IXATOM

Quantum technologies for high end Inertial Sensors

Baptiste Battelier, Pierrick Cheiney, Brynle Barrett, Olivier Jolly, Simon Templier, Quentin d'Armagnac de Castanet, Philippe Bouyer, Henri Porte and Fabien Napolitano

iXblue

Quantum systems for positioning and inertial navigation

LP2N
Institut d'Optique d'Aquitaine
33400 TALENCE.

INSTITUT d'OPTIQUE GRADUATE SCHOOL

cnrs

université de BORDEAUX

Context and Objectives

iXblue in France

750+ employees

135M€+ turnover

80% export

Founded in 2000

9 industrial sites

100% R&D and Production in France

Lannion
Specialty Fibers
Accelerometers
Navigation

Brest
Underwater Acoustic
Positioning

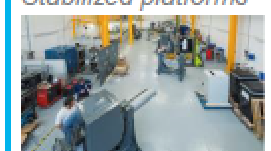
Talence New
Cold quantum
Quantum

Pessac New
Gravimeters
Space optics

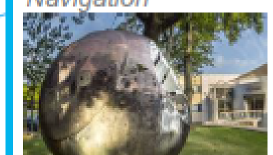
μQUANS

New Recent acquisition

Bonneuil-sur-Marne
Motion Simulators & Stabilized platforms



Saint-Germain-en-Laye
Headquarters
Navigation



Besançon
Integrated Optics

Six-Fours-Les-Plages
Artificial Intelligence
Robotics

La Ciotat
Sonars
Sea Operations
Shipyard

√ Cold atoms in Bordeaux

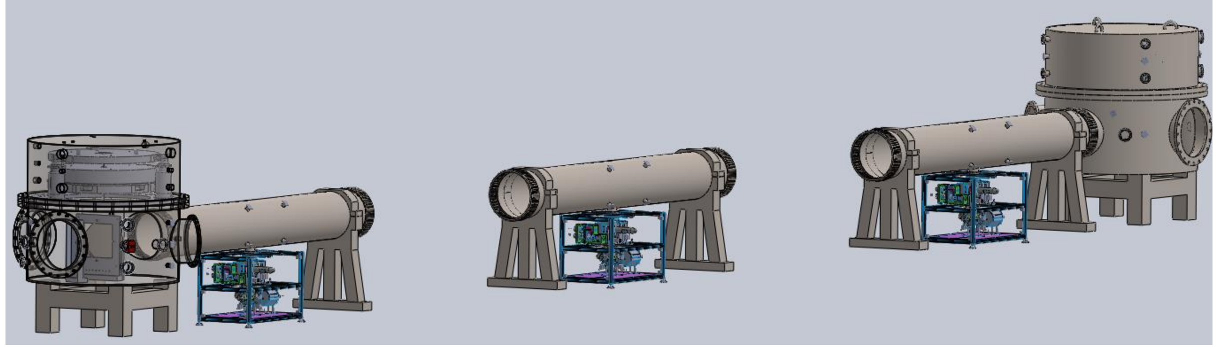
√ Key words:

⇨ **Matter waves**

⇨ **Cold atom interferometry**

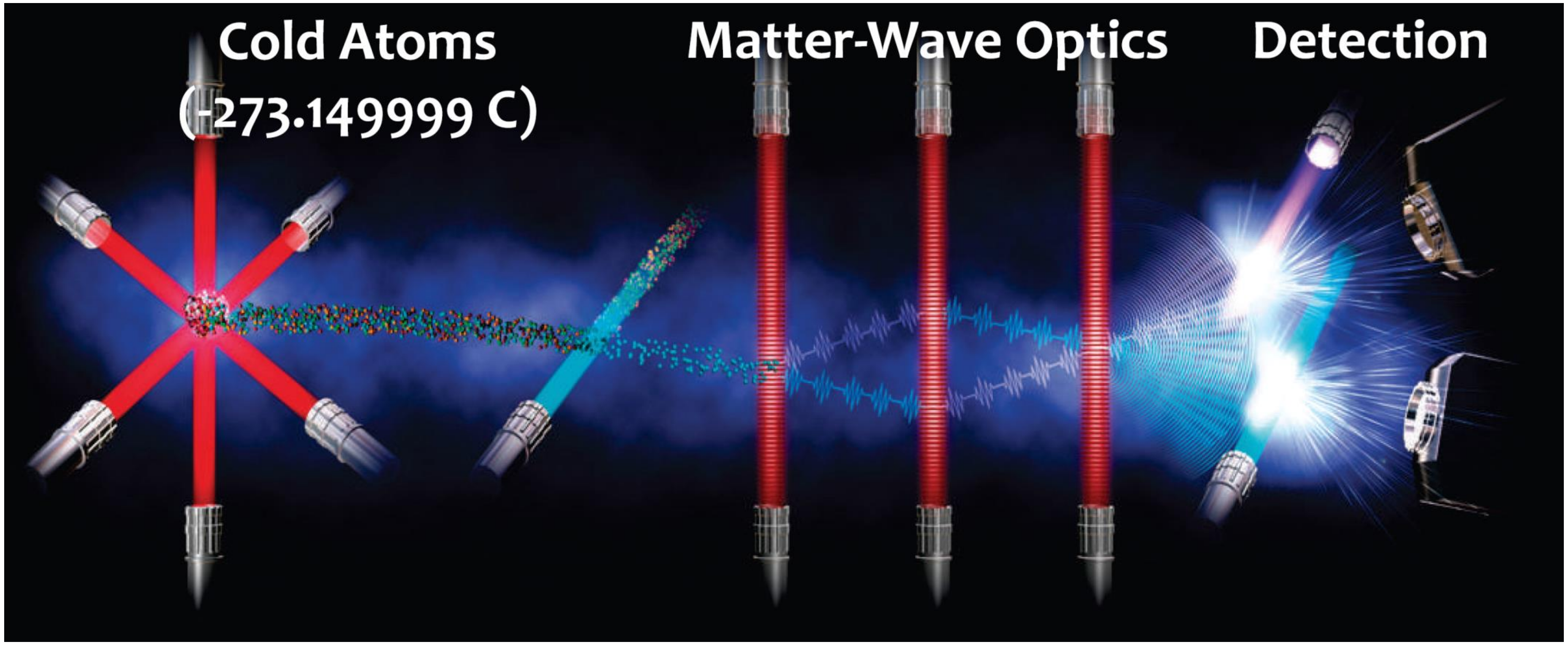
⇨ **Quantum simulation**

⇨ **Quantum metrology**



QUANTUM SENSORS: COLD ATOM INTERFEROMETERS

- Cold atoms (T~µK) are free-falling under vacuum.
- Acceleration is measured by imprinting the phase of a laser on the atomic wavepackets at 3 different times.



INSTITUT d'OPTIQUE GRADUATE SCHOOL

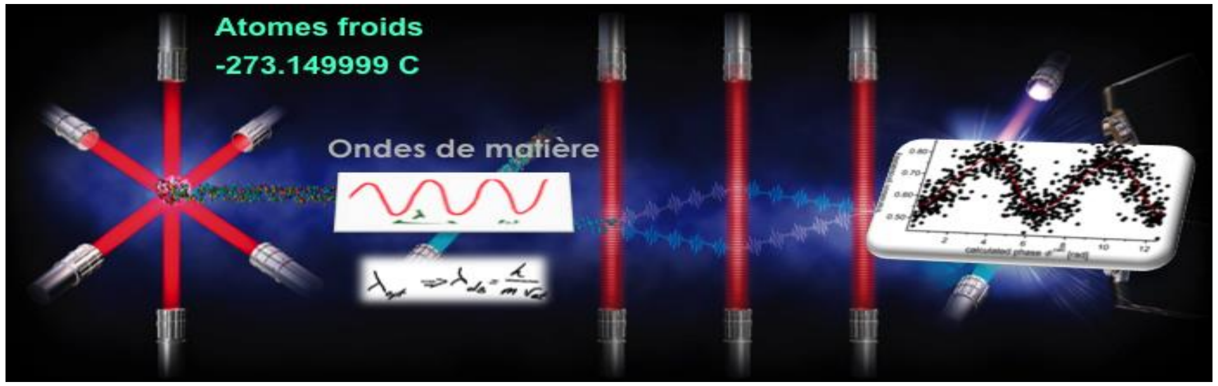
iXAtom JOINT LABORATORY

cnrs

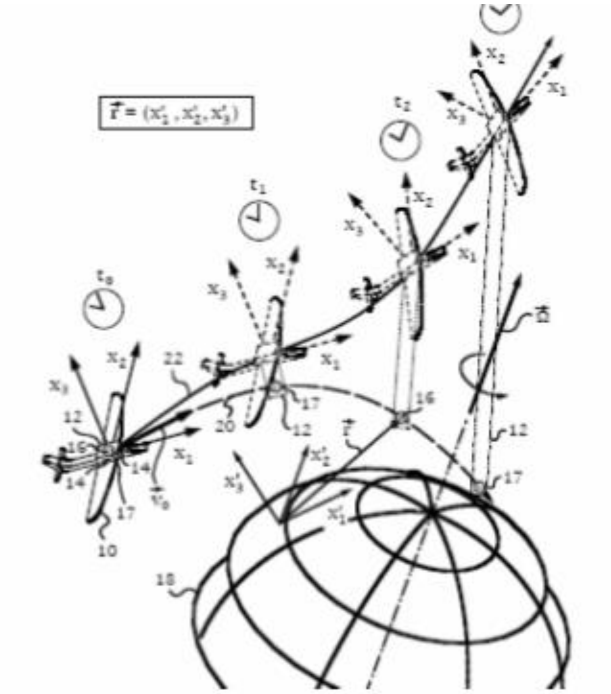
université de BORDEAUX

- Cold atoms: high sensitivity, high accuracy, high stability

- Joint Laboratory (Inertial Quantum Sensors for Position and Navigation)



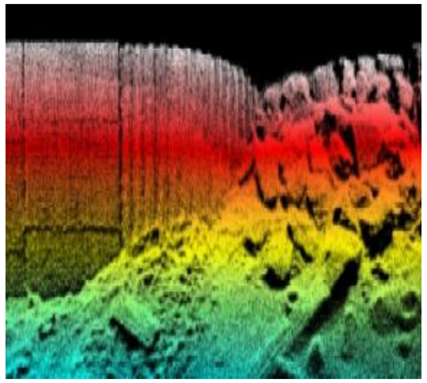
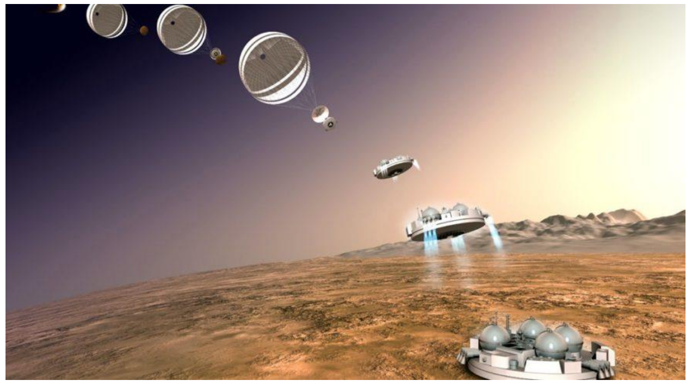
  - Institut d'Optique: atom interferometry
  - iXBlue: optical gyroscopes, photonics and inertial navigation



Inertial Navigation

Applications

- Land and sea mapping
- Space
- Geophysics survey
- Defense
- Autonomous vehicle

