CAI and GRICE studies

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https://syrte.obspm.fr/spip/science/iaci/

Outline

I. **Introduction**

II. CAI gradiometer study

III. GRICE Study

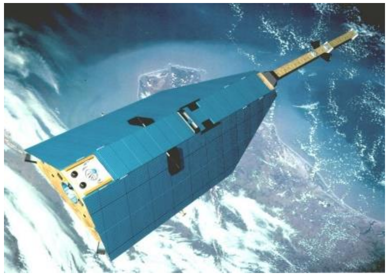
Conclusion & Prospects

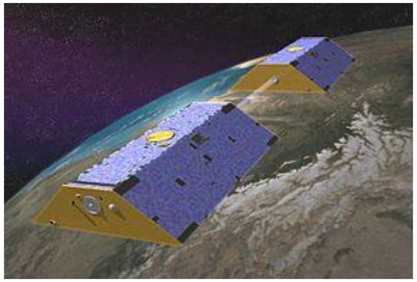
I. Gravity missions

General principle:
Precise tracking position of a satellite (in free fall) + measurement of non-inertial acceleration

Different mission scenarios:

- CHAMP : Orbitography + accelerometry





- GRACE : Twin satellites, Orbitography + SST (Microwave link) + accelerometry

- GOCE : 1 satellite, Orbitography + gradiometry
- GRACE FON : GRACE + SST with LRI

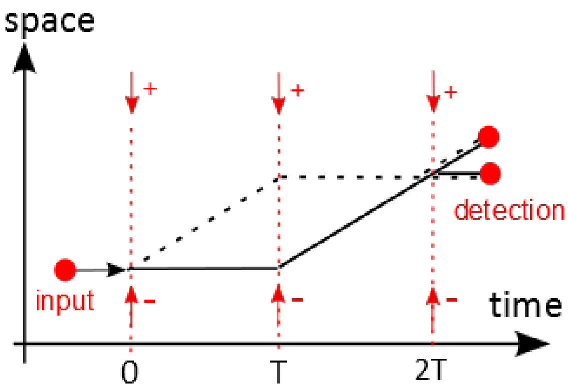
All missions rely on electrostatic accelerometers, which suffer from bias and drifts at low frequency

I. Atomic accelerometer

- Relies on atom interferometry methods

- Sequence of three laser beamsplitters
to create an « atomic » Mach Zehnder Interferometer

- Allows creating inertial sensors
(accelerometers, gyrometers …)



The interferometer phase is related to the interaction between atoms and light beam splitters:
At each pulse, the laser phase gets imprinted onto the atomic wavepacket

$$\begin{cases} \Delta\Phi = \varphi(0) - 2\varphi(T) + \varphi(2T) \\ \varphi(t) = -\vec{k}.\vec{z}(t) \end{cases}$$

$$\boxed{z(t) = \frac{1}{2} a\, t^2 \Rightarrow \Delta\Phi = k\, a\, T^2}$$

a measurement = measure of the relative displacement atoms/laser equiphases

Free falling atoms = « Inertial reference » & Lasers = Very fine, stable, accurate ruler

On Earth : interaction time limited by free fall, 2T ~ 0.1 s ⇒ sensitivity ~ 10^{-8} m/s^2/Hz$^{1/2}$
In Space : interaction time limited by residual expansion of the atoms/instrument size

2T = 10 s ⇒ sensitivity in the 10^{-12} m/s^2/Hz$^{1/2}$ range

I. Comparison

	Atomic Accelerometer	**Electrostatic Accelerometer**
Sensitivity	10^{-12} m/s^2/Hz$^{1/2}$ White Noise (potential)	10^{-12} m/s^2/Hz$^{1/2}$ MBW (demonstrated)
Scale factor	Absolute	Calibration required
Stability	No drift	Drift
Measurement capability	Single axis	Three axis
Proof mass motion	Residual velocities ⇒ Coriolis acceleration	-
SWaP	High	Low
TRL	Intermediate	High

