MEASURING THE EARTH GRAVITY FIELD WITH COLD ATOM INTERFEROMETERS

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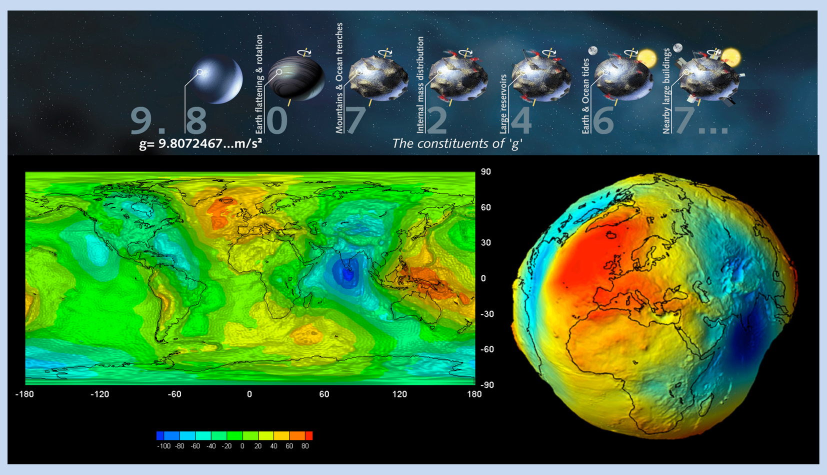
In the past decades, atomic quantum sensors have been identified as a newly emerging technology that can be used for measuring the Earth's gravity field [1,2]. There are two ways of making use of this technology: One is a gravity gradiometer concept and the other is in a low-low satellite-to-satellite ranging concept. Whereas classical accelerometers typically suffer from high noise at low frequencies, Cold Atom Interferometers are highly accurate over the entire frequency range. We recently proposed a concept using cold atom interferometers for measuring all diagonal elements of the gravity gradient tensor in order to achieve better performance than the GOCE gradiometer over a larger part of the spectrum [3], with the ultimate goals of determining the fine structures in the gravity field better than today. This concept relies on a high common mode rejection, which relaxes the drag free control, and benefits from a long interaction time with the free falling clouds of atoms due to the micro gravity environment in space. This instrument allows reaching sensitivity of 4.5mE/Hz$^{1/2}$, with the promise of a flat noise power spectral density also at low frequency. Another concept also under study in the frame of NGGM, relies on the hybridization between quantum and classical techniques to improve the performance of accelerometers [4]. This could be achieved analogously as done in frequency measurements where quartz oscillators are phase locked on atomic or optical clocks. This technique could correct the spectrally colored noise of the electrostatic accelerometers in the lower frequencies. In both cases, estimation of the Earth gravity field model from the instruments has to be evaluated taking into account different system parameters such as attitude control, altitude of the satellite, time duration of the mission, etc. Miniaturization, lower consumptions and upgrading Technical Readiness Level are the key engineering challenges that have to be faced for these space quantum technologies.

Gravity Gradient Missions in Space



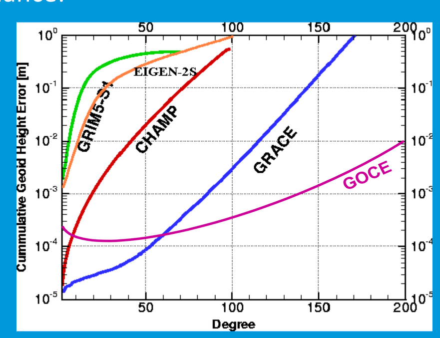
Application	Accuracy: Geoid (cm)	Accuracy: Gravity (mGal)	Spatial Resolution half wavelength (km)
Oceanography:			
- Short scale	1-2		100 km
	0.2		200 km
- Basin scale	~0.1		1000 km
Solid Earth:			
- Lithosphere and upper-mantle density structure		1-2	100 km
- Continental lithosphere			
• Sedimentary basins		1-2	50-100 km
• Rifts		1-2	20-100 km
• Tectonic motions		1-2	100-500 km
• Seismic hazards		1.0	100 km
- Ocean lithosphere & interaction with asthenosphere		0.5-1.0	100-200 km
Geodesy:			
- Levelling by GPS	1.0		100-1000 km
- Unification of worldwide height systems	1.0		100-20000 km
- Inertial navigation system		~1-5	100-1000 km
- Orbits (1 cm radial orbit error for altimetric satellites		~1-3	100-1000 km
Ice sheets:			
- Rock basement		1-5	50-100 km
- Ice vertical movements	2.0		100-1000 km
Sea-level change	Many of the above applications, with their specific requirements, are relevant to sea-level studies		