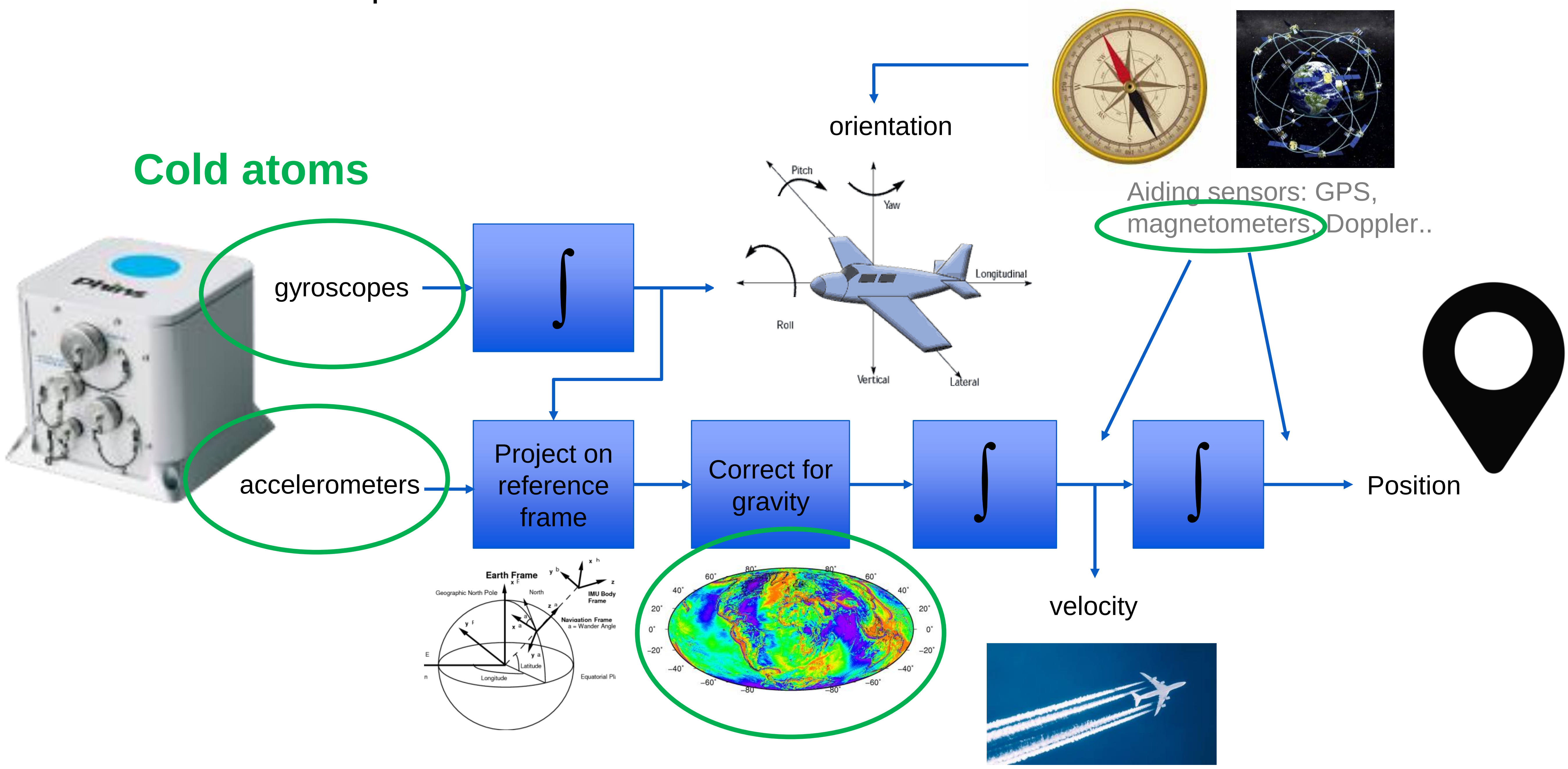



Advantages

- Autonomous system
- Higher resolution than GNSS
- Orientation and velocity information

