images https://ggos.org/item/satellite-gravimetry/

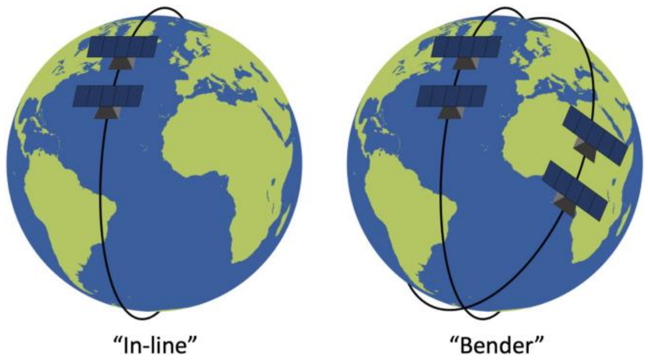
Missions for the Earth gravity field

	SST in the high-low mode	***Satellite-to-Satellite Tracking - SST in the low-low mode***		***Satellite Gravity Gradiometry - SGG***
	CHAMP (2000-2010)	***GRACE (2002-2017) GRACE-FO (2018-……)***	***NGGM/MAGIC (~2028)***	***GOCE (2009-2013)***
	A "pathfinder mission" for the SST concept (EA)	*GRACE / GRACE-FO (2018 - …) / NGGM long-term monitoring of the gravity field, time variations*		*Gradiometry + low orbit for high accuracy static gravity field*
				
Accuracy of EA (electrostatic accel.)	*~10^{-10} m/s²*	*~10^{-11} m/s²*	*~10^{-11} m/s²*	*~10^{-12} m/s²*
Accuracy of LRI inter-satellite tracking		*range std ~10^{-6} m range-rate std ~10^{-8} m/s*	*range std ~10^{-8} m range-rate std ~10^{-10} m/s*	
Geoid undulations	*~10 cm @ 350 km*	*~10 cm @ 175 km*	*~1 mm @ 500 km (every 3 days) ~1 mm @ 150 km (every 10 days)*	*~1 cm @ 100 km*
Gravity anomalies	*~0.02 mGal @ 1000 km*	*~1 mGal @ 175 km*		*~1 mGal @ 100 km*

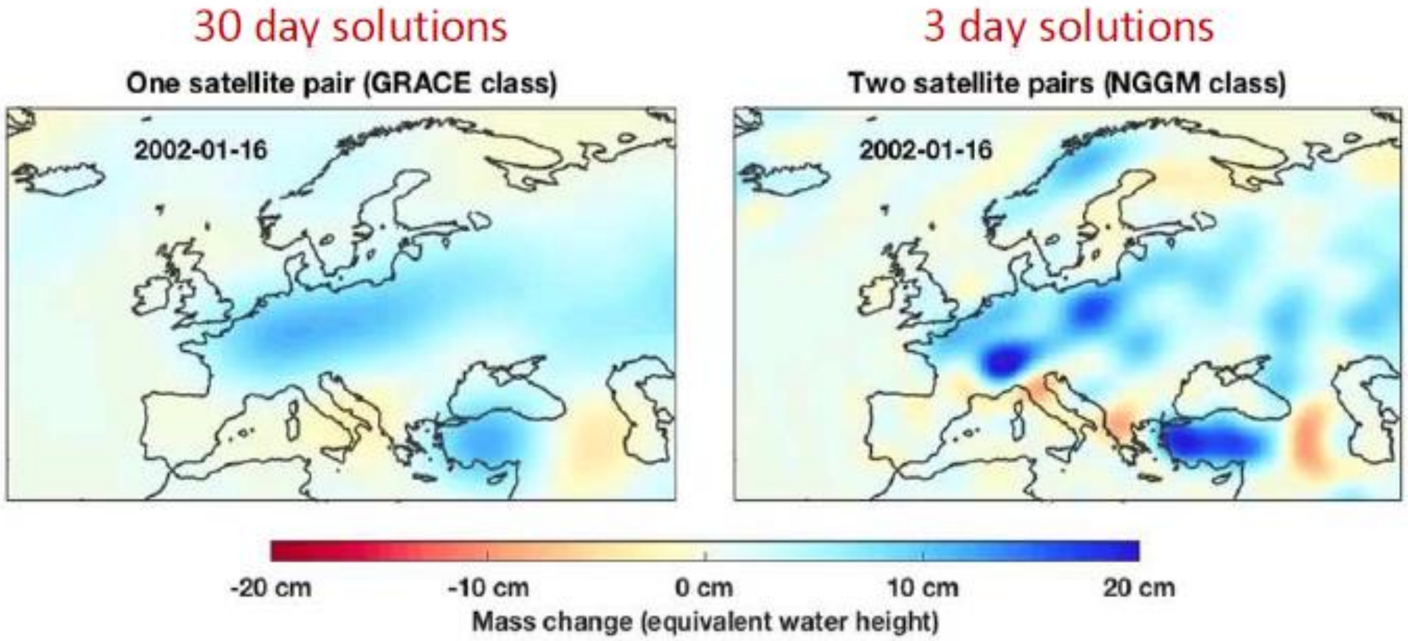
Future missions: higher spatial and temporal resolution from double-pair mission

- ***Higher spatial resolution** in the detection of gravity changes (movement of mass in Earth system) can be obtained with lower orbits (e.g., 300-350 km).*
  *Note that full detailed mapping of the spatial gravity field variations down to a few km resolution must be supplemented by **airborne and surface** gravity measurements.*

- ***Higher temporal resolution** can be obtained with satellite constellations (higher revisit time) → operational service applications*