Two kinds of measurements :
Microwave/Laser Ranging
Differential accelerations

Use of ultra sensitive accelerometers
Electro-static
Drifts at low frequency
Limits for improving the actual sensitivity

Previous missions:

Performance:

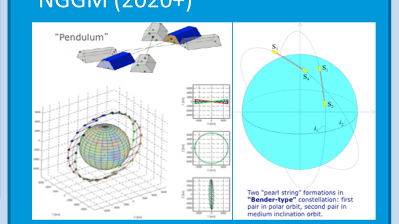


Electrostatic accelerometers down to 11mE/Hz$^{1/2}$

The Future:

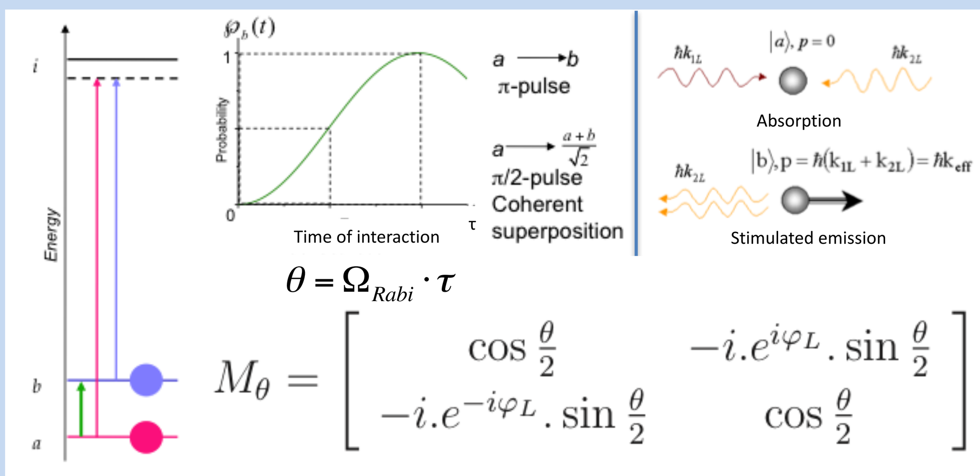
Grace Follow on(2017)

NGGM (2020+)



Cold Atom Interferometer

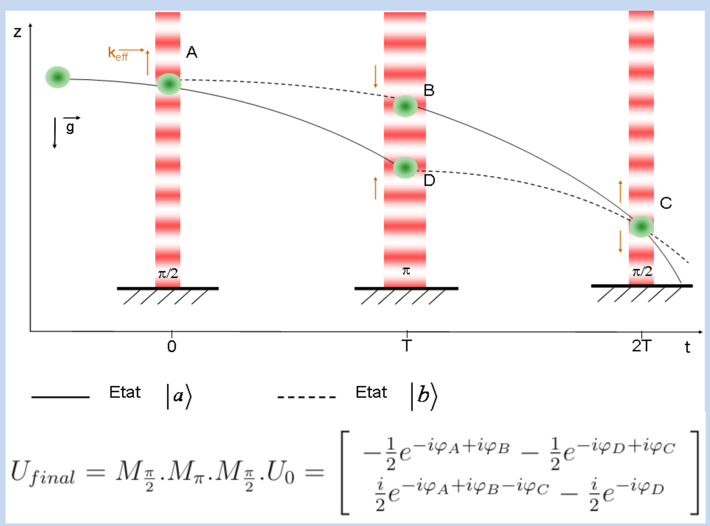
Measuring the motion of an object (Cold atom cloud) with high accuracy (Laser), stabilized by using frequency metrology of the atoms (Atomic clock).