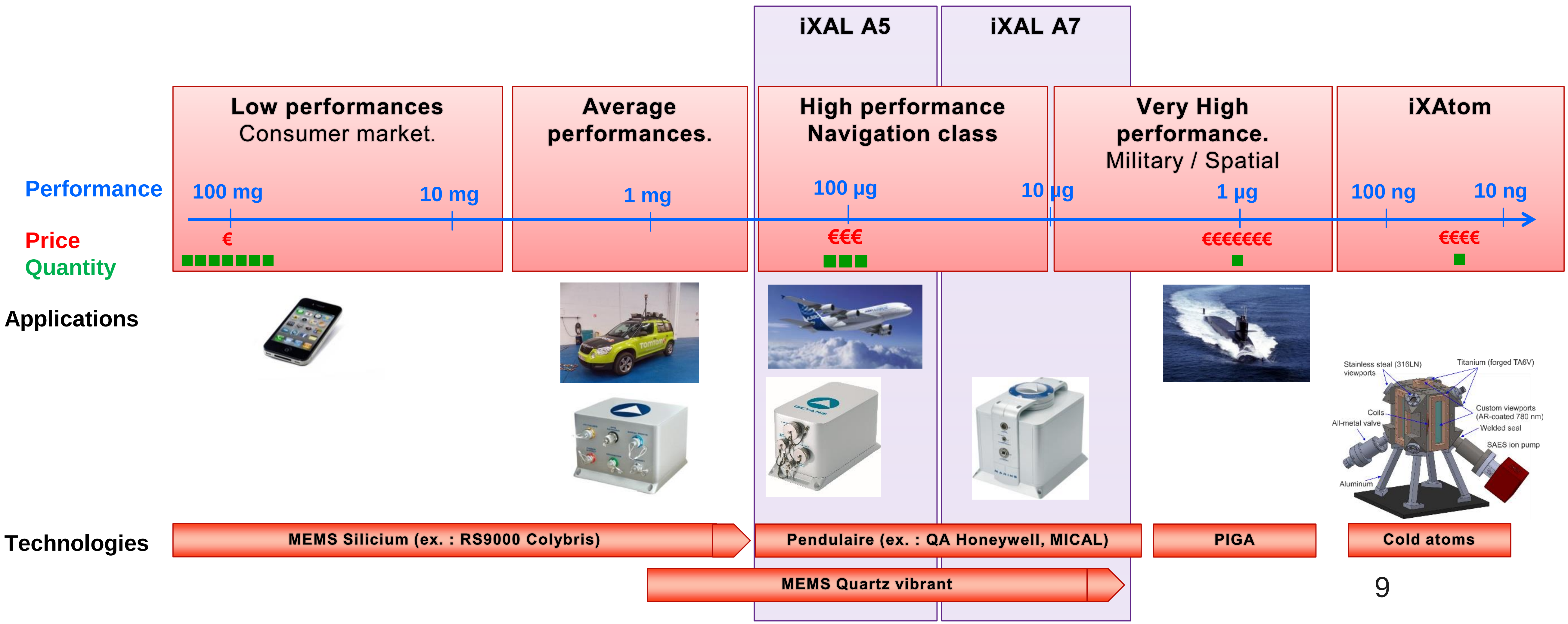

STRAPDOWN INERTIAL NAVIGATION

- Autonomous and quiet

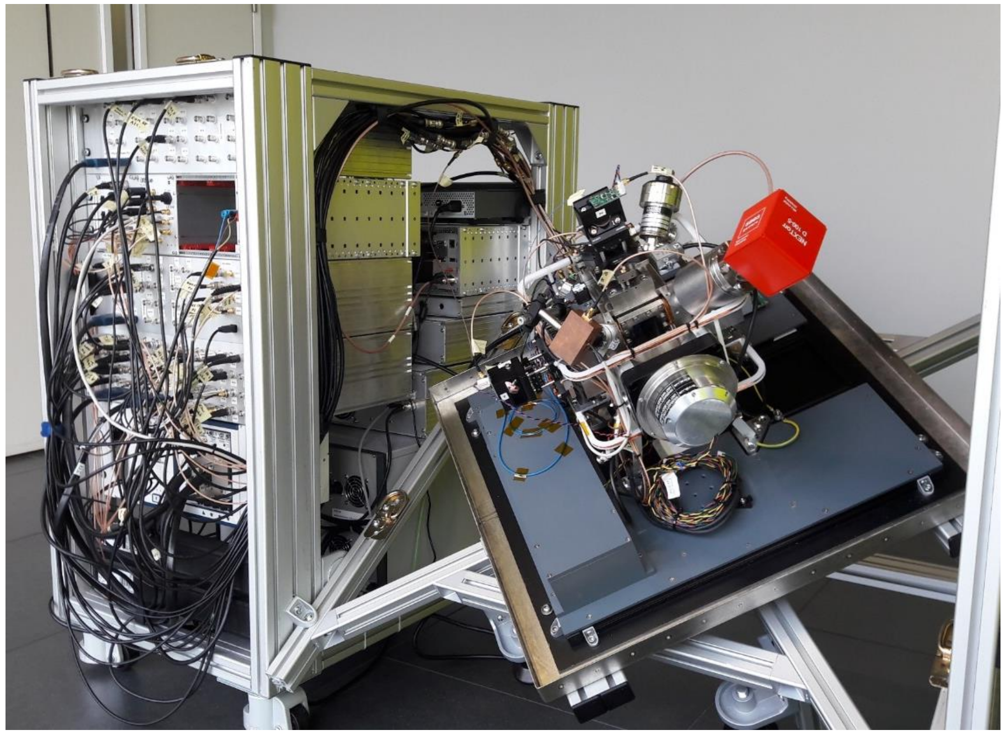


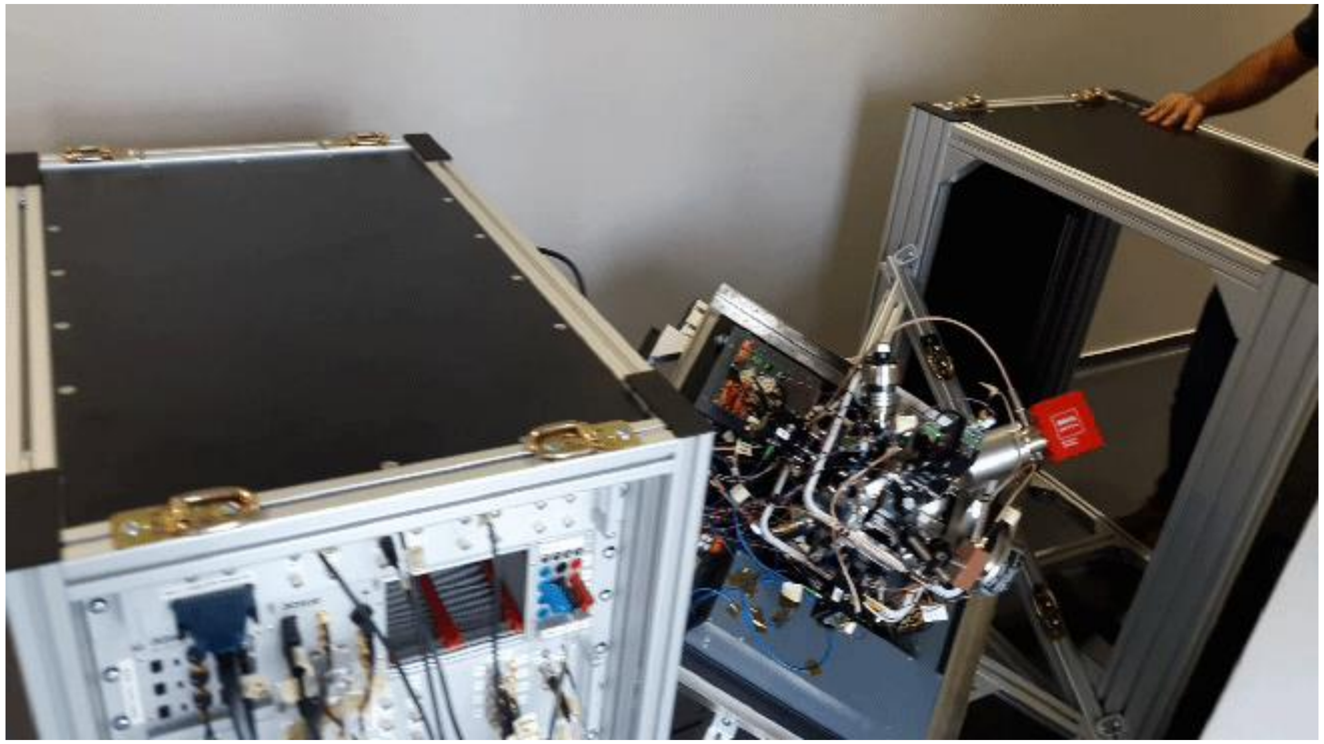
EXPECTED PERFORMANCES

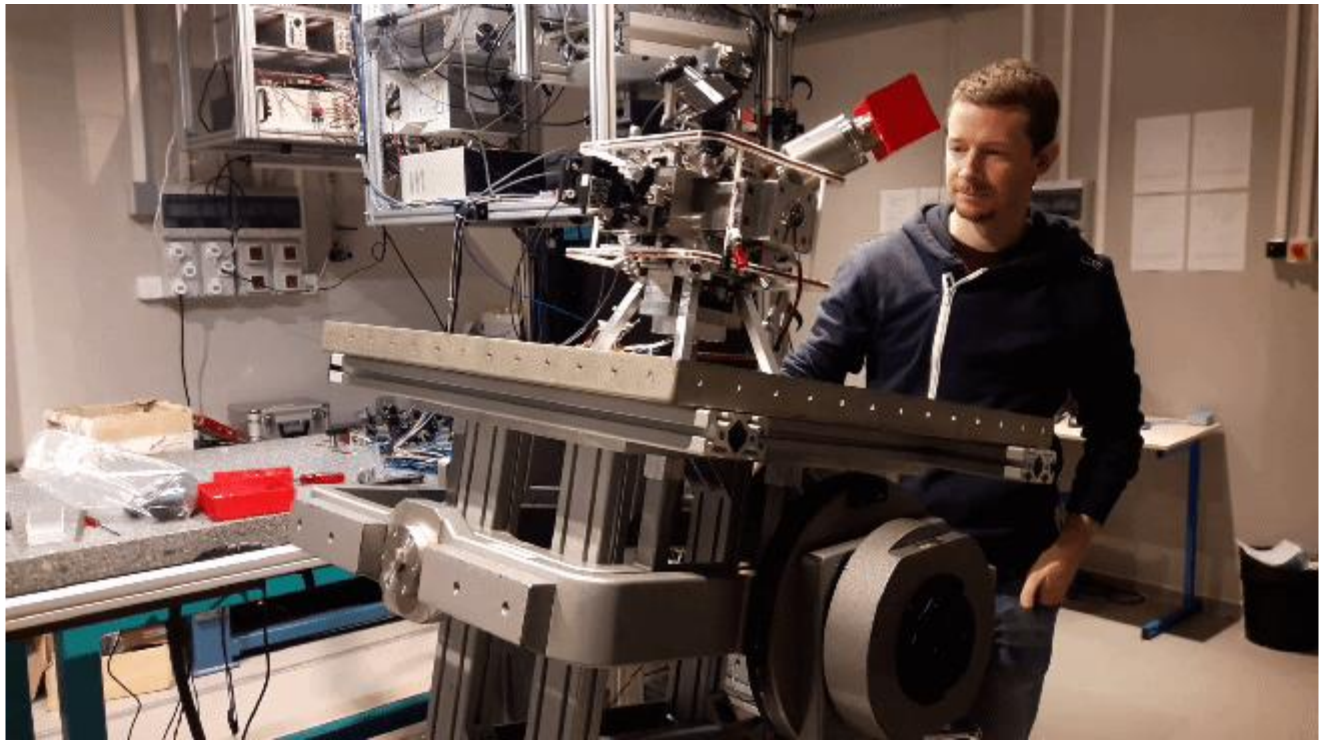
- Long term goal: “GNSS-free” navigation
- Bias free accelerometer
- Ultra high performance



Transportable 3D Accelerometer







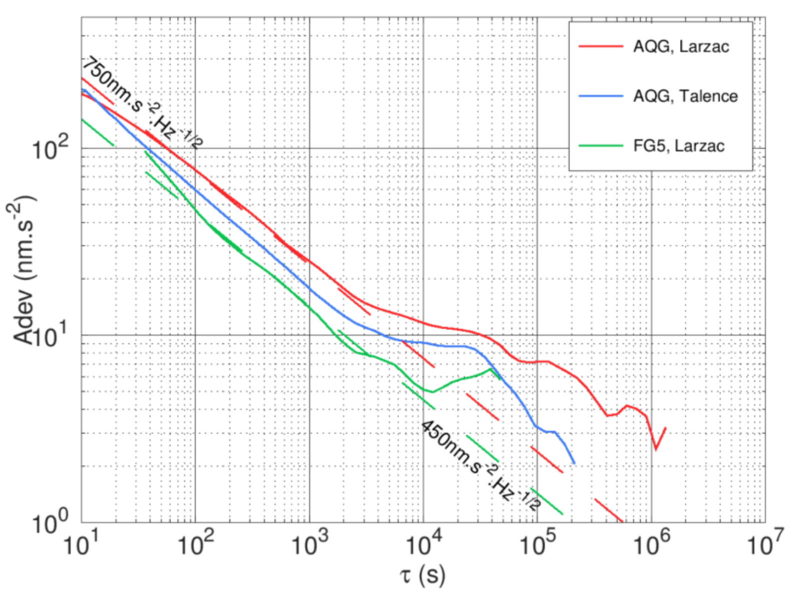
Ideal platform to tackle three main challenges of strapdown cold atom sensors:

- Multi-axis measurement
- Vibrations
- Rotations

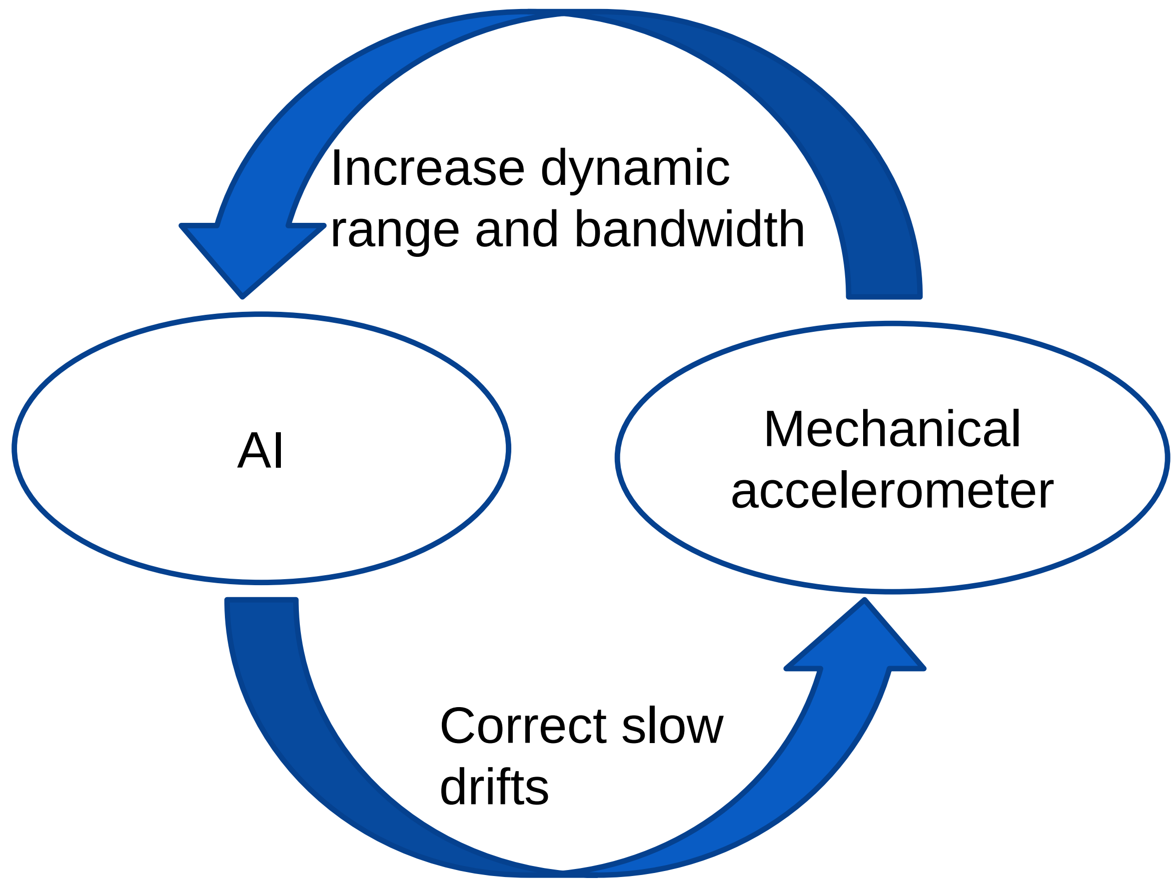
REAL TIME COMPENSATION OF VIBRATIONS AND ROTATIONS

DOUBLE HYBRIDIZATION

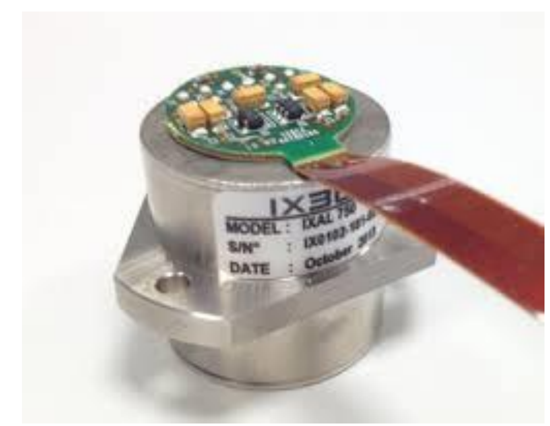
Large sensitivity
Very good stability



V. Menoret *et al,* Sci. Rep **8**,12300 (2018)

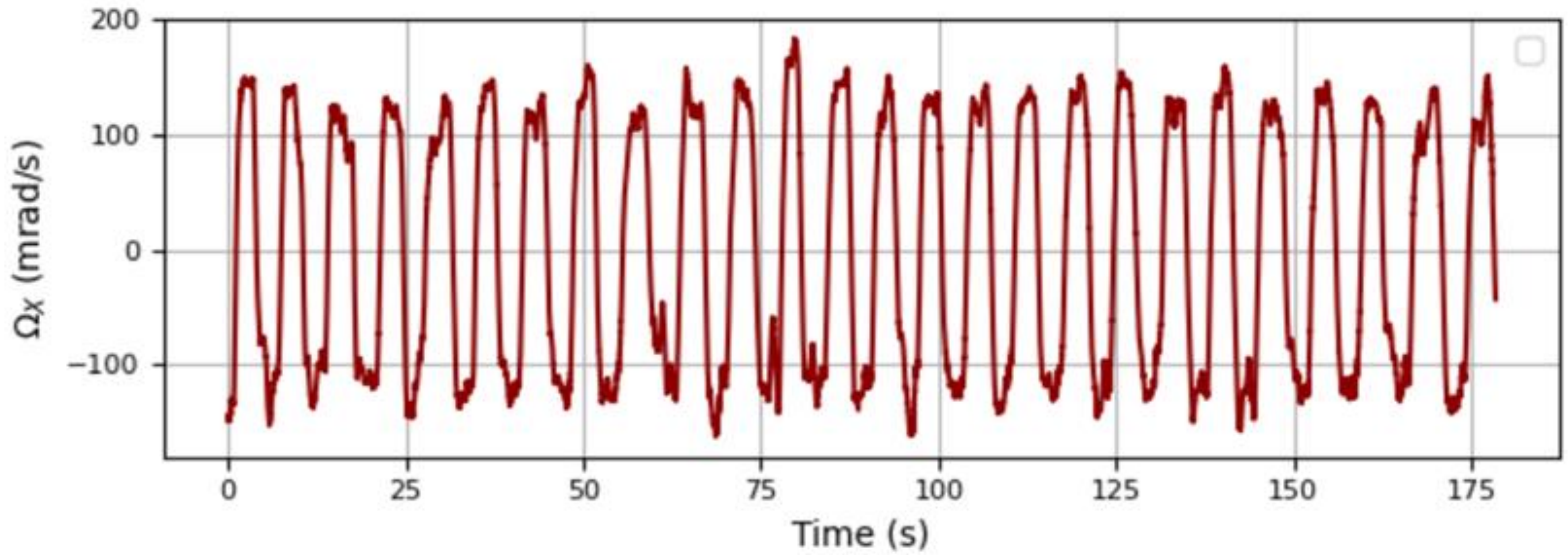


Large bandwidth
No dead time
Linear response

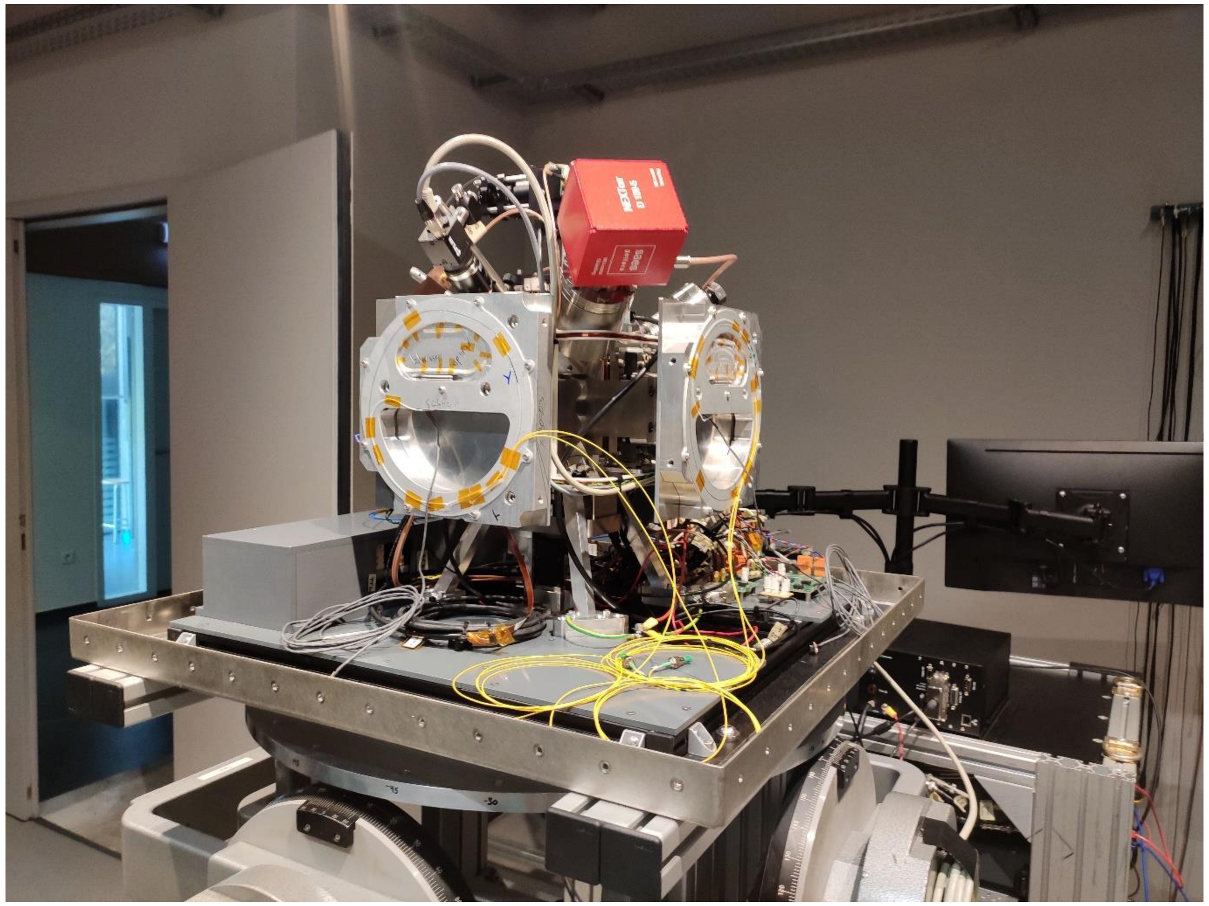


Bias drifts

Dead times
Low data rate
Limited dynamic range



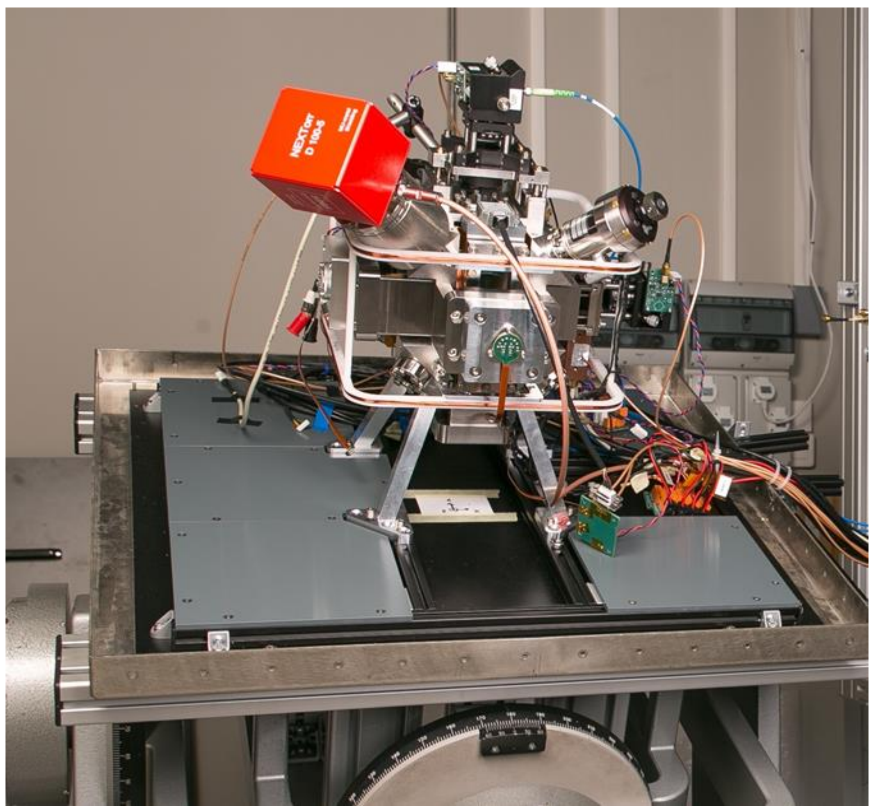
- Rotation rate measurement with
  Fiber-Optics Gyroscopes
- **Real-time** correction (FPGA) of the mirror orientation with a piezo tip-tilt stage

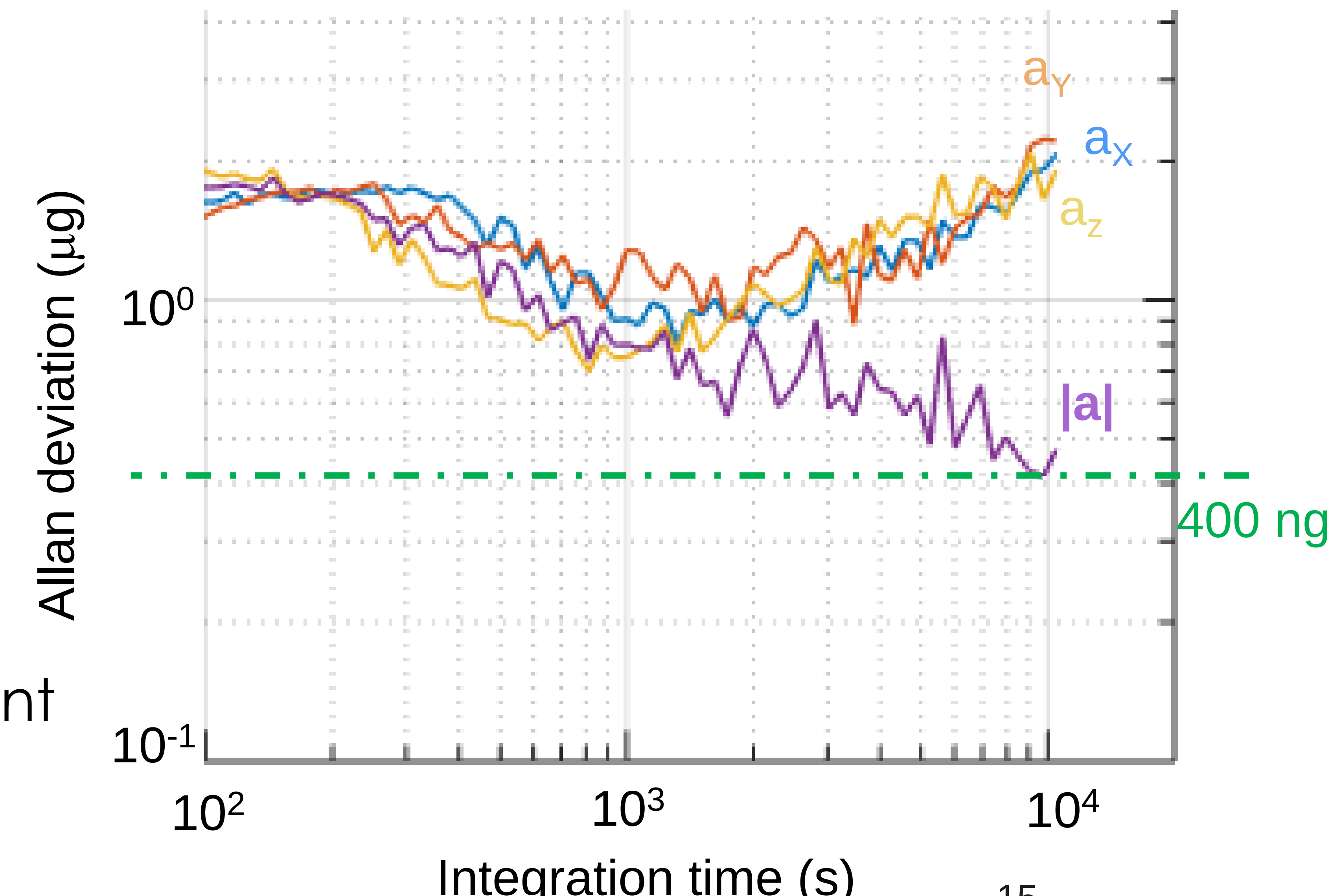


3D "STRAPDOWN" ATOM ACCELEROMETER FOR GRAVITY MAPPING/MATCHING

3D ATOM ACCELEROMETER

- Alternative measurement of the **three** axes ($\theta_{x,y,z}$~ 45° with the vertical) and the norm of the vector |**g**|
- Tilt of the experiment is drifting $\delta\theta$~6μrad over 10 hours

