CARIOQA
Quantum accelerometry for space geodesy

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Laboratoire Temps Espace

Workshop Application of Time-Frequency technologies to defense and space science
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Outline

- Quantum accelerometry on the ground and in space
- The CARIOQA project
- Challenges related to the space environment
- An instrument simulator

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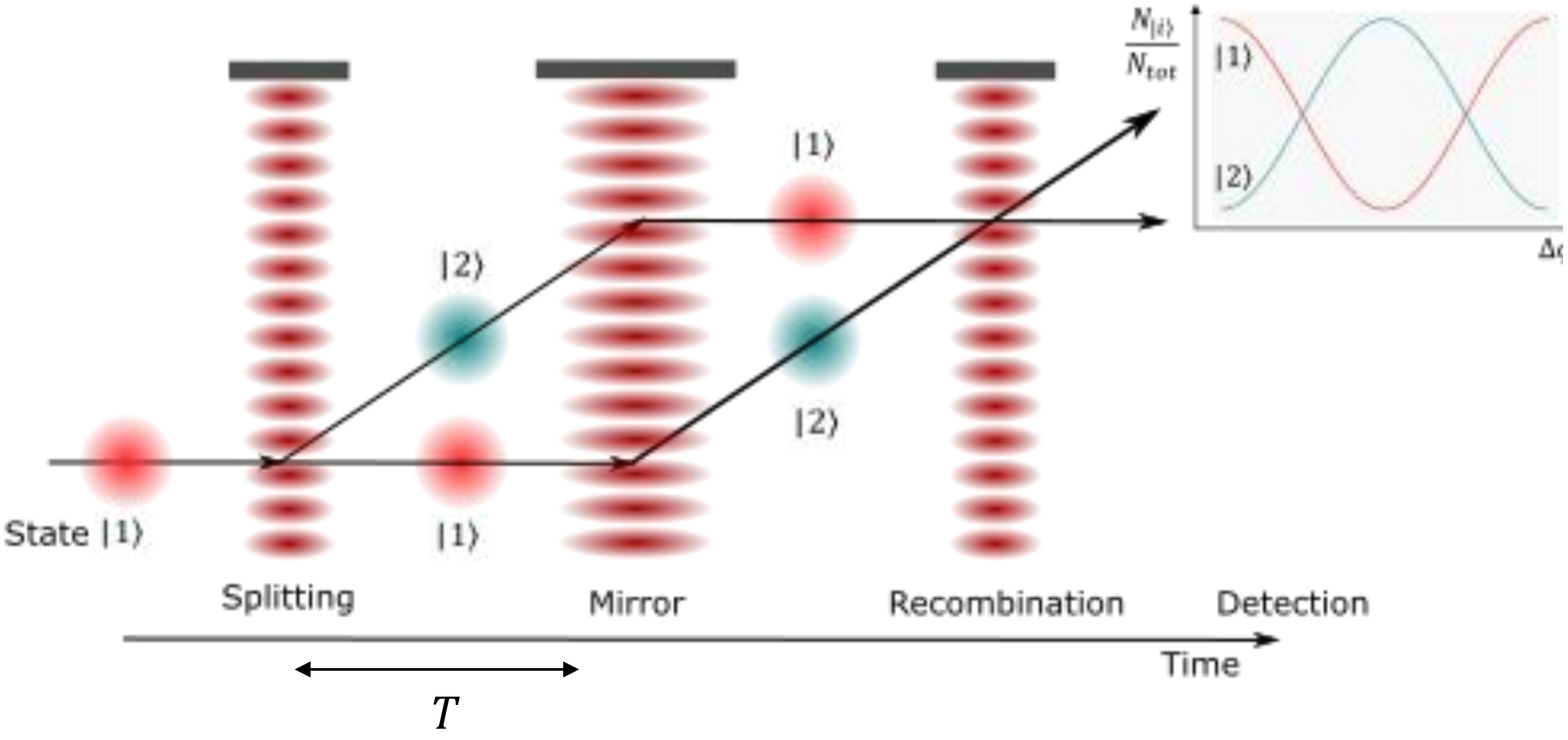
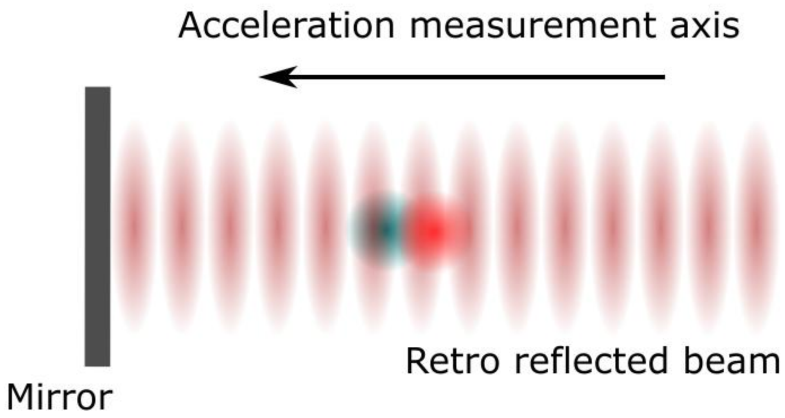
Principle of a cold atom accelerometer

A cloud of cold (1 μK) or ultracold (10 nK) atoms, free falling or trapped.





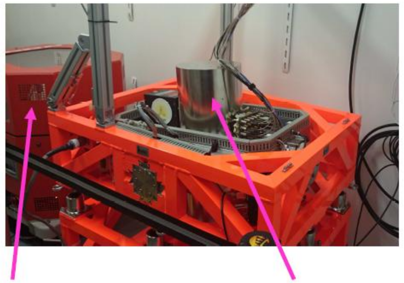
For a free falling accelerometer : $\Delta\Phi = k_{eff} a T^2$

Cycling measurement with $T_c = 2T + T_d$ $T_d \sim 0.1 - 2$ s dead time for preparation and detection

Maturity of the technology

Inertial sensing technologies based on atom interferometry : 30 years of development

SYRTE gravimeter



KSS32 relative Marine Gravimeter (Bodenseewerk)

Cold Atom Gravimeter (Onera)

A mature technology: industrial transfer from the lab to commercial products

eXail gravimeter

Many applications :

- Gravimetry
- Gradiometry
- Inertial sensing and navigation
- Fundamental physics

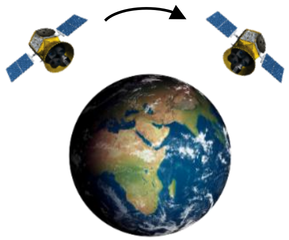
Adapting CAI to space

- Microgravity :

  - **Larger interrogation time** (sensitivity scales in T^2).
  - On ground : typical time 500 ms.
  - In space, T = 10 s possible : gain of 2-3 orders of magnitude.
  - New limiting factor : **temperature**. Expansion for a thermal cloud : 10 cm after 10 s.