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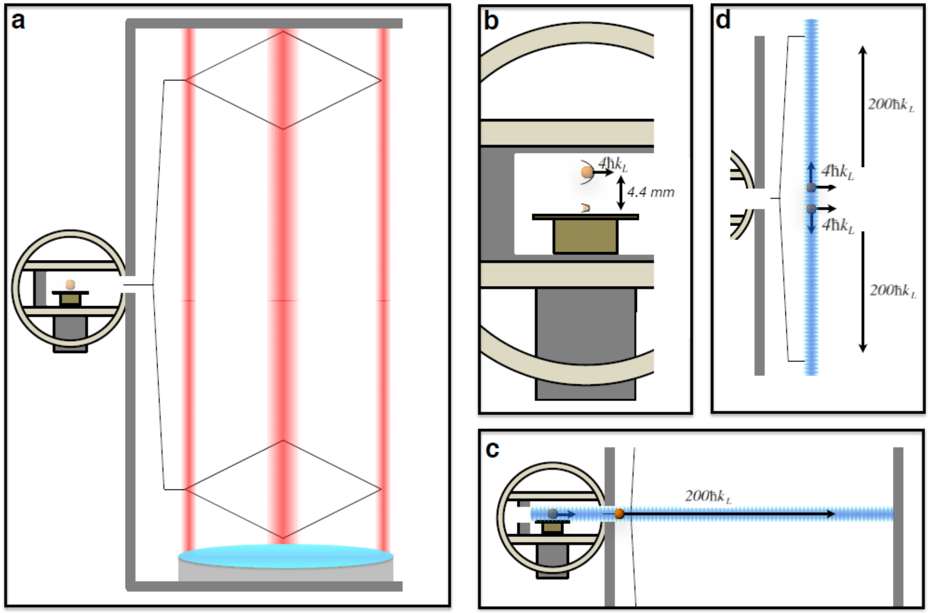
II. CAI gradiometer Study

l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace · CENTER OF APPLIED SPACE TECHNOLOGY AND MICROGRAVITY ZARM · LP2N Laboratoire Photonique, Numérique et Nanosciences · ife · IQ · Leibniz Universität Hannover

Builds on the concept proposed in Carraz et al., Microgravity Science and Technology 26, 139 (2014)



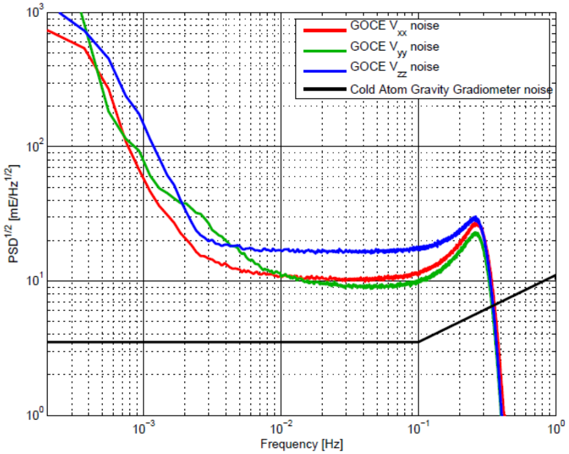
- Atom chip production of ultracold atoms T_{at}=100 pK

- Transport and splitting of a single source to feed two interferometer inputs

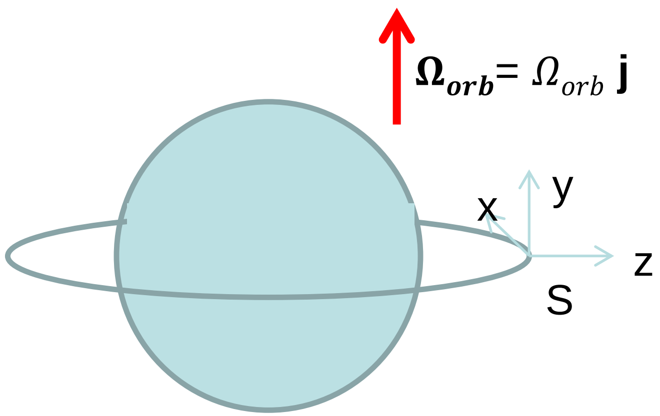
- Two interferometers separated by 50 cm Interferometer duration 2T = 10 s

Expected measurement noise : 3.5 mE/Hz$^{1/2}$

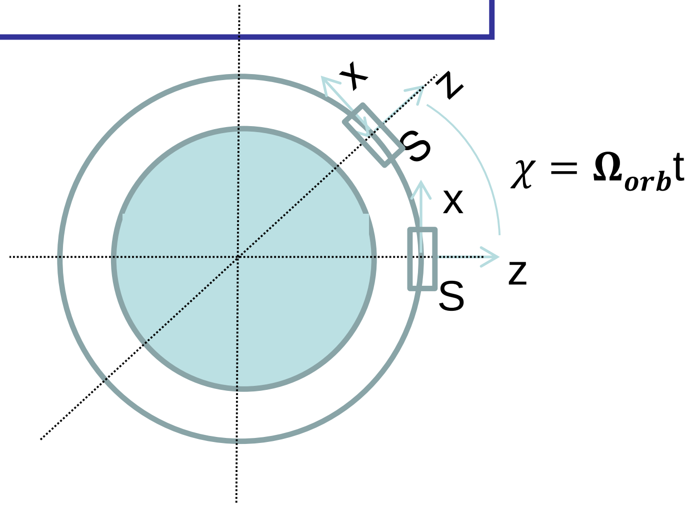
Competitive with GOCE gradiometers



II. Nadir mode



Nadir pointing: $\Omega_y \sim \Omega_{orb}$



1) Case where the measurement axis is in the orbital plane (along x or z)