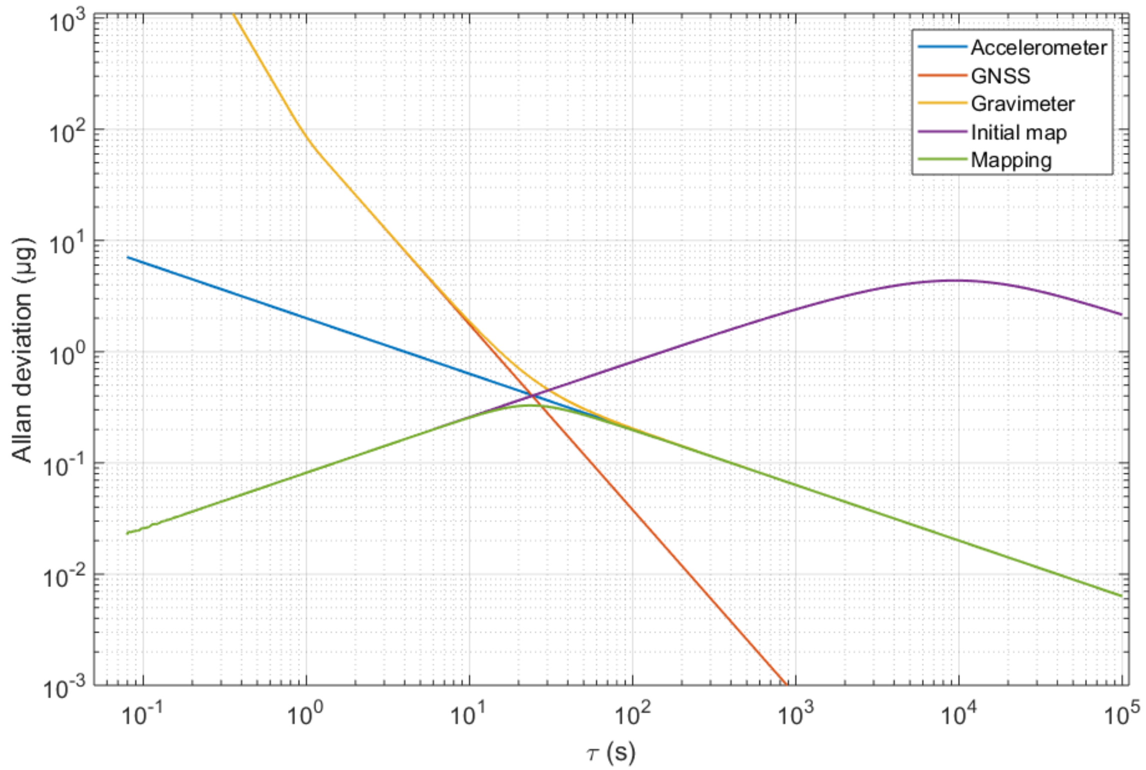




- Simultaneous measurement possible

TO BE PUBLISHED

GRAVITY MAPPING WITH A BIASLESS ACCELEROMETER



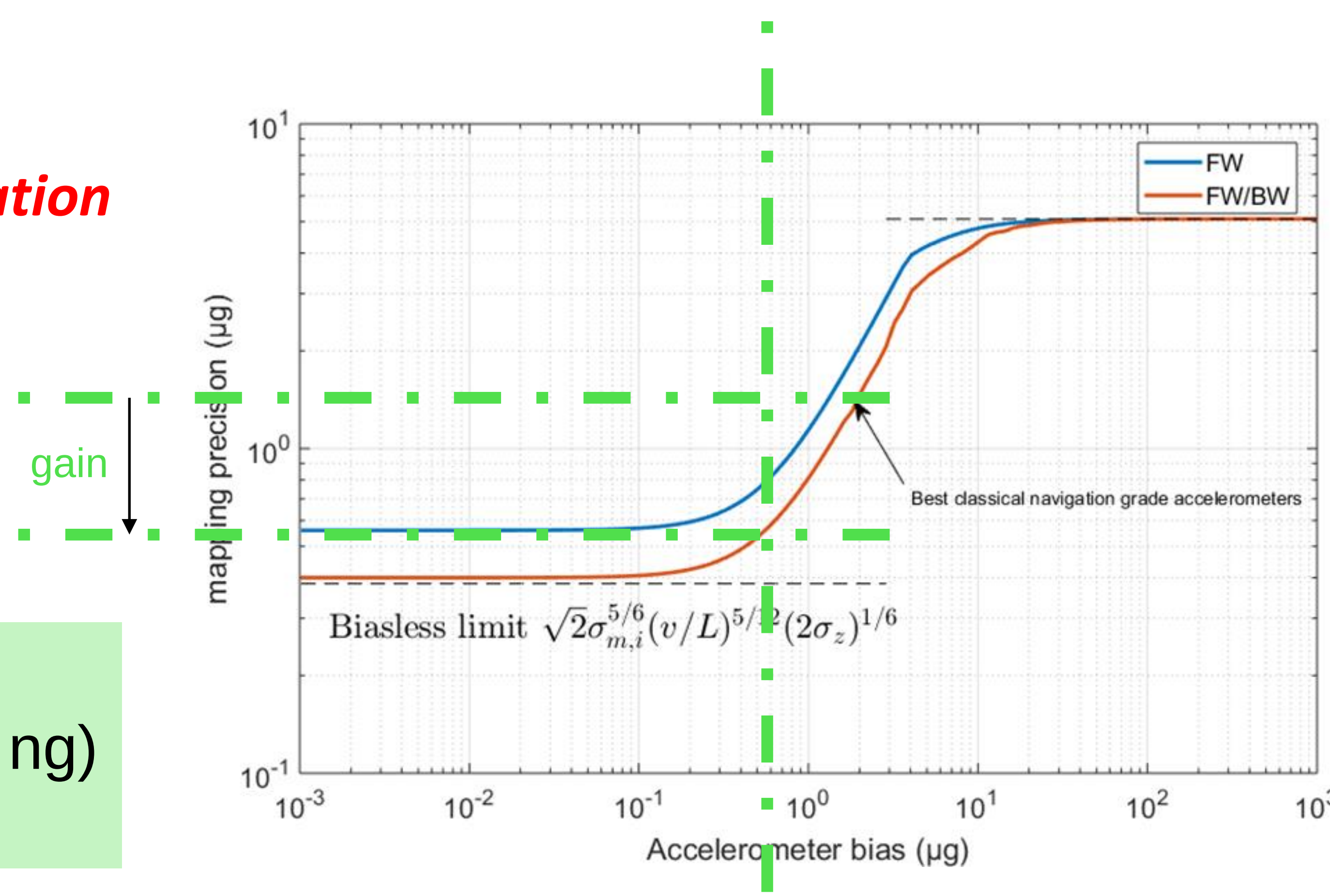
-GNSS signal provides direct position information with a position (white) noise σ_z $g = (\ddot{x}_{GNSS} - a_{acc})$

- Initial gravity map EGM2008 characterized by an error standard deviation $\sigma_{m,i}$ and a correlation length L_{corr}.

$$v = 2m/s \quad \sigma_n = 2\,\mu g/\sqrt{Hz} \quad \sigma_{m,i} = 5\,\mu g$$

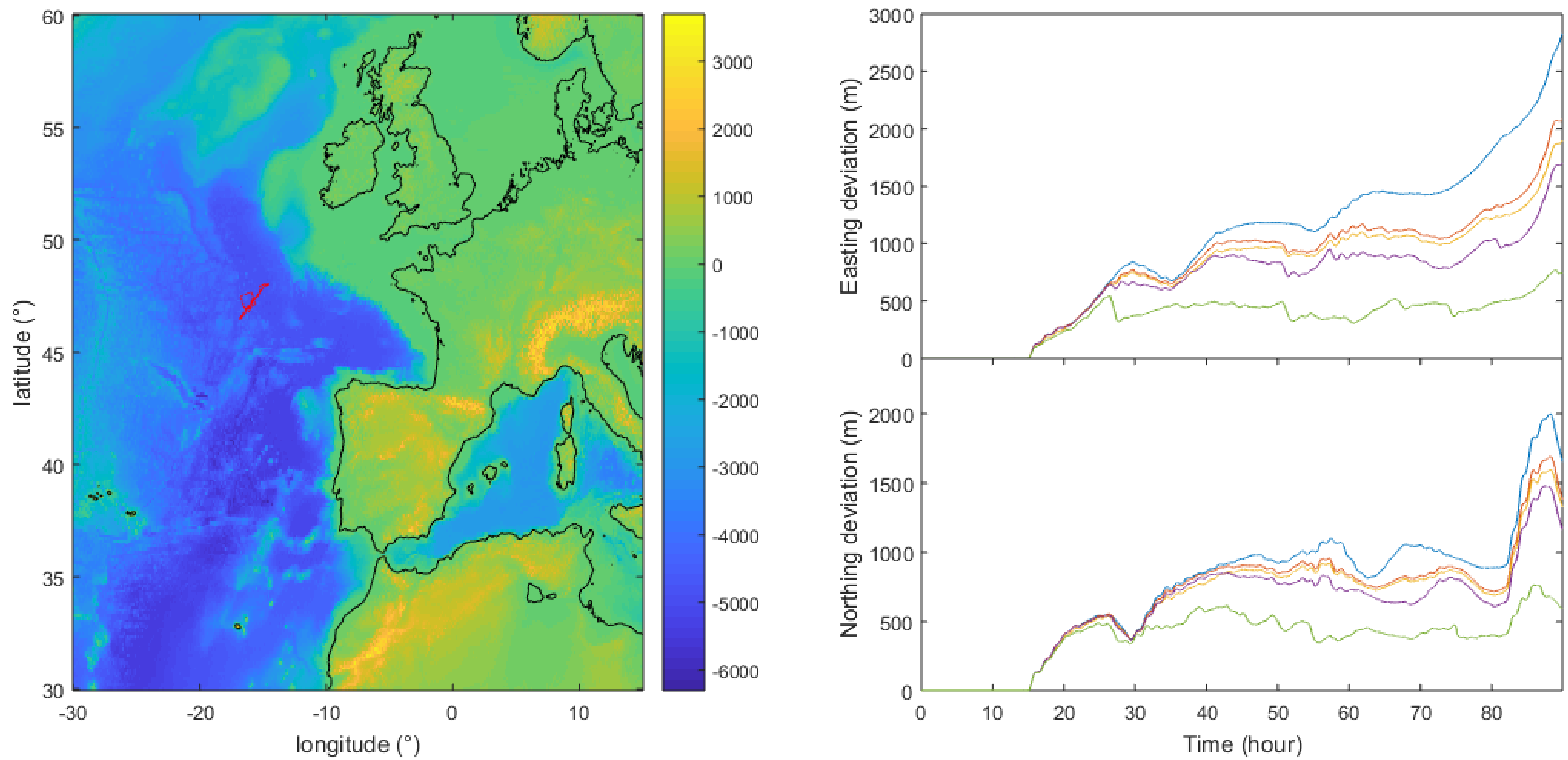
$$L_{corr} = 10\,km \quad \sigma_z = 1\,mm/\sqrt{Hz}$$

➢ ***Perfect accelerometer: 370 ng with a correlation length of 100 m***



Performances of our hybrid accelerometer:

Long term stability: 200 ng
Bias uncertainty: 700 ng (vertical axis 500 ng)
Goal : 500 ng (calibration improvement)



	Gravity Matching		Accelerometer	Gravity map
Blue	No		Classical	EGM2008 (5 µg)
Red	Yes		Classical	EGM2008 (5 µg)
Yellow	Yes		Quantum	EGM2008 (5 µg)
Purple	Yes		Classical	Improved map (1 µg)
Green	Yes		Quantum	Improved map (1 µg)

It requires a better map to benefit from the absolute character of the quantum accelerometer

Conclusion

- ✓ 3D strapdown atom interferometer: from the laboratory to the first industrial prototype