- Navigation (Altitude 300 km) :

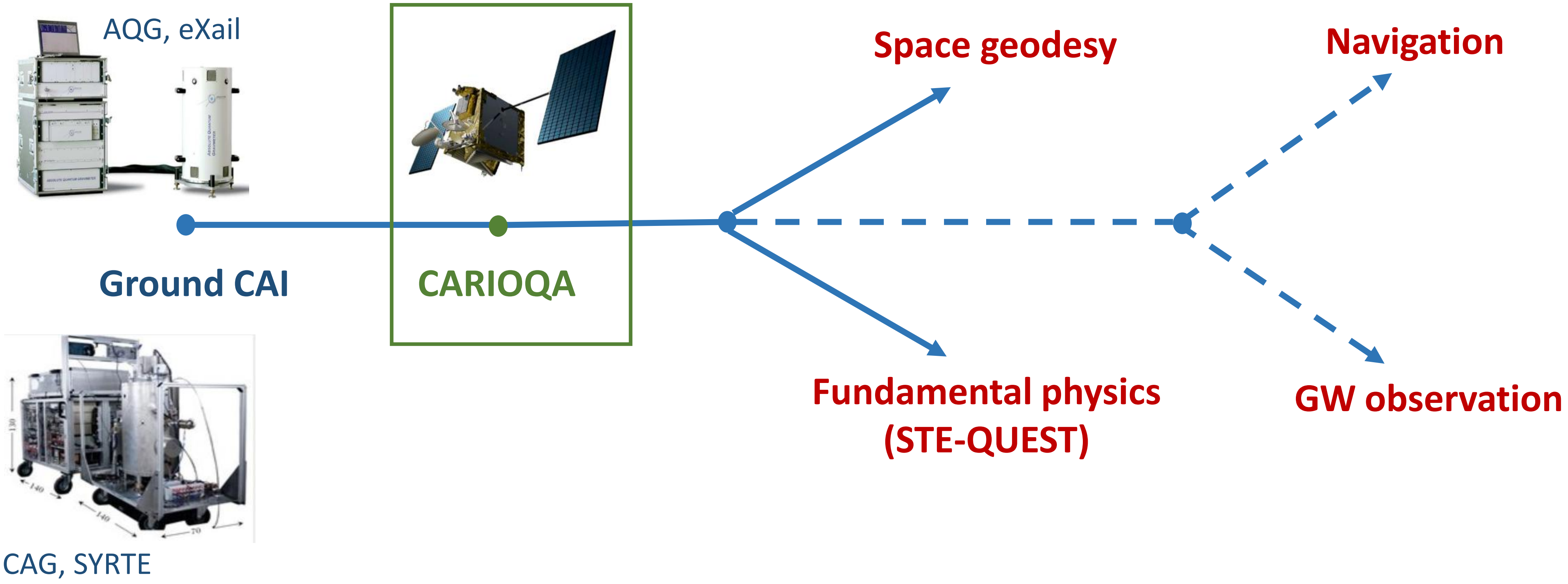
  - Acceleration is not constant.
  - Sensitivity to **residual rotations**.
  - **Nadir pointing** : constant rotation at 1.3 mrad/s.



- Limited size and power budget

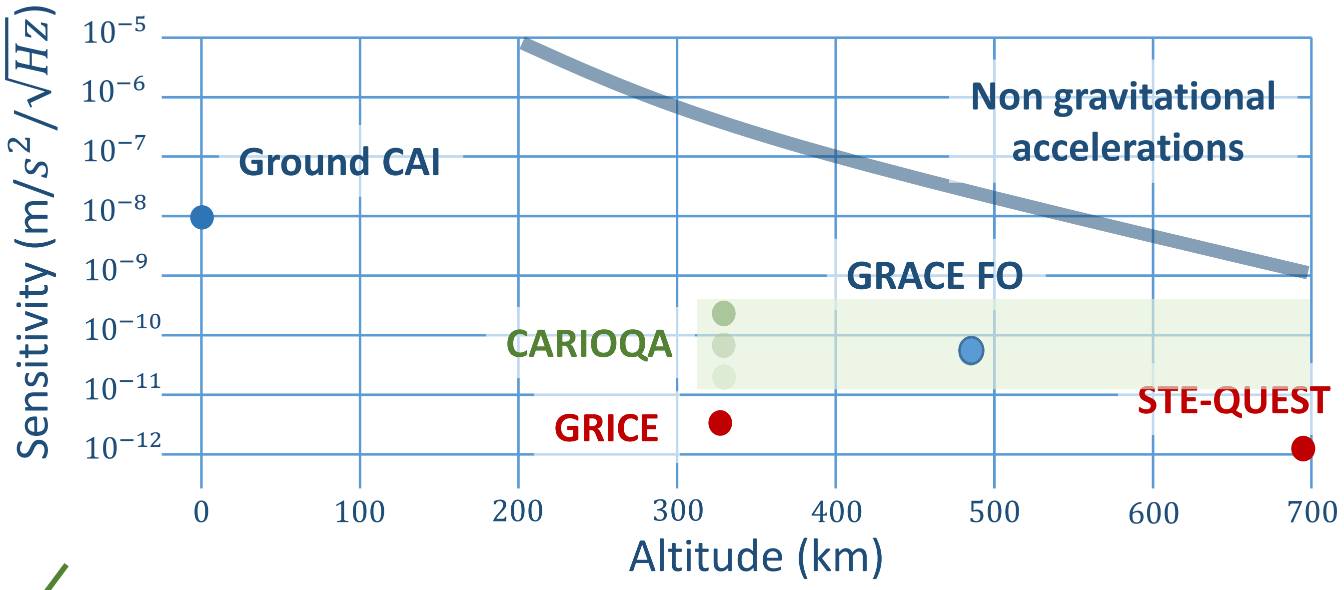
Perspectives

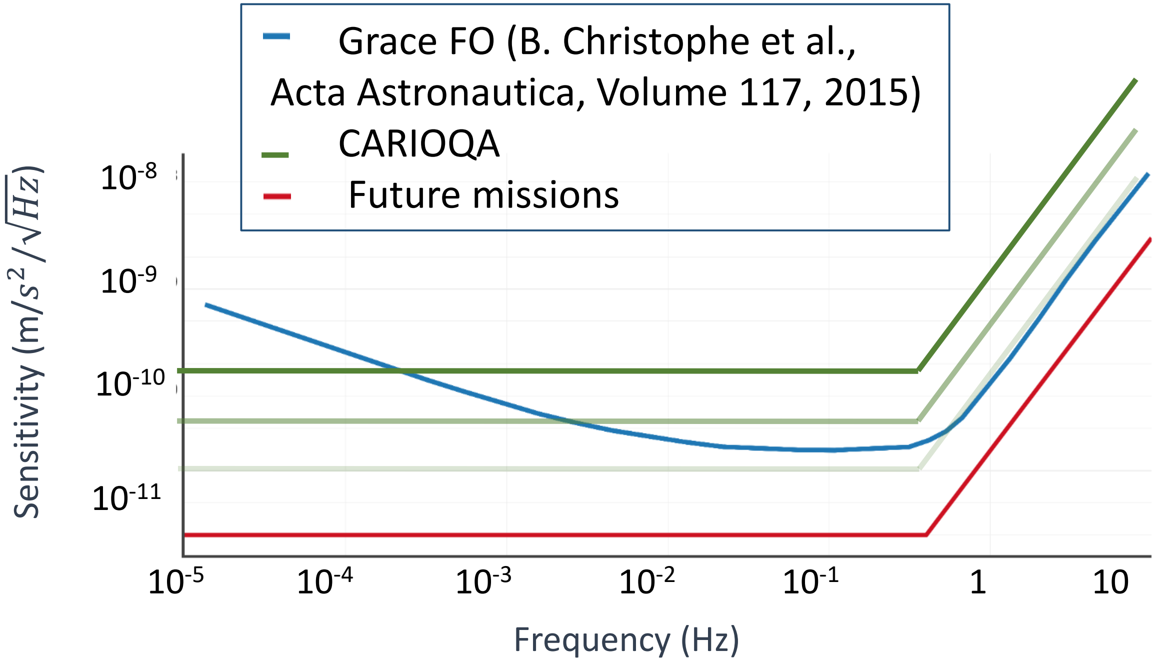
Towards Cold Atom Interferometer (CAI) based space missions



