Precision Experiments on Gravity by Atom Interferometry

Guglielmo M. Tino

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Outline

• Interferometry with cold atoms
• Measuring G with atoms
• Precision gravity measurement at µm scale with laser-cooled Sr atoms in an optical lattice
• Future experiments in space
Atom optics

lenses

mirrors

beam-splitters

interferometers

atom laser
Quantum interference

Initial state \( |\psi_i\rangle \)

Final state \( |\psi_f\rangle \)

Interference of transition amplitudes

\[
P(|\psi_i\rangle \Rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2 \text{Re}(A_I A_{II}^*)
\]
Δφ effects

- Accelerations
- Rotations
- Laser frequency detuning
- Laser phase
- Photon recoil
- Electric/magnetic fields
- Interactions with atoms and molecules
Stanford atom gravimeter

Resolution: $3 \times 10^{-9}$ g after 1 minute
Absolute accuracy: $\Delta g/g < 3 \times 10^{-9}$


G.M. Tino, Q2C3, Virginia - 9/7/2008
Stanford/Yale gravity gradiometer

Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

from M.A. Kasevich


G.M. Tino, Q2C3, Virginia - 9/7/2008
Stanford/Yale gyroscope

SYRTE cold atom gyroscope

- Maximum interaction time: 90 ms
- 3 rotation axes
- 2 acceleration axes
- Cycling frequency 2 Hz
- Expected sensitivity (10^6 at):
  - gyroscope: \(4 \times 10^{-8} \text{ rad.s}^{-1} \text{ Hz}^{-1/2}\)
  - accelerometer: \(3 \times 10^{-8} \text{ m.s}^{-2} \text{ Hz}^{-1/2}\)

G.M. Tino, Q2C3, Virginia - 9/7/2008
IQO Cold Atom Sagnac Interferometer

MAGIA
(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)

- Measure g by atom interferometry
- Add source masses
- Measure change of g

➢ Precision measurement of G
➢ Test of Newtonian law at micrometric distances

http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

G.M. Tino, Q2C3, Virginia - 9/7/2008
Measurement of the Newtonian gravitational constant $G$ by atom interferometry
Measurements of the Newtonian gravitational constant $G$

$G = 6.673 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$

Quinn 2001

$G = 6.67428 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$

[1.0×10^{-4}]

Why atoms?

- Extremely small size
- Well known and reproducible properties
- Quantum systems
- Precision gravity measurement by atom interferometry
- Potential immunity from stray fields effects
- Different states, isotopes,…
MAGIA: atom gravimeter + source mass

Sensitivity $10^{-9}$g/shot

one shot $\Rightarrow \Delta G/G \approx 10^{-2}$

Peak mass acceleration $a_G \approx 10^{-7}$g

500 kg tungsten mass

10000 shots $\Rightarrow \Delta G/G \approx 10^{-4}$
MAGIA: Experimental procedure

- trap, cool and launch two clouds of Rb atoms
- apply Raman light pulses masses in position I
- detect atoms state selectively
- repeat several times
- plot $N_d/N$ and fit the differential phase shift $\Delta \Phi_g$ between the clouds
- move masses to position II
- repeat all procedure
- subtract the differential phase shifts for the two mass positions

