A Hybrid Cold Atom Interferometer for Space Geodesy Missions

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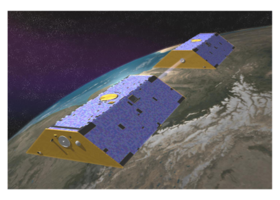
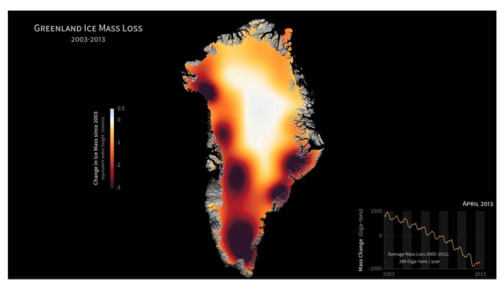
Space geodesy missions and applications

Past and current gravimetry missions

GRACE and GRACE FO missions (NASA, DLR)

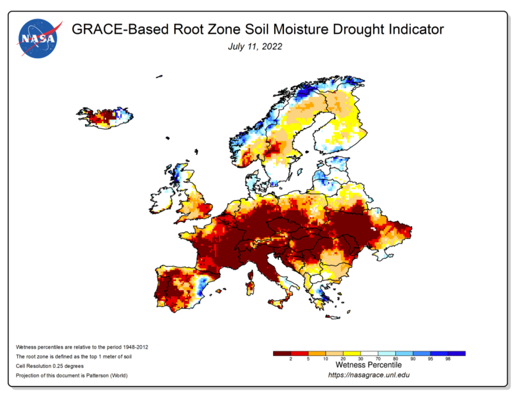


GOCE mission (ESA)



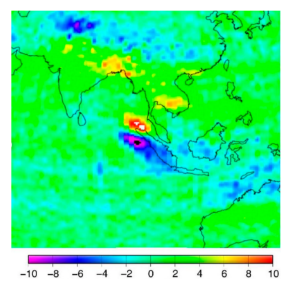
Hydrology

Study of Earth climate and global warming consequences: Droughts, ice melting, sea rise, ...



Geophysics

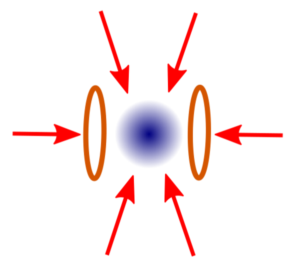
Volcanology, geology, sismology ...



Earthquake detected by GRACE .

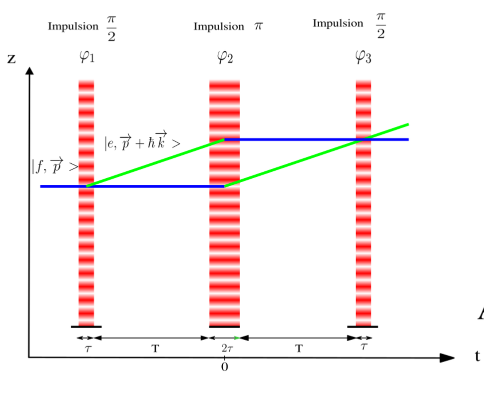
Atom interferometry

Principle of atom interferometry

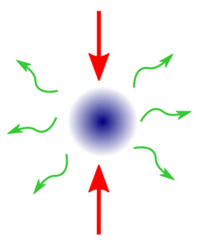


Cooling and state selection

Initial state $|f, \vec{p}\rangle$



Mach-Zehnder atom interferometer



Atomic states detection by fluorescence

Acceleration measurement [3]