Single interferometers have **additional Sagnac phase** terms : $k_x v_z \Omega_y T^2$ and $k_z v_x \Omega_y T^2$

Loss of contrast due to the phase dispersion $\sigma_{\Phi_S} \leq 1 \text{ rad} \Rightarrow \sigma_v \leq \dfrac{1}{2k\Omega T^2}$

$$\Omega_y = \Omega_{orb} \sim 10^{-3} \text{ rad/s} \Rightarrow \sigma_v < 0.6\ \mu\text{m/s} \Leftrightarrow \text{T}_{at} < 4 \text{ fK}$$

⇒ No contrast for measurement axes in the orbital plane (along x or z)

2) Case where the measurement axis is aligned with orbital rotation vector

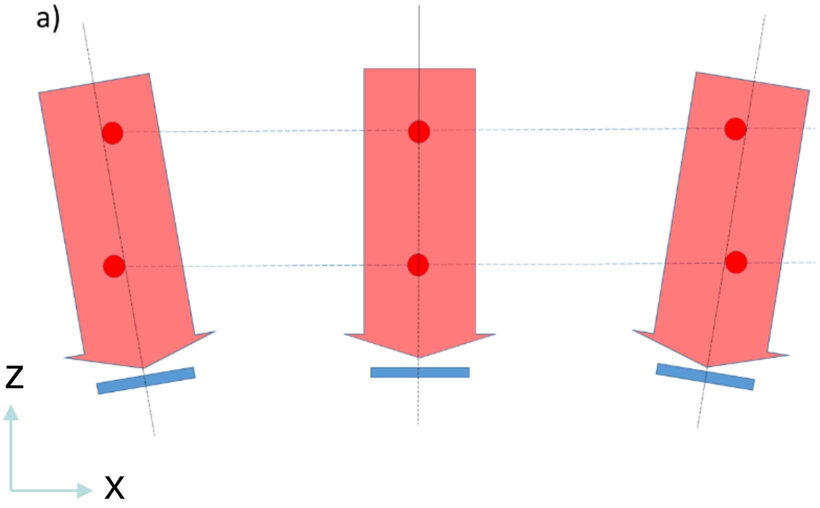
Single interferometers have no Sagnac phase scaling as Ω_y

Requirements: $\Omega_x, \Omega_z < 10^{-6}$ rad/s

II. Coping with rotations

Idea: Tilt the mirrors so as to compensate for the Orbital rotation rate

Angle given by $\Omega_m T = \Omega_y T$ where Ω_m: equivalent rotation rate of the mirrors



Eliminates

- Coriolis accelerations and the induced dephasing
- Centrifugal acceleration

Residual centrifugal acceleration still impose a bias on the gravity gradient: 2 Ω_y (Ω_{orb}-Ω_y)
To keep this term below 1mE, one needs a knowledge of Ω_{orb}-Ω_y at the **10^{-9} rad/s level**, which is challenging

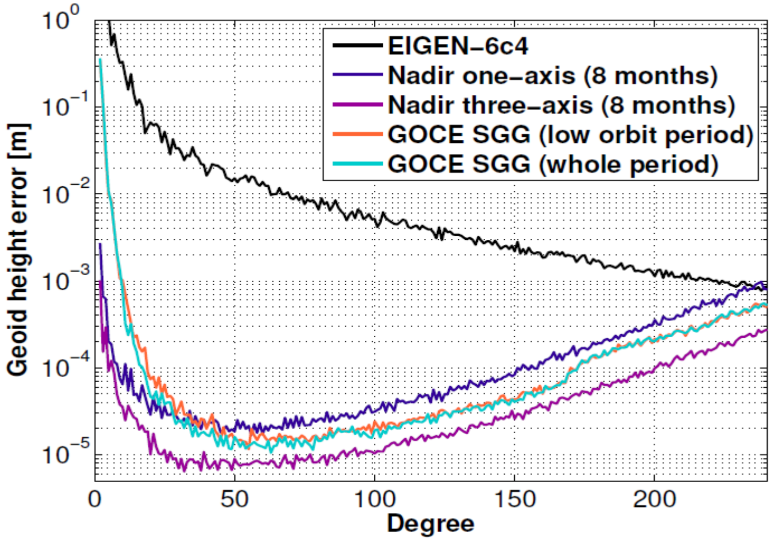
II. Results

Reconstruction of the Earth gravity field out of synthesized noisy signals

Decomposition on the spherical harmonics
(l is the degree, m the order)

$$V(r,\theta,\lambda) = \frac{GM}{R}\sum_{l=0}^{\infty}\left(\frac{R}{r}\right)^{l+1}\sum_{m=-l}^{m=l}K_{lm}Y_{lm}(\theta,\lambda)$$