$$\phi^I_1 - \phi^I_2 = \phi_g(z_1) + \phi_{SM} + \phi_{sys}(z_1, t_I)$$

$$- \left( \phi_g(z_2) - \phi_{SM} + \phi_{sys}(z_2, t_I) \right)$$

$$\phi^II_1 - \phi^II_2 = \phi_g(z_1) - \phi_{SM} + \phi_{sys}(z_1, t_{II})$$

$$- \left( \phi_g(z_2) + \phi_{SM} + \phi_{sys}(z_2, t_{II}) \right)$$

$$\Rightarrow (\phi^I_1 - \phi^I_2) - (\phi^II_1 - \phi^II_2)$$

$$= 4\phi_{SM} + \phi_{sys}(\Delta z, \Delta t)$$

G.M. Tino, Q2C3, Virginia - 9/7/2008
Atom gravity-gradiometer apparatus

Source masses and support

Laser and optical system


G.M. Tino, Q2C3, Virginia - 9/7/2008

## Experimental sequence

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trapping</strong></td>
<td>$N = 5 \times 10^8$ $^{87}\text{Rb}$</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>$T = 4 , \mu\text{K}$</td>
</tr>
<tr>
<td><strong>Launch</strong></td>
<td>$h = 20-120 , \text{cm}$</td>
</tr>
<tr>
<td><strong>Double launch</strong></td>
<td>$\Delta t = 80 , \text{ms}$</td>
</tr>
<tr>
<td><strong>Selection</strong></td>
<td>$F = 1$, $m_F = 0$</td>
</tr>
<tr>
<td><strong>Interferometer</strong></td>
<td>$\Delta \varphi$</td>
</tr>
<tr>
<td><strong>Detection</strong></td>
<td>$N_1, N_2$</td>
</tr>
<tr>
<td><strong>Laser cooling - MOT</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Laser cooling - Optical molasses</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Moving opt. mol. - Atomic fountain</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Juggling</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Two-photon Raman transition</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Raman sequence with phase locked lasers</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Fluorescence detection</strong></td>
<td></td>
</tr>
</tbody>
</table>
Gradiometer

\[ \varphi(g) = 4.0 \cdot 10^3 \text{ rad} \]
\[ \varphi(\nabla g) = 0.4 \text{ mrad} \]
\[ \text{res} = 220 \text{ mrad/\sqrt{Hz}} \]
\[ = 5.5 \times 10^{-5} \text{ g/\sqrt{Hz}} \]
\[ = 2.3 \times 10^{-5} \text{ g/shot} \]

\[ \varphi(g) = 4.0 \cdot 10^5 \text{ rad} \]
\[ \varphi(\nabla g) = 40 \text{ mrad} \]
\[ \text{res} = 1.0 \text{ rad/\sqrt{Hz}} \]
\[ = 2.5 \times 10^{-6} \text{ g/\sqrt{Hz}} \]
\[ = 1.0 \times 10^{-6} \text{ g/shot} \]

\[ \varphi(g) = 3.6 \cdot 10^6 \text{ rad} \]
\[ \varphi(\nabla g) = 380 \text{ mrad} \]
\[ \text{res} = 290 \text{ mrad/\sqrt{Hz}} \]
\[ = 7.6 \times 10^{-8} \text{ g/\sqrt{Hz}} \]
\[ = 3.2 \times 10^{-8} \text{ g/shot} \]

\[ \Delta \varphi_{\text{grad}} = k_R \Delta g T^2 \]
\[ \Delta \varphi_{\text{rot}} = -2 \Omega \Delta \varphi_{\text{rot}} \kappa_R T^2 \cos \theta_{\text{lat}} \]
\[ \Delta \varphi_B = 2 \pi a_\parallel B^2 \Delta t \]

$G = 6.64 (6) \times 10^{-11}\text{ m}^3\text{ kg}^{-1}\text{s}^{-2}$


Source mass

**COMPOSITION**

- **INTERMET IT 180**
  (PLANSEE)

**PROPERTIES**

- Density: 18 kg/m³
- Resistivity: 12 x 10⁻⁸ Ωm
- Amagnetic
- CTE: 5 x 10⁻⁶ K⁻¹
- Roughness: 3 µm

**REALIZATION**

- SINTERING
  - T=1500°C - P=1 bar
- Hot Isostatic Pressing
  - T=1200°C - P=1000 bar

**MICROSCOPE ANALYSIS**

holes: Ø ~ 100 µm

**DENSITY TEST**

(INRIM, Torino)

- \( \rho = 18.249 \text{ kg/m}^3 \)
- res: 10 mg/m³
- \( \sigma_\rho = 12 \text{ kg/m}^3 \times (6 \times 10^{-4}) \)
- \( \Delta \rho = 47 \text{ kg/m}^3 \times (2 \times 10^{-3}) \)

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G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo, S. Pettoruso, M. Prevedelli, G.M. Tino,
Appropriate trajectories

Masses separation in the two configurations and atomic clouds initial position have been chosen in order to minimize the dependence on atomic initial parameters and reach the accuracy on $G$ of $10^{-4}$.

