Precise measurements with quantum sensors based on atom interferometry: an opportunity for the geosciences

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Applications of accurate inertial sensors

Inertial navigation

- Onboard accelerometers, gyroscopes and a clock

→ planes, satellites, submarines, ...

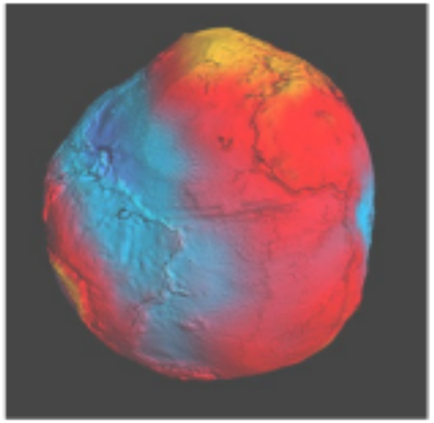
bias ~ 10^{-5} $m.s^{-2}$

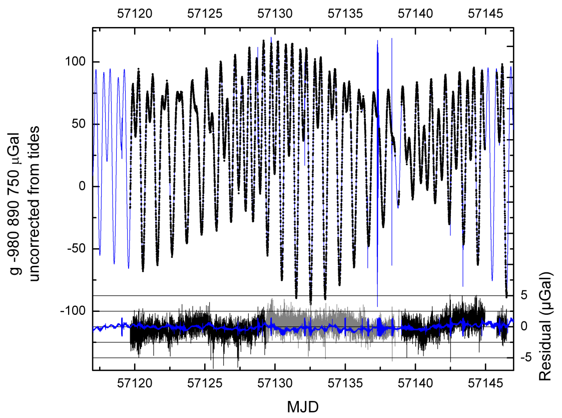
↓

Drift in position ~ 100 m after one hour of flight

Geophysics

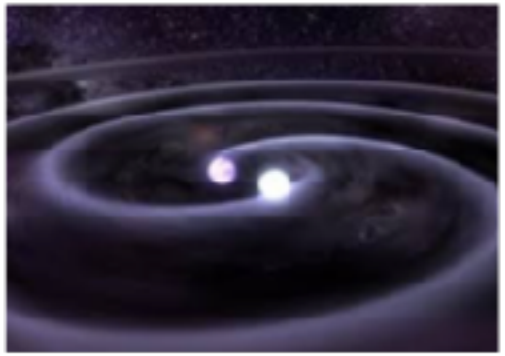
- Determination of the geoid
- Study of the underground
- Time variation





Fundamental physics

- test of the equivalence principle
- detection of gravitational waves
- measurement of G, h/M ...

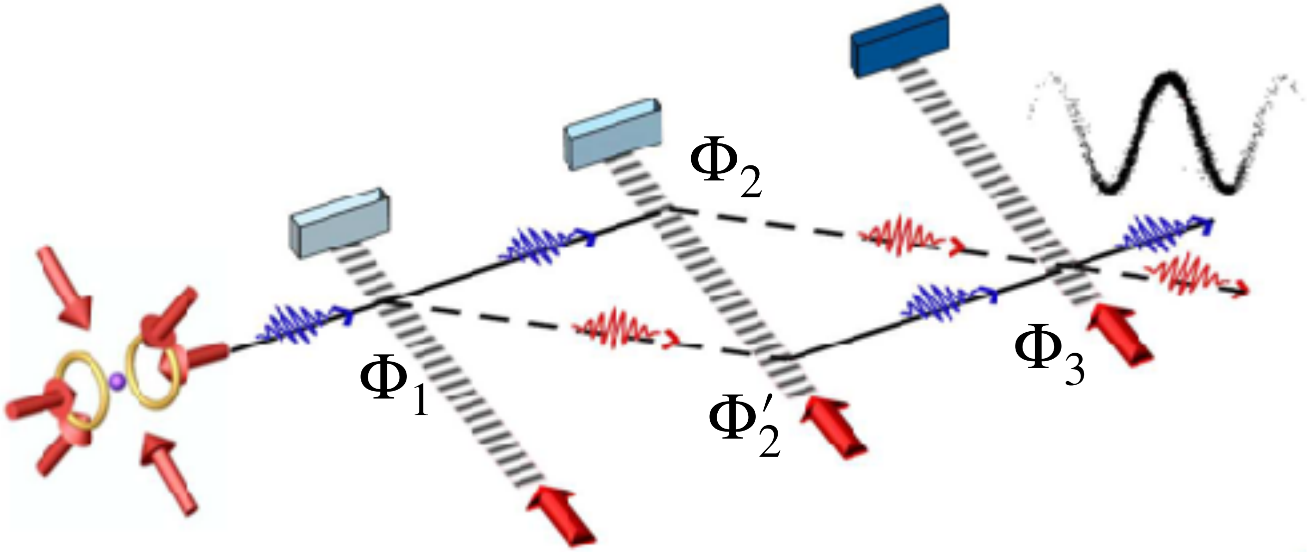


Required sensitivity: ~ 10^{-15} $m.s^{-2}$ at f_{GW} (~ 1 Hz for example)

Two arm atom interferometer: accuracy and reproducibility

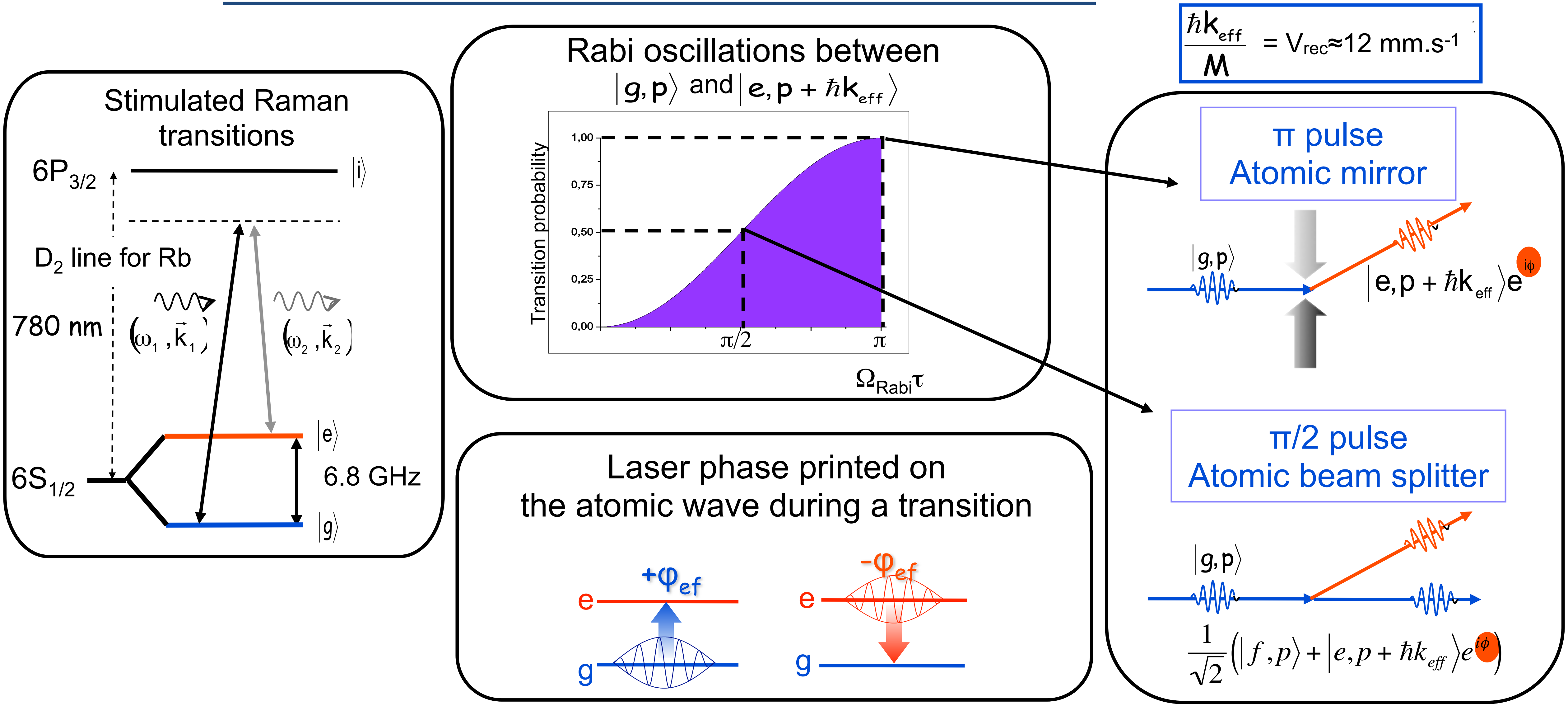
- Interference of de Brooglie waves
- Example of a 3 pulses interferometer
- Atom wave-packets diffracted by laser pulses
- Most of the inertial sensors used **two photon Raman transitions**

$\Delta\phi$: difference of accumulated phase shift along the **two arms interferences**



$$P_1 = \frac{1}{2}(1 + \cos \Delta\Phi)$$

Wave-packet manipulation in alkaline atom



Interferometer Phase shift

Phase shift contributions along the perturbed trajectories:

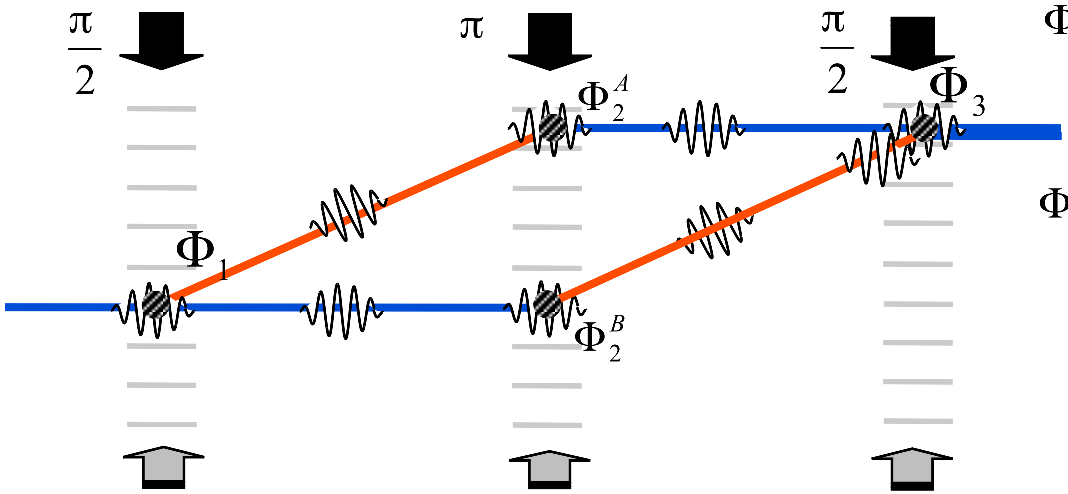
(for acc, gradient and rotation...)