$$\theta = \Omega_{Rabi} \cdot \tau$$

$$M_\theta = \begin{bmatrix} \cos\frac{\theta}{2} & -i.e^{i\varphi_L}.\sin\frac{\theta}{2} \\ -i.e^{-i\varphi_L}.\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

Raman transition:
The phase (position) of the Laser is printed on the atoms each transition. Control of the transfer from one state to another, act like a beam splitter when half of the atoms is transferred, act like a mirror when all atoms are transferred.
Two photons transfer ➔ High recoil kick.



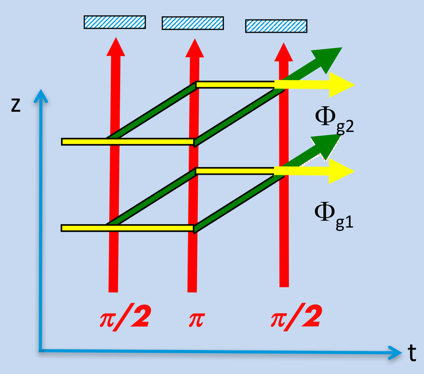
$$U_{final} = M_{\frac{\pi}{2}}.M_\pi.M_{\frac{\pi}{2}}.U_0 = \begin{bmatrix} -\frac{1}{2}e^{-i\varphi_A+i\varphi_B} - \frac{1}{2}e^{-i\varphi_D+i\varphi_C} \\ \frac{1}{2}e^{-i\varphi_A+i\varphi_B-i\varphi_C} - \frac{1}{2}e^{-i\varphi_D} \end{bmatrix}$$

Atom interferometry:
The number of the atoms in one state is directly proportional to the gravity field.

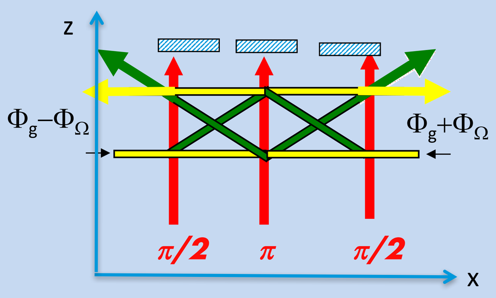
$$N_a = \frac{1}{2}\left(1+\cos(\Delta\phi)\right) = N_{total} - N_b$$
$$\Delta\phi = k_{eff}\left(z_C - z_B - z_D + z_A\right) = k_{eff}\, g T^2$$

Accuracy : up to 10^{-12} m.s^{-2} per measurement
White noise : No long term drift

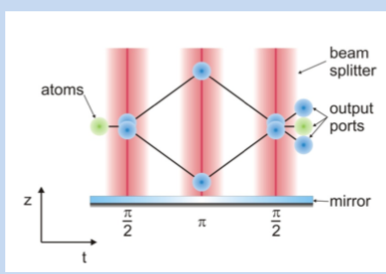
Concept for a Space Cold Atom Gravity Gradient Interferometer [3]