- the interferometer is realized around an acceleration max/min
- the Earth's gravity gradient must be over-compensated
- only high density material can be used
New results from MAGIA

$G = 6.667 (11) (3) \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$

G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, G. M. Tino

*Determination of the Newtonian Gravitational Constant Using Atom Interferometry*

*Phys. Rev. Lett. 100, 050801 (2008)*
## Present error budget

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>$\Delta G/G \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial position</td>
<td>1.2</td>
</tr>
<tr>
<td>Vertical position in $C_1$</td>
<td>2.7</td>
</tr>
<tr>
<td>Vertical position in $C_2$</td>
<td>2.1</td>
</tr>
<tr>
<td>Cylinders mass</td>
<td>0.9</td>
</tr>
<tr>
<td>Cylinders density inhomogeneity</td>
<td>0.21</td>
</tr>
<tr>
<td>Support platforms mass</td>
<td>0.8</td>
</tr>
<tr>
<td>Initial position of the atomic clouds</td>
<td>0.18</td>
</tr>
<tr>
<td>Initial velocity of the atomic clouds</td>
<td>2.3</td>
</tr>
<tr>
<td>Gravity gradient</td>
<td>1</td>
</tr>
<tr>
<td>Stability of the on-axis B-field</td>
<td>0.3</td>
</tr>
<tr>
<td>Stability of the launch direction</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.6</strong></td>
</tr>
</tbody>
</table>
MAGIA – Relevant numbers

- time separation between pulses $T=150$ ms
- $10^6$ atoms
- shot noise limited detection
- launch accuracy: $1$ mm e $\Delta v \sim 5$ mm/s
- knowledge of the masses dimensions and relative positions: $10$ $\mu$m
- 10000 measurements

$\Delta G/G \leq 10^{-4}$
Experiments on gravity at small spatial scale
Motivation

• Physics beyond the standard model

Extra space-time dimensions
  Deviations from $1/r^2$ law
  Hierarchy problem: why is gravity so weak?

New boson-exchange forces
  Radion – low-mass spin-0 fields with gravitational-strength couplings
  Moduli – massive scalar particles producing gravity-like forces
  Dilaton – Light scalar in string theory, coupling to nucleons
  Axion – pseudoscalar particles explaining smallness of CP violation in QCD for strong nuclear force

Multi-particle exchange forces

• Small observed size of Einstein cosmological constant

• Experimental challenge
Parametrizations for deviations from Newtonian gravity

1. Modification of power law in Newton-type force

\[ F(r) = G \frac{M_1 M_2}{r^{2+\delta}} \]

2. Newton+Yukawa potential

\[ V(r) = -G \frac{M_1 M_2}{r} \left[ 1 + \alpha e^{-\frac{r}{\lambda}} \right] \]

- Exchange of a boson with \( m = \frac{h}{\lambda c} \)
- Extra dimensions

3. Modified power-law potential

\[ V(r) = -G \frac{M_1 M_2}{r} \left[ 1 + \alpha_n \left( \frac{r_0}{r} \right)^{N-1} \right] \]

- Exchange of 2 massless particles
**Torsion balance - Washington experiment**

- Test bodies: “missing masses” of holes bored into plates
- Torsion pendulum
  - 7075 aluminum, gold coated
  - disk height = 2 mm
  - 10 cylindrical holes evenly spaced about the azimuth
- Attractor
  - high-purity copper disk
  - top surface coated with gold
  - 10 cylindrical holes evenly spaced about the azimuth uniformly rotating
- Electrostatic shield
  - tightly stretched 20-µm-thick BeCu foil

- Distance from top of attractor to bottom of pendulum
  - from 9.53 mm to 55 µm


**Microcantilever - Stanford experiment**

**Probe mass** (gold)
50 µm x 50 µm x 30 µm
m_t ~ 1.6 µg

**Cantilever** (<100> Si)
50 µm x 250 µm x 0.33 µm
Q ~ 80 000
ω_o ~ (k/m_t)^1/2 ~ 300 Hz

**Source mass**
5 sets of gold and silicon bars
100 µm x 1mm x 100 µm

**Separation** 25 µm

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**Microcantilever - Colorado experiment**