Simulation performed by IFE, includes both instrument noise and attitude noise



Degree medians of the true errors for gravity field solutions that are extrapolated to 8 months for the CAI gradiometer as well as the errors for the GOCE SGG (Satellite Gravity Gradient) solutions. Two GOCE SGG solutions are included here. One is based on the gravity gradients of the whole mission period, while the other one corresponds to the period where the satellite was in lower orbits.

GOCE

Whole period :
47 months

Low orbit period :
3 months at 239 km
+ 5 months below 239 km

⇒ Clear improvement with respect to GOCE

A. Trimeche, B. Battelier, D. Becker, A. Bertoldi, P. Bouyer, C. Braxmaier, E. Charron, R. Corgier, M. Cornelius, K. Douch, N. Gaaloul, S. Herrmann, J. Müller, E. Rasel, C. Schubert, H. Wu, F. Pereira dos Santos,
"Concept study and preliminary design of a cold atom interferometer for space gravity gradiometry", arXiv:1903.09828

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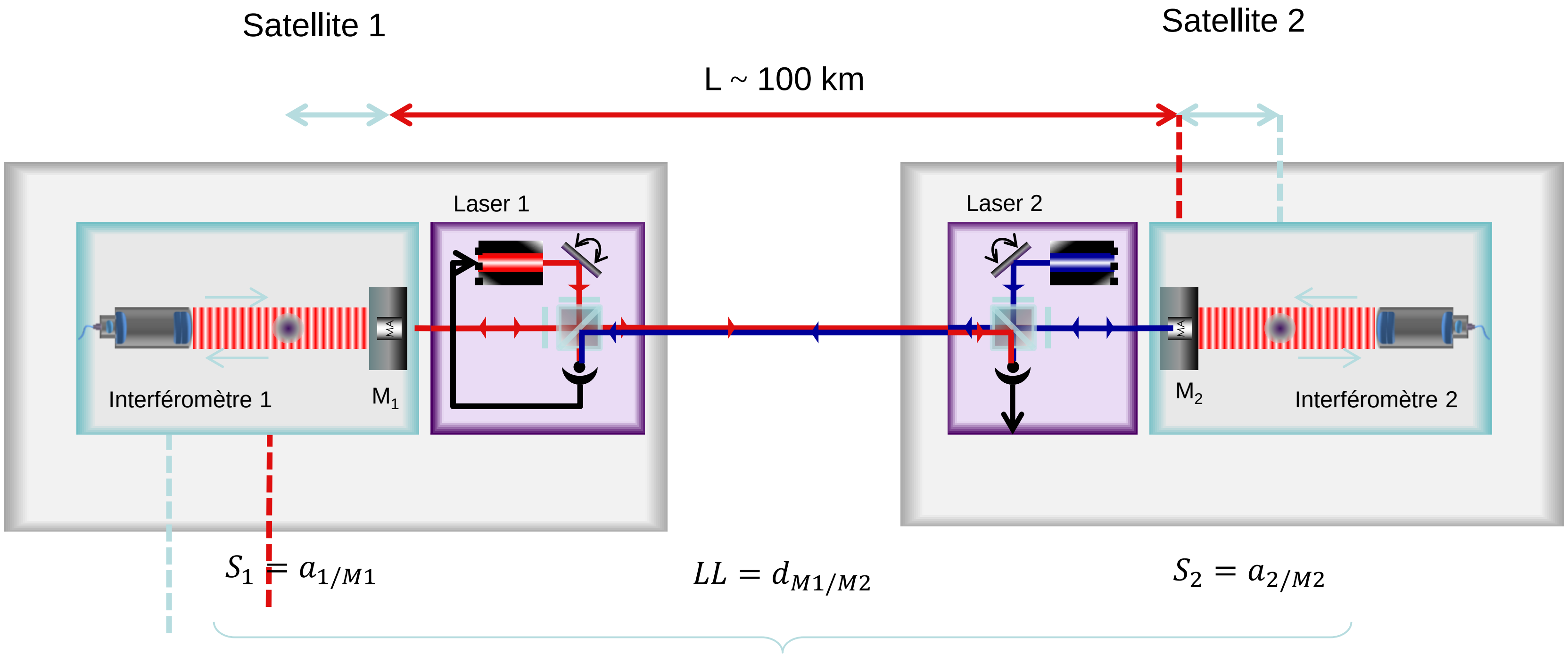
III. GRICE study