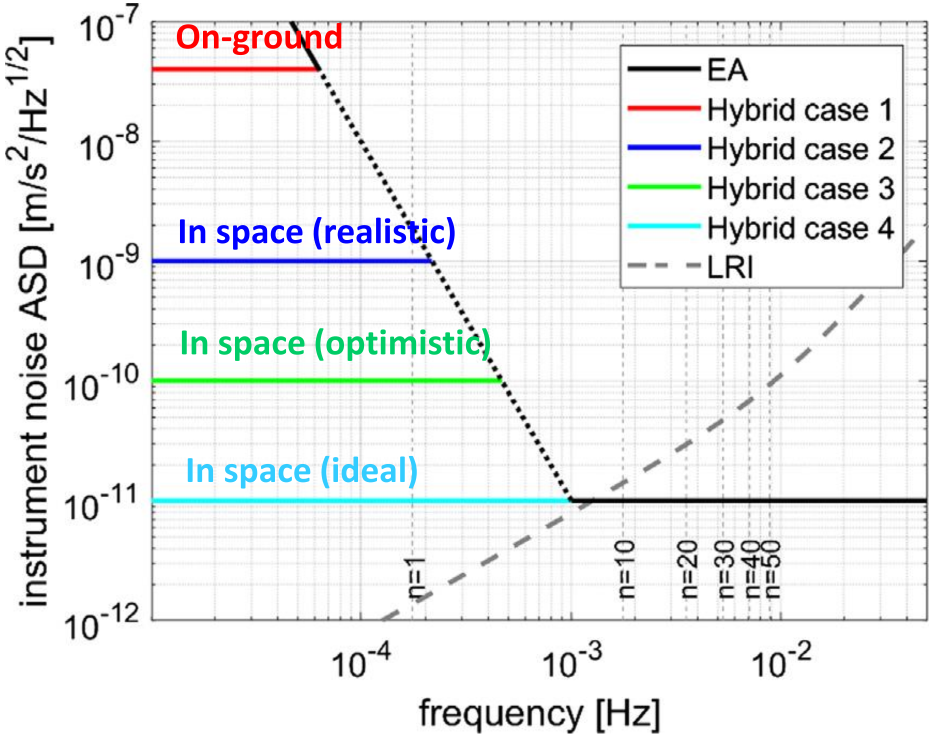
"In-line" (GRACE class) formation (left)
and "Bender" (NGGM class) formation (right)
(Haagmans et al., 2020)



(Massotti, Haagmans and Silvestrin, 2021)

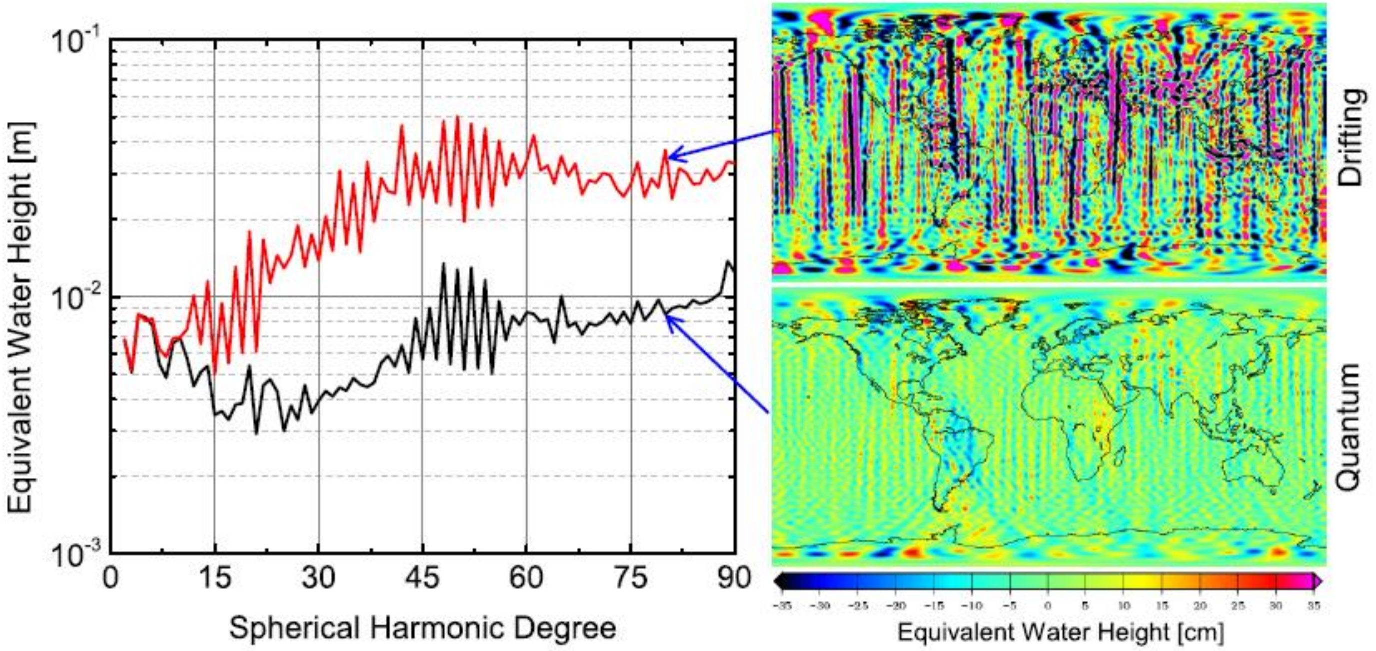
Quantum sensors: potential gain in Earth Observation by quantum accelerometers

Hybrid accelerometer noise specifications (ONERA) - EA/CAI-hybridization in one axis



(Abrikosov et al., Advances in Space Research, 2019)

Spectra of gravity field recovery in equivalent water height considering quantum (black) or drifting (red) accelerometers (computations carried out without any empirical periodic parameter adjustment in the gravity field reconstruction).



(Lévèque et al., Journal of Geodesy, 2021)

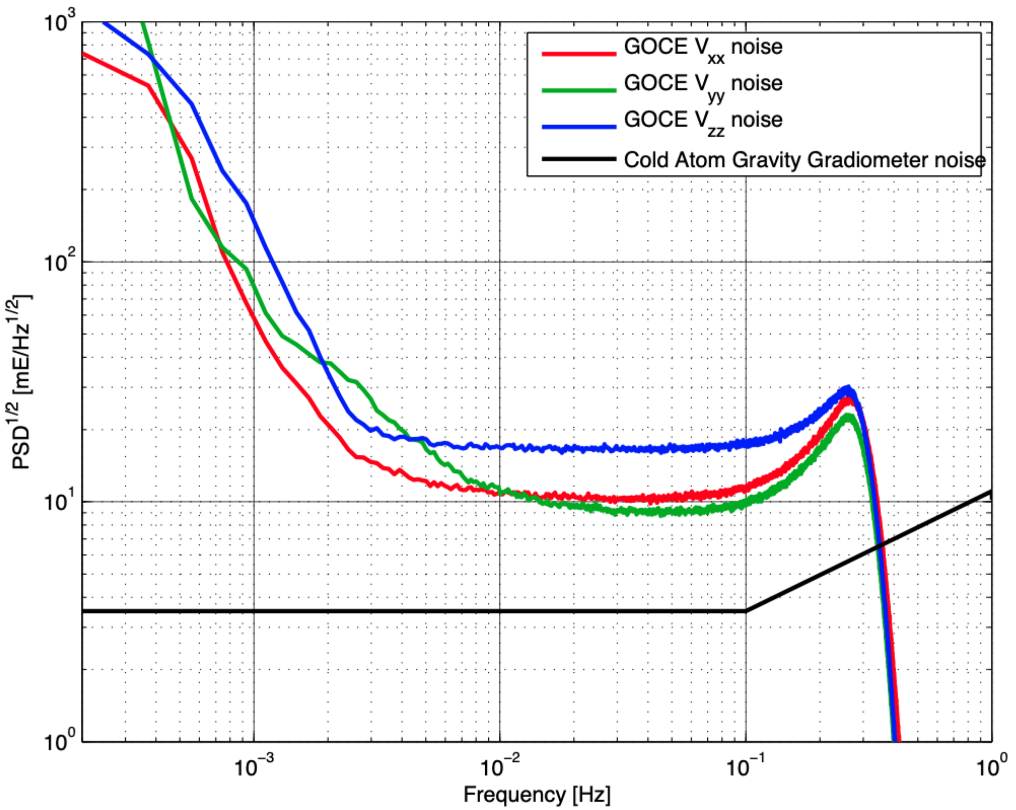
Quantum sensors for Space Gravimetry: cold atom gradiometer