Detector (tungsten)  
11.455 mm x 5.080 mm x 195 μm

Q ~ 25 000  
ω₀ ~ 1173 Hz

Source mass (tungsten)  
35 mm x 7 mm x 305 μm

Separation 108 μm

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Experiments on gravity at small spatial scale

Experiments based on torsion balances ($\lambda \leq 1 \text{ mm}$)

J. Gundlach and E. Adelberger (Washington) – torsion balance

Experiments based on high-frequency oscillators ($\lambda \leq 0.1 \text{ mm}$)

J. Long and J. Price group (Colorado) – torsional oscillator
A. Kapitulnik group (Stanford) - microcantilever
R. Decca and E. Fischbach group (Purdue, Indiana) – torsional oscillator

New experiments based on atomic probes ($\lambda \leq 0.01 \text{ mm}$)

E.A. Cornell group (Colorado) – Oscillations of a Bose-Einstein condensate
G.M. Tino group (Firenze) – Atom interferometry

Also experiments on Casimir effect ($\lambda \leq 0.001 \text{ mm}$)
**Ultracold Sr – The experiment in Firenze**

- Optical clocks using visible intercombination lines

  - Optical trapping in Lamb-Dicke regime with negligible change of clock frequency
  - Comparison with different ultra-stable clocks

- New atomic sensors for fundamental physics tests


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Double stage trapping and cooling of Sr atoms

- Optical setup

- Capture Sequence:
  - Blue MOT ($\Delta t \sim 100$ ms)
    \[
    \begin{aligned}
    &I_{\text{sat}} \approx 4.0 \text{ I}_{\text{g/cm}^2} \\
    &\Delta t \sim 100 \text{ ms}
    \end{aligned}
    \]
  - Blue molasses ($\Delta t \sim 5$ ms)
    \[
    \begin{aligned}
    &I \approx 0.06 \text{ I}_{\text{sat}} \\
    &\approx 6 \times 10^7 \\
    &\nu_{\text{rms}} \approx 40 \text{ cm/s} \\
    &T = 2 \text{ mK} \\
    &\delta \omega_D \approx k_{689} \nu_{\text{rms}} \approx 2\pi \times 600 \text{ kHz}
    \end{aligned}
    \]
  - Red MOT broad band ($\Delta t \sim 100$ ms)
    \[
    \begin{aligned}
    &\Delta v = 2 \text{ MHz} \\
    &f = 50 \text{ kHz} \\
    &I_{\text{sidebands}} = 40 \text{ I}_{\text{sat}} \\
    &\delta = -1.2 \text{ MHz} \\
    &dB/dz = 4 \text{ Gauss/cm} \\
    &\eta \approx 25 \%
    \end{aligned}
    \]
  - Red MOT Single frequency ($\Delta t \sim 10$ ms)
    \[
    \begin{aligned}
    &\delta = -350 \text{ kHz} \\
    &I = (10^3 + 1) \text{ I}_{\text{sat}} \\
    &dB/dz = 4 \text{ Gauss/cm} \\
    &N_{\text{max}} = 3 \times 10^6 \\
    &\eta \approx 10 \%
    \end{aligned}
    \]

- MOT Picture

\[
\begin{aligned}
&N = 5 \times 10^5 \text{ atoms} \\
&T = 400 \text{ nK}
\end{aligned}
\]
Sr MOT picture

LENS, Firenze
Precision gravity measurement at \( \mu \text{m} \) scale with Bloch oscillations of Sr atoms in an optical lattice.

\[ v = m \, g \frac{\lambda}{2 \, h} \]
**Particle in a periodic potential: Bloch oscillations**

Periodic potential

\[ V(z + \lambda/2) = V(z) \]

\[ \Psi(z) = e^{i\frac{q}{\hbar}z} u(z) \]

\[ u(z + \lambda/2) = u(z) \]

Bloch's theorem

\[ \Psi(z + \lambda/2) = e^{i\frac{q}{\hbar}\frac{\lambda}{2}} \Psi(z) \]

with a constant external force \( F \)

\[ q(t) = q(0) + \frac{Ft}{\hbar} \]