GRICE: a Phase 0 study carried out by CNES, with the participation of (french) scientists
End user requirements + Review of mission concepts + Analysis of a chosen concept

Mission and instrument concept
Sheng-wey Chiow, Jason Williams, and Nan Yu, PRA 92, 063613 (2015)

Twin satellites with onboard quantum accelerometers and laser ranging
Instrument concept: double diffraction Raman interferometer (as in the CAI study, but T lower)



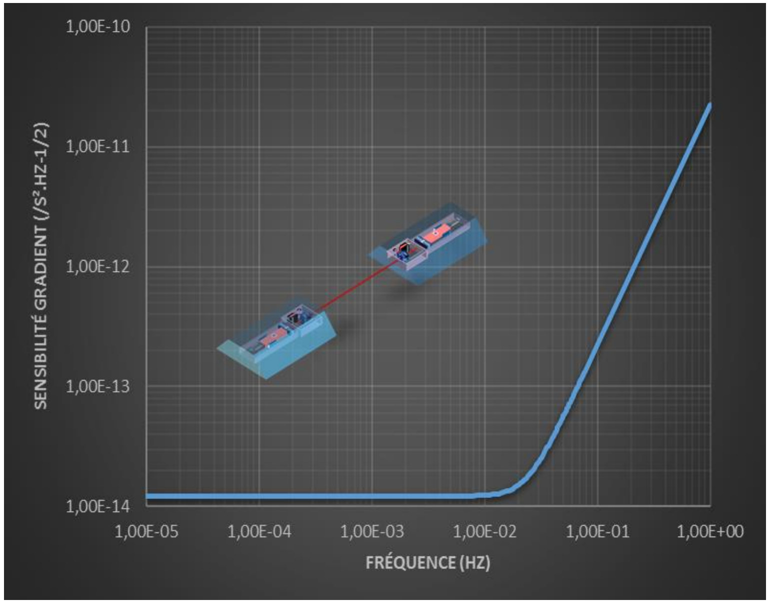
$S_1 = a_{1/M1}$ $\quad$ $LL = d_{M1/M2}$ $\quad$ $S_2 = a_{2/M2}$

$$\frac{\partial a_x}{\partial x} = \frac{1}{d}\left(S_1 - S_2 + \ddot{LL}\right)$$

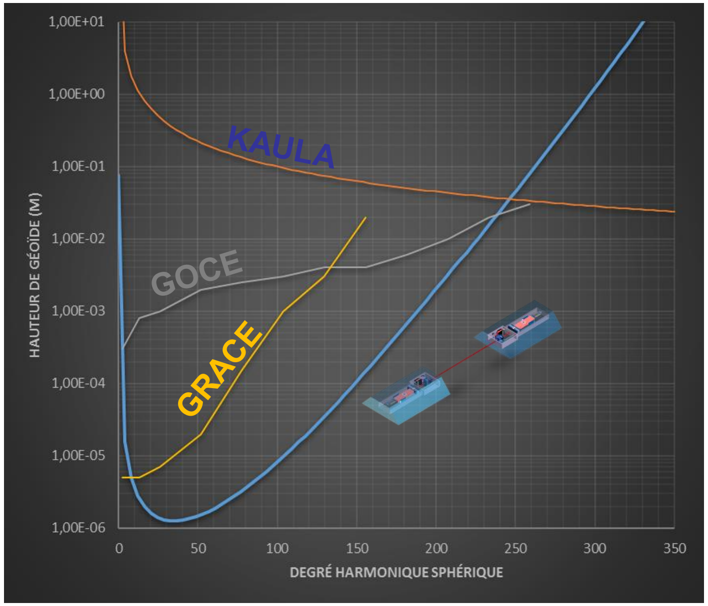
Sensitivity : $\sim 10\ \mu\text{E.Hz}^{-1/2}$