Atomic signal

Proportion of atoms in the excited state

Number of atoms in the excited state

$$P_e = \frac{N_e}{N_e + N_f}$$

Fringes contrast

$$P_e = P_0 - \frac{C}{2}\cos(\Delta\Phi)$$

Phaseshift

Phaseshift

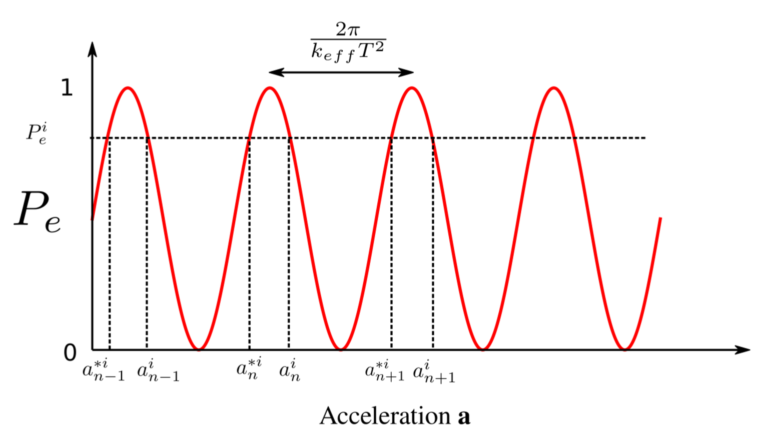
$$\Delta\Phi = \varphi_{upper\ path} - \varphi_{lower\ path}$$

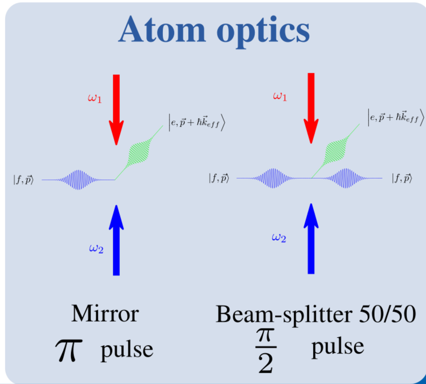
Interrogation time

$$\Delta\Phi \approx T^2 \vec{k}_{eff} . \vec{a}_{atom/mirror}$$

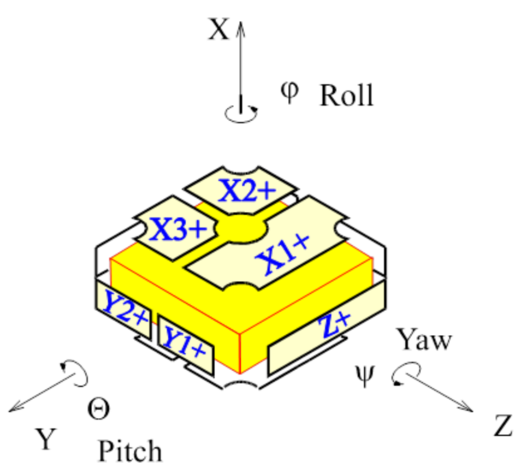
Effective laser wave vector

Interference fringes

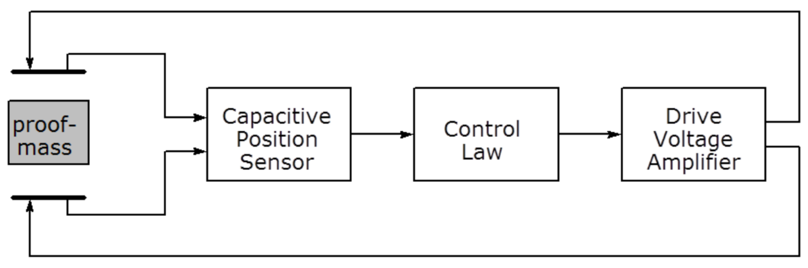




Electrostatic accelerometer



- ★ Centimetric mass in electrostatic levitation
- ★ Electrodes on the cage around the proof-mass
- ★ Six degrees of freedom controlled by six servo-control loops
- ★ Acceleration measurement thanks to the electrostatic force



Hybridisation

The two instruments complement each other [1,4]