Bloch oscillations

Quantum theory for electrons in crystal lattices: **F. Bloch, Z. Phys. 52, 555 (1929)**

Never observed in natural crystals (evidence in artificial superlattices)

Direct observation with Cs atoms: **M. Ben Dahan, E. Peik, J. Reichel, Y. Castin, C. Salomon, PRL 76, 4508 (1996)**
Persistent Bloch oscillations

Bloch frequency $v_B = 574.568(3) \text{ Hz}$

damping time $\tau = 12 \text{ s}$

8000 photon recoils in 7s

$g_{\text{meas}} = 9.80012(5) \text{ ms}^{-2}$

Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials

\[ v_B = (574.8459 \pm 0.0015) \text{ Hz}, \]
\[ g = (9.805301 \pm 0.000026) \text{ m/s}^2 \]

Scheme for the measurement of small distance forces

Objective: $\lambda = 1$-$10$ $\mu$m, $\alpha = 10^3$-$10^4$


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Atom elevator

Vertical size of the atomic sample: 15 µm

Atom elevator:
- upward acceleration (1.35 g) for 10 ms
- uniform velocity (133 mm/s) for variable time
- downward acceleration (-1.35 g) for 10 ms
- rest for 470 ms
- reverse motion back to the starting point

Vertical position fluctuations: 3 µm rms

• Vertical size reduced to 4 µm with an optical tweezer
Measuring close to a surface

Δz \sim \phi

beam translation

I

II

III
Other proposals


Accessible region with atomic probes
Applications of new quantum sensors based on atom interferometry

- Measurement of fundamental constants $G \alpha$
- New definition of kg
- Test of equivalence principle
- Short-distances forces measurement
- Search for electron-proton charge inequality
- New detectors for gravitational waves?
- Development of transportable geophysics
  atom interferometers $\rightarrow$ space
Conclusions

• New atomic quantum devices can be developed with unprecedented sensitivity using ultracold atoms and atom optics

• Applications: Fundamental physics, Earth science, Space research

• Well developed laboratory prototypes

• Work in progress for transportable/space-compatible systems
Team members

- Gabriele Ferrari, Researcher, INFM/CNR
- Nicola Poli, Researcher, Università di Firenze
- Fiodor Sorrentino, Post-doc, Università di Firenze
- Marion Jacquey, Post-doc, LENS
- Andrea Alberti, PhD student, LENS
- Marco Schioppo, PhD student, Università di Firenze
- Antonio Giorgini, PhD student, Università di Napoli
- Marco Tarallo, PhD student, Università di Pisa
- Giulio Campo, Diploma student, Università di Firenze
- Gabriele Rosi, Diploma student, Università di Firenze
- Luigi Cacciapuoti, Long term guest, ESA-Noordwijk
- Marella de Angelis, Long term guest, CNR
- Marco Prevedelli, Long term guest, Università di Bologna

Previous members

- Andrea Bertoldi, Post-doc
- Robert Drullinger, Long term guest
- Giacomo Lamporesi, PhD student
- Marco Fattori, PhD student
- Torsten Petelski, PhD student
- Juergen Stuhler, Post-doc

Support and funding

- Istituto Nazionale di Fisica Nucleare (INFN)
- European Commission (EC)
- Ministero dell’Istruzione, dell’Università e della Ricerca (MIUR)
- European Laboratory for Non-linear Spectroscopy (LENS)
- Ente Cassa di Risparmio di Firenze (CRF)
- European Space Agency (ESA)
- Agenzia Spaziale Italiana (ASI)
- Istituto Nazionale per la Fisica della Materia (INFM)
- Istituto Nazionale Geofisica e Vulcanologia (INGV)
Gravitational wave detection
by atom interferometry

Can we use atom interferometers in searching for gravitational waves?