- A space quantum accelerometer is expected to reach sensitivities in the low 10^{-12} $m/s^2/Hz^{-1/2}$ when stretching the interrogation times to 20 s, similar to the very best electrostatic accelerometers, such as used for GOCE, but in a wider measurement band extending down to lower frequencies.
- Absence of drifts is a consequence of the absolute character of quantum sensors, with stable scale factors determined by the wavelength of the laser beam-splitters and the duration of the measurement, and the possibility of evaluating accurately systematic effects.

Limits (so far):

- Single axis measurements.
- Much higher Size, Weight and Power (SWaP) budget.
- Angular rotations put a serious limitation to the gradiometer sensitivity measurement in the orbital plane (x and z directions) → need of rotation compensation to a level not yet achieved.

However, whilst the technology is currently less mature, it is being demonstrated in a number of national and international projects.



Comparison between the noise spectra in GOCE gradiometers and in a prospective cold atom gradiometer, illustrating the latter's reduced level at low frequencies (Carraz et al., 2014)

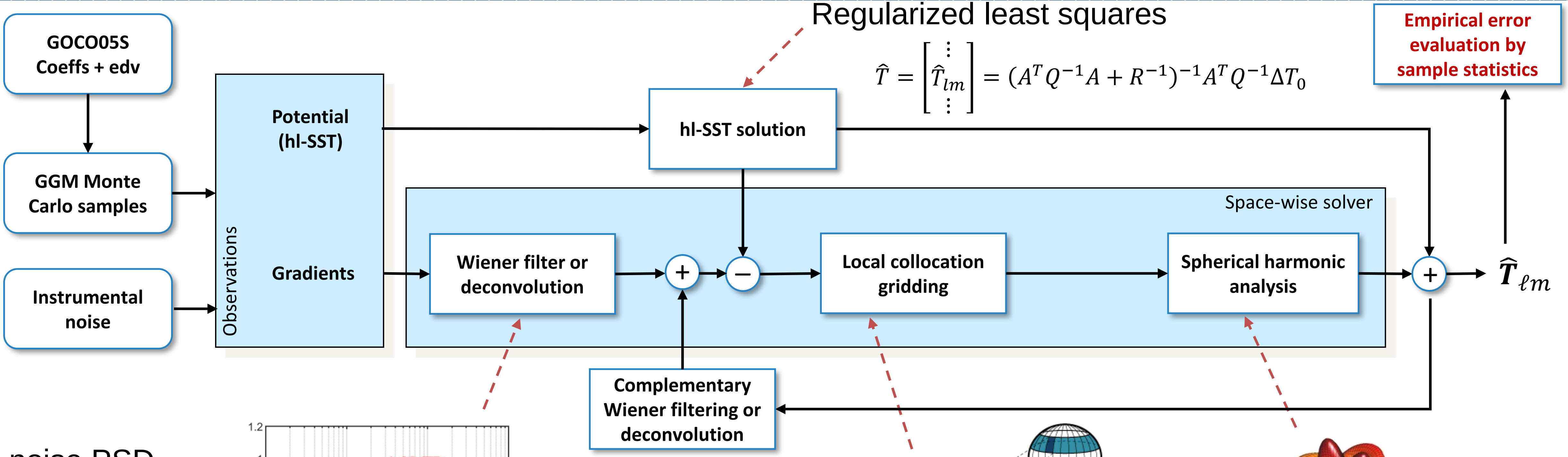
Applying the space-wise approach to observations of future Quantum Satellite Gravity (QSG) missions

- In the framework of gravity field modelling from satellite mission data, the POLIMI SATGEO group had designed and developed a **space-wise approach** based on multi-step collocation, which has been applied to process **gradiometric** data, like those observed by GOCE.

Basics of the space-wise approach:

- Exploit the local **spatial correlation** of the Earth gravity field to **estimate** the spherical harmonic **coefficients** of the gravity field model, as well as regional solutions adapted to local geophysical features.
- Solution obtained by collocation, where the covariance of the signal is modelled as a local function of the space and the covariance of the instrumental noise as a function of the time.
- A single collocation procedure is not computationally feasible, and local covariance modelling in a unique covariance matrix is complicated --> **multi-step space-wise procedure**.

The space-wise approach applied to gradiometric data



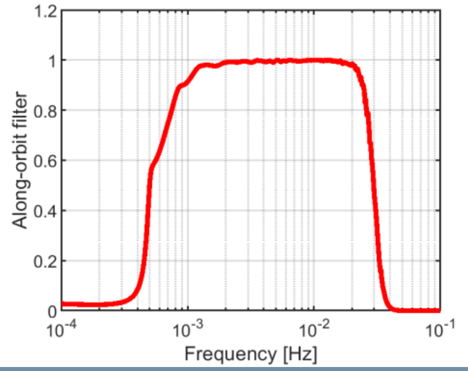
Regularized least squares

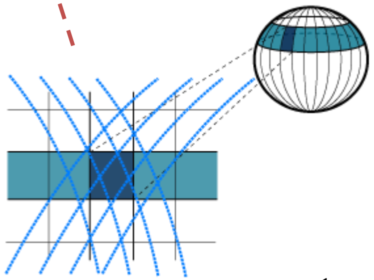
$$\hat{T} = \begin{bmatrix} \vdots \\ \hat{T}_{lm} \\ \vdots \end{bmatrix} = (A^T Q^{-1} A + R^{-1})^{-1} A^T Q^{-1} \Delta T_0$$

$$\hat{\boldsymbol{T}}_{\ell m}$$

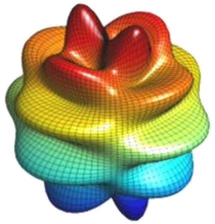
noise PSD

$$W(f) = \frac{S_y(f)}{S_y(f) + S_v(f)}$$





$$\hat{z}(\vartheta, \lambda) = C_{z\delta y}\left(C_{\delta y \delta y} + C_{\hat{e}\hat{e}}\right)^{-1} \delta \hat{y}_0$$

