Towards a two-axis cold-atom gyroscope for rotational seismology

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Context

- Cold-atom interferometry: 1991
- 2020: more than 45 research groups (academic) and 7 companies
- **Main idea:** use well-controlled atoms and light-matter interaction to measure accurately inertial signals → same spirit as for atomic clocks
- Target applications:
  - Tests of fundamental physics (quantum mechanics, relativity)
  - Metrology (kg, G, α)
  - Geosciences
  - Inertial navigation?
  - Gravitational wave detection?

Outline

• Few examples of important achievements
• Principle of light-pulse atom interferometry
• High-stability cold-atom rate gyroscope
Famous example: the gravimeter

- First participation to international comparisons of absolute gravimeters (2009)
- State-of-the-art accuracy: $1.2 \times 10^{-9} \text{ g}$ (stability $< 10^{-10} \text{ g}$)
- Used in the French Kibble Balance for the realization of the kg

*SYRTE ultracold-atom gravimeter: R. Karcher et al, NJP 20, 113041 (2018)*
Onboard atom interferometers

Gravity gradient survey

Kasevich group (Stanford)
X. Wu PhD thesis (2009)

Accelerometer

Absolute marine gravimetry

ONERA team (France)
Nature Commun. 9, 627 (2018)

Bouyer’ group (France)
Nature Commun. 2, 474 (2011)
Simplified principle

Use free falling atoms to read the phase of a laser linked to an accelerated frame

→ Measurement of distances in units of laser wavelength

Number of graduations $\sim \frac{aT^2}{\lambda_{laser}}$

Orders of magnitude:

• $T = 100 \, ms$ ; $\lambda = 0.5 \, \mu m$ ;

• Resolution $\sim \lambda/100$ (SNR = 100)

• 1 measurement per second

→ Acceleration sensitivity $\sim 10^{-7} \, m.s^{-2}/\sqrt{Hz}$
Principle of Atom Interferometry

- Analogy with a Mach-Zehnder optical interferometer
- Use laser pulses to coherently split and recombine an atomic wave

Two-wave interference signal: \( P = P_0 + A \cos(\Delta \Phi) \)
Stimulated Raman transitions

Cesium atom, $D_2$ line @ 852 nm

Momentum transfer

$k_{\text{eff}} = k_1 + k_2 \sim 0.7 \text{ cm/s}$

Laser phase difference imprinted on the atoms

$$\varphi = \phi_1 - \phi_2 = \vec{k}_{\text{eff}} \cdot \vec{r}(t)$$
Interferometer phase

Top path: $\varphi(0) - \varphi(T)$
Bottom path: $\varphi(T) - \varphi(2T)$

$$\Delta \Phi = \varphi(0) - 2\varphi(T) + \varphi(2T) = \frac{4\pi g T^2}{\lambda}$$

Sampling of the atomic trajectory with a laser ruler at 3 different times.
Absolute inertial sensor

Sensor output signal: $\Delta \Phi = \frac{4\pi T^2}{\lambda} \times g$

→ the scale factor can be known with high accuracy ($< 10^{-9}$)

Inertial sensitivity scales with $T^2$

→ want long $T$ (few 100 ms typically)

→ need atoms with rms velocities $\sim cm/s \rightarrow \mu K$ temperatures

Orders of magnitude:

• $T = 100\ ms; \lambda = 0.5\ \mu m; \ SNR = 100$

• 1 measurement per second

→ Acceleration sensitivity $\sim 10^{-7} m. s^{-2}/\sqrt{Hz}$
Cold-atom gyroscope
Photons versus atoms

Sagnac effect

\[
\Delta \Phi = \frac{4\pi E}{\hbar c^2} \mathbf{A} \cdot \mathbf{\Omega}
\]

C.R. Physique 15, 875-883 (2014)
arxiv:1412.0711
Photons versus atoms

Sagnac effect

\[ \sigma_{\phi} \approx \frac{1}{\sqrt{n}} \]

- \( 10^{-9} \text{ rad}/\sqrt{\text{Hz}} \) for photons
- \( 10^{-3} \text{ rad}/\sqrt{\text{Hz}} \) for atoms

Photons:
- \( A : \text{cm}^2 \text{ to m}^2 \)
- \( E \sim 1 \text{eV} \)

Atoms:
- \( A : \text{mm}^2 \text{ to cm}^2 \)
- \( E \sim 10^{11} \text{eV} \)

\(+11 - 2 = 9 \text{ orders of magnitude}\)

Gyroscope-accelerometer

\[ \Phi = \phi(0) - 2\phi(T) + \phi(2T) = \vec{k}_{eff} \vec{a} T^2 + 2\vec{k}_{eff} (\vec{\nu} \times \vec{\Omega}) T^2 \]

acceleration

rotation
4-light pulse atom interferometer

\[ \Phi = \phi_1 - 2\phi_2 + \phi' - (\phi' - 2\phi_3 + \phi_4) \]

→ Zero sensitivity to DC acceleration (still sensitive to AC accelerations)

→ Pure rate gyroscope.