Expected level of performances

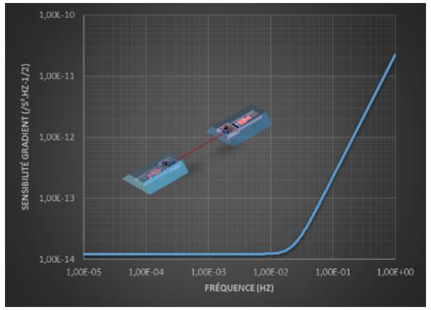
To be competitive,
CAI should demonstrate
in orbit performances
$< 10^{-11} \mathrm{m/s^2/\sqrt{Hz}}$
3 orders of magnitude improvement!





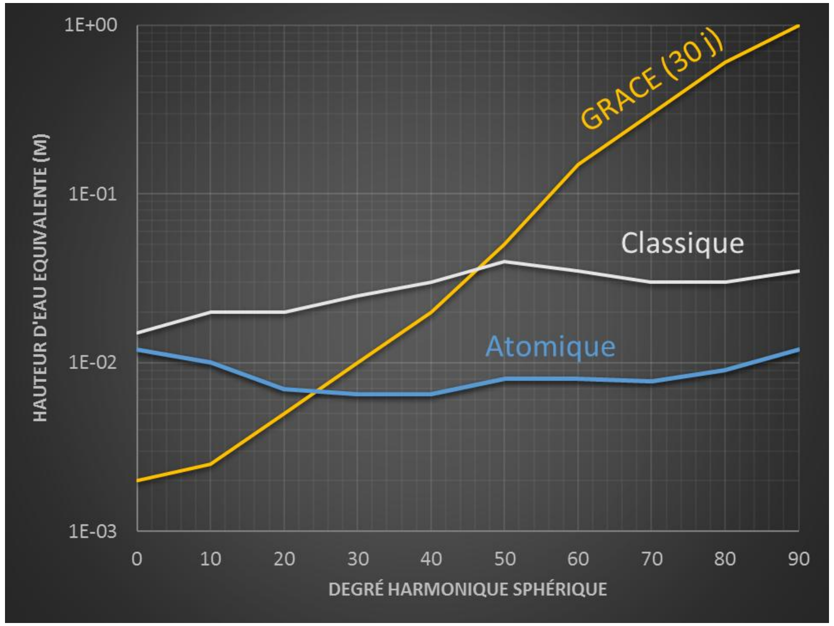
Key advantage of CAI :
Long term stability (absolute measurement)

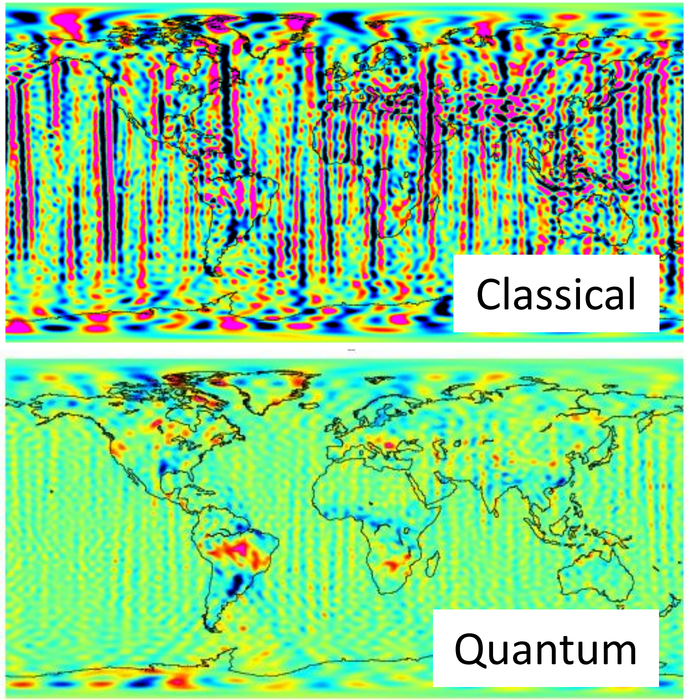
GRICE: a CNES Phase 0 (2016-2018)



Mission configuration GRACE-like (L=100 km)
Instrument performances (LRI 40 nm/Hz$^{1/2}$ and QA 6 10^{-10} m/s^2/Hz$^{1/2}$

Comparison between restitution errors with different accelerometers applying the same data processing
Classical accelerometer 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)

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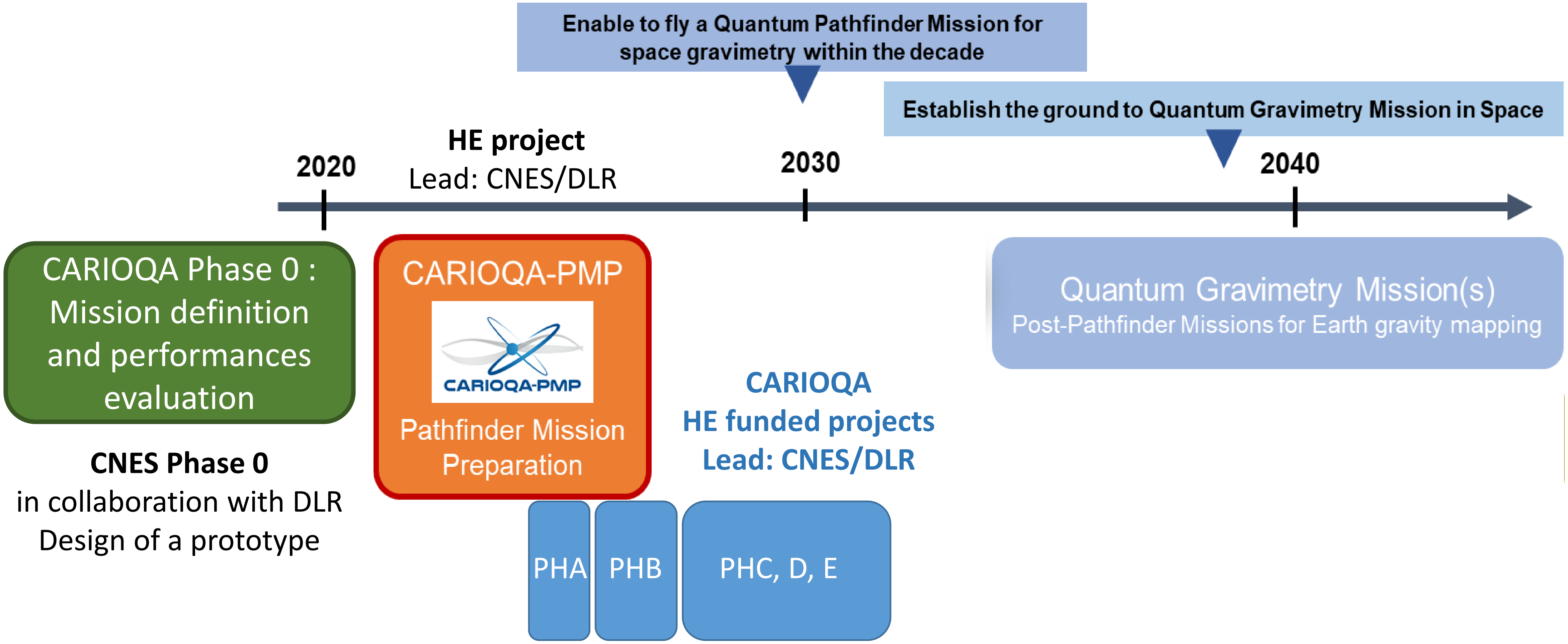
The CARIOQA project



https://carioqa-quantumpathfinder.eu/

Mission objectives

Primary objectives:

Demonstrate the acceleration measurement capability
Assess the level of noise
Evaluate the accuracy of the accelerometer
Manage rotations

→ Technological demonstrator

Secondary objectives:

Gravity field recovery (HL-SST)
Measurement of the thermosphere density

CARIOQA

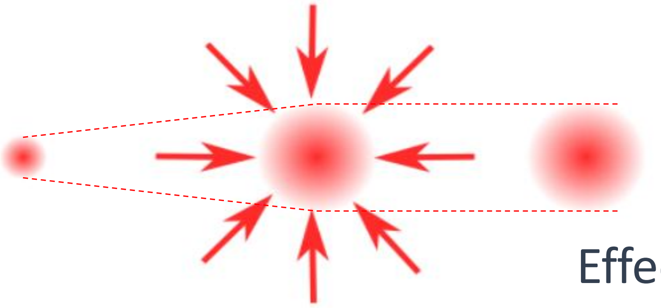
Funded by
the European Union

Space heritage

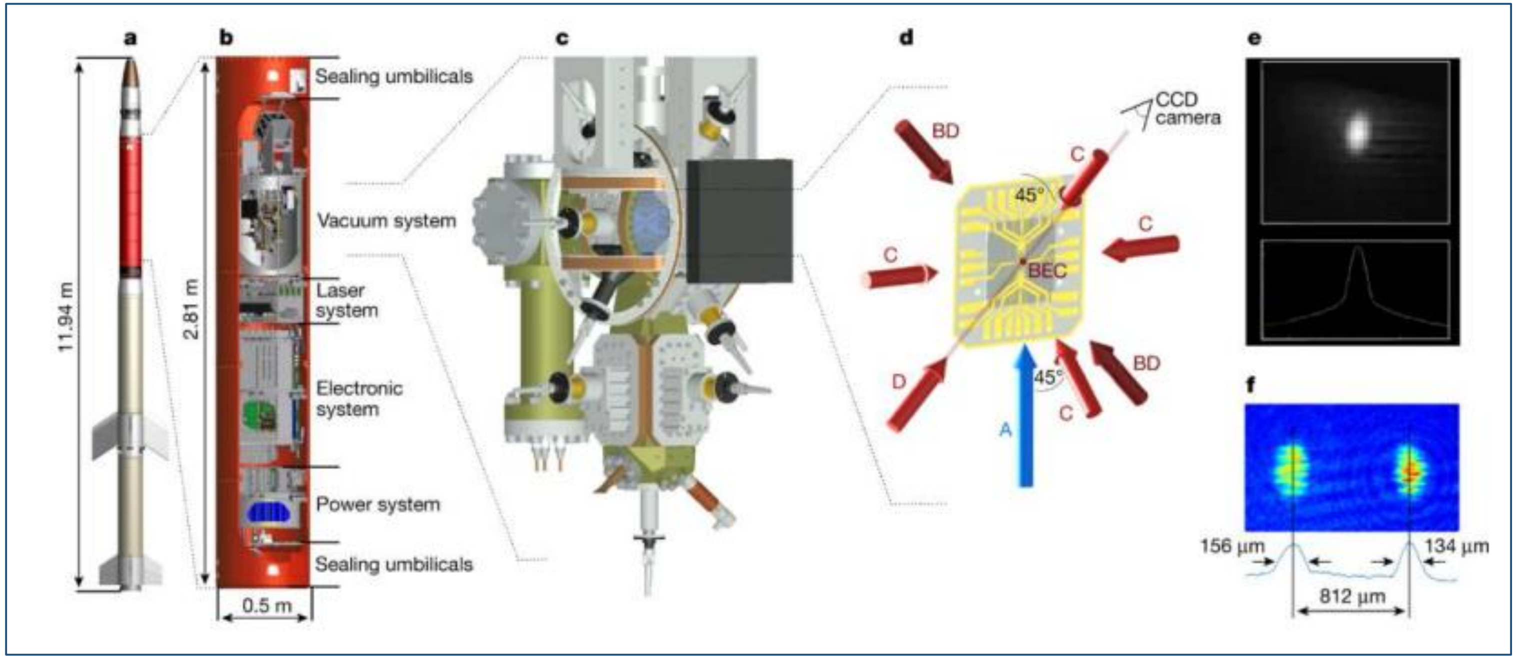
PHARAO: cold atoms in space

MAIUS: ultracold atoms in space

- Laser and evaporative cooling on an atom chip.
- delta-kick collimation.