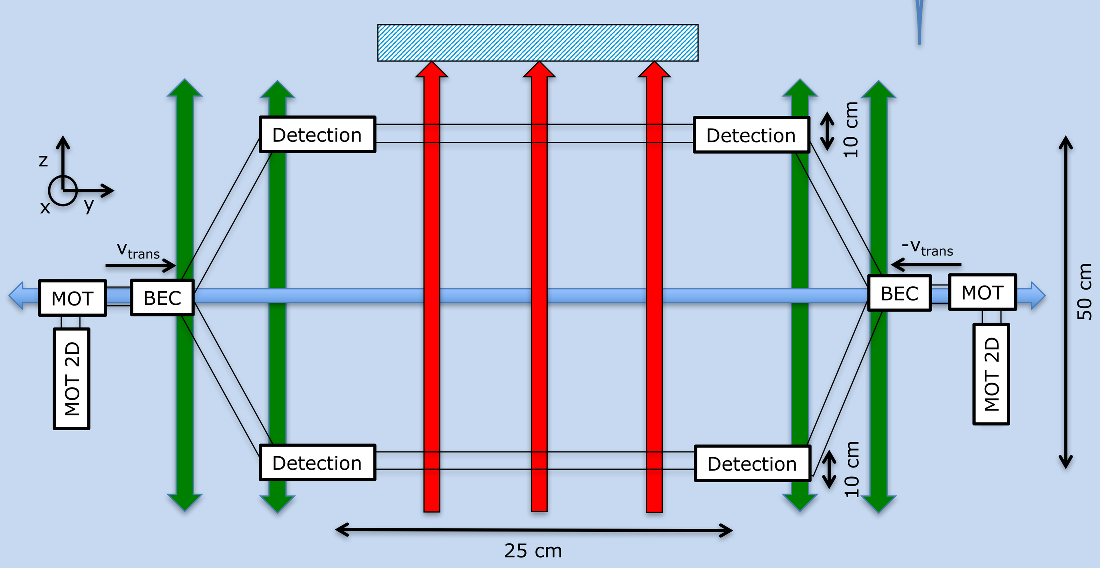
Differential acceleration measurements :
Access to gravity gradient
High rejection of common mode vibrations

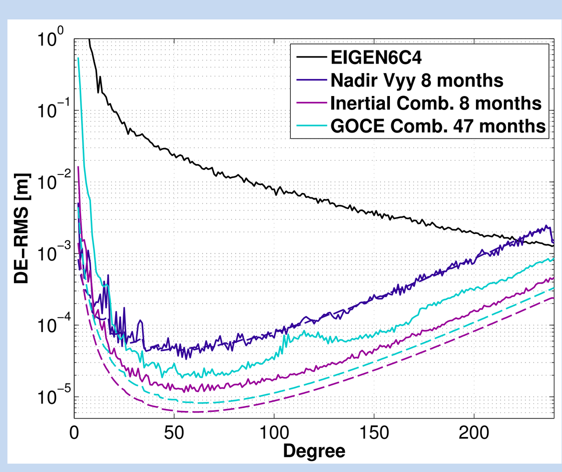


Gyroscope
High sensitivity to rotation rate



Double diffraction scheme :
Interferometer in 0-g
Suppression of most parasitic noises (RF, B,…)

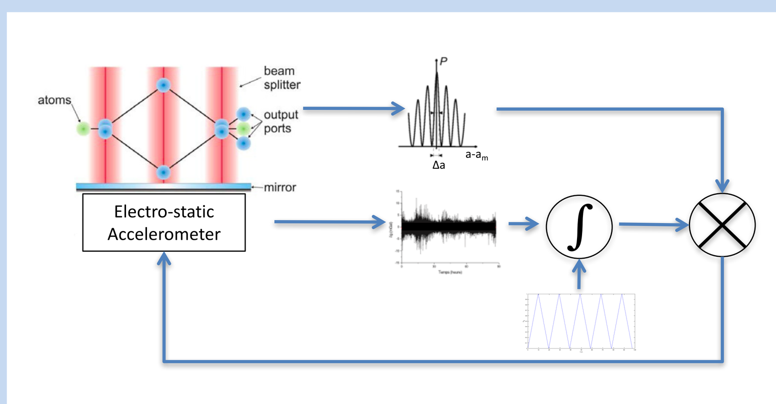


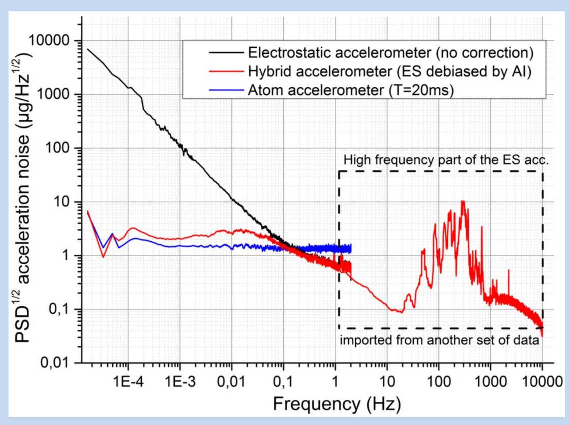


$$\Delta\gamma = \frac{\sqrt{2}}{\sqrt{N}k_{eff}dT^2}\sqrt{T_{cycle}} = 3.5mE/\sqrt{Hz}$$