B. Canuel et al., PRL 97, 010402 (2006)
4-light pulse gyroscope

Mean Trajectory

$\phi_1$

$\phi_2$

$\phi_3$

$\phi_4$

« Butterfly » configuration

Raman collimators

2D MOT

3D MOT

interferometer detection

region
Scale factor of the gyroscope

\[ \Phi_\Omega = \frac{1}{2} \vec{k}_{\text{eff}} \cdot (\vec{g} \times \vec{\Omega}) T^3 \]

Area: \[ A = \frac{1}{4} \frac{\hbar k_{\text{eff}} T^3 g}{M} \]

800 ms interrogation time \(\rightarrow 11 \text{ cm}^2\) area

Earth rotation rate (52 \(\mu\text{rad. s}^{-1}\)) \(\rightarrow 220\) rad phase shift
- **Size**: 1.5 m x 0.7 m x 0.7 m
- **$10^7$ Cesium atoms at 1.2 µK**
- **launched vertically at 5 m/s**
- **passive isolation platform (> 0.4 Hz)**
- **2 Magnetic shields**
- **...**
Vibration noise rejection

Vibration noise covers several rad rms

Vibration isolation platform
Vibration noise rejection

Merlet et al., Metrologia 46, 87–94 (2009)
Operation in the linear regime

Real-time calculation of the vibration-induced phase (at each shot)
+ feedback to the Raman laser relative phase
+ lock at mid-fringe → operation in the linear regime.

Operation in the linear regime
Removing dead times and increasing the sampling rates

I. Dutta et al., PRL 116, 183003 (2016)

Dead times in quantum sensors

Sequential operation of cold atom interferometers:

Dead times $\rightarrow$ (inertial) noise aliasing + loss of information
$\rightarrow$ prevents from reaching the quantum noise limit.
Ingredient # 1: Continuous sensor

**Joint interrogation:** prepare the cold atoms and operate the interferometer in parallel.
Ingredient #2: interleaving

We interleave several sequences of long-T interferometers

\[ T_c = \frac{2T}{3} = 267 \text{ ms} \text{ (3.75 Hz cycling frequency)} \]
Gyroscope stability

Gyroscope stability

M. Altorio et al, arxiv: 1912.04793
Dynamic rotation rates

Apply sinusoidal modulations of the rotation rate

\[ \vec{\Omega} = \Omega_0 \cos(\omega t) \hat{u}_y \]

with \( \Omega_0 \sim \text{few } 10^{-7} \text{ rad. s}^{-1} \)
Dynamic rotation rates

Modulation with 5 s period

Modulation with 10 s period
Dynamic rotation rates

Our measurements match with the expectation within 5% accuracy.

Fourier analysis
Next generation of gyroscope

- Current sensitivity to ground rotations (detection noise limit): $5 \text{nrad.s}^{-1}/\sqrt{\text{Hz}}$
- Maximum sampling rate: 4 Hz
- One axis gyro (horizontal)

Design of a new setup

- Two axes (horizontal)
- Improved detection noise floor: $0.1 \text{nrad.s}^{-1}/\sqrt{\text{Hz}}$
- Sampling rate of 10 Hz
- Improved stability: operation during several days
The cold-atom gyroscope team

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A. Landragin
Thank you for your attention

PhD and postdoc positions available

https://syrte.obspm.fr
Dynamic rotation rates

\[ \Phi = \frac{1}{2} k_{\text{eff}} \cdot (\vec{\Omega}_E \times \vec{g}) T^3 \]

\[ + \frac{3}{4} k_{\text{eff}} \cdot (\vec{\Omega}_F \times \vec{g} + \vec{\Omega}_E \times \vec{a} + \vec{\Omega}_F \times \vec{a}) T^3 \]

(usual term)

(modulation term)

\[ \Phi_{\text{dyn}}(t) \simeq \frac{3}{4} k_{\text{eff}} \cdot (\vec{\Omega}_F(t) \times \vec{g}) T^3 \]