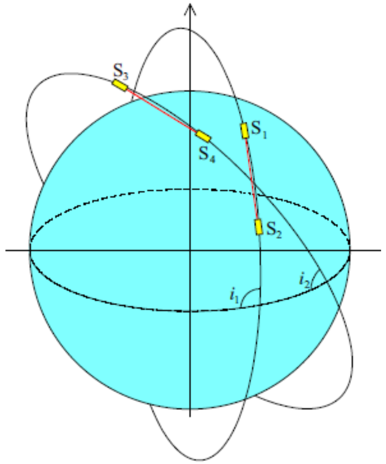


$$\hat{T}_{\ell m} = \frac{1}{4\pi a_{\ell m}} \int_{\Sigma} \hat{z}(\vartheta, \lambda) Y_{\ell m}(\vartheta, \lambda) d\sigma$$

The MOCAST+ study

MOnitoring mass variations by Cold Atom Sensors and Time measures
(funded by the Italian Space Agency - ASI)
2020 - 2022

- Proposed mission scenario: **Bender formation** with two or three satellites per orbit
    - h = 371 km, I = 88° (polar orbit)
    - h = 347 km, I = 66° (inclined orbit)



- An **“enhanced” quantum payload** consisting of a **Cold Atom Interferometer** (^{88}Sr atoms) and an **atomic clock** (^{87}Sr atoms).

Migliaccio et al. *Surveys in Geophysics,* **44**, 665–703 (2023). **DOI** 10.1007/s10712-022-09760-x
Rossi et al. *Quantum Science and Technology*, **8**, 014009 (2023) **DOI** 10.1088/2058-9565/aca8cc

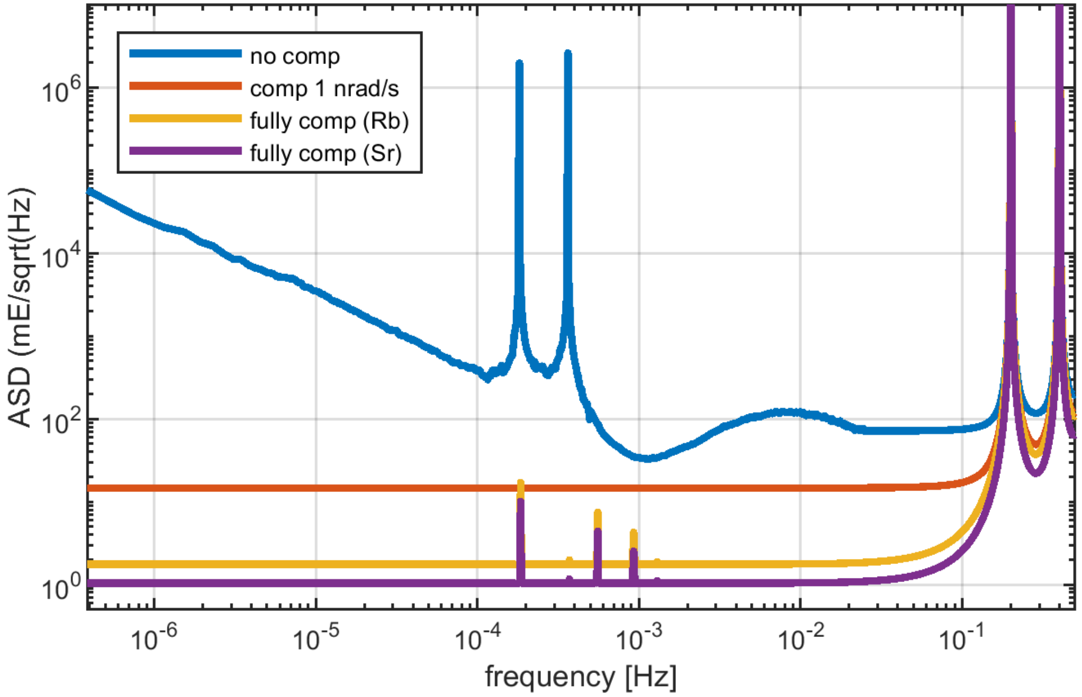
MOCAST+ scenario, gradiometry data only

Orbit

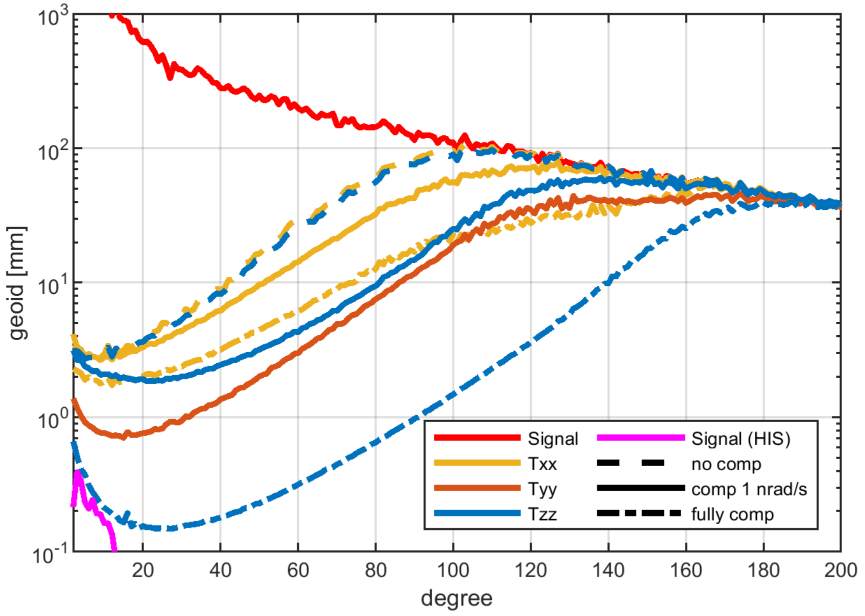
- h = 371 km, I = 88° (polar orbit)