Effective temperature
< 100 pK

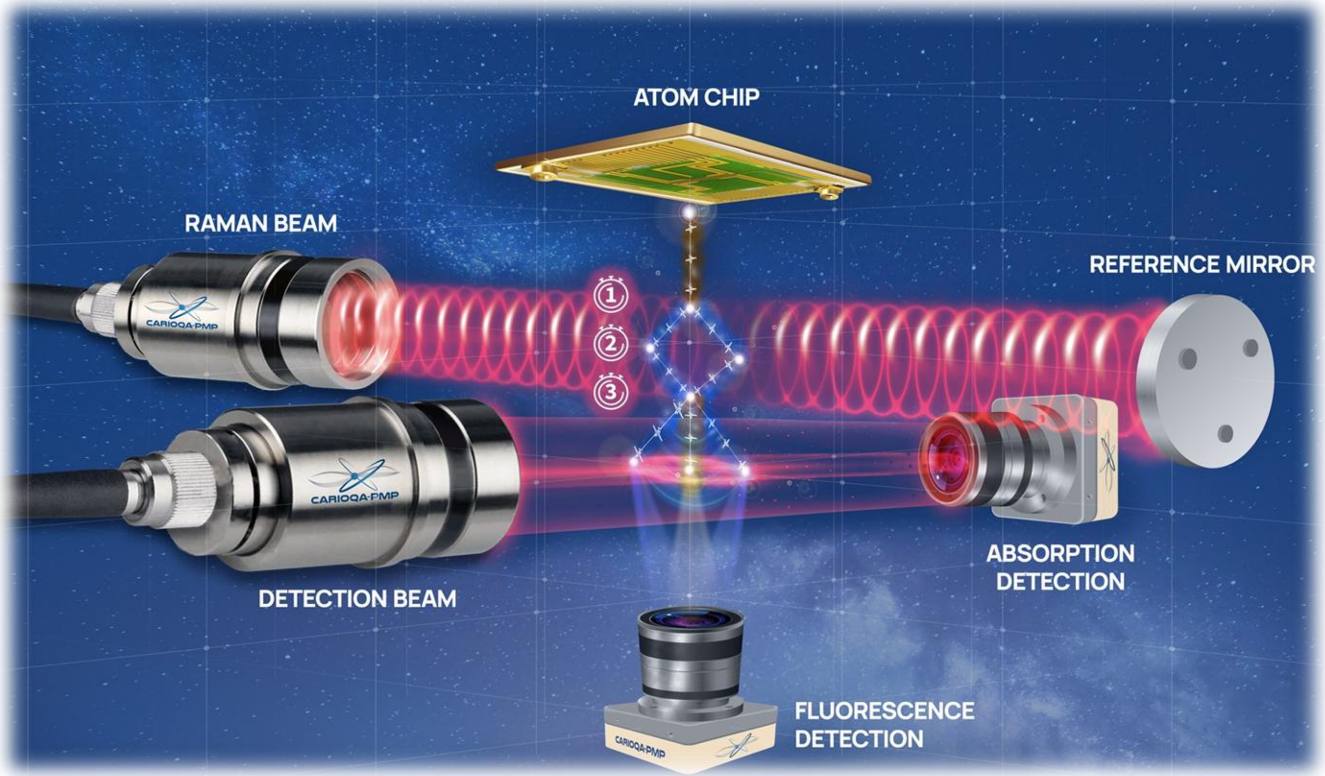


Becker, D., Lachmann, M.D., Seidel, S.T. *et al.* Space-borne Bose–Einstein condensation for precision interferometry. *Nature* **562,** 391–395 (2018)

CARIOQA-PMP

Realisation of an engineering model by an industrial consortium

Airbus, exail, Leonardo for space qualified hardware (PP, laser system and RF source) + Teletel for EGSE



Integration and tests in CNES facilities

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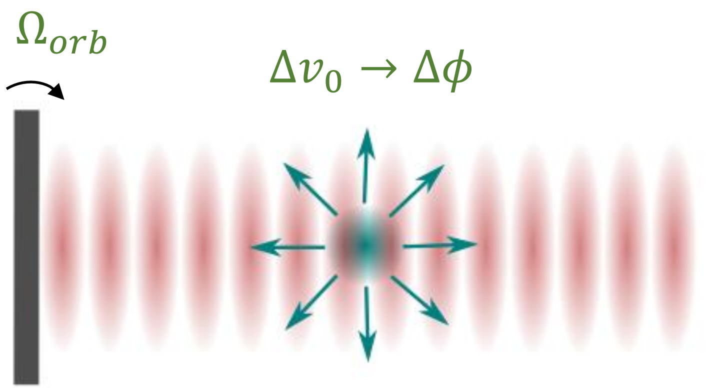
Coping with rotations

Phase of the rotating interferometer:

$$\phi = k_{eff} T^2 [a_x - 2 v_{0z} \Omega_y + x_0 \, \Omega_y^2] + O[\Omega T]^3$$

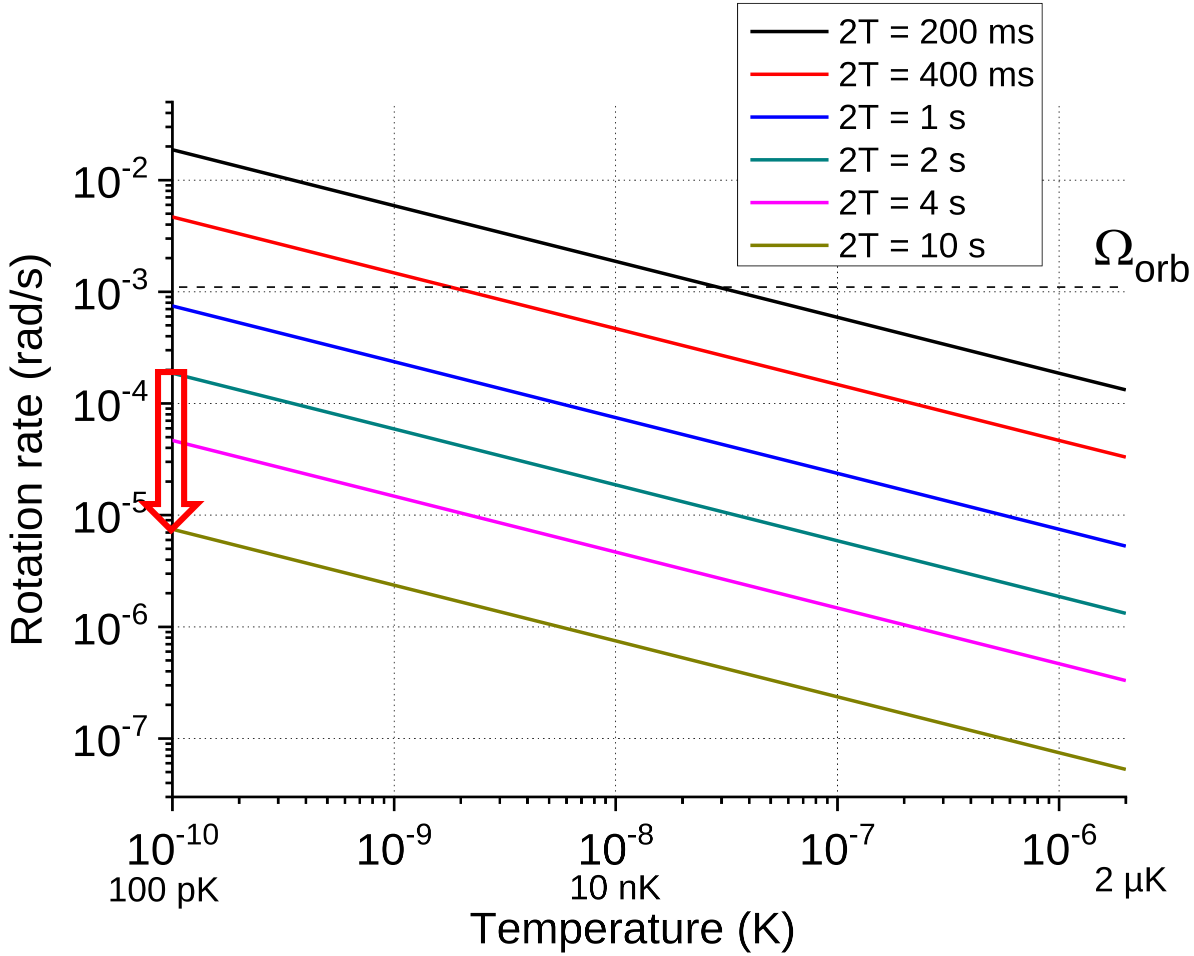
Non inertial acceleration   Coriolis   centrifugal

Velocity dispersion induces a **phase inhomogeneity**



This leads to a **loss of contrast**

$$C = e^{-\frac{\sigma_\varphi^2}{2}} = e^{-2\left(k\sigma_v \Omega T^2\right)^2}$$



<u>Max residual rotation to keep contrast above 50%</u>

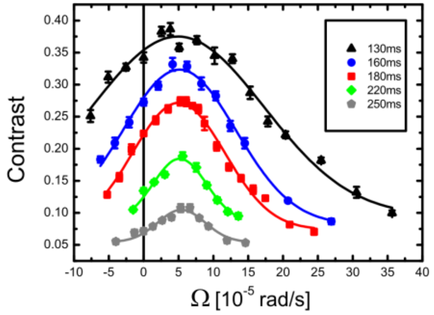
Even at very low temperature,
Nadir rotation has to be compensated