DGA

AGENCE NATIONALE DE LA RECHERCHE ANR

esa

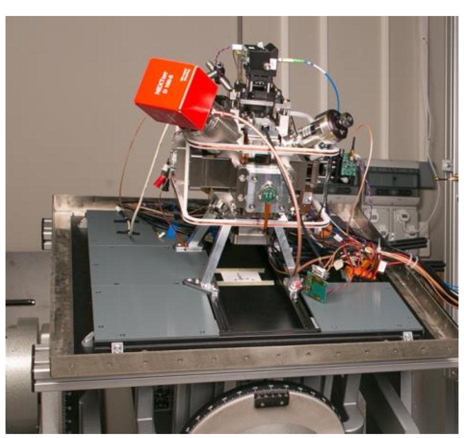
- ✓ Proof of concepts for real time compensation of vibrations and rotations
- ✓ Classical/quantum sensors hybridization

- ✓ Tests on the field (onboard)
- ✓ Exploration of « not so mature » technology: atom chips, ultra-cold atoms, 3D atom interferometry, miniaturized laser source

ROADMAP

2016 — 2020 — 2023 — 2025 — 2030 — 2035

2020: Bias free 3D accelerometer

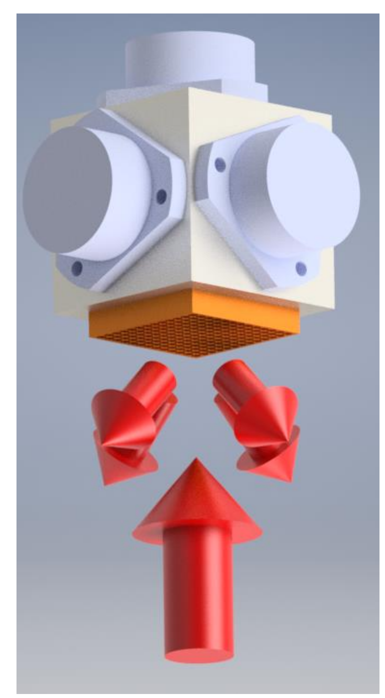


2023: Starting a gyroscope activity

2023: Bias free 3D accelerometer on the field

Gravity mapping
Gravity matching
Navigation

2025: Miniaturized accelerometer



2030: First gyroscope prototype

2030: First Space atom accelerometer

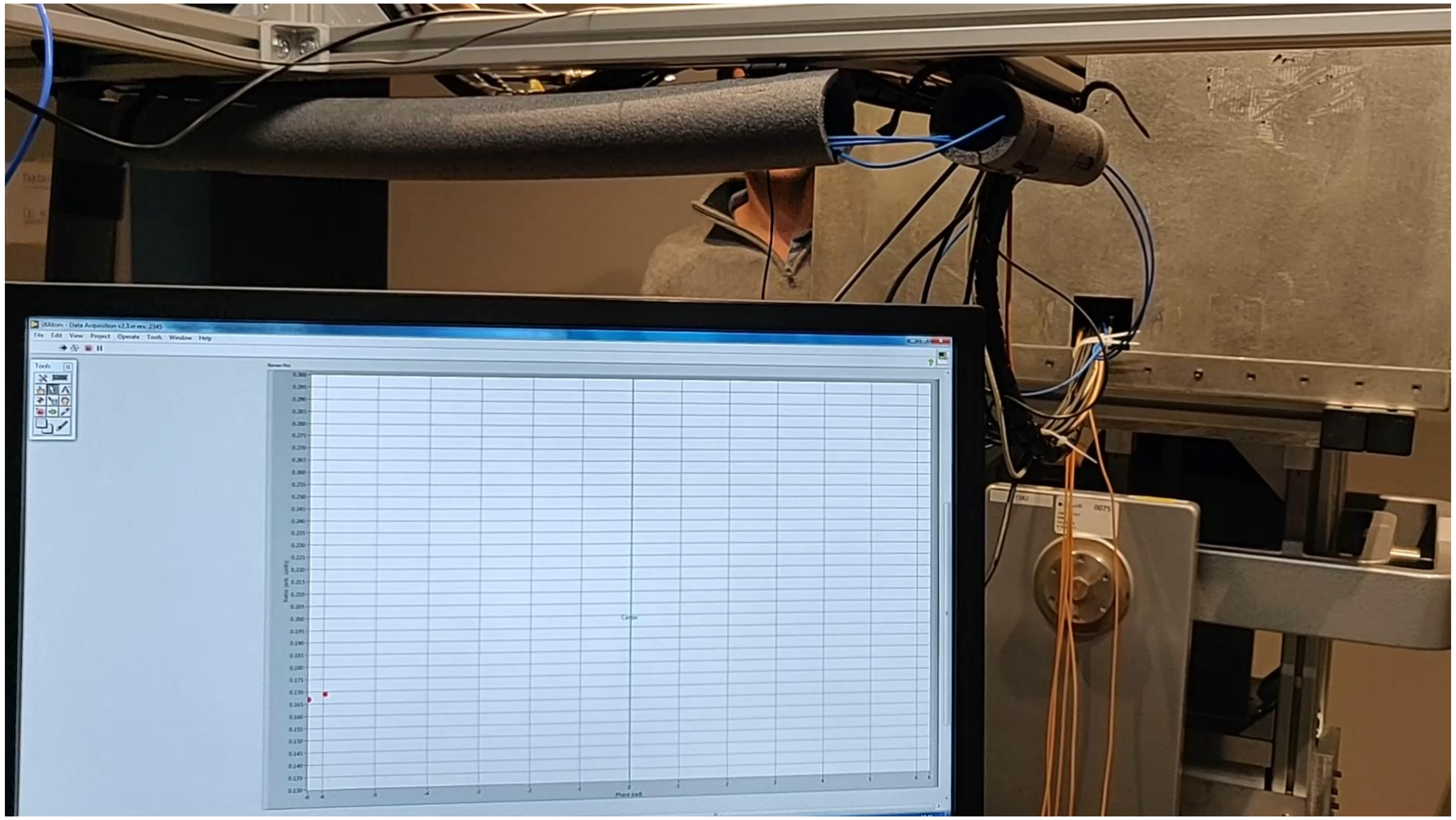
Space applications

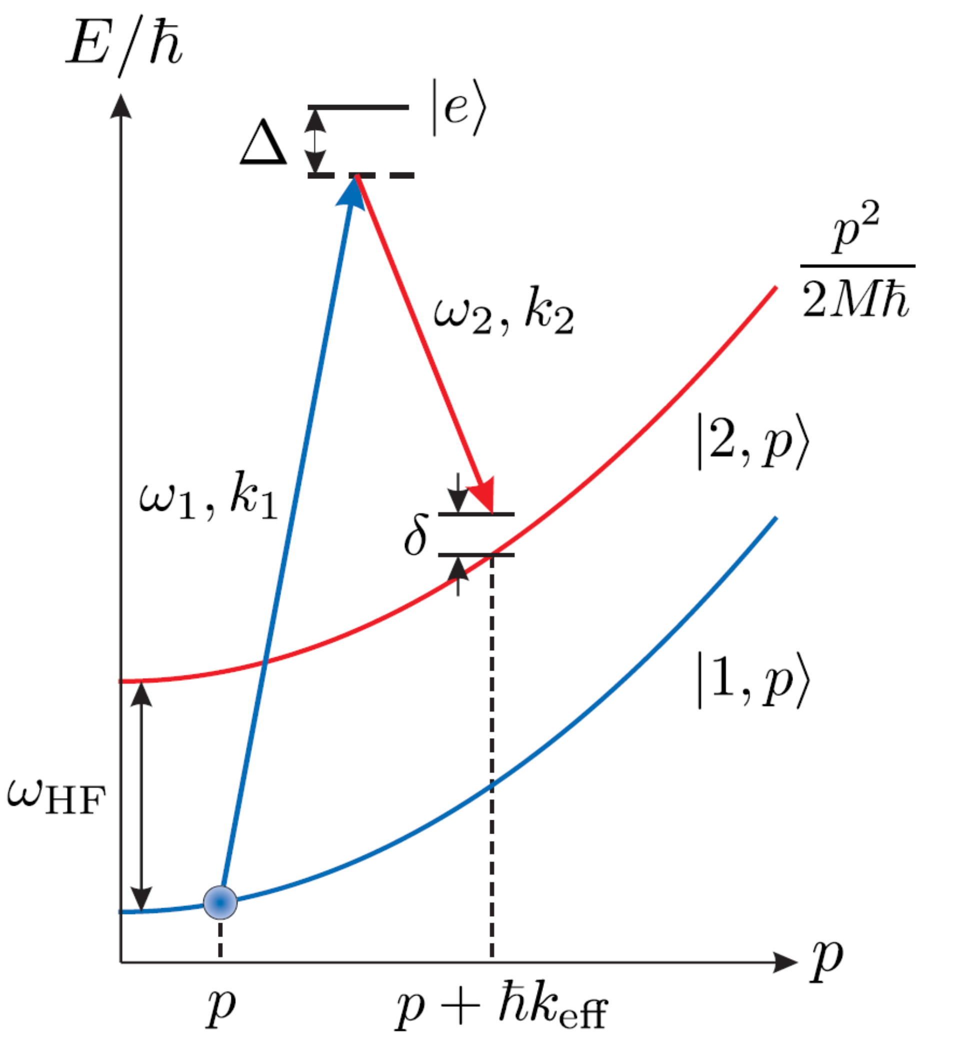
2035: gyroscope on the field

Navigation

BACKUP

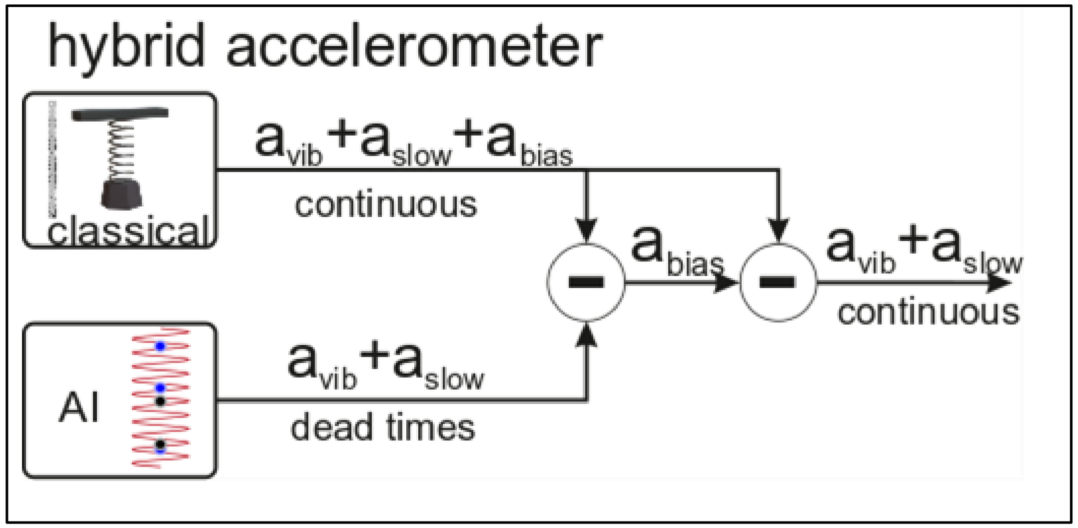
ATOMIC FRINGES WHILE ROTATING THE SENSOR HEAD