Laser : at center of the wave packet $\varphi_i = k.r_i + \varphi_l$

Action : ~~Propagation~~ of the atomic wave

Overlapping ~~at exit of~~ the interferometer

Ch.J. Bordé, Metrologia 39, 435-463 (2002)



$$\Phi^A = \Phi_1 - \Phi_2^A$$

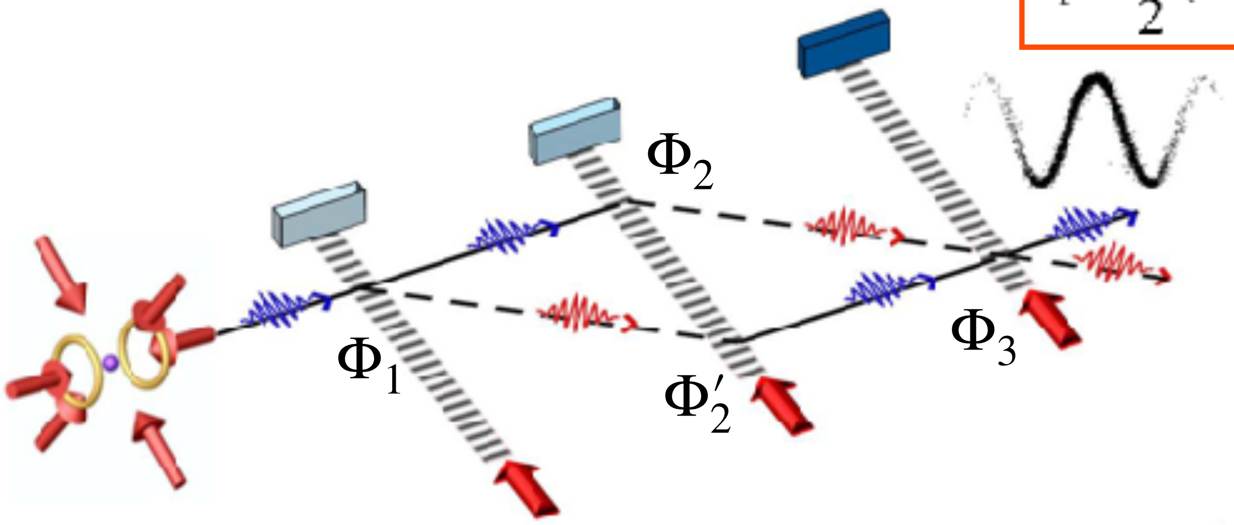
$$\Phi^B = \Phi_2^B - \Phi_3$$

$$\Delta\Phi = \Phi^A - \Phi^B = \Phi_1 - 2\Phi_2 + \Phi_3$$

Relative displacements of the referential frame of the center of mass of the atoms / laser

Two arm atom interferometer: accuracy and reproducibility

$$P_1 = \frac{1}{2}(1 + \cos\Delta\Phi)$$



Δϕ: difference of accumulated phase shift along the **two arms interferences**

$$\Delta\Phi = \Phi_1 - (\Phi_2' + \Phi_2) + \Phi_3$$

acceleration

$$\Delta\phi = \overrightarrow{k_{eff}} \cdot \vec{a}\, T^2$$

Rotation

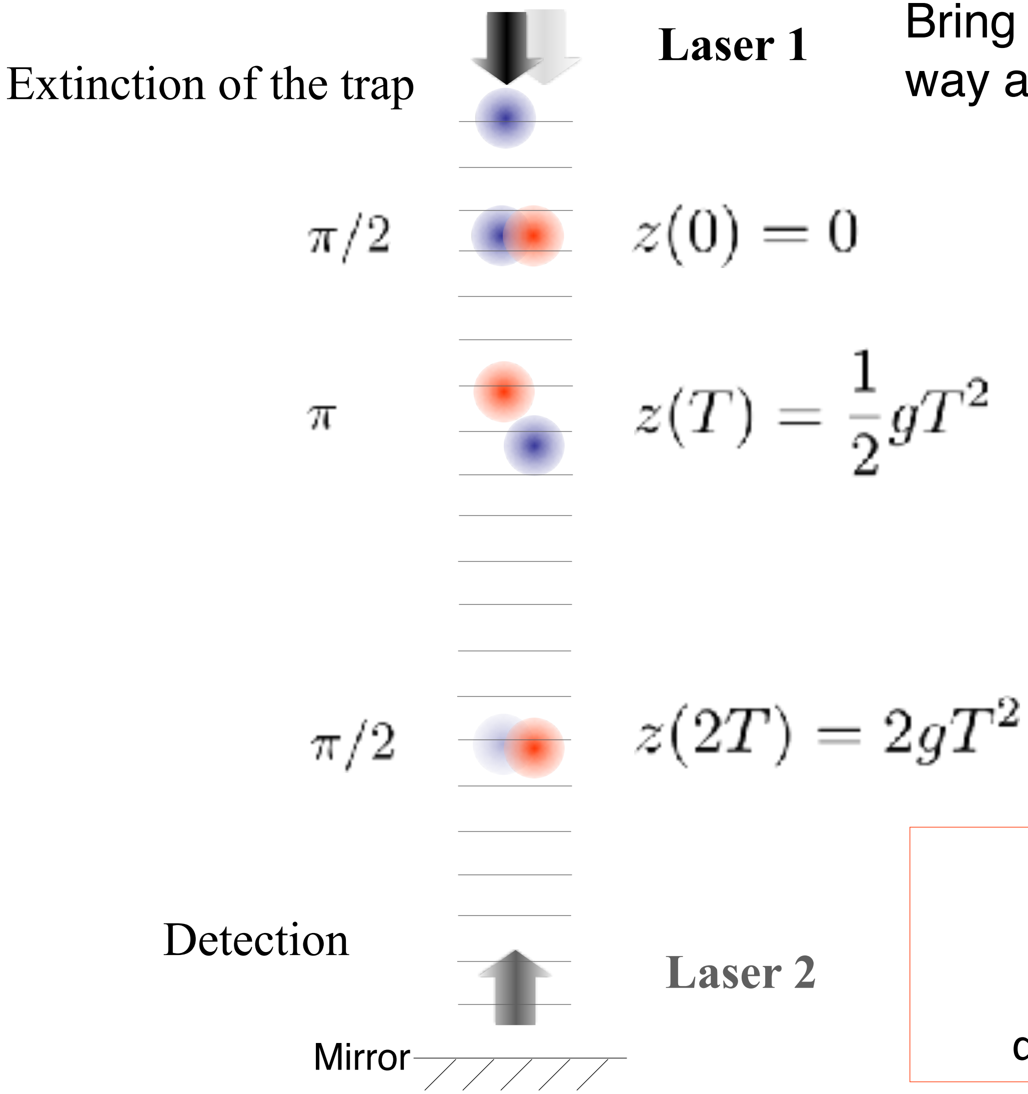
$$\Delta\Phi = -2\left(\vec{k}_{eff} \wedge \vec{V}\right) T^2 \cdot \vec{\Omega}$$

Relative displacements of the referential frame of the center of mass of the atoms / laser

Key advantages

- Depends on frequency (k_{eff}) and on time (T) and ⇒ SI traceable, accurate, bias free
- Benefit from cold atoms :
  - scales as T^2
  - control of the velocity of the atoms

Atom interferometer sequence



Bring two lasers in a co-propagating way and retroreflect them on a mirror

Vertical interferometer

⇒ Free fall along the equiphase planes

$$\Delta\Phi_{\mathrm{int}} = -\vec{k}_{eff}\,\vec{g}\,T^2 + \delta\Phi_{noise} + \delta\Phi_{sys}$$

Position of the equiphases defined by the mirror position $\alpha\ (z_1 - 2\, z_{2+}\, z_3)$

atomic measurement
=
measure of the relative displacement atoms/mirror

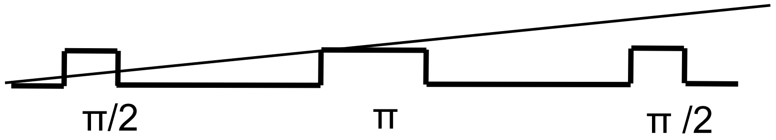
Meassurement of g

Free fall → Doppler shift of the resonance condition of the Raman transition

$$\omega_1 - \omega_2 = G + \omega_R + \omega_D = G + \frac{\hbar k_{eff}^2}{2m} + \frac{\vec{k}_{eff} \times \vec{p}}{m}$$

$$\delta(\vec{v}) = \overrightarrow{k_{eff}}.\vec{v} = \overrightarrow{k_{eff}}.(\vec{g}\,t + \vec{v_0})$$

