Navigation, Gravitation and Cosmology with Cold Atom Sensors

Atom Interferometry Group
Stanford Center for Position, Navigation and Time
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**de Broglie wave sensors**

**Gravity/Accelerations**

As atom climbs gravitational potential, velocity decreases and wavelength increases

(longer de Broglie wavelength)

**Rotations**

Sagnac effect for de Broglie waves

Current ground based experiments with atomic Cs: wavepacket spatial separation ~ 1 cm, phase shift resolution ~ 10^{-5} rad
(Light-pulse) atom interferometry

Resonant optical interaction

Resonant traveling wave optical excitation, (wavelength $\lambda$)

Recoil diagram

Momentum conservation between atom and laser light field (recoil effects) leads to spatial separation of atomic wavepackets.
Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.

**Laser cooling:**
Laser light is used to cool atomic vapors to temperatures of ~10^{-6} deg K.

Image source: www.nobel.se/physics

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**The Nobel Prize in Physics 1997**

*for development of methods to cool and trap atoms with laser light*

1. **Steven Chu**
   - USA
   - Stanford University
   - Stanford, CA, USA
   - 1948 -

2. **Claude Cohen-Tannoudji**
   - France
   - Collège de France
   - Paris, France
   - 1933 -

3. **William D. Phillips**
   - USA
   - National Institute of Standards and Technology
   - Gaithersburg, Maryland, USA
   - 1948 -
Laboratory gyroscope

ARW \(3 \mu\text{deg/hr}^{1/2}\)

Bias stability: < 60 \(\mu\text{deg/hr}\)

Scale factor: < 5 ppm

(submitted for publication)
Laboratory gravity gradiometer

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

Demonstrated differential acceleration sensitivity:

$$4 \times 10^{-9} \, \text{g/Hz}^{1/2}$$

(2.8x10^{-9} g/Hz^{1/2} per accelerometer)
Gravity Gradiometer: Measurement of G

Pb mass translated vertically along gradient measurement axis.

<table>
<thead>
<tr>
<th>Systematic</th>
<th>$\frac{\delta G}{G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Atom Velocity</td>
<td>$1.88 \times 10^{-3}$</td>
</tr>
<tr>
<td>Initial Atom Position</td>
<td>$1.85 \times 10^{-3}$</td>
</tr>
<tr>
<td>Pb Magnetic Field Gradients</td>
<td>$1.00 \times 10^{-3}$</td>
</tr>
<tr>
<td>Rotations</td>
<td>$0.98 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Positioning</td>
<td>$0.82 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Mass Density</td>
<td>$0.36 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Mass Dimensions</td>
<td>$0.34 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gravimeter Separation</td>
<td>$0.19 \times 10^{-3}$</td>
</tr>
<tr>
<td>Source Mass Density inhomogeneity</td>
<td>$0.16 \times 10^{-3}$</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$3.15 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Status: $\frac{\delta G}{G} \sim 3 \text{ ppt}$ (submitted for publication). See also Tino, MAGIA
Light-pulse AI accelerometer characteristics

- Bias stability: $<10^{-10}$ g
- Noise: $4 \times 10^{-9}$ g/Hz$^{1/2}$
- Scale Factor: $10^{-12}$

Light-pulse AI gyroscope characteristics

- Bias stability: $<60$ µdeg/hr
- Noise (ARW): $4$ µdeg/hr$^{1/2}$
- Scale Factor: $<5$ ppm
Navigation performance

Determine geo-located platform path.

Necessarily involves geodetic inputs.

Simulated navigation solutions. 5 m/hr system drift demonstrated.
Multi-function sensor measures gravity gradient, rotation and linear acceleration along a single input axis.

Interior view

Laser system
Sensor electronic/laser subsystems

Control electronics frames (controls 6 sensor heads)

Laser frames (scalable architecture provides light for 2-6 sensor heads)
Next generation integrated INS/GPS

Integration of RF satellite, inertial, and clock sensors into one quasi-optimal Navigation, Attitude, Time estimator

Stanford Center for Position, Navigation and Time. In collaboration with Per Enge, Jim Spilker

Atomic physics contributions
Space-based applications

- Platform jitter suppression
  - High resolution line-of-sight imaging from space
  - Inertial stabilization for next-generation telescopes

- Satellite drag force compensation at the $10^{-10}$ g accuracy level
  - GPS satellite drag compensation
  - Pioneer-type experiment

- Autonomous vehicle navigation, formation flying

Existing technology:
- ESGN (submarine navigation)
- Draper LN-TGG gyro
- Litton/Northrop HRG (Hemispherical Resonator)