$$\Delta\omega = \frac{1}{2\sqrt{N}k_{eff}v_{trans}T^2}\sqrt{T_{cycle}} = 25prad.s^{-1}/\sqrt{Hz}$$

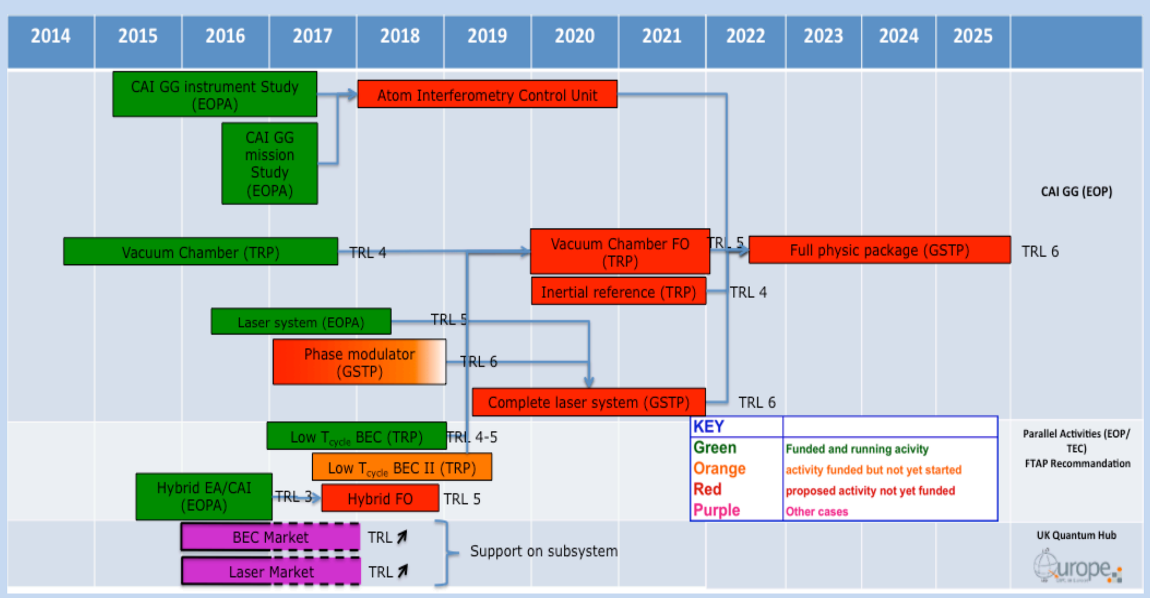
Hybridization Classical/Quantum sensors [5]





Benefits of the performance of electro static accelerometers at high frequency.
Calibration for long term measurements.
Compacity

Timeframe/Roadmap



[1] A. Peters et al., High-precision gravity measurements using atom interferometry, *Metrologia*, **2001**, 38, 25-61.
[2] F. Sorrentino et al., Sensitivity limits of a Raman atom interferometer as a gravity gradiometer, *Phys. Rev. A*, **2014**, 89, 023607.
[3] O. Carraz et al., A spaceborne gravity gradiometer concept based on cold atom interferometers for measuring Earth's gravity field, *Microgravity Science and Technology,* **2014,** 26(3), 139-145.
[4] J. Lautier et al., Hybridizing matter-wave and classical accelerometers, *Appl. Phys. Lett.,* **2014,** 105, 144102.
[5] O. Carraz et al., Measuring the Earth's gravity field with cold atom interferometers, Proceedings '5th International GOCE User Workshop', *ESA SP-728,* **2015**.

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