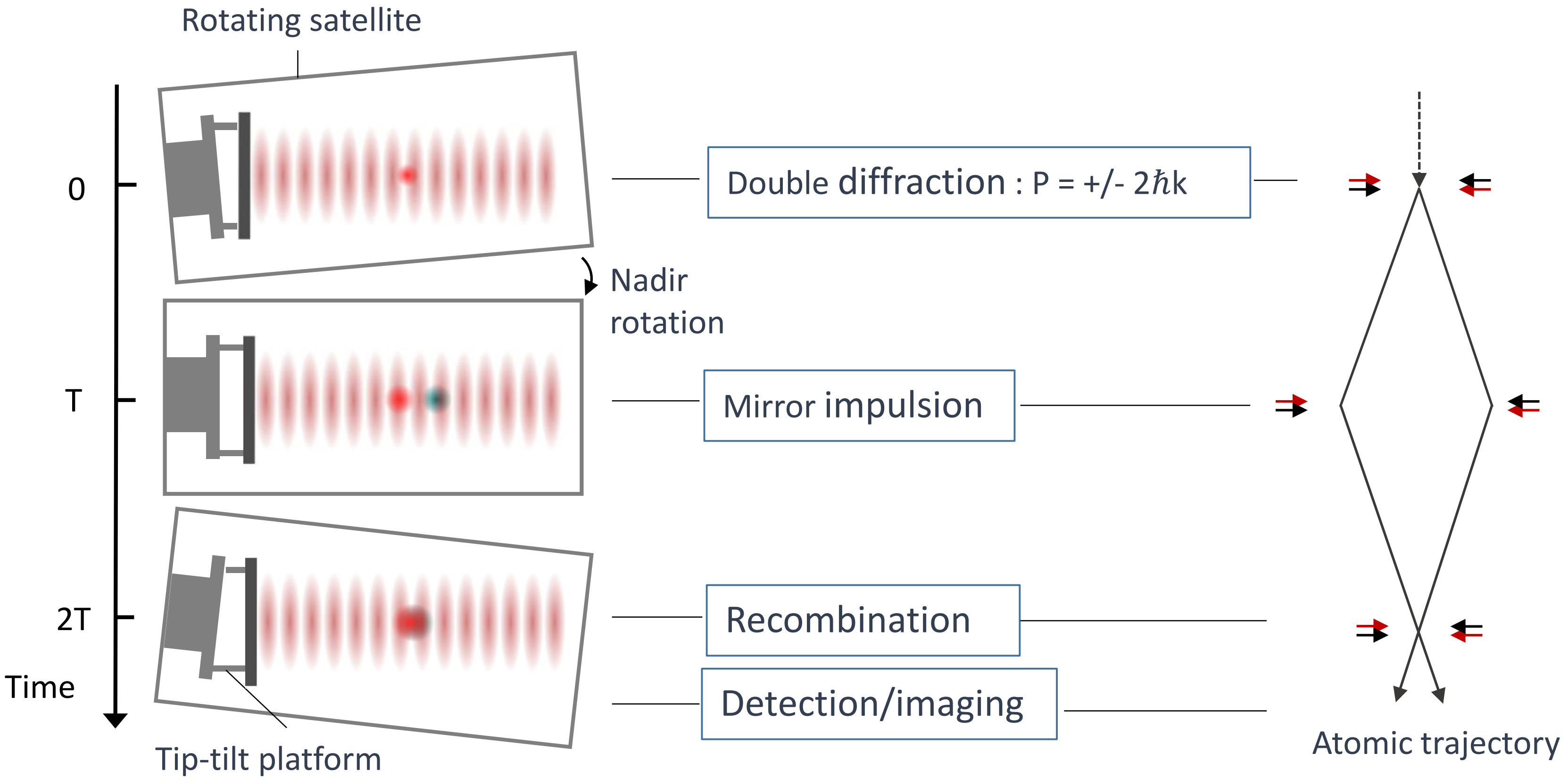
Compensation of nadir rotation

Counter-rotating the mirror:
$\Omega_m = -\Omega_y \approx 1\ \mathrm{mrad/s}.$

Technical solution:
piezo tip-tilt

Demonstrated on the ground
(Earth rotation compensation)





Rotation of the mirror at angular velocity Ω_m and rotation of the incoming laser Ω_I

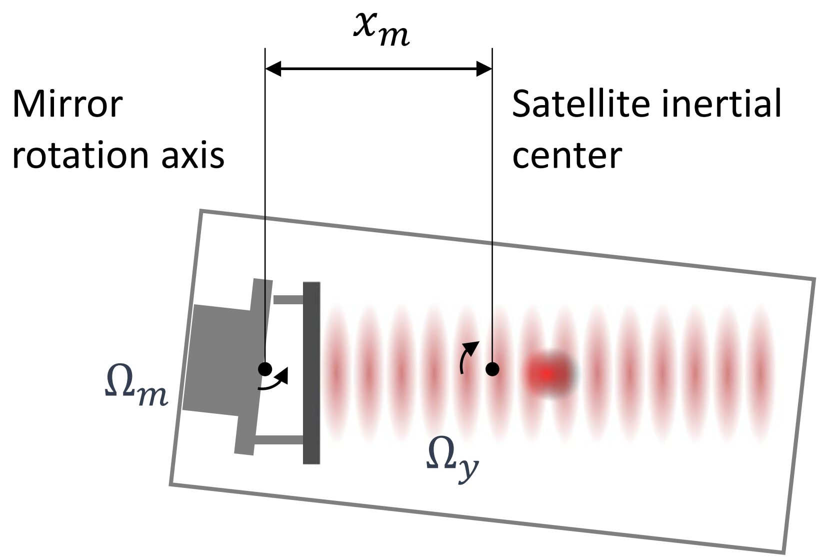
$$\phi = k_{eff}T^2[a_x + 2v_{0z}(\Omega_y + \Omega_m) - x_0\Omega_y^2 + (x_0 - x_m)(\Omega_m^2 + (\Omega_m - \Omega_I)^2) + O[\Omega T]^3$$