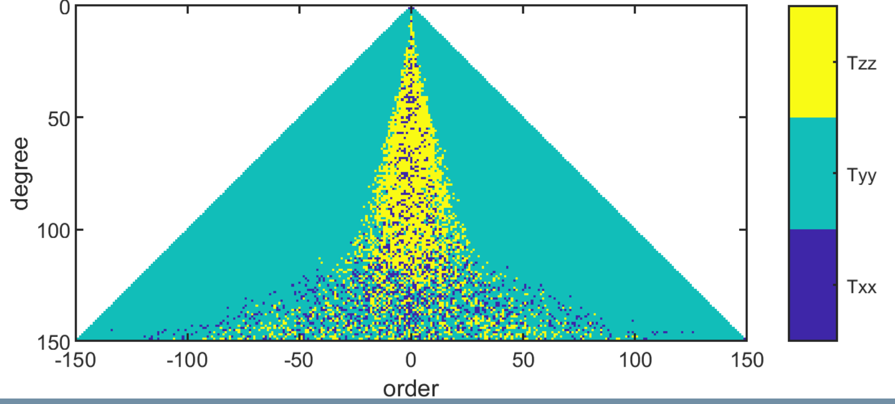
Cold Atom Interferometer (^{88}Sr atoms):

- observations of gravitational gradients
- low sensitivity to magnetic fields
- angular rotations, through the centrifugal term, put a serious limitation to the gradiometer sensitivity measurement in the orbital plane (x and z directions)



Quantum gradiometry: contribution depending on the gradio axis direction





IDEAL SCENARIO (angular rotation fully compensated)

Main contributor to the final accuracy is the T_{zz} gradiometer

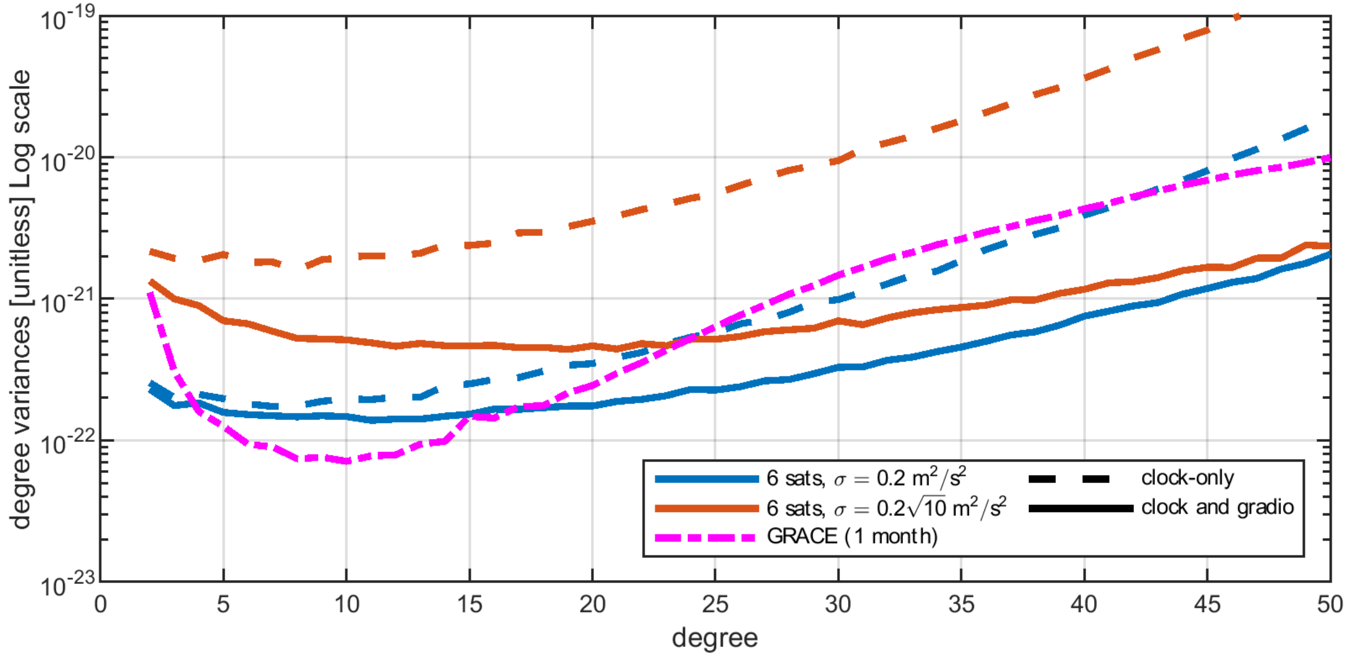
REALISTIC SCENARIOS (1 nrad/s and no compensation)

Main contributor to the final accuracy is the T_{yy} gradiometer, where the residual rotation error is almost negligible (red line)

Impact of different gradiometer axis orientations at the level of the single spherical harmonic coefficient error has been evaluated.

The main contributions to the coefficient estimation comes from T_{yy}, but the best estimate of low-order coefficients comes from T_{zz}, due to better numerical conditioning of this observation.

Impact of atomic clocks



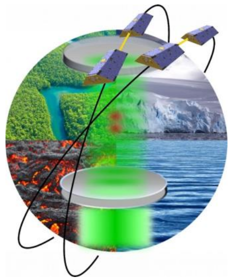
Simulation parameters:

- degraded accuracy in ΔT observations (factor 10 in the noise variance)
- two triplets of satellites
- attitude control at 1 nrad/s level

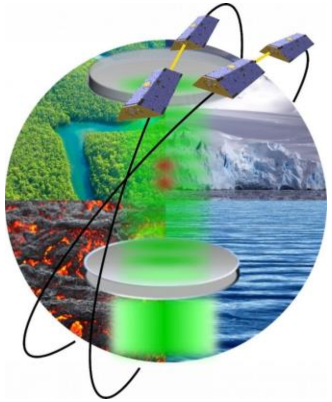
- clock-only solution never “dominates” the error curve at low degrees,
- better measurements from clocks implies better quality of the overall solution at low degrees (up to one order of magnitude),
- the improvement could be partly related to the role of the clock-only solution in the space-wise approach (data reduction before the gridding having a beneficial effect on the signal covariance modelling).

MOCAST+: results of the study

- The proposed MOCAST+ mission could contribute to improve the current knowledge of the Earth gravity field and of its time variations, provided that the mission configuration is a quite complex one, with 1 Hz clock observations, longer inter-satellite distances (about 1000 km) and a Bender formation with three satellites for each orbit. Without these "complications", the mission profile would not be competitive with GRACE / GRACE-FO in the low-medium degrees.
- Using only gradiometers as payload on the central satellites of the formation could reduce costs and increase spacecraft constellation symmetry, without degrading the quality of the solution too much. The optimization of the instrument configuration can have a significant impact on the platform design and associated costs.
- With current available technology, a quantum SST mission in the low-low mode (e.g., GRACE-like) is superior to a quantum gradiometry mission in detecting time-variable effects in the gravity field modelling.