- C.J. Bordè, University of Paris N.
- G. Tino, University of Firenze
- F. Vetrano, University of Urbino

• G.M. Tino, F. Vetrano, "Is it possible to detect gravitational waves with atom interferometers?", Class. Quantum Grav. 24, 2167 (2007)
• R.Y. Chiao, A. D. Speliotopoulos, “Towards MIGO, the matter-wave interferometric gravitational-wave observatory, and the intersection of quantum mechanics with general relativity”, Journal of Modern Optics (2004), 51(6-7), 861-899
• A. Roura, D.R. Brill, B. L. Hu, C.W. Misner, W.D. Phillips, “Gravitational wave detectors based on matter wave interferometers (MIGO) are no better than laser interferometers (LIGO)”, Physical Review D: Particles and Fields (2006), 73(8), 084018/1-084018/14

G.M. Tino, Q2C3, Virginia - 9/7/2008
**Atom Interferometers for Space**

**Proposal coordinator:**  
Prof. Guglielmo M. Tino  
Dipartimento di Fisica/LENS  
Università di Firenze, Italy

**Participants**

**Academic Teams**
- Dipartimento di Fisica, Università di Firenze: I (UNIFI)
- Institut d’Optique, Orsay (+ ONERA): F (IOTA)
- Institut für Quantenoptik, Universität Hannover: D (IQO)
- Universität Hamburg: D (UH)
- Institut für Physik, Humboldt-Universität zu Berlin: D (HUB)
- SYRTE, Observatoire de Paris: F (SYRTE)
- LENS, Firenze: I (LENS)
- Universität Ulm: D (ULM)
- ZARM, University of Bremen: D (ZARM)

**Industrial Partners**
- Carlo Gavazzi Space: I
- EADS Astrium: D
- Galileo Avionica: I
- IXSEA: F
- Kayser Italia: I
- Techno System: I
- THALES: F
- TOPTICA: D
Space Atom Interferometer - SAI

Space Atom Interferometer: Pre-phase A study of a space instrument based on matter-wave interferometry for inertial sensing in space

Team: Firenze Univ. (I), IOTA (F), IQ (D), Hamburg Univ. (D), HU Berlin (D), SYRTE (F), LENS (I), Ulm Univ. (D), ZARM (D)

Objective: Ground based prototype of an atom interferometer for precision measurements

Duration: 3 years, funded within the ELIPS-2 Programme

ESA AO-2004 peered review: Outstanding

From M. Kasevich

<table>
<thead>
<tr>
<th>Gyroscope</th>
<th>Demonstrated on ground</th>
<th>Anticipated on ground</th>
<th>Projected in space</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARW</td>
<td>2x10^{-6} deg/hr^{1/2}</td>
<td>&lt;1x10^{-6} deg/hr^{1/2}</td>
<td>&lt;10^{-8} deg/hr^{1/2}</td>
</tr>
<tr>
<td>Bias stability</td>
<td>6x10^{-5} deg/hr</td>
<td>&lt;10^{-5} deg/hr</td>
<td>&lt;10^{-7} deg/hr</td>
</tr>
<tr>
<td>Scale factor</td>
<td>5 ppm</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accelerometer</th>
<th>Sensitivity</th>
<th>Bias stability</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10^{-9} g/Hz^{1/2}</td>
<td>&lt;10^{-10} g</td>
<td>&lt;10^{-13} g/Hz^{1/2}</td>
</tr>
<tr>
<td></td>
<td>&lt;10^{-10} g</td>
<td>&lt;10^{-10}</td>
<td>&lt;10^{-16} g ?</td>
</tr>
<tr>
<td></td>
<td>&lt;10^{-10}</td>
<td>&lt;10^{-10}</td>
<td>&lt;10^{-12}</td>
</tr>
</tbody>
</table>
Abstract

Prepare a brief description of the application stating the broad, long-term objectives and specific aims of the proposed work. Describe concisely the research design and methods for achieving these objectives and aims. This abstract is meant to serve as a succinct and accurate description of the proposed work when separated from this application. Limit abstract to 300 words or fewer.

Optical atomic clocks based on ensembles of ultra-cold neutral atoms stored in periodic potentials generated by standing-wave light fields will lead to the next leap in accuracy and stability in clock technology. The expected improvement is by a factor of 100 compared to microwave atomic clocks now in operation in several national metrology laboratories worldwide and under deployment for the ISS within the ACES project. Space represents the best environment for such ultra-stable clocks because the well-defined location and the microgravity environment maximize accuracy and stability.