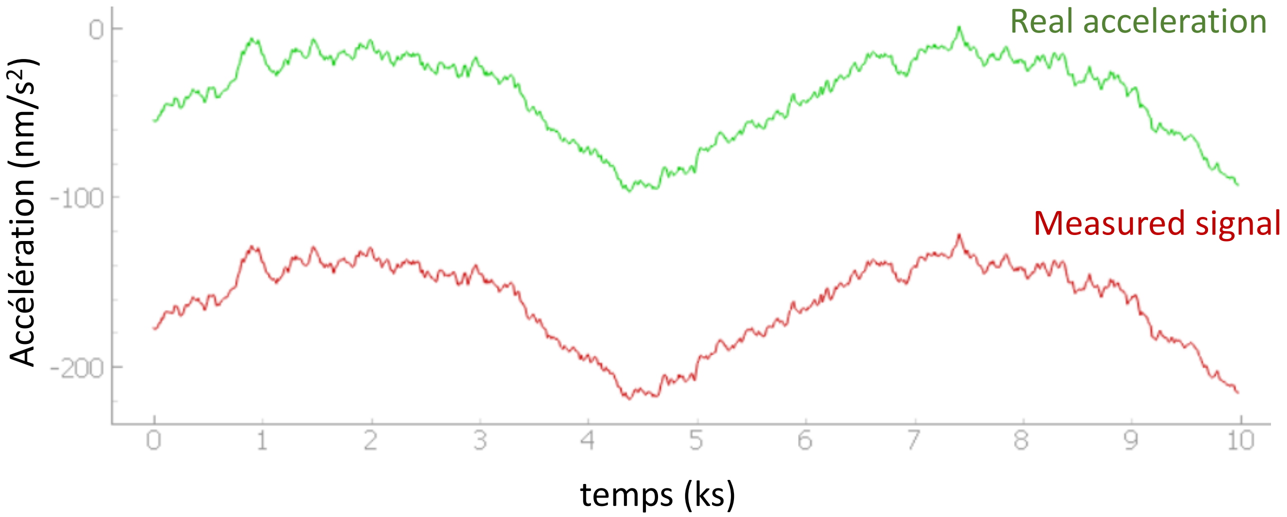
Compensation bias

Assuming that the incoming laser beam is co-rotated Ω_m=Ω_I :

$$\phi = k_{eff}T^2[a_x + 2v_{0z}(\Omega_y+\Omega_m) \; -x_0\;(\Omega_y^2-\Omega_m^2) - x_m\Omega_m^2] + O[\Omega T]^3$$

For $\Omega_m = -\,\Omega_y$, acceleration bias : $x_m\Omega_m^2$





Acceleration signal for x_m=10 cm

Importance of the rotation center's position for accuracy : for $10^{-10}\mathrm{m}/s^2$, x_m must be know better than 0.1 mm.

Non-linearity of the response

Measurand : the transition probability : $P = A + \frac{C}{2}\cos\varphi = A + \frac{C}{2}\cos(kaT^2)$

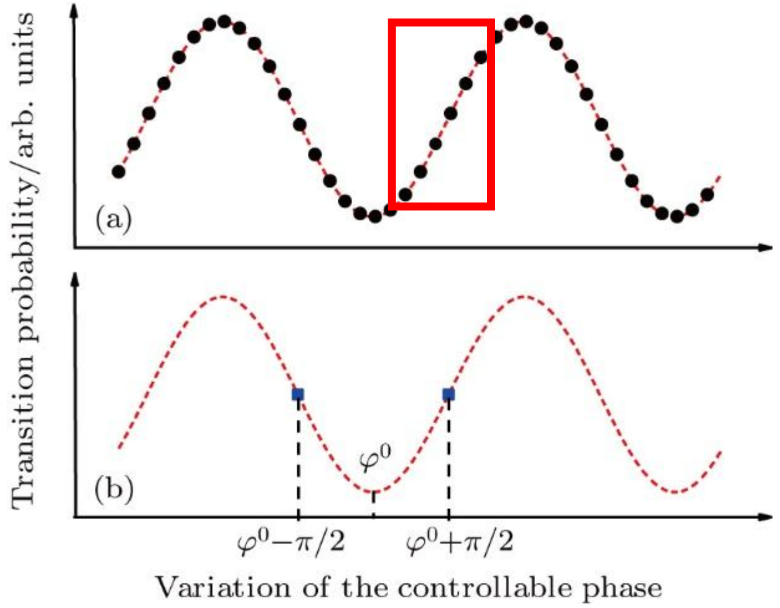
=> Non-linear response + phase ambiguity

Ideally, operation at mid fringe
and for acceleration fluctuations such that $k\delta aT^2 < \pi/2$

For $T = 1$ s, $\delta a < \sim 5\ 10^{-8}$ m/s2

But, one can tolerate larger fluctuations provided they are slow,
since we can compensate for them and remain close to mid-fringe

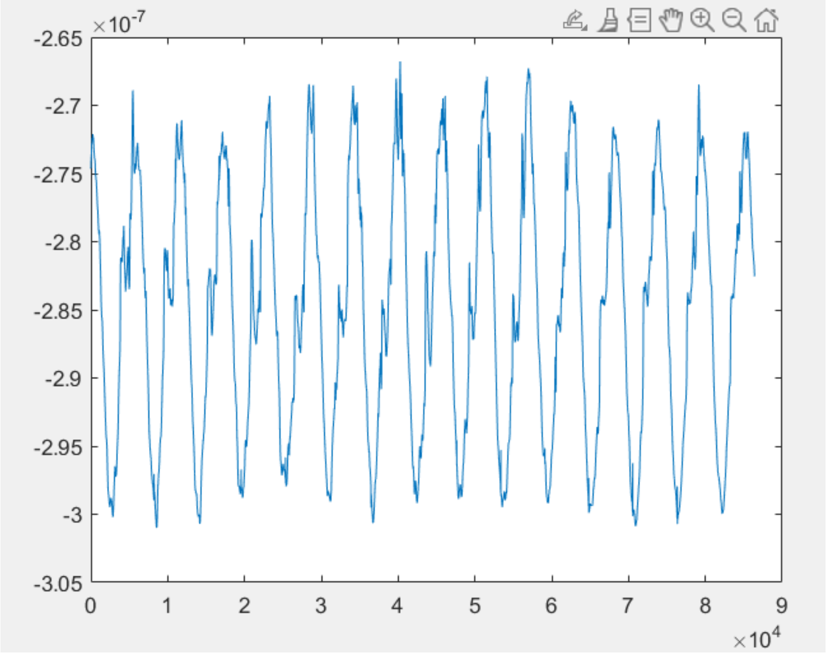
Showstopper : $k\ \delta a\ T^2 > \pi$, with δa the cycle to cycle variation



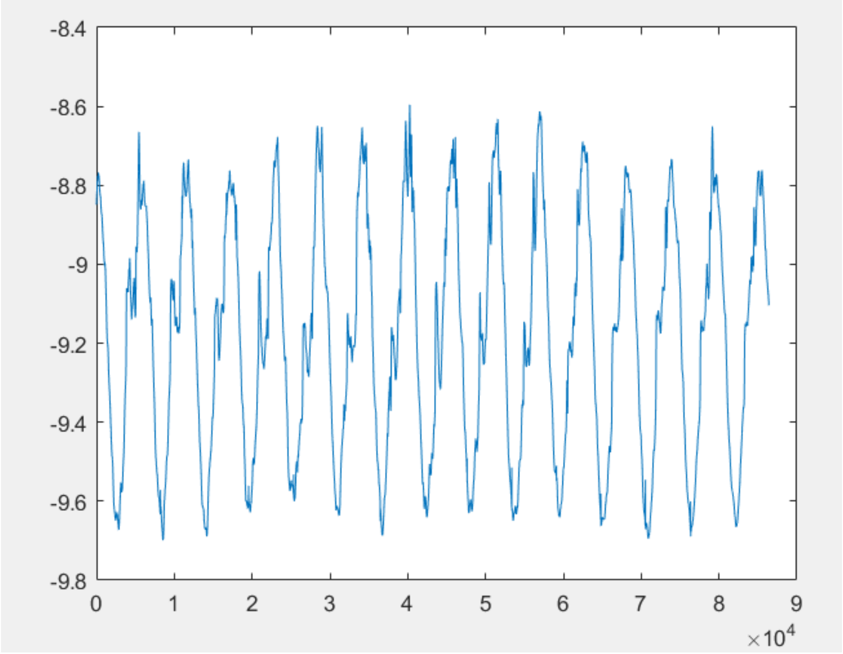
Impact of non-inertial accelerations

GRACE FON (1Hz data, 2019-01-01)