Quantum Space Gravimetry for monitoring Earth's Mass Transport Processes (funded by ESA, 2022 – 2024)



Quantum Space Gravimetry for monitoring Earth's Mass Transport Processes (funded by ESA) 2022 – 2024

https://www.asg.ed.tum.de/iapg/qsg4emt/

TUM POLITECNICO DI MILANO TUDelft hcu HafenCity Universität Hamburg UNIVERSITÄT BONN UNIVERSITY OF TRIESTE esa European Space Agency

In this project the impact and the potential of quantum sensors is being evaluated and quantified for future gravity observation from space, and their potential for an improved monitoring of climate-induced processes in the Earth system in the fields of continental hydrology, climate modelling, oceans and solid Earth.

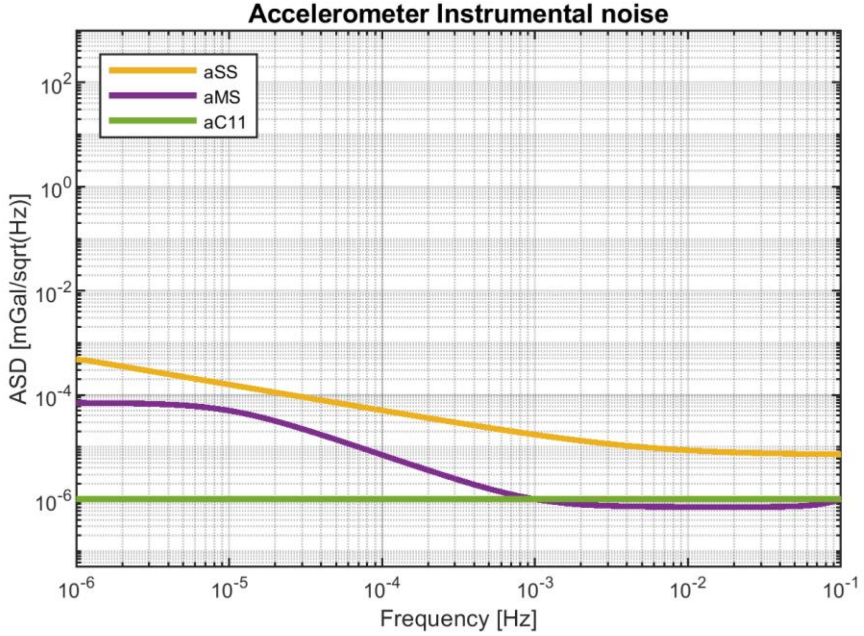
LL-SST: geometric to gravity functional conversion for the space-wise approach

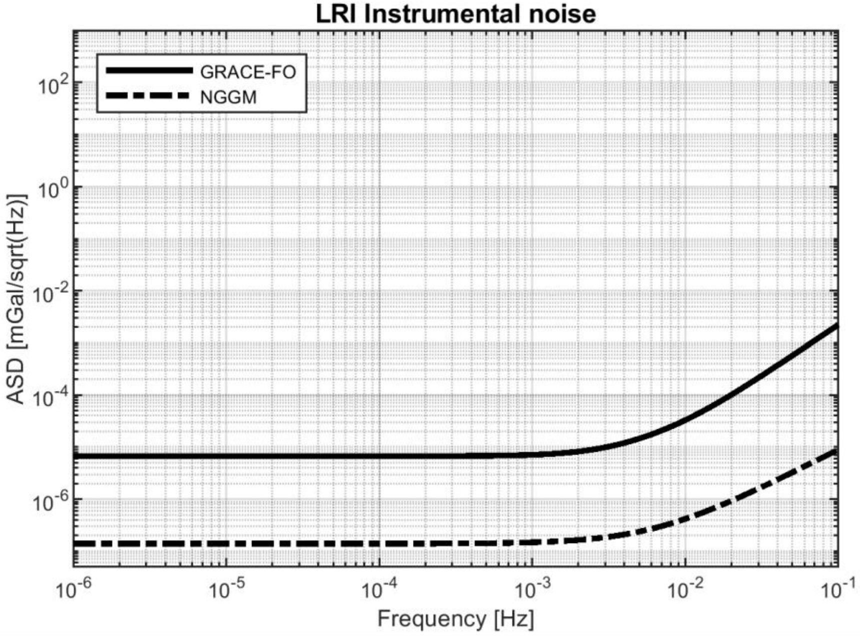
- While gradiometric observations are a direct functional of the gravity field, **low-to-low satellite-to-satellite tracking missions, like GRACE or NGGM/MAGIC, observe a geometric quantity**, namely the range or range-rate between pairs of satellites. Therefore, a conversion from the geometric quantity to an along-orbit gravity functional is required for the space-wise approach.

Possible strategies:

- energy balance approach to retrieve the **potential difference** between the two satellites;
- exploiting accelerometers and range-acceleration observation to retrieve the Line-Of-Sight (LOS) **gravitational acceleration difference** between the two satellites;
- solving Hill’s equations to retrieve the **along-orbit gravitational accelerations**;
- exploiting accelerometers range-acceleration as a **gradiometer**.