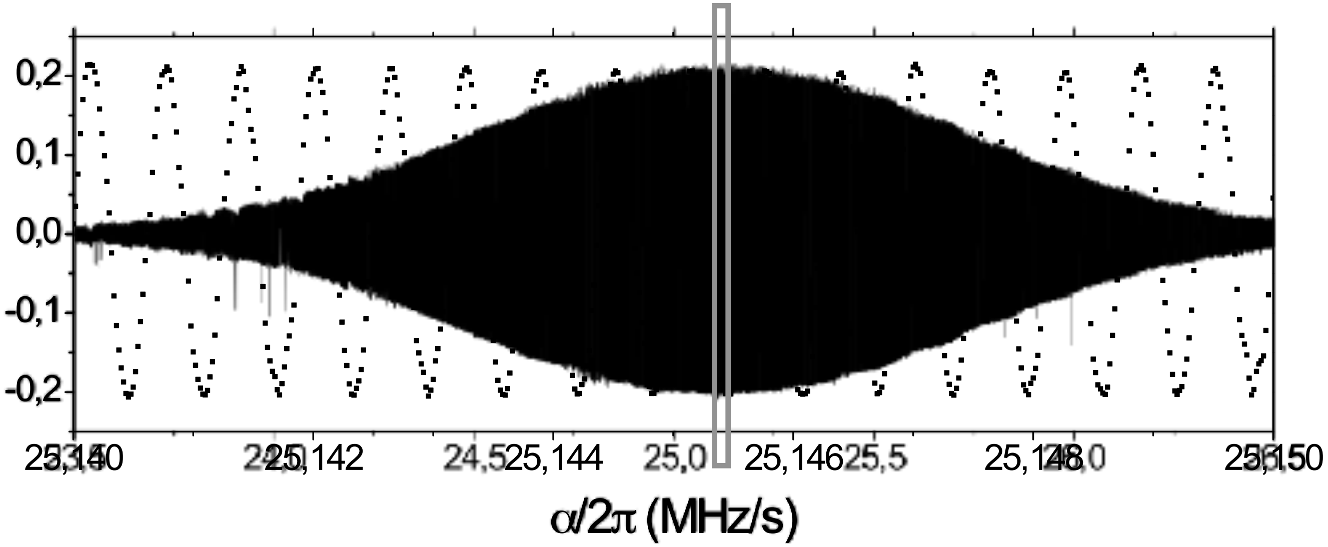
Ramping of the frequency difference to stay on resonance:



$$\Delta\Phi = k_{eff}.g.T^2 - \alpha T^2$$

$$g = \frac{a_0}{k_{eff}}$$

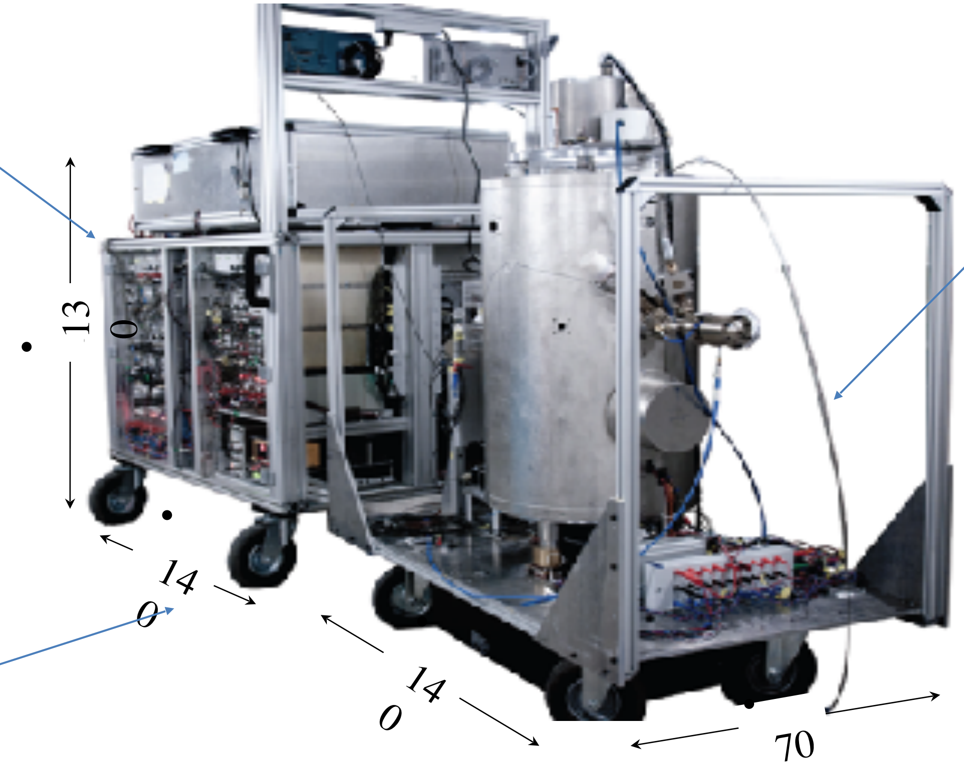
Scan of the slope of the frequency ramp:

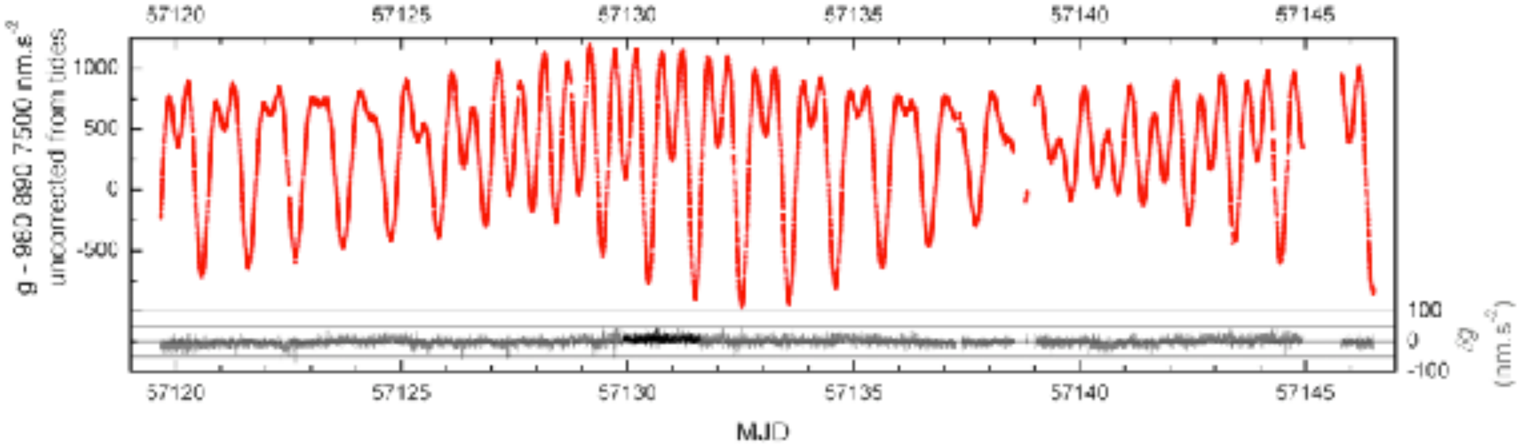


Center fringe :
independent of T,
of pulse durations...

Measure of g =>
frequency measurement accuracy

The LTE gravimeter





Performances

Short term stability
57 nm/s^2 @ 1s
Long term stability
< 1 nm/s^2

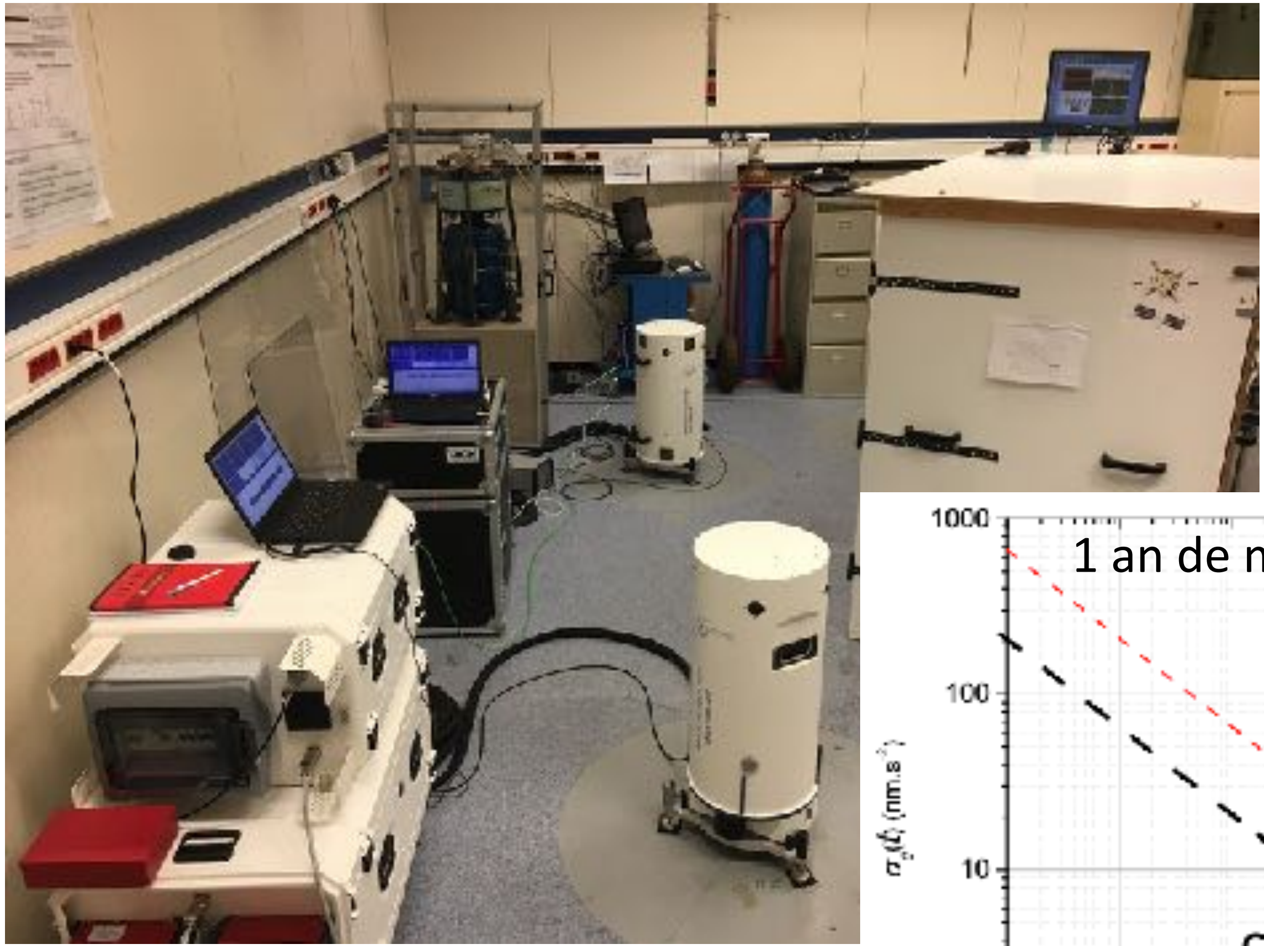
Better than the reference "classical" instrument = corner-cube gravimeter