Drift correction

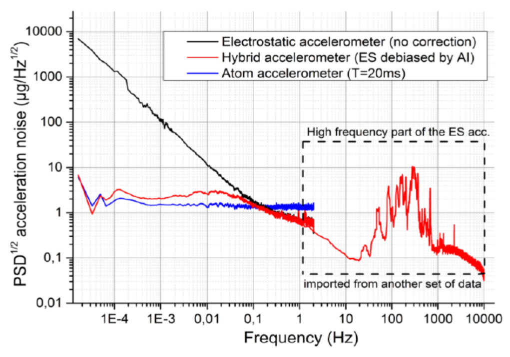
Dead times — Long term drift

Atomic accelerometer ⇄ Electrostatic accelerometer

Stability — Sensitivity

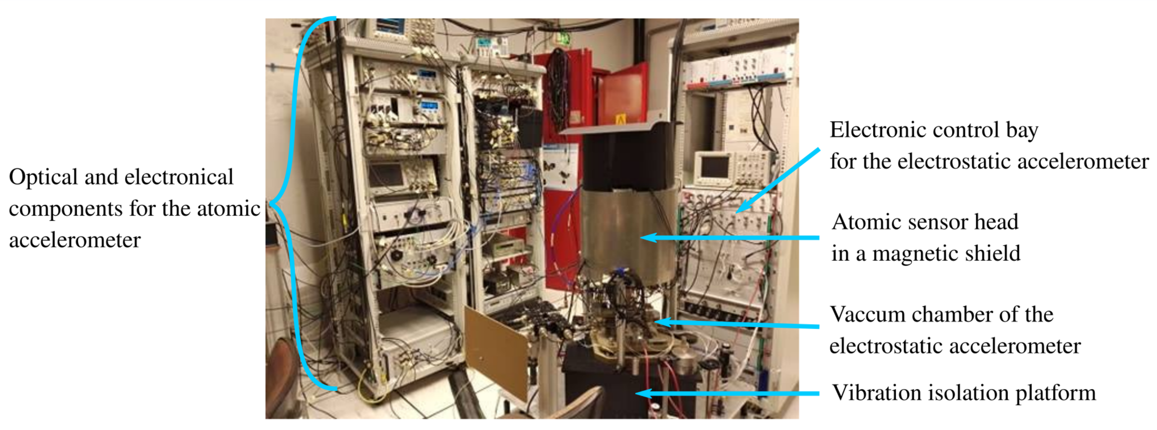
Fringe index determination

Aliasing effect removal



⟹ Noise reduction at low frequency

Experimental setup

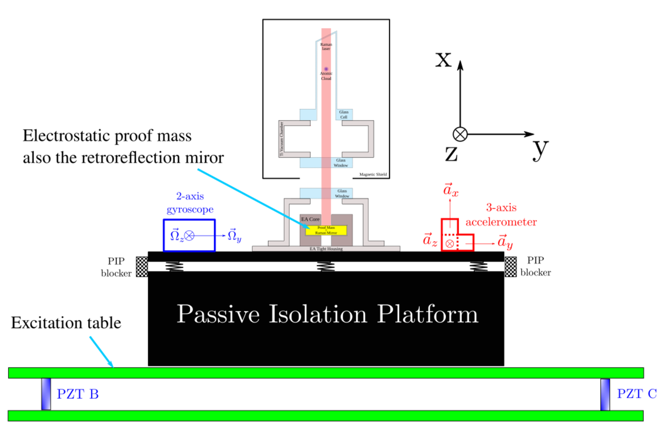


Cold atom accelerometer

- ★ Fibered laser system
- ★ 4 Hz repetition rate
- ★ Interrogation time 46 ms
- ★ Temperature $\approx 1\,\mu K$
- ★ Interferometer input : $\approx 10^6\ {}^{87}Rb\,atoms$

Electrostatic accelerometer

- ★ Three measurement axes
- ★ Designed to sustain vertically up to 2g acceleration
- ★ Robustness against tilting
- ★ Possibility to detect the proof-mass position
- ★ Window in the vacuum chamber for the laser beam