Simulation setup





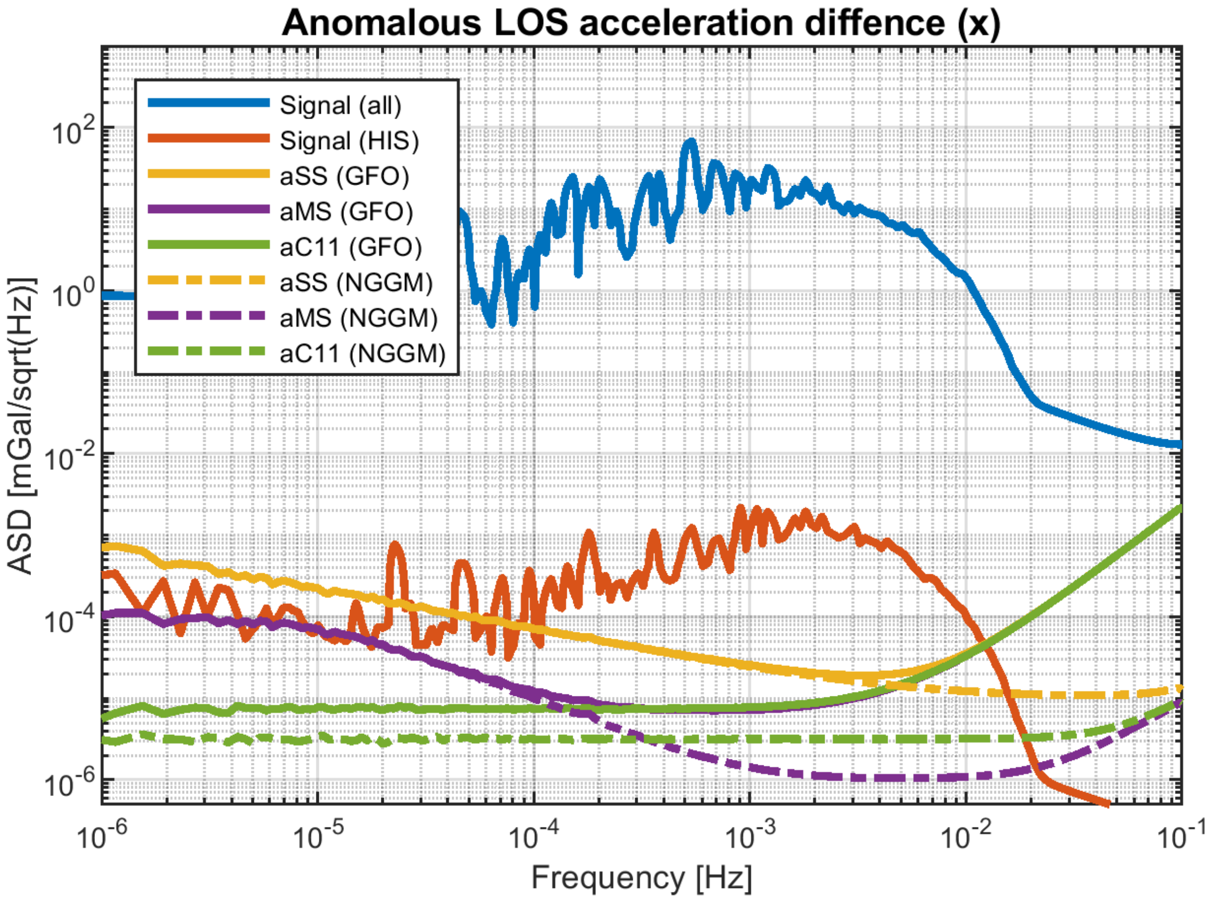
ACCELEROMETERS: SuperStar (SS), MicroStar (MS), CAI

LRI: GRACE-FO (GFO) and NGGM

BACKGROUND MODELS: EGM2008 and Updated ESA Earth System Model (ESM) for temporal variations (HIS)

ORBITS: Bender configuration (89° at 470 km and 70° at 440 km)

Impact of the instrumental noise



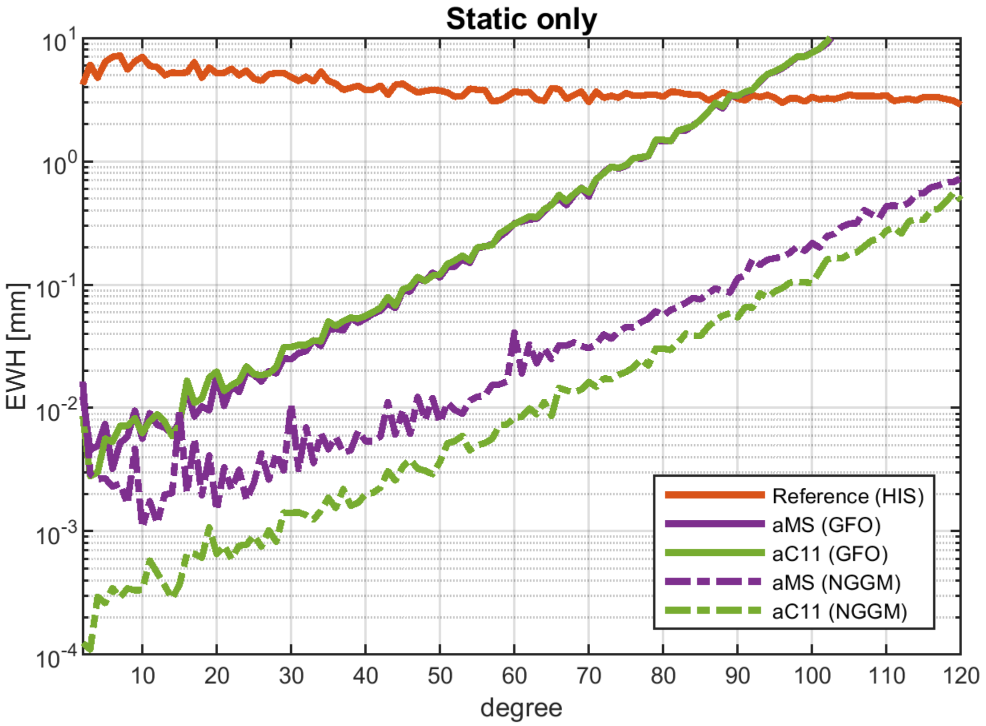
The **LOS acceleration difference** approach has a **general better behavior**, especially at low frequencies.