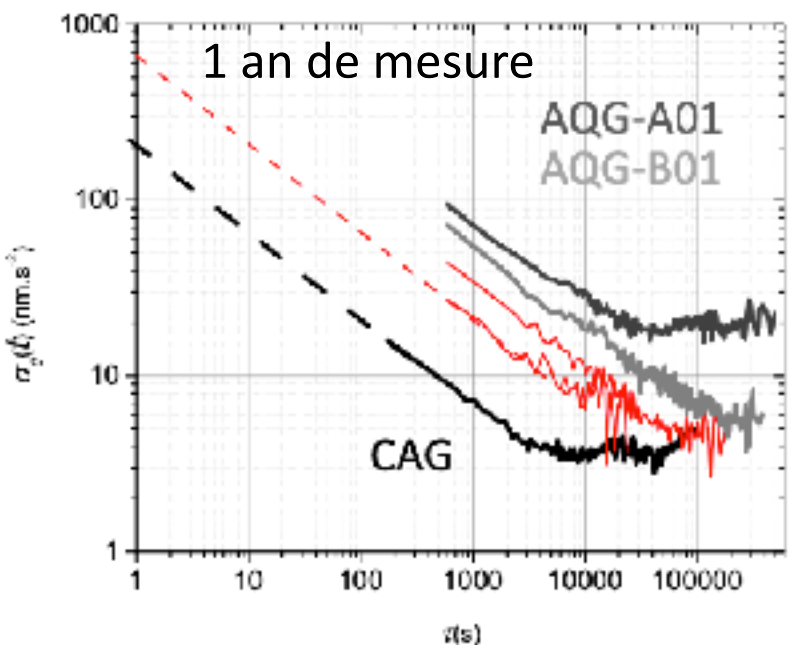
Accuracy
20 nm/s^2

New Journal of Physics 13, 065025 (2011)
New J. Phys. 20, 113041 (2018)
Optics Express 33, 18843-18854 (2025)

Metrology with the gravimeter

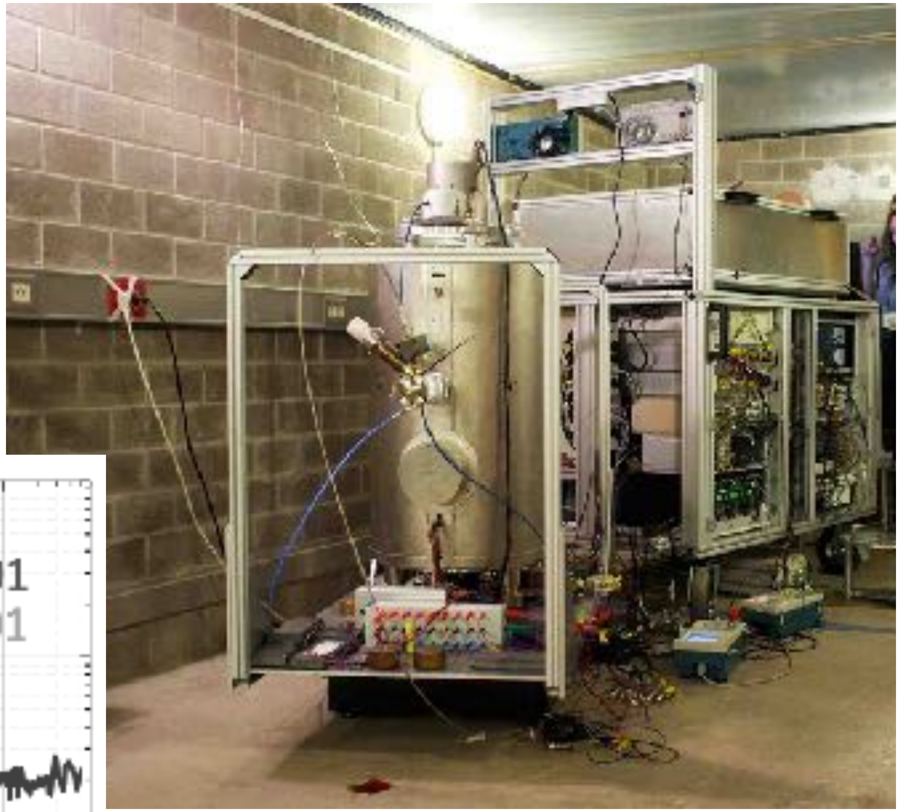
Comparison between atomic gravimeters and others, calibration of a superconductor gravimeter





Metrologia 51 (2014) L15–L17

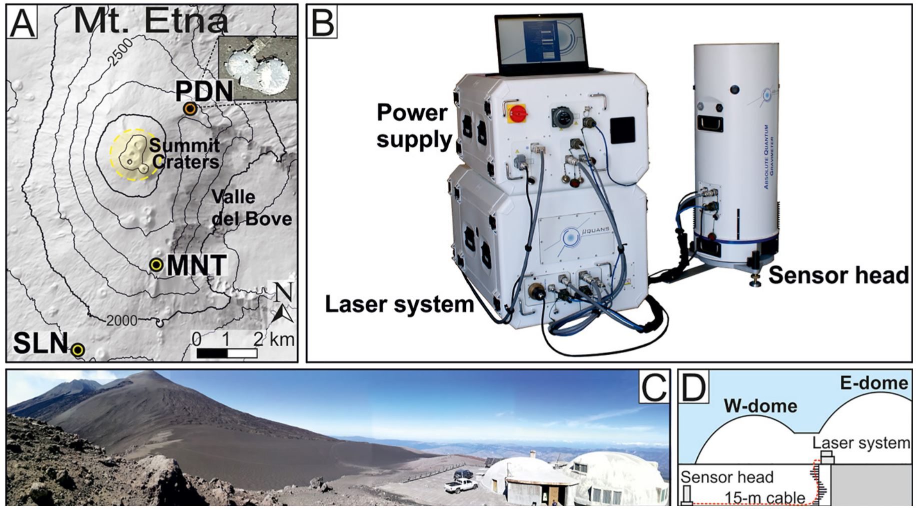
Laboratory and on filed gravimeter
Underground laboratory in Luxembourg



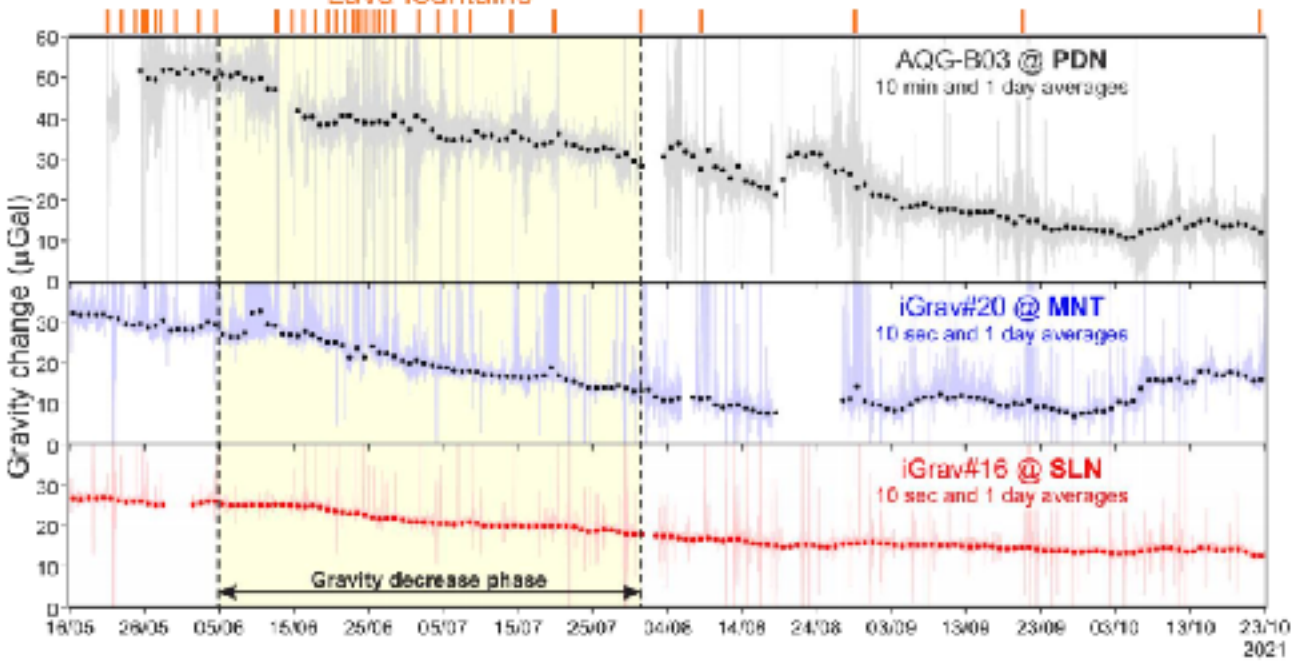
Example of application: vulcanology

- Production of compact gravimeters for in lab and on-field operation (Exail company)
- Targeted field of applications: geosciences
- Geodesy, hydrology, vulcanology …