The electrostatic proof mass ⟺ The retro-reflexion mirror

Rotation Impact

A satellite = a dynamical environement spinning at $\Omega \approx 1\,mrad/s$

⟹ **Phaseshift and contrast loss**

For a single atom :

$$\vec{a}_{atom/mirror} = \vec{a}_{atom/earth} + \vec{a}_{rotation}$$

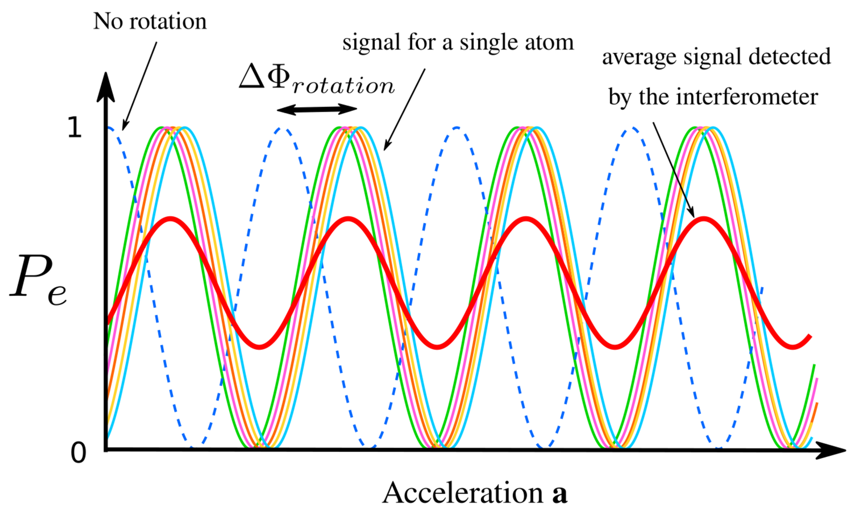
$$P_{e\ atom} = P_0 - \frac{C}{2}\cos\left(T^2 \vec{k}_{eff} . \vec{a}_{atom/mirror}\right)$$

For an atomic cloud :

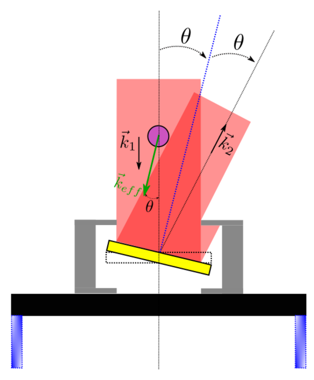
Velocity distribution

$$P_{e\ cloud} = \iint P_{e\ atom}(\vec{v}, \vec{r}) D_{\vec{v}}(\vec{v}) D_{\vec{r}}(\vec{r}) d\vec{v} d\vec{r}$$

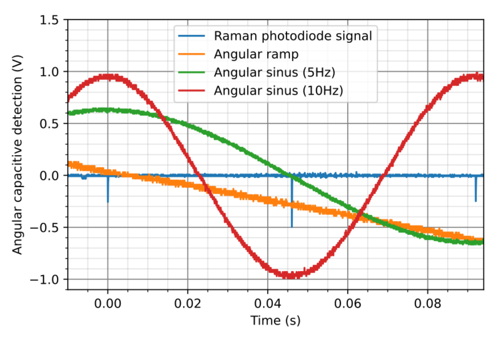
Position distribution



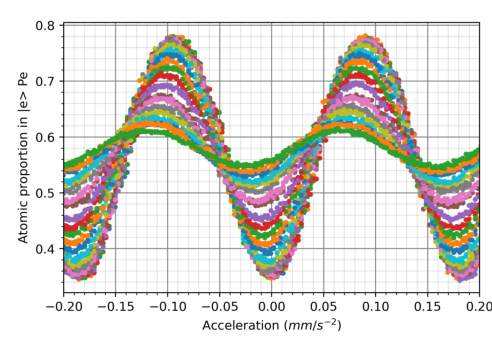
Study of the effect of the mirror rotation [1][2]