III. GRICE study

Instrument performances



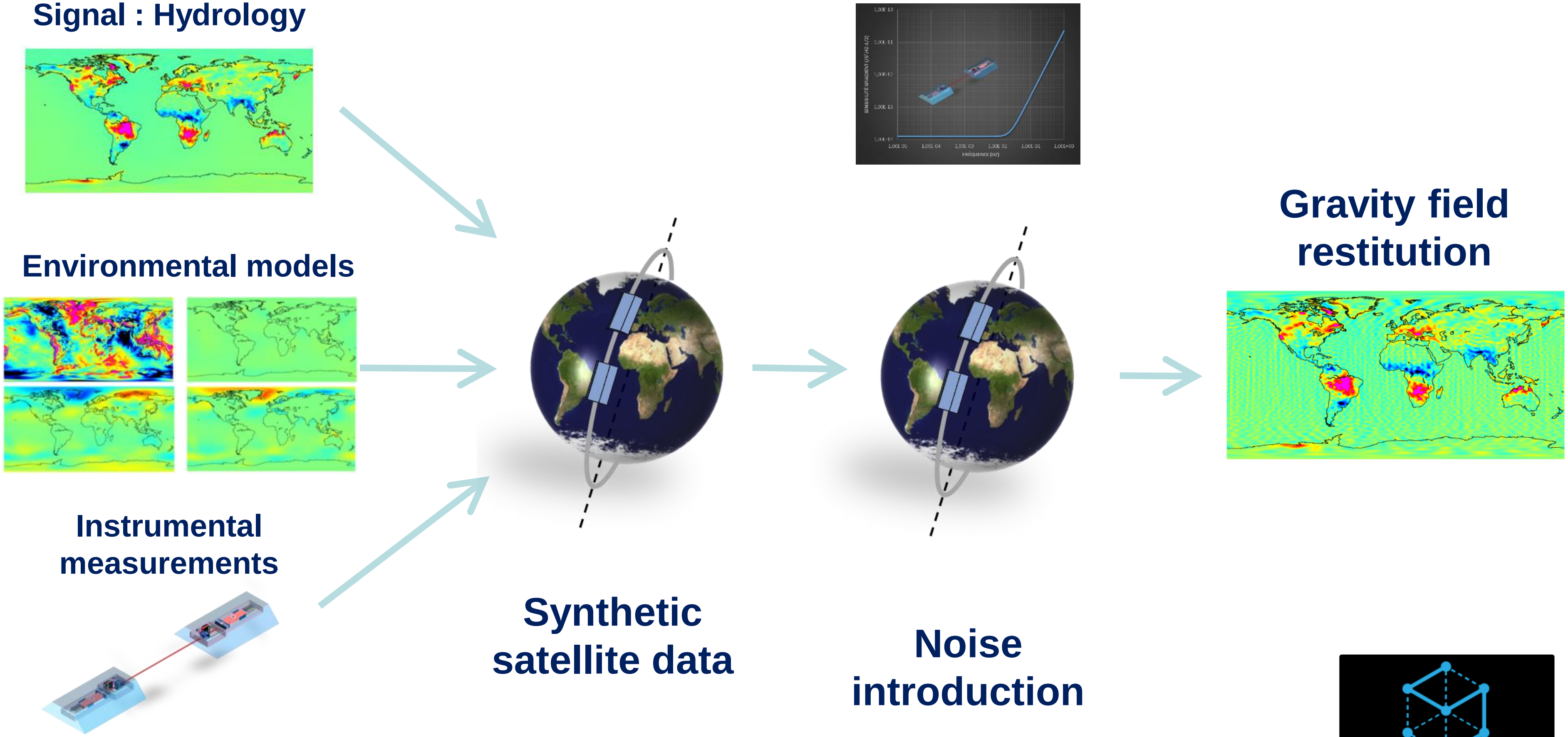
Expected mission performances



Parameter	Notation	Value	Unit
Noise LL	σ_l	40×10^{-9}	$m/Hz^{1/2}$
Noise AI	σ_a	6×10^{-10}	$m/s^2/Hz^{1/2}$
Baseline	L	100	km

III. GRICE study

Mission performances simulation



Signal : Hydrology

Environmental models

Instrumental measurements

Synthetic satellite data

Noise introduction

Gravity field restitution

Introducing noise in the models for hydrology and environment introduces additional errors in the restitution