Atom gravimeter on the Mount Etna

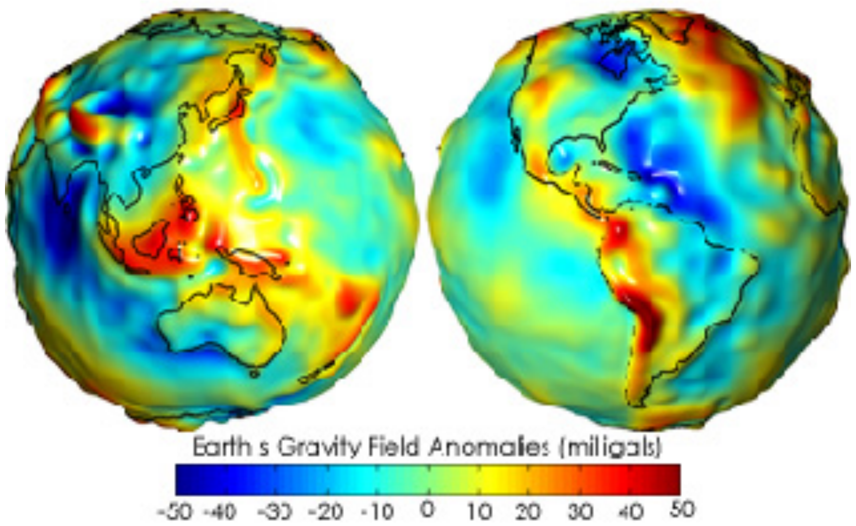


Geophysical Research Letters (2022), 10.1029/2022GL097814



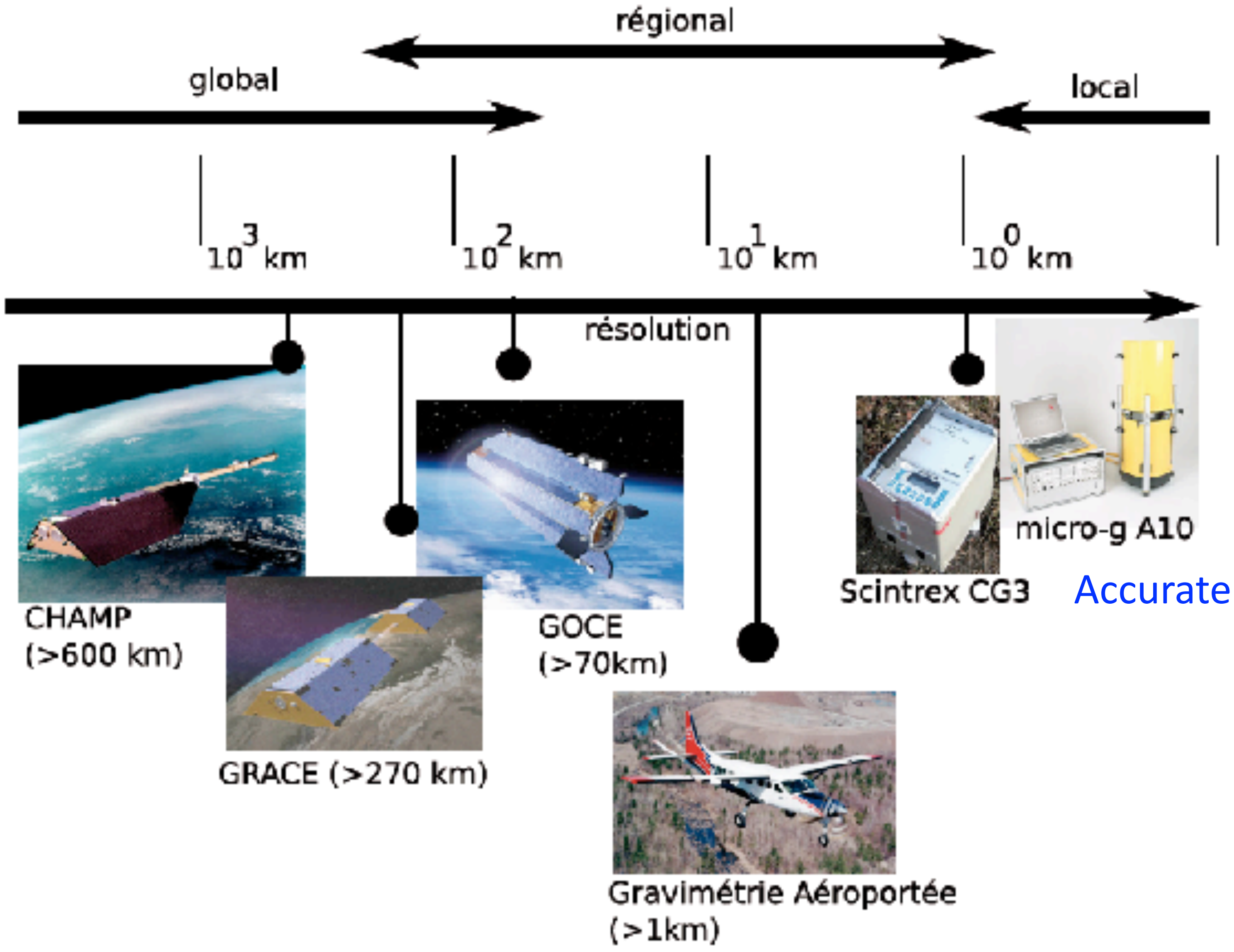
2021 lava fountains at Mt. Etna

Measurements of gravity field at different length scales with classical sensors



Relative apparatus:

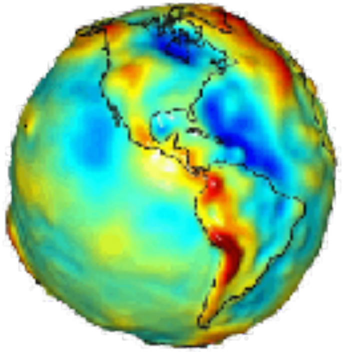
but no direct accuracy



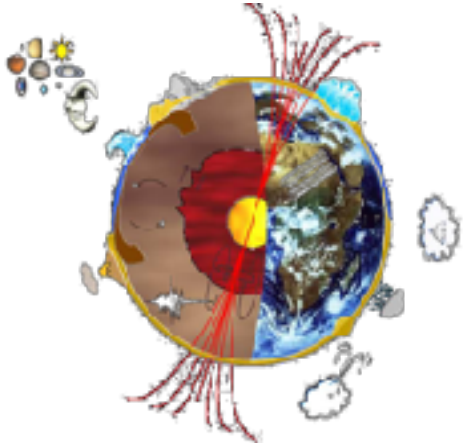
Accurate

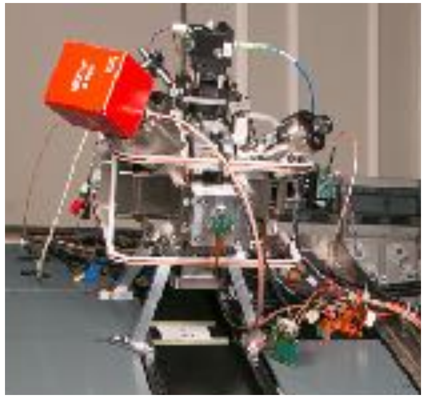
Interest of quantum sensor for geophysics: accuracy

- Geodesy context: global and dynamic models and reference frames (United Nations Resolution A/RE/69/266)
  - **Climate change:** sea level, ice melt, hydrology, sediment mass redistribution…
  - **Natural disaster** management: vulcanology, seismology...



- Gravity field at all spatial scales: => **4D modeling of the global Earth system**
  - Ground gradiometry: field derivative => very small scales, mobile measurements
  - Ground gravimetry : gravity field
  - Ground optical clocks (chronometric geodesy): gravitational potential => intermediate scales
  - On-board accelerometry and gradiometry: wide ground coverage => intermediate scales
  - Spatial atomic accelerometry/gradiometry: very large scales
  - Ground gyrometry: additional information, seismology





On board gravity measurements: boats and planes

- Development of a compact gravimeter for marine gravimetry by ONERA
- Measurement campaigns on the Beautemps-Beaupré (French Navy)

KSS32 relative Marine Gravimeter (Bodenseewerk)

Cold Atom Gravimeter (Onera)

- Better performance for gravity mapping with the absolute atom gravimeter
- Suppression of calibration errors and drift corrections

→ • Gain of a factor 2-3 on the uncertainty (mGal level)

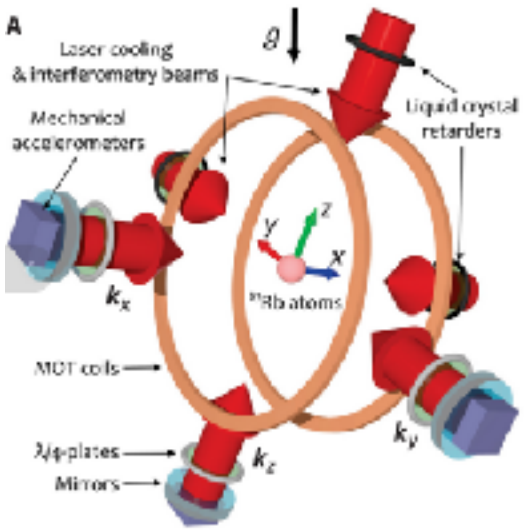
+ Campaign in plane: Iceland and Greenland

Y. Bidel et al., Absolute marine gravimetry with matter-wave interferometry, Nat. Comm. (2018) 9:627
T. E. Jensen et al.: Airborne gravimetry with quantum technology, Earth Syst. Sci. Data, 17, 1667–1684, 2025

Development for strapdown measurements

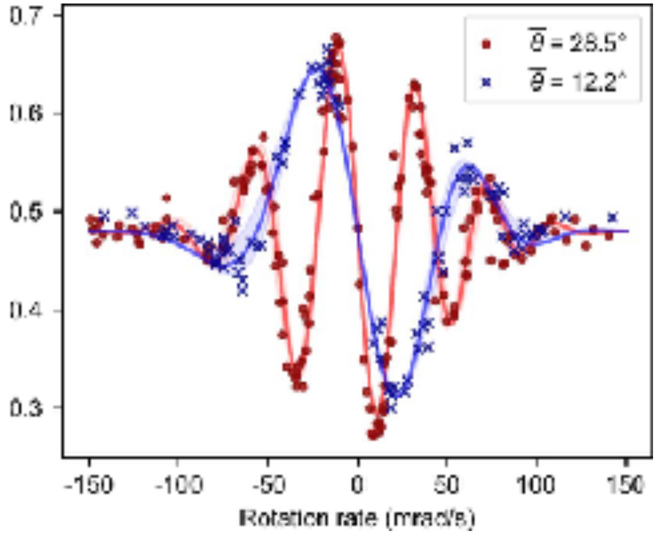
Application for large scale mapping on boat, plane … : more compact, improved on the field operability

Labcom iXAtom (LP2N-iXblue/Exail)



- Demonstration of the first quantum accelerometer triad (QuAT)
- Measures accelerations along three mutually orthogonal directions
- Long-term stability of 60 ng
- absolute magnitude accuracy below 10 µg

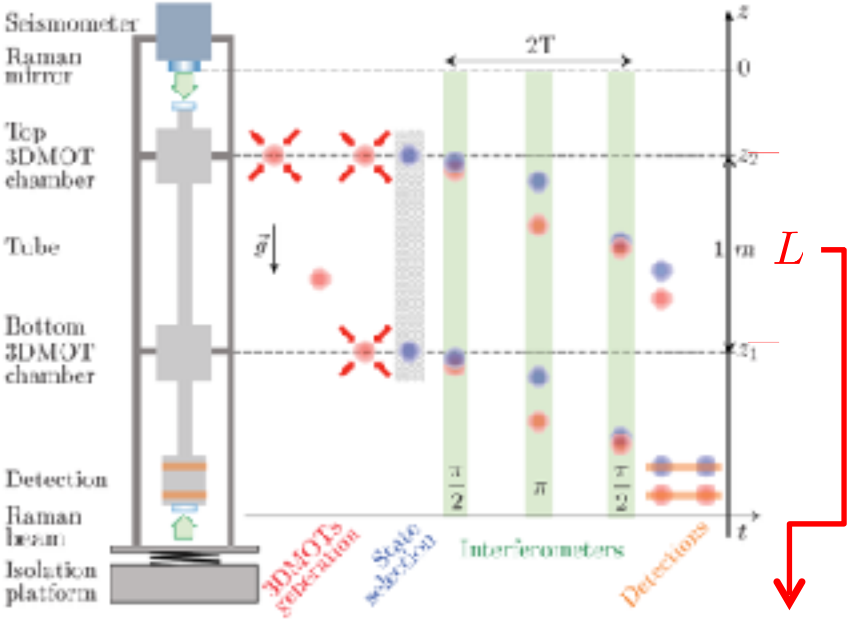
S. Templier et al, Science Advances Vol 8, Issue 45 (2022)



Real-time compensation for rotation: up to 30° et 14 °/s

d'Armagnac de Castanet et al., Nat Commun 15, 6406 (2024).