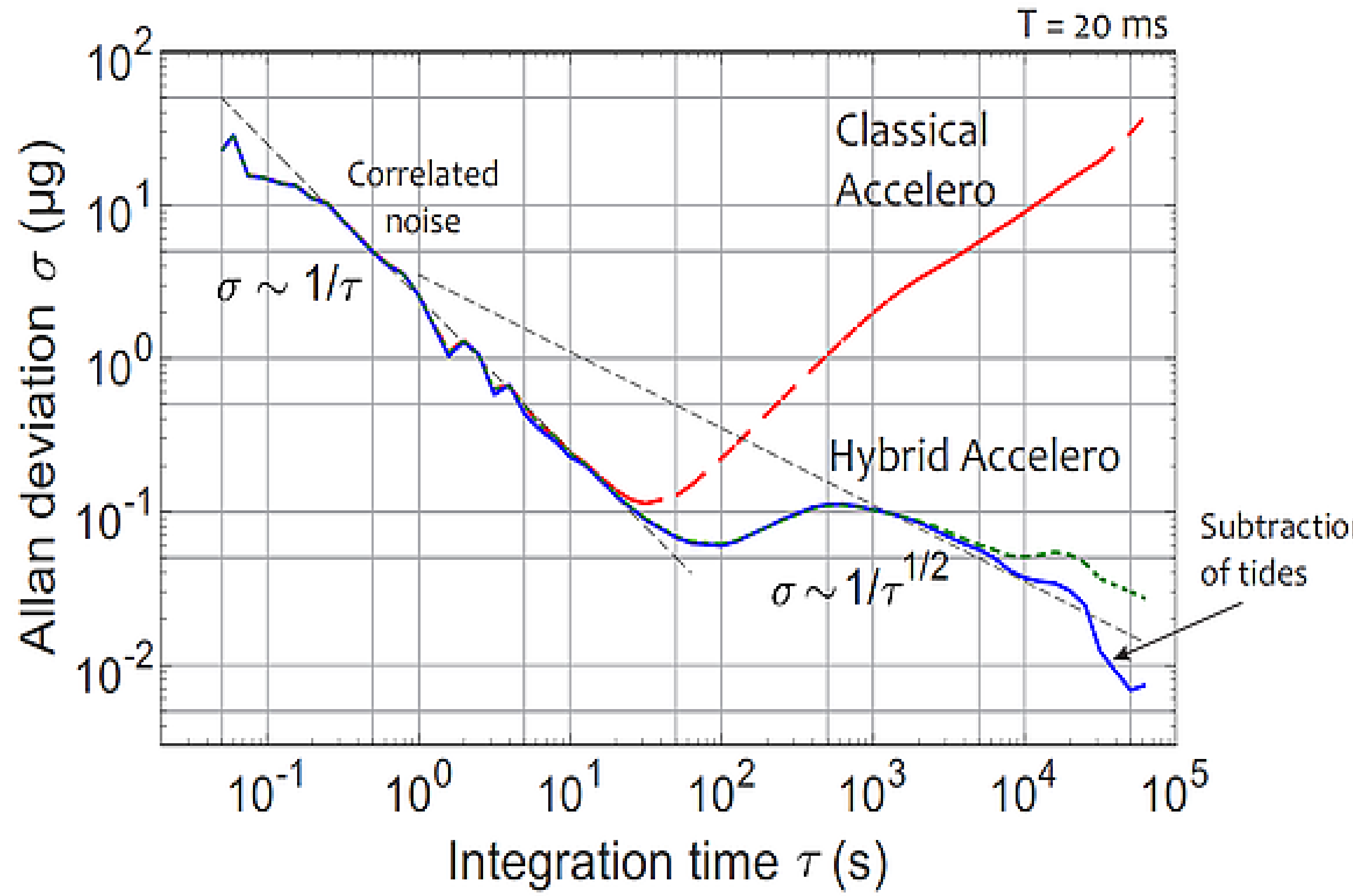


$\delta_D = k_{eff}\, g \cos\theta(t)\, T^2$ *corrected in real time!*

FULL HYBRID SENSOR



- Bias subtracted from the classical accelerometer output



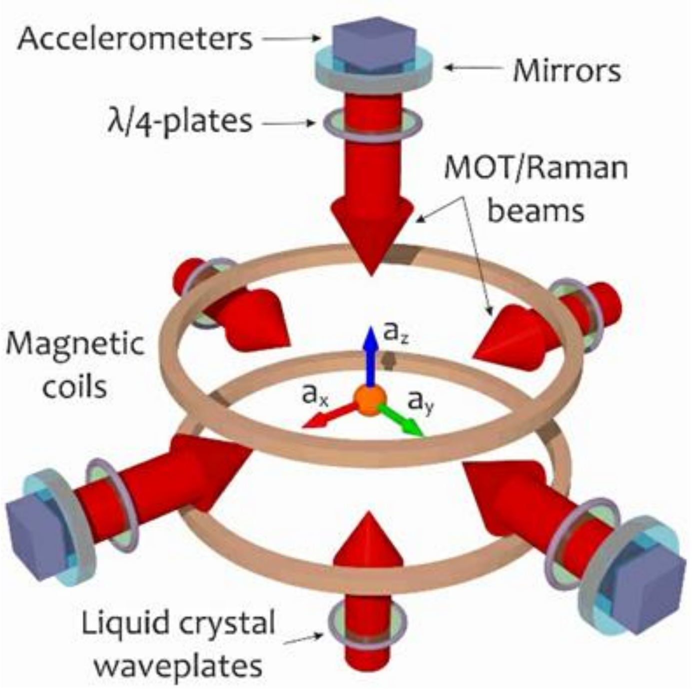
- Hybrid sensor:
  - High bandwidth
  - Stability ~10 ng
  - Sensitivity (long-term): $3{,}2\ \mu g/\sqrt{Hz}$

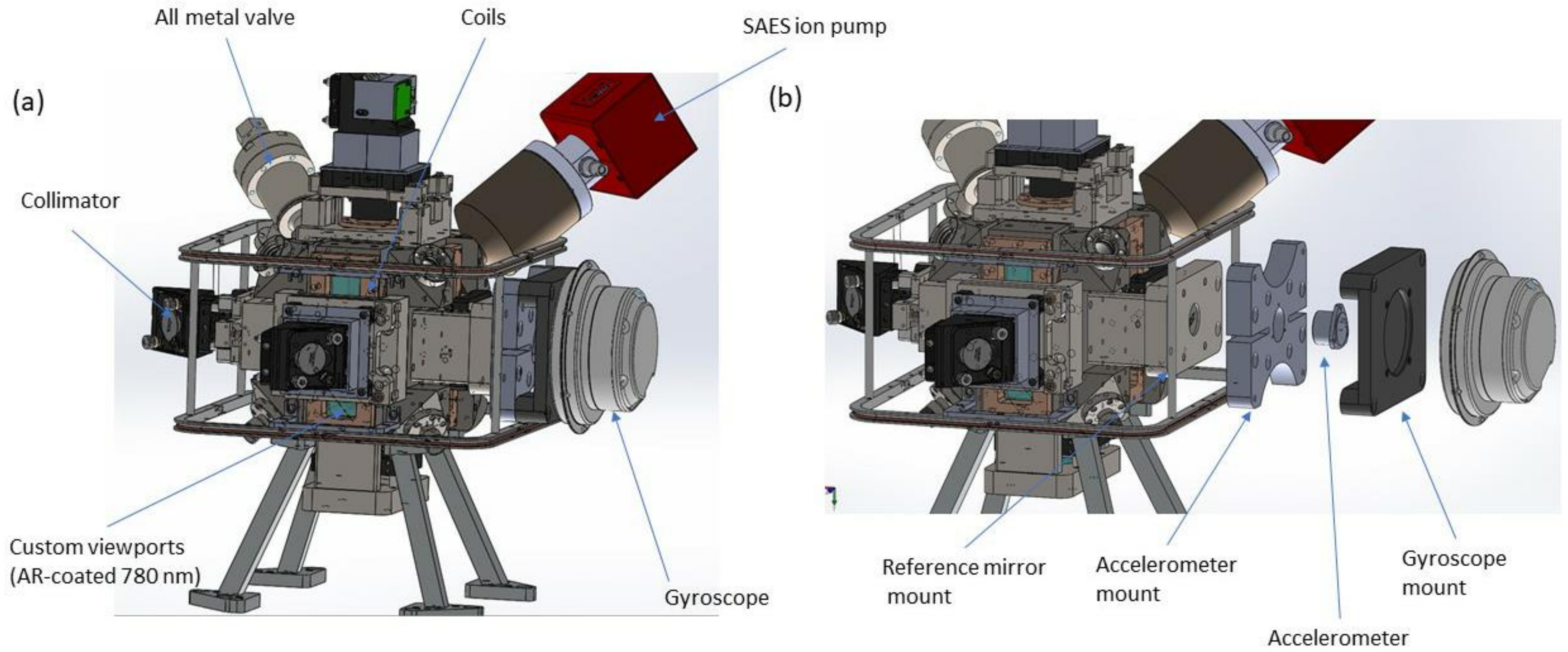
P. Cheiney *et al*, *Phys. Rev. Applied* **10**, 034030 (2018)

REAL TIME COMPENSATION OF ROTATIONS

3D ATOM ACCELEROMETER

- Use the same beam for cooling and the Raman atom interferometer along the 3 axes
- Compact sensor head using state of the art technology





Loss of contrast due to strong rotations

- Lagrangian for a body undergoing rotations and linear accelerations

$$L(\boldsymbol{r},\boldsymbol{v}) = \frac{1}{2}M(\boldsymbol{v}+\boldsymbol{\Omega}\times\boldsymbol{r})^2 + M\boldsymbol{a}\cdot\boldsymbol{r}$$

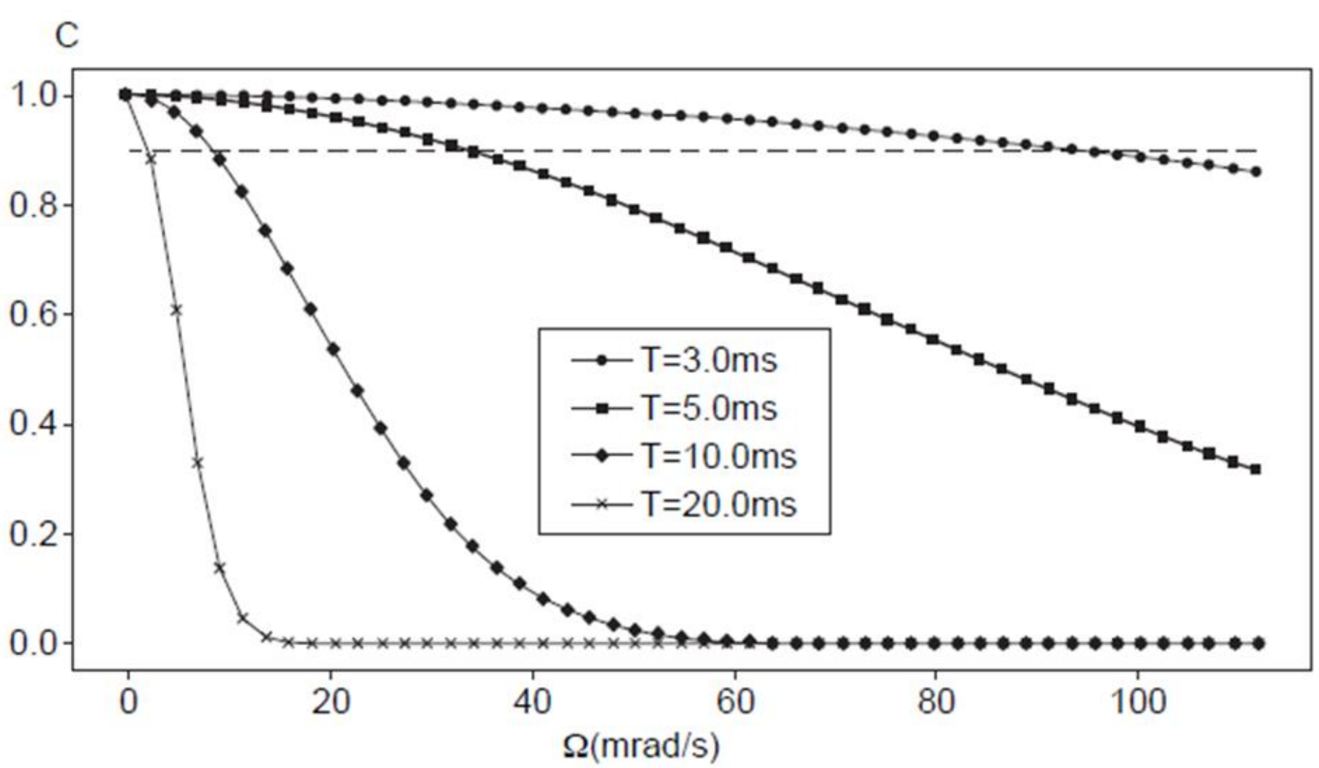
- Evaluate interferometer trajectories and insert into Roura model: [Roura2014]