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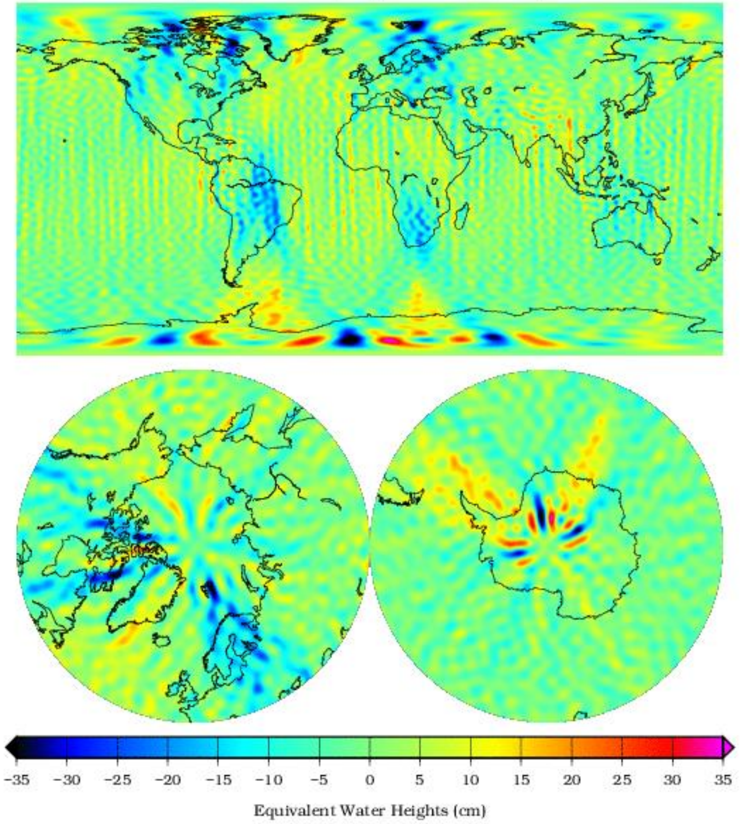
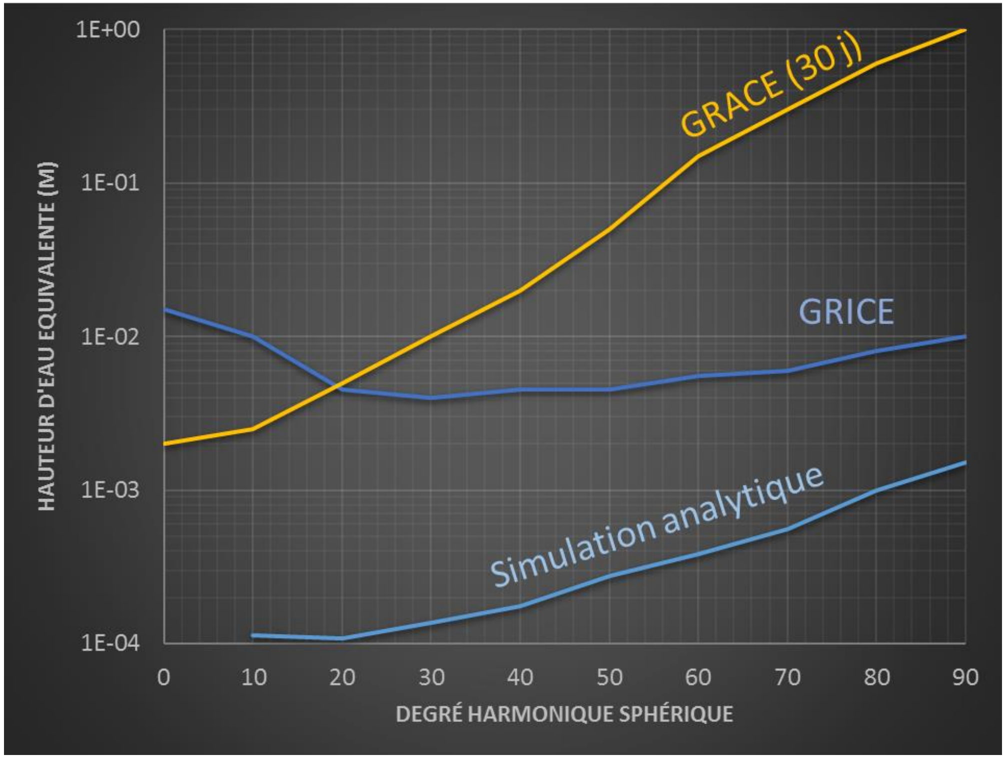
III. GRICE study