Dual Gravity-Gradiometry sensor



Frequency rampe between Raman lasers => g

Frequency jump of both Raman lasers => γ

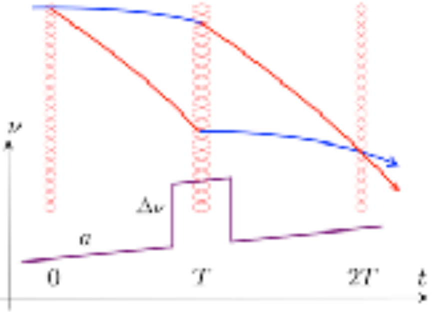
$$g = a/k_{\text{eff}}$$

$$\Delta\nu_\gamma = -\gamma\frac{kT^2c}{8\pi}$$

Accurate both for gravity acceleration (at the mirror position) and the gradient, **independent from the baseline**

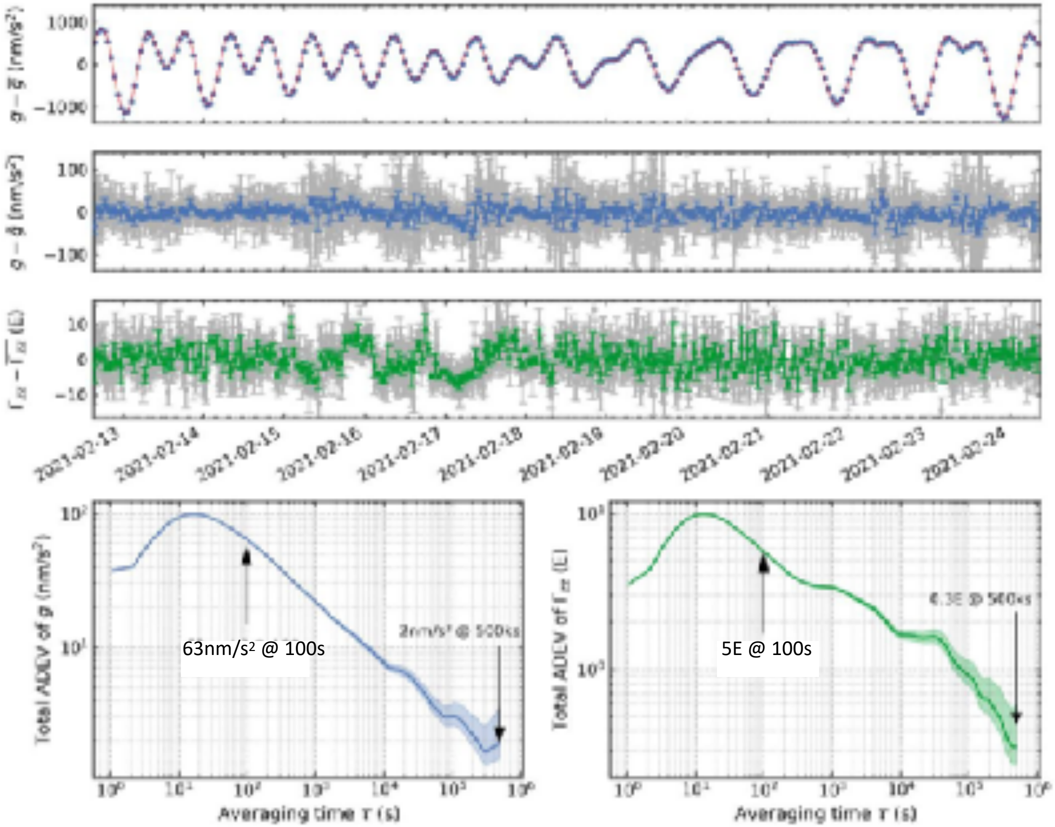
$$\Delta\Phi = \Phi_2 - \Phi_1 = kg_2T^2 - kg_1T^2 = k\gamma LT^2$$

$$\Phi_i = kg_iT^2 + aT^2 + K_i\Delta\nu \quad \begin{cases} \Delta\Phi_i^{\text{FC}} = aT^2 \\ \Delta\Phi_i^{\text{FJ}} = K_i\Delta\nu \end{cases}$$



Frequency jump

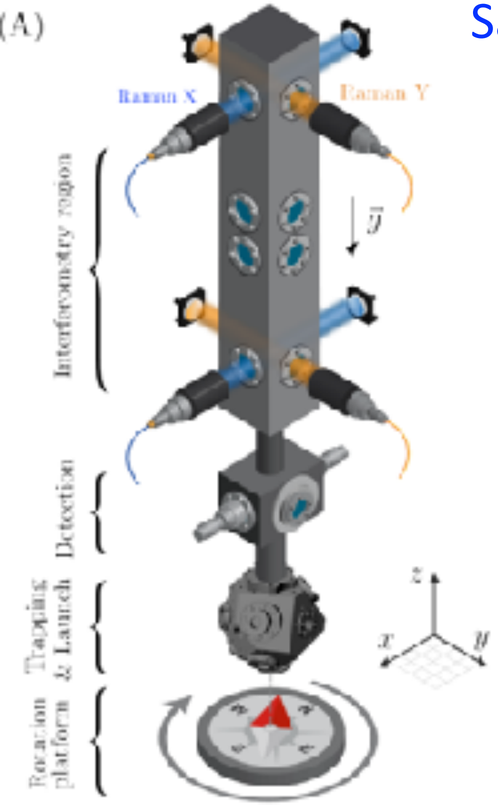
$$\Delta k_{eff}L = k_{eff}\gamma LT^2$$



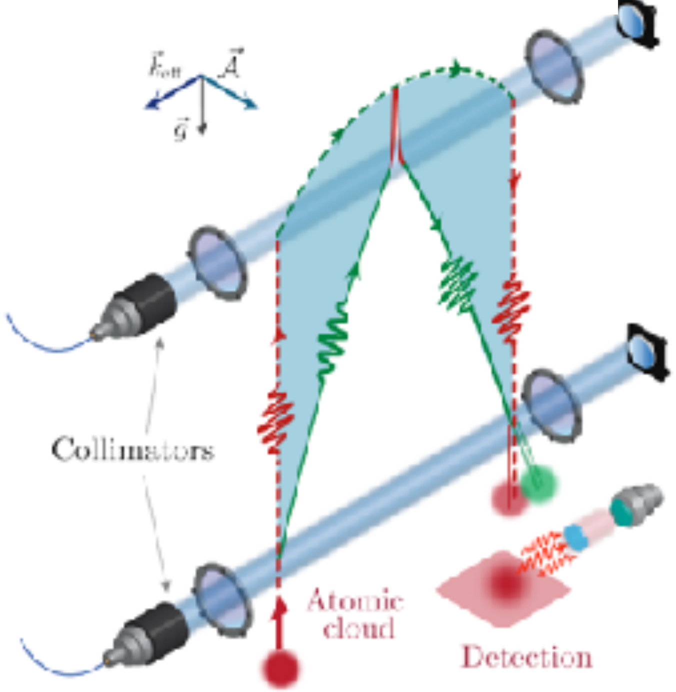
R. Caldani et al., Phys. Rev. A **99** 033601 (2019)

C. Janvier et al., Phys. Rev. A 105, 022801 (2022)

Atom gyroscope: rotational seismology



Sagnac effet with matter waves



$$\Phi_\Omega = \frac{T^3}{2}\left(\vec{k}_{\text{eff}} \times \vec{g}\right).\vec{\Omega}_E$$

Applications in seismology

- Additional local information on earthquakes wave propagation
- Acceleration/rotation correlations
- Subsurface investigation, civil engineering, risk assessment