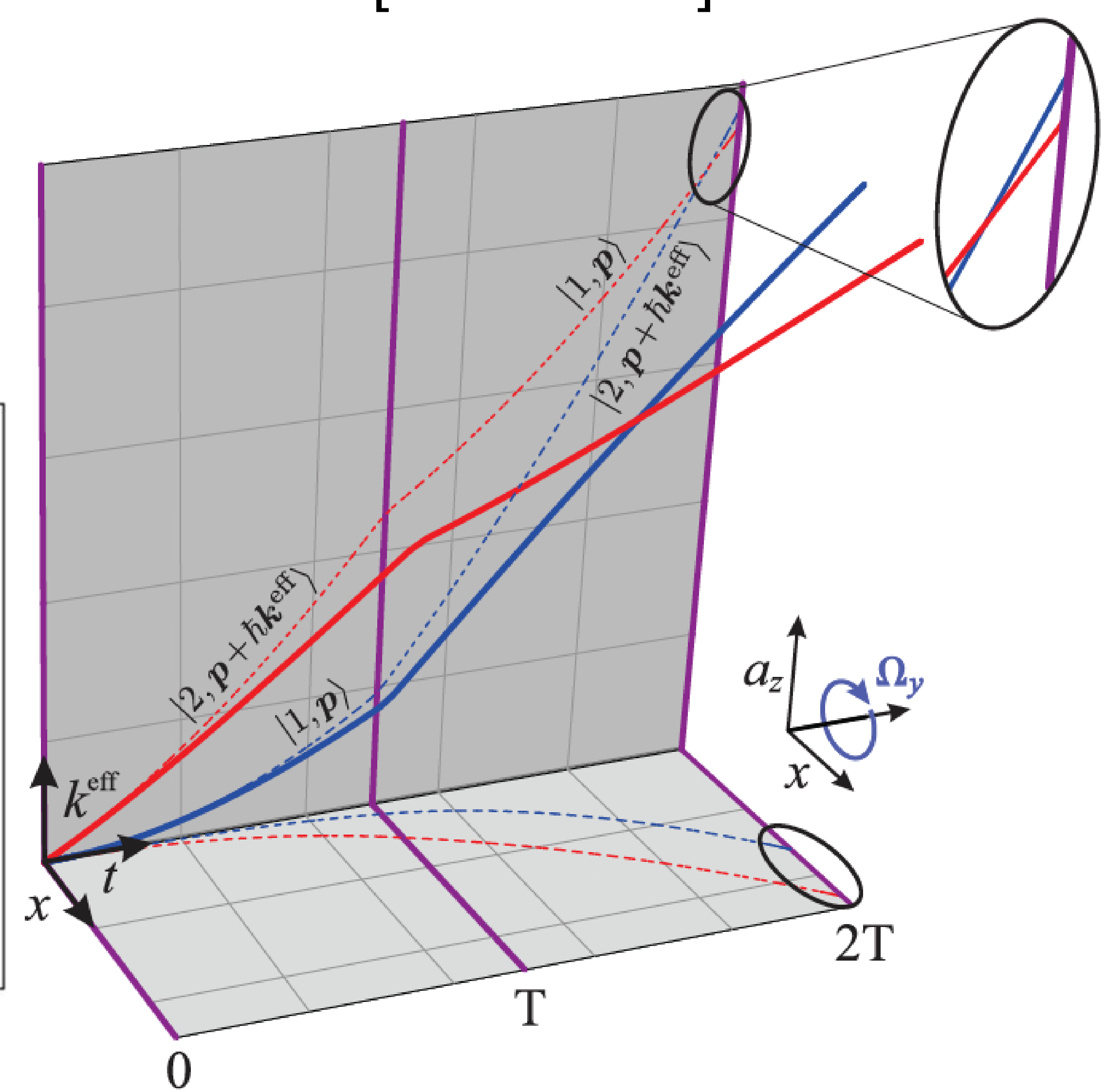
$$C \sim \exp\left[-(k_{\text{eff}}\sigma_v T)^2\,(|\boldsymbol{\Omega}_{\text{T}}|T)^2\right]$$

Velocity spread

Interrogation time

Rotation rate transverse to $\mathbf{k}_{\text{eff}}$

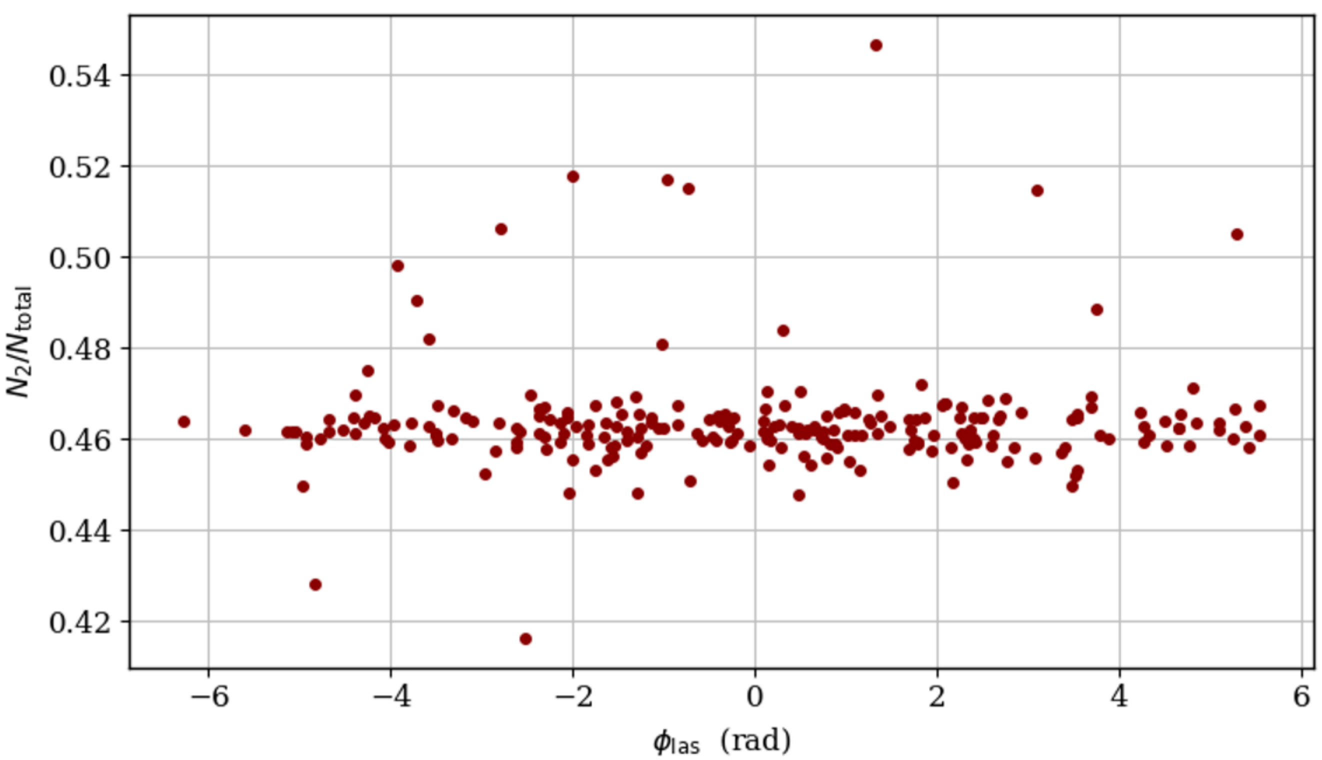


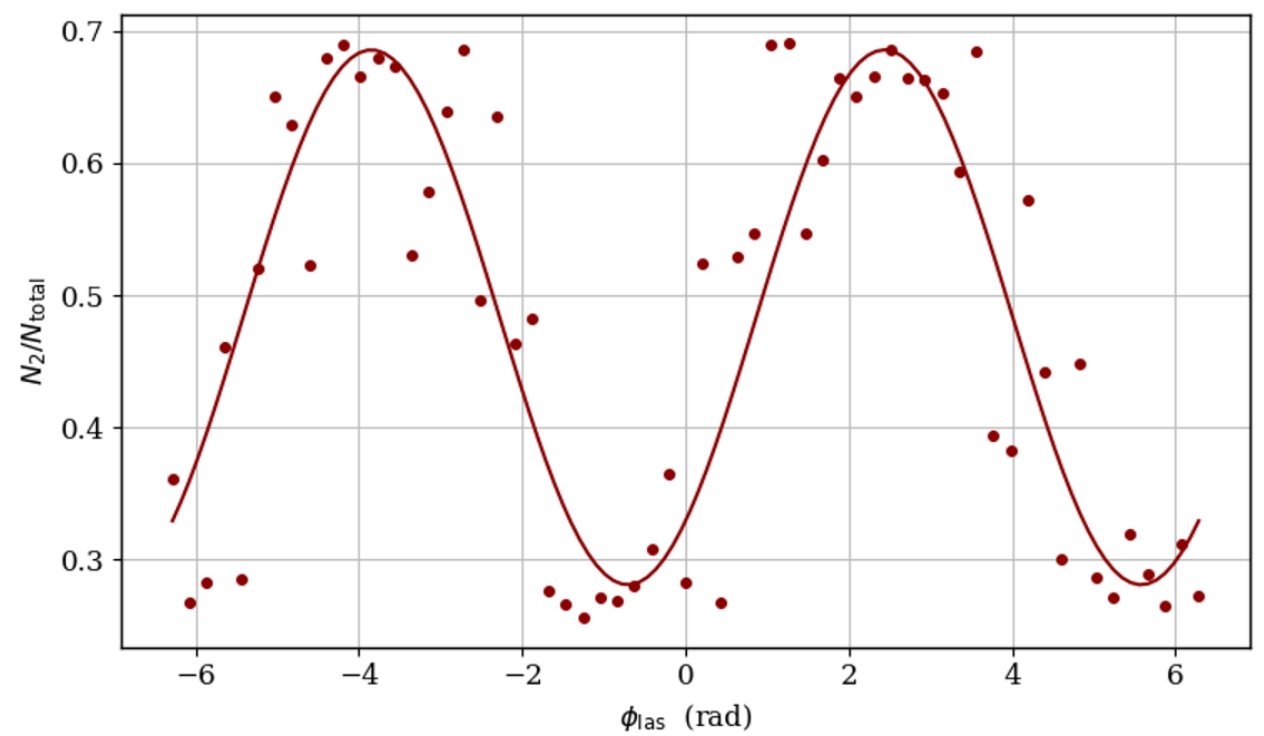


[Roura2014] A. Roura, W. Zeller, and W. P. Schleich. Overcoming loss of contrast in atom interferometry due to gravity gradients. New Journal of Physics, 16:12312, 2014

REAL TIME COMPENSATION OF ROTATIONS

- Full contrast retrieval for any rotation rate and interrogation time
- **Visible fringes without additional phase correction for:**
  - Rotation rates up to 100 mrad/s
  - **Interrogation times up to 10 ms**





- Next step: real time correction of the residual Coriolis phase

PATENT FR2203057 4th April 2022