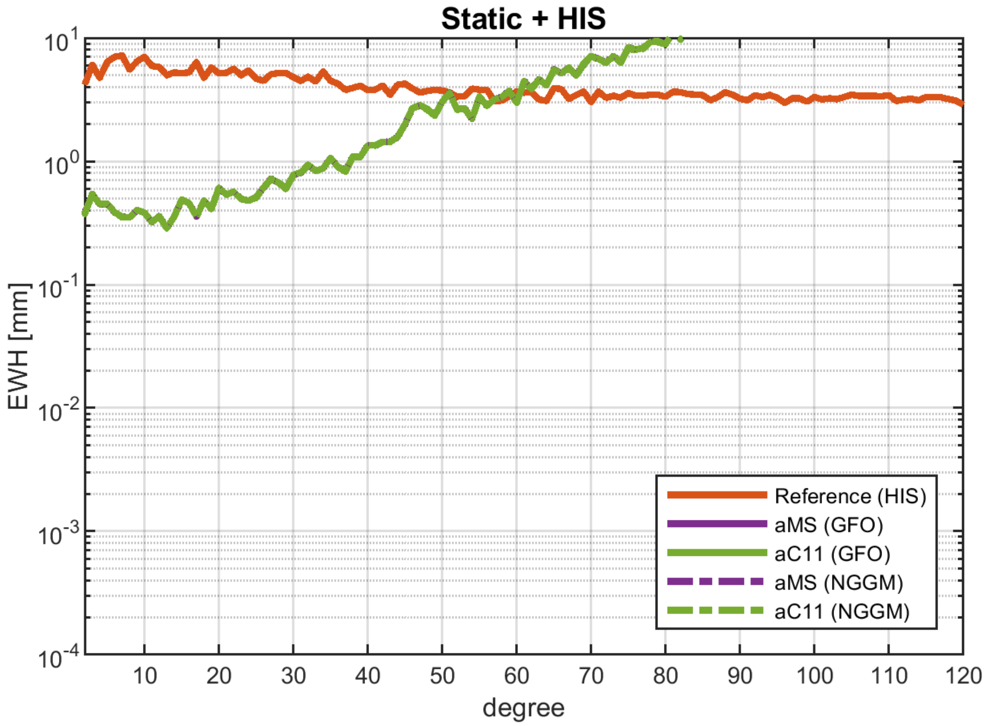
The **CAI** accelerometers show, as expected, a **better** behavior at **low frequencies** with respect to the electrostatic ones (both MS and SS).

To fully exploit the potential of CAI accelerometers also the LRI must be improved:

- in the case of GRACE-FO, the **LRI** is the **limiting factor;**
- when considering the **NGGM** instrument, the LRI is not the limiting factor.

GRAVITY FIELD RETRIEVAL





- Static only results from the space-wise approach are compatible with those found in literature for the NGGM studies.
- In presence of temporal aliasing the limitation is related to the quality of de-aliasing models and to the computational strategy. This limitation can be addressed by orbit configurations or algorithm developments.
- Quantum instruments could carry an improvement when coupled with a LRI better than the GRACE-FO one.

Towards a Quantum Space Gravimetry pathfinder mission

Goals of a QSG pathfinder mission

- To demonstrate the maturity of the cold atom technology to operate in space (technical maturity of key components in space, such as long operation times or rotation compensation).
- To prepare for a fully-fledged QSG mission with larger interrogation times (more than 10 s) with performance of $\sim 10^{-11} – 10^{-12}$ m/s^2/sqrt(Hz), suitable for the end user community.
- For geodesy and geophysics: the pathfinder will in any case provide interesting observations and useful results for the recovery of the gravity field, even though a clear improvement will be available to end-users in geodesy and geophysics only from a subsequent fully-fledged quantum gravimetry mission.

Possible scenarios

- Embarking the quantum sensor as a passenger on the ESA/NASA NGGM/MAGIC mission (Next Generation Gravity Mission / Mass-change and Geosciences International Constellation).
- Dedicated PM within this decade with a performance of up to 10^{-10} m/s^2/sqrt(Hz) -> CARIOQA-PMP project.

Towards a Quantum Space Gravimetry pathfinder mission

CARIOQA-PMP

Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry – Pathfinder Mission Preparation

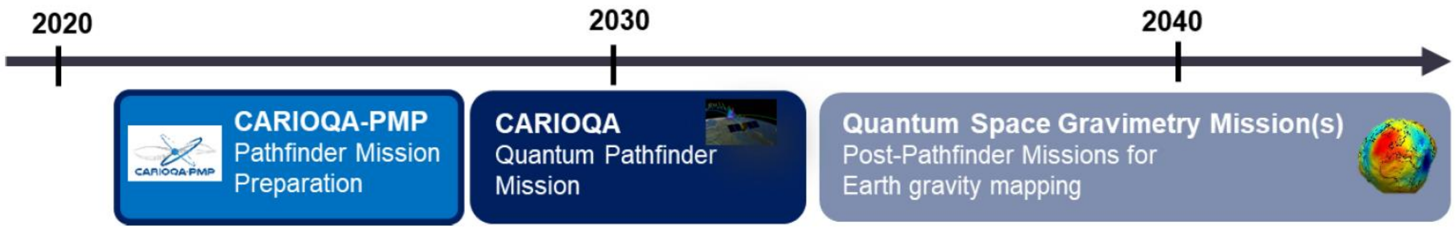
(funded by the European Union, under the HE program) 2022 – 2026

https://carioqa-quantumpathfinder.eu/

The CARIOQA-PMP project

The CARIOQA-PMP project was kicked-off in December 2022 and will last 40 months (end: April 2026).

The objective is to successfully prepare a Quantum Pathfinder Mission and Post-Pathfinder activities, developing with European industry the engineering model of the atomic accelerometer for the CARIOQA pathfinder mission.



- Within the CARIOQA-PMP Consortium, Earth Sciences are represented by LUH-IFE, DTU, TUM, POLIMI.
- Our role is to define the needs of scientific users in geodesy and geosciences, and to define optimal scenarios for the pathfinder and for a post-pathfinder mission through validation by simulations.

The CARIOQA-PMP project

Questions to be addressed:

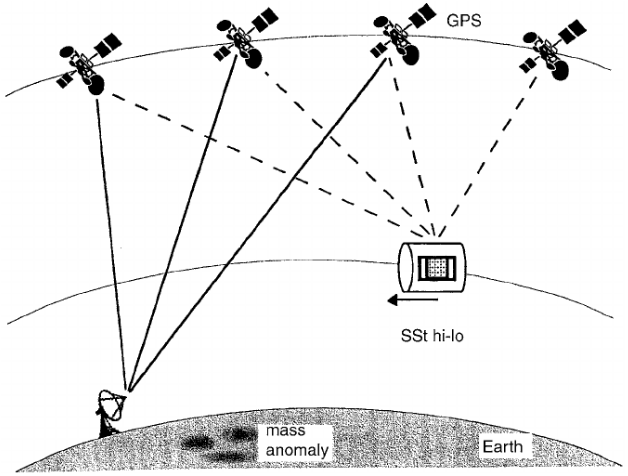
- Which observation technique is best suitable
- What type of constellation is suitable and what problems must be addressed
- What is the instrument accuracy that can meet the user needs

Hypothesis for the instruments:

CAI: flat noise spectrum with 10^{-10} m/s^2 and 10^{-11} m/s^2

LRI: GRACE-FO

Mission scenario: high-low SST



Conclusion

Quantum technology, among many different application areas, is gaining interest in the field of satellite geodesy for the determination of the Earth gravity field (and also for the gravity field of other planets), as well as in the geosciences which will benefit from the improved knowledge of the gravity field, especially for the time-variable component due to mass changes which are in turn connected to climate changes.