- **Main features**

  Very large area: 11 cm^2
  with T_{int} = 800 ms

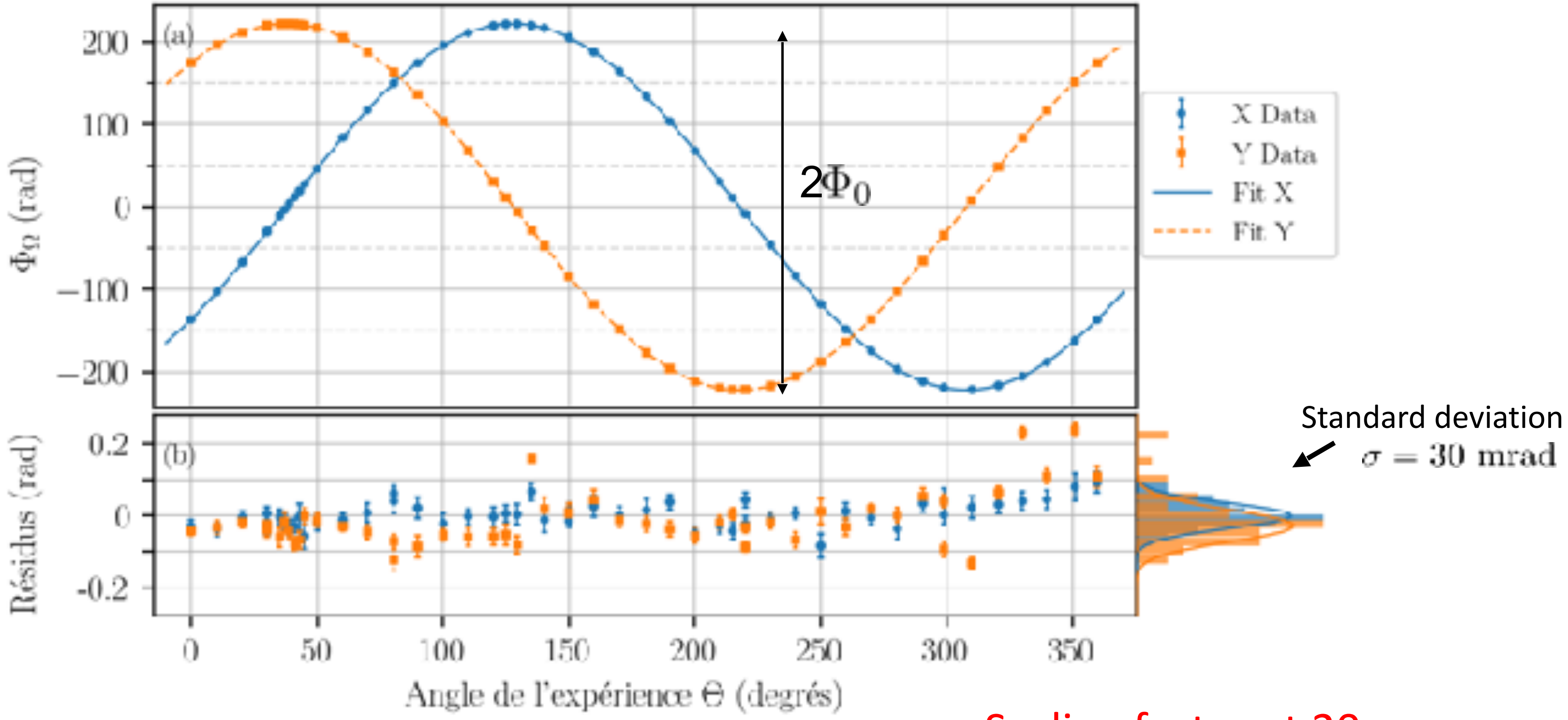
- Zero dead time interrogation with interleaved measurements

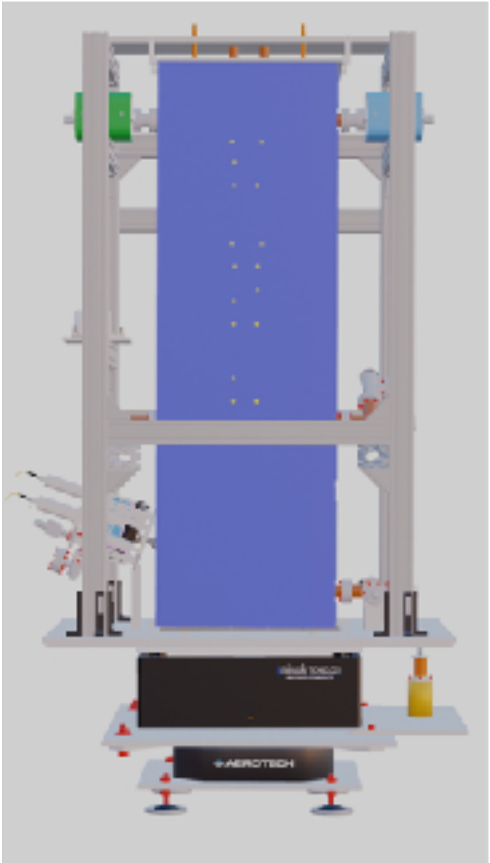
Record stability: 0.3 nrad/s
and accuracy: scaling factor at 20 ppm

D. Savoie et al, Science Advances 2018;4:eaau7948
R. Gautier, et al, .Science Advances, Vol. 8, no. 23, eabn8009 (2022)

Sagnac effect measurement

Rotation over 360° : measurement on both X and Y axes





Scaling factor at 20 ppm

Sinusoidal fit for both axes: 16 times

$$\Phi_{\text{ajust}}(\Theta) = B + \Phi_0 \cos(\Theta_0 - \Theta_N)$$

Amplitude: **Sagnac effect**

	Axe X	Axe Y
Expected Sagnac phaseshift	221.5707(3) rad	221.5638(2) rad
Measured Sagnac	**221.527(9) rad**	**221.561(8) rad**

R. Gautier, et al, .Science Advances, Vol. 8, no. 23, eabn8009 (2022)

Pushing the limits

Single interferometer at the standard quantum limited

$$\sigma_\Phi = \frac{1}{C\sqrt{N}} \quad \text{(atomic shot noise)}$$

$$\Rightarrow \sigma_a = \frac{\sigma_\Phi}{k_{eff}T^2} = \frac{1}{C\sqrt{N}k_{eff}T^2}$$

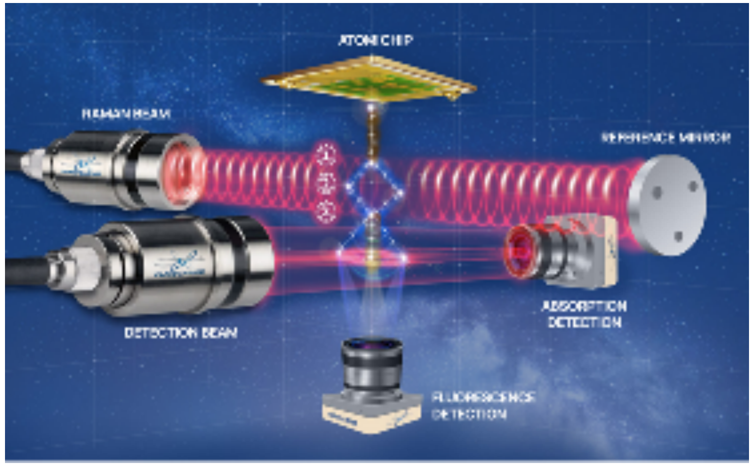
To boost the sensitivity :

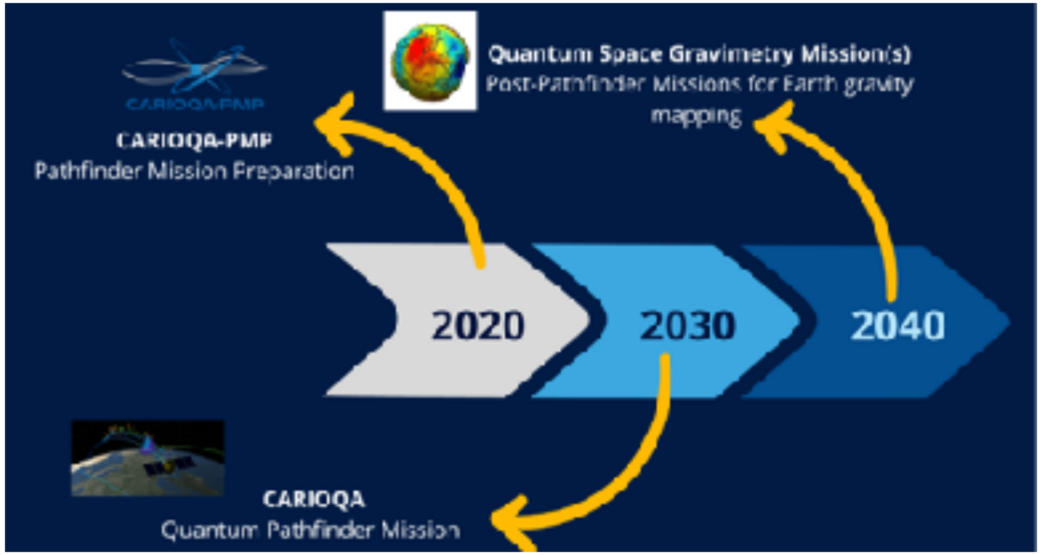
- Increase N and/or k_{eff} and/or T
- Below the SQL

CARIOQA: a pathfinder for geodesy mission

Demonstrator within the next decade of a space quantum accelerometer for geodesy applications
-> demonstrate 10^{-10} m.s^{-2} in 1s in space (for 2T = 2s)

- Horizon Europe project
  16 partners from academia and industry
- https://carioqa-quantumpathfinder.eu/





- Two follow-on projects in HE (WP 2023-2024)
- CARIOQA-PHA: completed in 2024
- CARIOQA-PHB: Kickoff October 2025 (2Y)

T. Lévèque, et al., Gravity Field Mapping Using Laser-Coupled Quantum Accelerometers in Space
Journal of Geodesy 95, 15 (2021)

Beyond free falling atoms

Advantages:

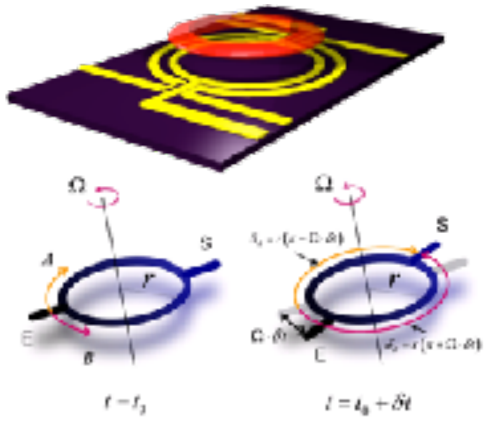
- Longer interaction times T >> 1 s possible
- Compact sensors
- Local probing at µm scale possible

Analogy with fiber optics:

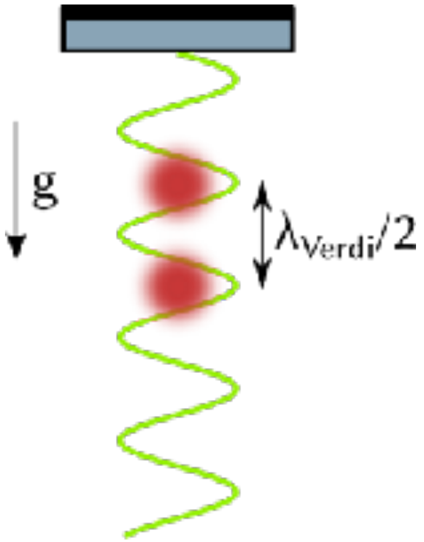
- Guided architecture
- Trapped atom interferometry