The goal of this project is to demonstrate operation and characterize the performance of an optical clock ensemble in a space environment with an expected accuracy 10 times higher than ACES. This clock ensemble will be launched with 10 parts in 17 accuracy, which is a factor of 10 increase compared to the ACES clock. The clock will be placed on an orbiting platform to reduce gravity gradient and thermal effects.

The aim of the first funding period (three years) is to implement several optical clock laboratory demonstration systems using Strontium and Ytterbium atomic systems to characterize and compare them, to test and validate different operational procedures and specifications required for operation in space. Subcomponents of the clock demonstration will be tested with the aim of developing transportability and robustness techniques that are suitable for future space use, such as small solid-state lasers, low power consumption, and small volume, will be developed and validated.

At the end of the 3-year project, the specifications for a space clock will be finalized, enabling the start of Phase B.

The clock development will be based on the experience that the team members have acquired in the field of precision optical measurements and quantum optics, in particular on their successful laboratory microwave and optical clock development based on cold atoms, which have resulted in the space clock PHARAO.
Space Optical Clocks - SOC

Space Optical Clocks: Pre-phase A study of an atomic clock ensemble in space based on the optical transitions of strontium and ytterbium atoms. Optical clocks will take advantage of the ACES heritage and will push stability and accuracy of atomic frequency standards down to the $10^{-18}$ regime.

Team: Düsseldorf Univ. (D), SYRTE (F), ENS (F), PTB (D), Firenze Univ. (I)

Objective: Ground based prototypes of atomic clocks based on Sr and Yb optical clocks

Duration: 3 years, funded within the ELIPS-2 Programme

ESA AO-2004 peered review: Outstanding
Future Inertial Atomic Quantum Sensors

FINAQS

A Specific Targeted Research Project (STREP)

FULL Proposal

for

NEST-2003-1 ADVENTURE

Duration: 3 years

Co-ordinator: Prof. Dr. Wolfgang Etzner
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Participants

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<td>FIRENZE</td>
<td>I</td>
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</table>
FINAQS
compact laser systems
Differential measurement between two atom gyroscopes and a star tracker orbiting around the Earth

Resolution: $3 \times 10^{-12} \text{rad/s/Hz}$

- Expected Overall Performance: $3 \times 10^{-18} \text{rad/s}$ over one year of integration i.e. a S/N~100 at twice the orbital frequency

Mapping Lense-Thirring effect close to the Earth

Improving knowledge of fine-structure constant

Testing EP with microscopic bodies

Atomic gyroscope control of a satellite

http://sci.esa.int/home/hyper/index.cfm
Cosmic Vision

Space Science for Europe 2015-2025
- Free Fall: up to 9 sec
- Duration > 1 BEC-Experiment
- 3 flights per day
- Test of a robust BEC Facilities
  Dimensions < 0.6 Ø x 1.5 m < 234 kg
- Height 110 m
I.C.E
Interferometry with Coherent Sources for Applications in Space

Project members
Philippe BOUYER
Robert NYMAN
Gaët VAROQUAUX
Jean-Philippe CLEMENT
Jean-Philippe BRANTUT
Arnaud LANDRAISIN
Frank PENA
Alexandre PRESSON
Yannick BIODEL
Pierre TOUSOUL

THE PROJECT
The objective of I.C.E is to produce an interferometer for space with consistent atomic source. It uses a mixture of Rb-Einstein concentic on 2 species of atoms (Rb and Xe).

The major objective for 2007 is to carry out a first test campaign, in parabolic flight for example, to test the various components together and to carry out a first comparison of accelerations measured by the 2 atomic species.

Partners

OPTIQUE ATOMIQUE

GROUPE ATOMES FRIOIS

GRUPE SENSEURS INERTIELS

Internal Pages
International Workshop on
"ADVANCES IN PRECISION TESTS AND EXPERIMENTAL
GRAVITATION IN SPACE"
Arcetri, Firenze (Italy), September 28-30, 2006

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G.M. Tino, Q2C3, Virginia - 9/7/2008