Constrast loss

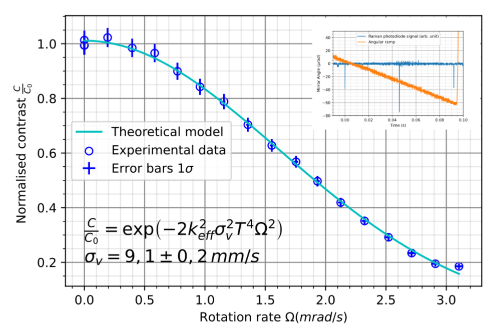


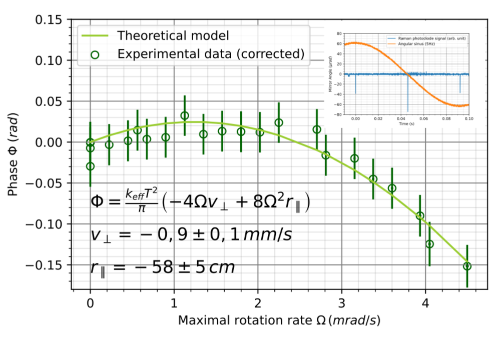
Capacitive detection of the angular position



Scan of the interference fringes

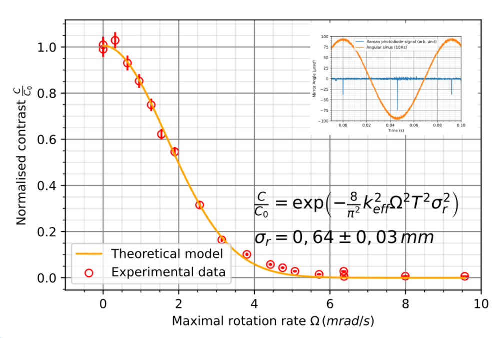
Phaseshift

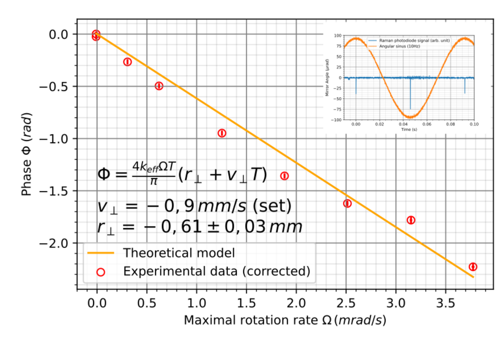




Experimental study for constant and time dependent rotation rates

- ★ Verification of the theoretical model
- ★ Characterisation of the atomic cloud



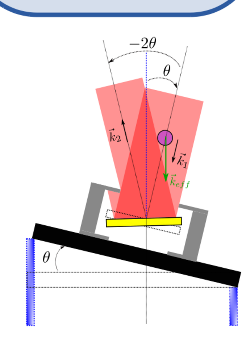


Rotation Compensation

Compensation of the excitation table rotation with the electrostatic proof-mass (mirror) [1,2]

Excitation rotation → Ω_{Table} → Gyrometer → Ω_{Gyro} → Integrator and adjustable gain → θ_{EA} → Electrostatic accelerometer → Ω_{Mirror} → Mirror rotation

Ideal case : $\vec{\Omega}_{Mirror} = -\vec{\Omega}_{Table}$



Conclusions and perspectives

- ★ Allows to characterize the cold atomic cloud
- ★ Better understanding of the rotation impact on constrast and phase shift
- ★ Beginning of the compensation rotation experiments
- ★ Toward a multi species atomic accelerometer

References

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[3] A. Peters, K. Y. Chung, S. Chu, High-precision gravity measurements using atom interferometry, Metrologia 38, 25-61 (2001)
[4] J. Lautier, L. Volodimer, T. Hardin, S.Merlet, M. Lours, F. Pereira Dos Santos, A. Landragin, Hybridizing matter-wave and classical accelerometers, Appl. Phys. Lett. 105, 144102 (2014)