Difficulty/novelty: control of the trapping potential

- Magnetic Traps

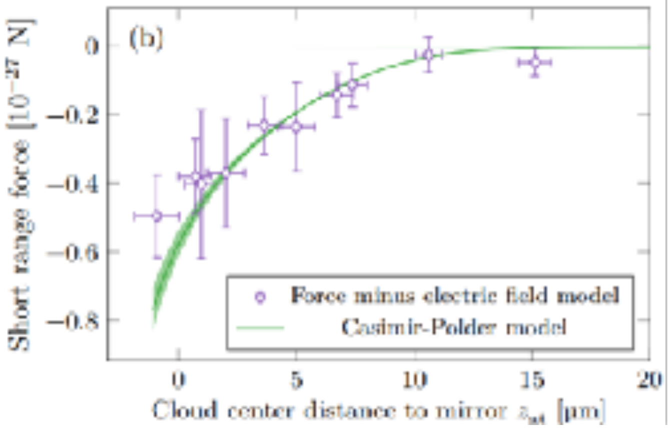


- Optical Traps



- Short term stability
- $3.4\ 10^{-28}$ N @ 1s

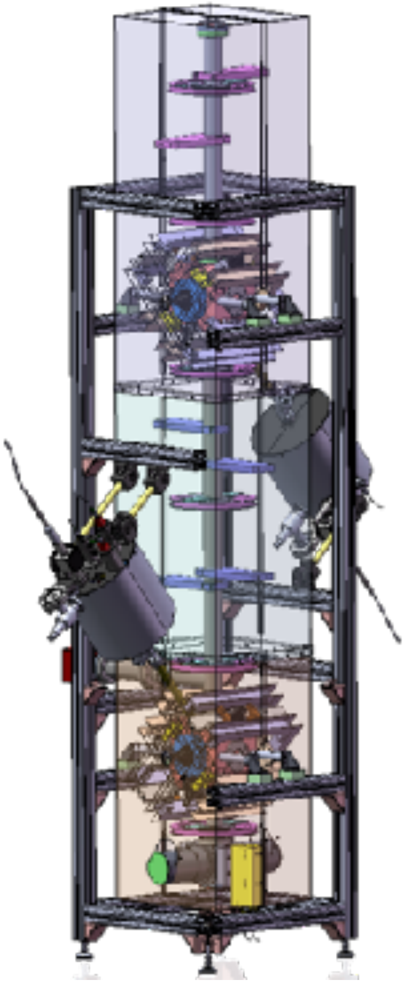
- Long term stability
- $4\ 10^{-30}$N (4 qN)



- Y. Balland, et al., Quectonewton local force sensor, Phys. Rev. Lett. 133, 113403 (2024)

Gravimeter – Gradiometer: next generation

Development of a dual sensor for gravity acceleration and gradient, based on Large Momentum tranfer and ultra-cold atoms

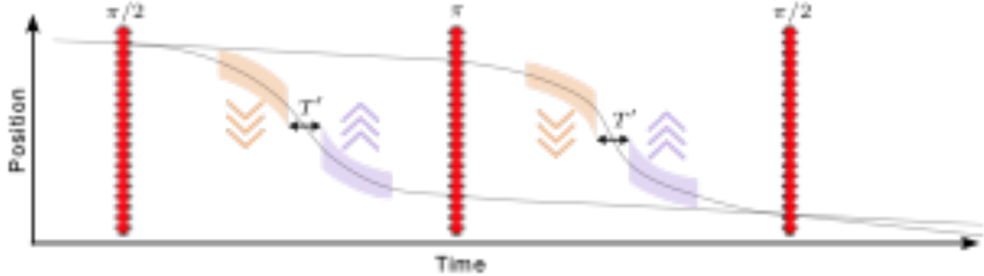


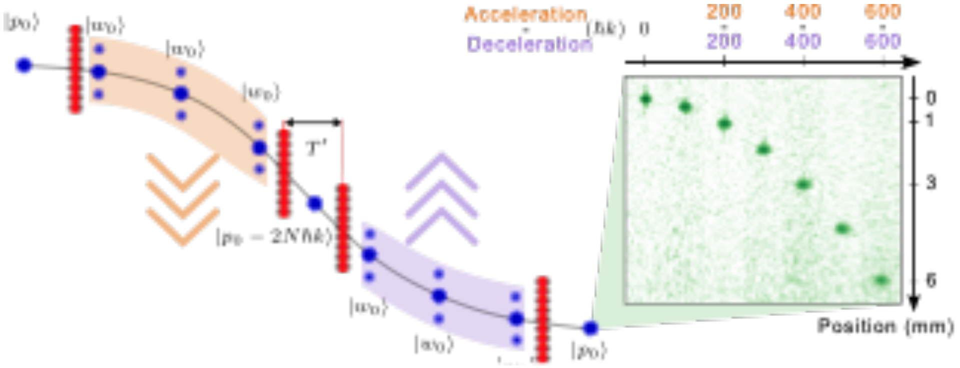
Aim of using 2 ultra-cold atomic sources with very large splitting

Bragg transition order N=3 : $\Delta p = 6\hbar k$
Quantum control: improve contrast x2

R. Caldani, et al., gradient, Phys. Rev. A 99, 033601 (2019)

- New methods for Large Momentum Transfer
- Optimal control + Floquet formalism

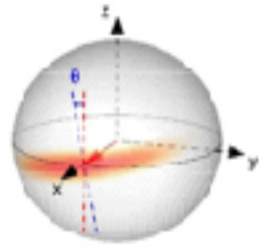




Record momentum splitting: 600 $\hbar k$ record with alkaline
LCAR Toulouse

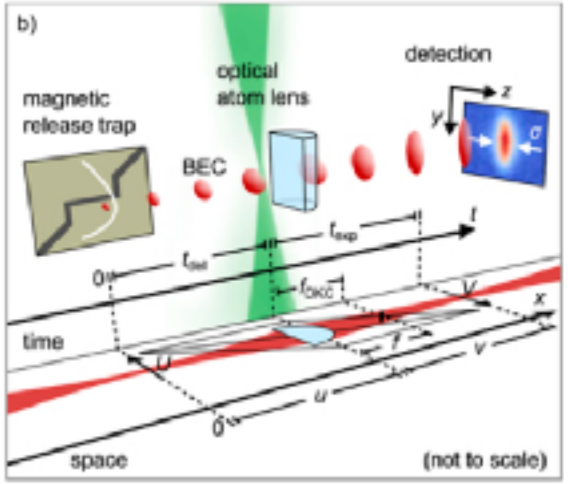
- Béguin et al. Phys. Rev. Lett. 131, 143401 (2023).
- Rodzinka et al. Nat Commun 15, 10281 (2024).

Beating the quantum limit



SQL: Quantum Projection Noise $\Delta\phi = 1/\sqrt{N}$

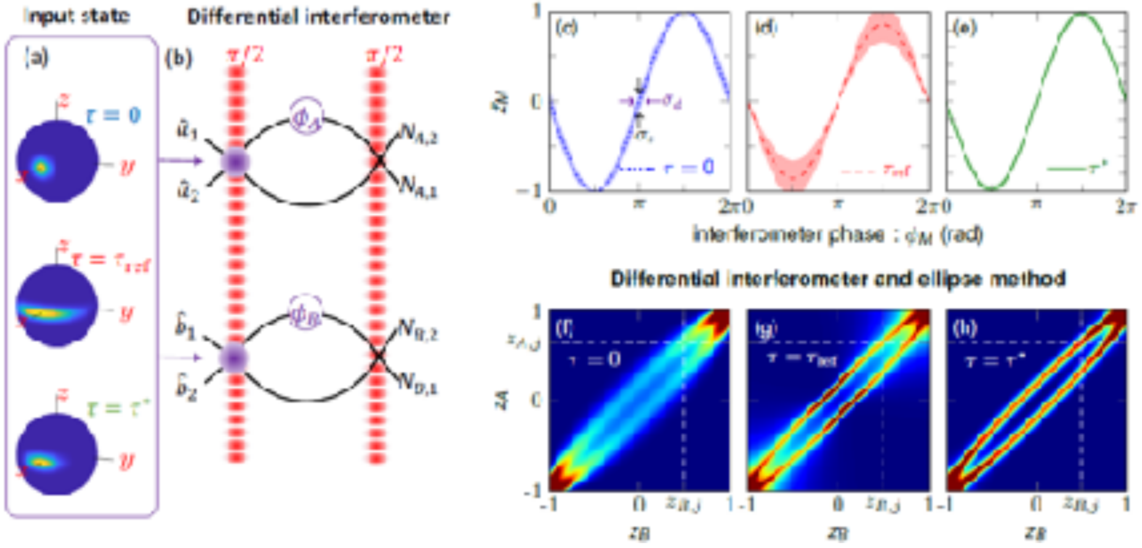
Implementation in a free-fall interferometer: Use of matter-wave lensing



R. Corgier et al., Delta-Kick squeezing, PRL 127, 183401 (2021)

$G = \Delta\phi_{SQL}/\Delta\phi \rightarrow$ Up to 32 dB in $\Delta\theta^2$

- Developing methods
- Tacking care of the imperfections
- Demonstrate the usefulness: keeping the accuracy…



R. Corgier et al., Optimized squeezing for accurate differential sensing under large phase noise,
2025 Quantum Sci. Technol. 10 045016

Conclusions

- Main advantage: **accuracy and reproducibility** (use of laser for manipulation)
  - Scaling factor
  - Laser/atom interaction
  - Cold/ultra-cold atoms : control velocity
- **Maturity** of atom interferometry techniques for the development of inertial sensors
  - Performances comparable to, or overpass, classical technologies
  - Current efforts towards compactness and improved on the field operability
- Room for **improvements and new systems** (LMT, optimum quantum control, squeezing, trap atom interferometers …)
- **New fields of applications in geosciences**: reservoir monitoring, exploration, civil engineering… and full 4D evolution monitoring.

  and as well fundamental physics, navigation.

Thank you

Thanks to colleagues of IACI team of LTE

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Sébastien Merlet
Quentin Beaufils
Leonid Sidorenkov
Robin Corgier
Remi Geiger

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

And collaborator in the QAFCA project of PERP-Q

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Baptiste Allard, Alexandre Gauguet

LKB (Paris)
Pierre Cladé, Saïda Guellati

LP2N/iXatom (Bordeaux)
Baptiste Batelier

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