Acceleration a_x (m/s2)

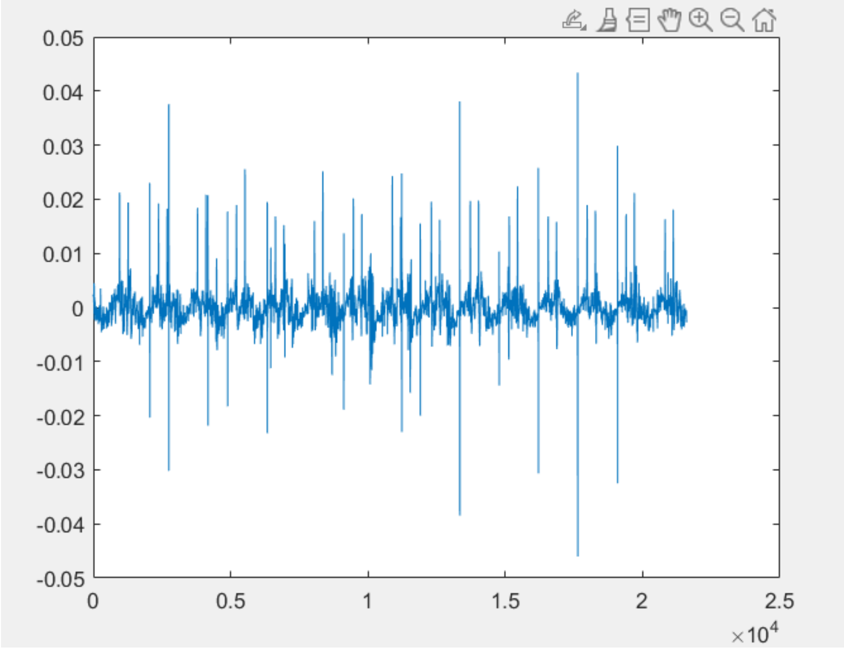


Phase (rad)



Phase difference
between consecutive cycles (rad)

2T = 2s



1 rad ptp, but slow fluctuations

Operation at 500 km altitude : 2T = 2s OK. Can be extended to 2T = 5-10 s
But at 350 km, 2T limited to < 2s, except if hybridization with a classical sensor

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Development of the instrument simulator

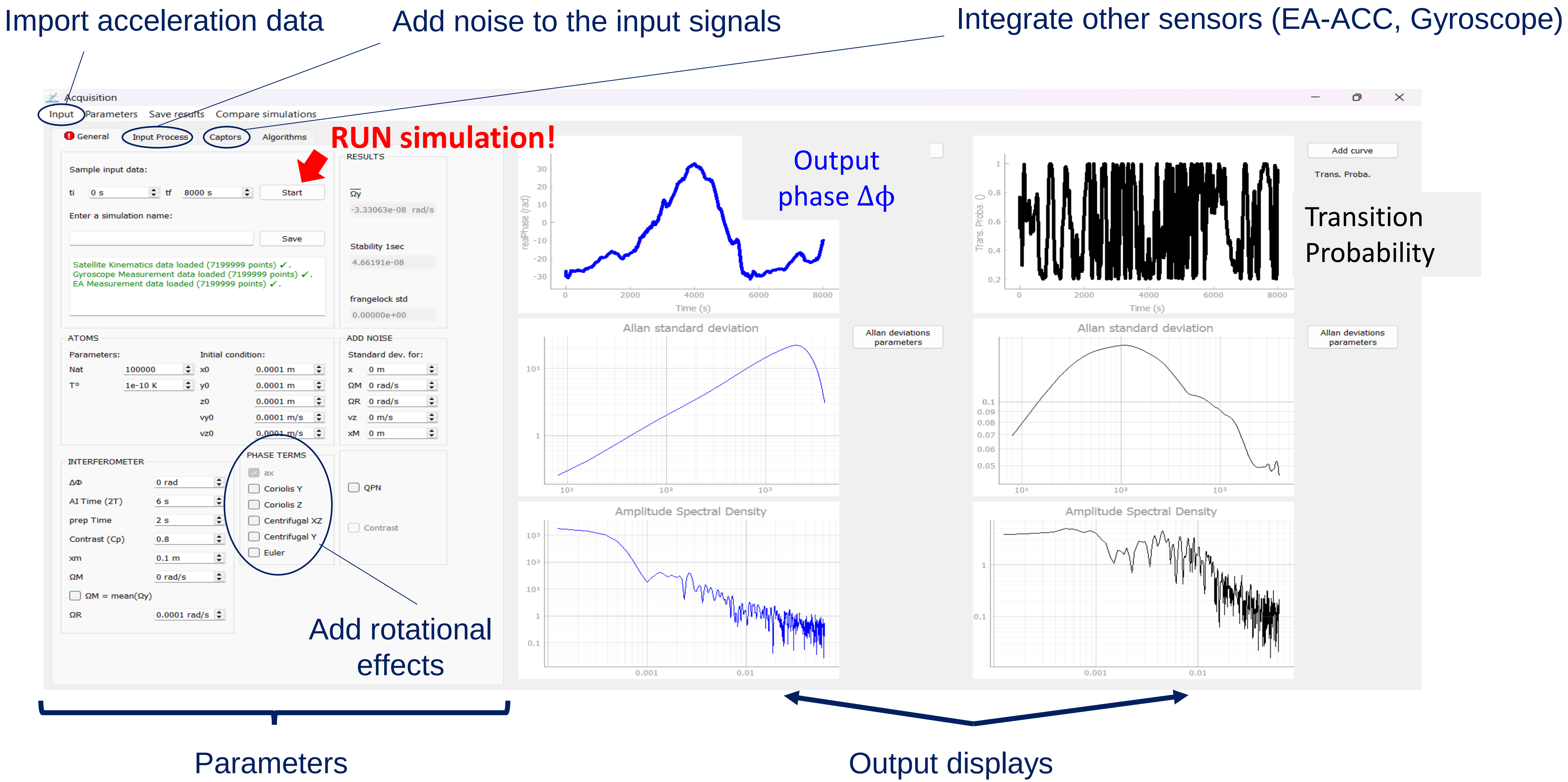
LTE responsible for the development of a simulation tool for the generation of synthetic data

Inputs
- Source parameters (position, velocity, temperature, number of atoms …), mean values and fluctuations
- Environmental conditions (non gravitational accelerations, satellite attitude …)

Outputs
- Atomic populations, transition probability time series
- Corresponding accelerations

Used for validation of
- Measurement methods
- Calibration phases (determination of drift velocities and positions wrt center of mass of the satellite)
- Hybridization protocols with classical sensors (bias determination …)
- Gravity field recovery methods (in collaboration with geodesists)

Instrument simulator



Conclusion

Quantum accelerometry is a candidate technology for future accelerometers in space

Space geodesy could benefit from its improved measurement noise, in particular at low frequency

Strong push by the EC (+CNES/DLR) to make the first demonstration of a quantum accelerometer in orbit and to prepare future geodesy missions