LN-TGG; 1 nrad 0.1-100 Hz source: SPIE 4632-15
Fibersense/NG IFOG
Space-based geodesy (also lunar geodesy)

Accelerometer sensitivity: $10^{-13} \text{ g/Hz}^{1/2}$
- Long free-fall times in orbit

Measurement baseline
- 100 m (Space station)
- 100 km (Satellite constellation)

Sensitivity:
- $10^{-4} \text{ E/Hz}^{1/2}$ (Space Station)
- $10^{-7} \text{ E/Hz}^{1/2}$ (Satellite constellation)

*Earthquake prediction; Water table monitoring*

http://www.esa.int/export/esaLP/goce.html
Co-falling $^{85}\text{Rb}$ and $^{87}\text{Rb}$ ensembles

Evaporatively cool to < 1 $\mu\text{K}$ to enforce tight control over kinematic degrees of freedom

Statistical sensitivity

$\delta g \sim 10^{-15}$ with 1 month data collection

Systematic uncertainty

$\delta g \sim 10^{-16}$ limited by magnetic field inhomogeneities and gravity anomalies.

Also, new tests of General Relativity

*Precursor to possible space-based system.*

10 m atom drop tower.

*~10 cm wavepacket separation (!!)*
Error Model

Use standard methods to analyze spurious phase shifts from uncontrolled:

- Rotations
- Gravity anomalies/gradients
- Magnetic fields
- Proof-mass overlap
- Misalignments
- Finite pulse effects

Known systematic effects appear controllable at the $\delta g \sim 10^{-16}$ level.

$[\delta G/G \sim 10^{-5}$ is feasible (limited by test mass)]
Equivalence Principle Installation

Atomic source

10 m atom drop tower.
Light-pulse interferometer phase shifts for Schwarzschild metric:

- Geodesic propagation for atoms and light.
- Path integral formulation to obtain quantum phases.
- Atom-field interaction at intersection of laser and atom geodesics.

**Objective:**

Ground-based precision tests of post-Newtonian gravity.

*Post-Newtonian trajectories for classical particle:*

\[
\frac{dv}{dt} = -\nabla(\phi + 2\phi^2 + \psi) - \frac{\partial \zeta}{\partial t} + v \times (\nabla \times \zeta) + 3v \frac{\partial \phi}{\partial t} + 4v(\nabla \cdot \nabla)\phi - v^2 \nabla \phi
\]

From Weinberg, Eq. 9.2.1

Ground-based Post-Newtonian Interferometry

Calculated phase shifts for **ground based**, 10 m, apparatus.

- Analysis indicates that several post-Newtonian terms are comfortably within apparatus reach.
- In-line, accelerometer, configuration (milliarcsec link to external frame NOT req’d).
- New constraints of PPN parameters.
- Identification of most-promising space-based tests.

**Collaborators:** Savas Dimopoulos, Peter Graham, Jason Hogan.
Are there (local) observable phase shifts of cosmological origin?

Analysis has been limited to simple metrics:

- **FRW:** \( ds^2 = dt^2 - a(t)^2(dx^2 + dy^2 + dz^2) \)
- **McVittie:** \( \sim \)Schwarzschild + FRW
  \[
g = \left( \frac{1 - m(t)/2r}{1 + m(t)/2r} \right)^2 dt^2 - \left( 1 + \frac{m(t)}{2r} \right)^4 a^2(t) (dr^2 + r^2 d\Omega^2).
\]

**Work in progress …**

**Future theory:** Consider phenomenology of exotic/speculative theories (after validating methodology)

Collaborators: Savas Dimopoulos, Peter Graham, Jason Hogan.
Future technology: Quantum Metrology

Atom shot-noise limits sensor performance.

Recently evolving ideas in quantum information science have provided a road-map to exploit exotic quantum states to significantly enhance sensor performance.

- Sensor noise scales as $1/N$ where $N$ is the number of particles
- “Heisenberg” limit
- Shot-noise $\sim 1/N^{1/2}$ limits existing sensors

Challenges:

- Demonstrate basic methods in laboratory
- Begin to address engineering tasks for realistic sensors

Impact of successful implementation for practical position/time sensors could be substantial.

Enables crucial trades for sensitivity, size and bandwidth.
Quantum Metrology

- Exploit exotic quantum states to measure phase shifts at Heisenberg (1/N) limit
- Possible 10x to 100x improvement in sensor noise.

Spin squeezed state enables 1/N sensitivity

Possible QND detection of atom number (~5 atom resolution).
Summary

• Precision navigation
  – Pioneer
• Equivalence Principle
• Post-Newtonian gravity
• Cosmology

• + quantum metrology in future sensor generations
Thanks

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