Restitution error



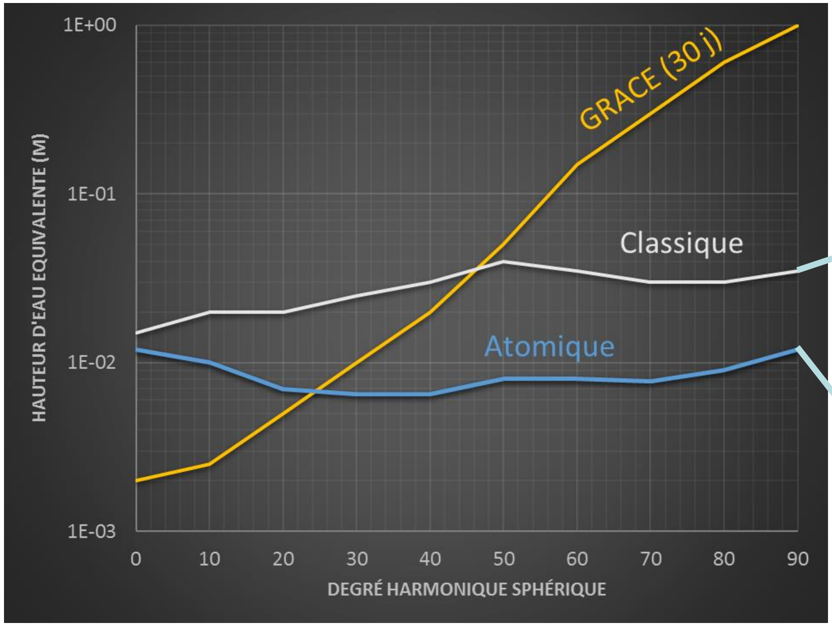


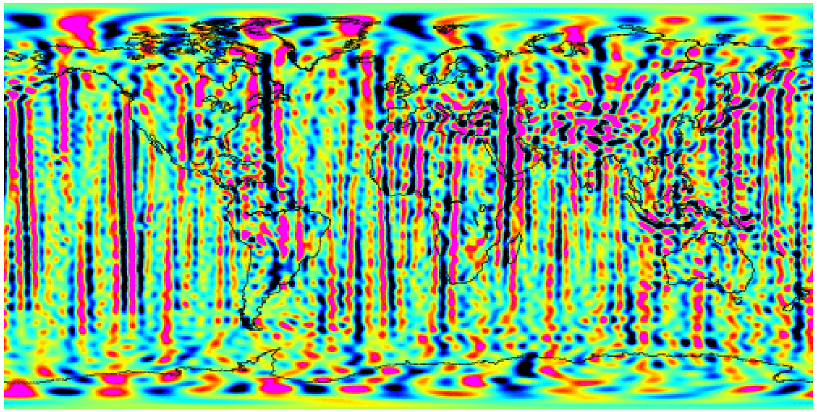
→ Aliasing from « background » models degrade the performance
→ What is then the impact of the acelerometer performance ?

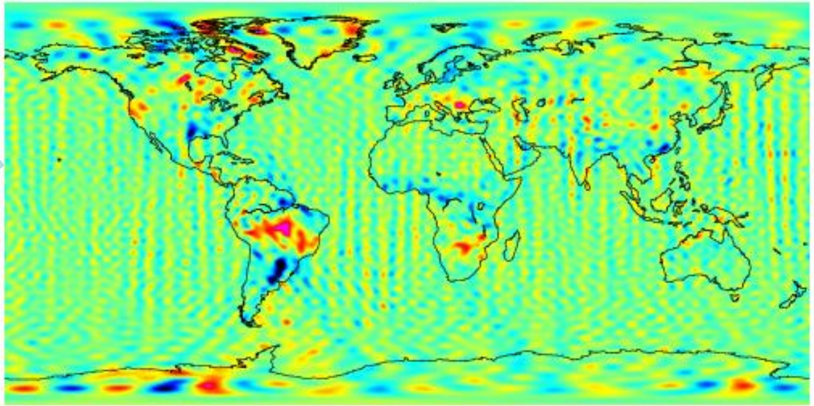
III. GRICE study

Quantum vs Classical technologies

Comparison between restitution errors with different accelerometers applying the same data processing (classical accelerrometer has a « typical » drift + no empirical parameters to reduce the impact of the drift)







→ Less stripes for the quantum sensor

→ No (less) need for data reduction that modify the gravity field

T. Lévèque, C. Fallet, M. Mandea, R. Biancale, J. M. Lemoine, S. Tardivel, S. Delavault, A. Piquereau, S. Bourgogne, F. Pereira Dos Santos, B. Battelier, Ph. Bouyer, "Gravity Field Mapping Using Laser-Coupled Quantum Accelerometers in Space« , Journal of Geodesy 95, 15 (2021)

Conclusion and Prospects

- **Atomic accelerometers provide better long term stability**

(ie lower measurement noise at the lowest frequencies, below 10 mHz)

- **Allows improving the reconstruction of the Earth gravity field**

(at low degrees especially, if not all degrees)

- **Influence of the variable field to be taken into account**
  Degrades the quality of the reconstruction
  See also Abrykosov et al., Advances in Space Research 63, 3235 (2019)

- **But a lower measurement noise will allow for**
- better accounting for fluctuations/noise arising from aliasing of the variable field
- improving the modelling of the variable field

- **Atomic sensor technology is under maturation**
  R&D and engineering developments still needed

- **Refined studies are required**