Atom Interferometric Gravity Wave Detectors

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Outline

• Basic concepts
• Current instrumentation
• AGIS detectors
  – Space-based/LEO
  – Terrestrial
  – Systematics
• Status of instrument development
Young’s double slit with atoms

One of the first experiments to demonstrate de Broglie wave interference with atoms, 1991 (Mlynek, PRL, 1991)
Inertial sensors

Optical Interferometry

• Future atom optics-based sensors may outperform existing inertial sensors by a factor of $10^6$.
• Current (laboratory) atom optics-based sensors outperform existing sensors.

Atom Interferometry

Performance of current generation atom interferometric sensors

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.
Phase shifts: Semi-classical approximation

Three contributions to interferometer phase shift:

\[ \Delta \phi_{\text{total}} = \Delta \phi_{\text{prop}} + \Delta \phi_{\text{laser}} + \Delta \phi_{\text{sep}} \]

Propagation shift:

\[ \frac{S_{\text{cl,B}} - S_{\text{cl,A}}}{\hbar} \]

Laser fields (Raman interaction):

\[ k(z_c - z_b + z_d - z_a) + \phi_I - 2\phi_{II} + \phi_{III} \]

Wavepacket separation at detection:

\[ \vec{p} \cdot \Delta \vec{r}/\hbar \]

Falling rock

- Determine trajectory curvature with three distance measurements $\ell(t_1)$, $\ell(t_2)$ and $\ell(t_3)$
- For curvature induced by acceleration $\mathbf{a}$, $\mathbf{a} \sim [\ell(t_1) - 2\ell(t_2) + \ell(t_3)]$

Falling atom

- Distances measured in terms of phases $\phi(t_1)$, $\phi(t_2)$ and $\phi(t_3)$ of optical laser field at position where atom interacts with laser beam
- Atomic physics processes yield $\mathbf{a} \sim [\phi(t_1)-2\phi(t_2)+\phi(t_3)]$
Light-pulse atom sensors

- Atom is in a near perfect inertial frame of reference (no spurious forces).
- Laser/atomic physics interactions determine the relative motion between the inertial frame (defined by the atom deBroglie waves) and the sensor case (defined by the laser beams).
- Sensor accuracy derives from the use of optical wavefronts to determine this relative motion.
- Sensor is kinematic: directly reads angular and linear displacements.
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. <10 μm/sec velocity control is demonstrated with current methods.

Image source: www.nobel.se/physics
Gyroscope, Measurement of Earth rotation rate

Gyroscope output vs. orientation.

200 $\mu$deg/hr$^{1/2}$

Contrast at high rotation rate (> 10 deg/sec)
Differential accelerometer

Applications in precision navigation and geodesy

~ 1 m
Gravity gradiometer

Demonstrated accelerometer resolution: $\sim 10^{-11}$ g.
General Relativity/Phase shifts

Light-pulse interferometer phase shifts in GR:

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

Gravity waves

Metric (tt): \[ ds^2 = dt^2 - (1 + h \sin (\omega (t - z) + \phi_0)) dx^2 - (1 - h \sin (\omega (t - z) + \phi_0)) dy^2 - dz^2 \]

Differential accelerometer configuration for gravity wave detection.

Atoms provide inertially decoupled references (analogous to mirrors in LIGO).

Gravity wave phase shift through propagation of optical fields.


Satellite configuration (dashed line indicates atom trajectories)
Possible sensitivity of AI gravity wave detector.

AGIS-LEO concept

In collaboration with GSFC (Bernie Seery, Babak Saif and co-workers)

Considering ISS, free-flyer LEO configurations
Boom implementation (free flyer/ISS)

Atom delivery and wavepacket manipulation telescope

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Location in tex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Position</td>
<td>$&lt; 10 \frac{\text{nm}}{\sqrt{\text{Hz}}}$</td>
<td>Wavefront Aberration (Sec. I V B)</td>
</tr>
<tr>
<td>Angle Jitter</td>
<td>$&lt; 1 \frac{\text{nrad}}{\sqrt{\text{Hz}}}$</td>
<td>Laser Pointing Angle Jitter (Sec. V F)</td>
</tr>
<tr>
<td>Angular Rate</td>
<td>$&lt; 1 \frac{\text{nrad/s}}{}$</td>
<td>Rotational Effects (Sec. V A)</td>
</tr>
</tbody>
</table>

Boom lengths: $\sim 30 \text{ m}$
Pulse sequences for LEO configurations

Developed atom interferometric pulse sequences to mitigate Coriolis bias for orbiting apparatus.

<table>
<thead>
<tr>
<th>Phase shift</th>
<th>Size (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (-60Lk_{\text{eff}}\Omega_y^2\delta\Omega T^4)</td>
<td>(-1.15)</td>
</tr>
<tr>
<td>2 (60Lk_{\text{eff}}T_{xx}\Omega_y^2\delta\Omega T^4)</td>
<td>(+1.15)</td>
</tr>
<tr>
<td>3 (888Lk_{\text{eff}}\Omega_y^5\delta\Omega T^6)</td>
<td>(+3.67 \times 10^{-4})</td>
</tr>
<tr>
<td>4 (444Lk_{\text{eff}}T_{xx}\Omega_y^2\delta\Omega T^6)</td>
<td>(-3.67 \times 10^{-4})</td>
</tr>
<tr>
<td>5 (-444Lk_{\text{eff}}T_{xx}T_{xx}\Omega_y^2\delta\Omega T^6)</td>
<td>(+3.67 \times 10^{-4})</td>
</tr>
<tr>
<td>6 (30k_{\text{eff}}\delta v_z \Omega_y^3 T^4)</td>
<td>(+1.92 \times 10^{-4})</td>
</tr>
<tr>
<td>7 (15k_{\text{eff}}T_{xx}\delta v_z \Omega_y \Omega_y T^4)</td>
<td>(-1.92 \times 10^{-4})</td>
</tr>
<tr>
<td>8 (-444Lk_{\text{eff}}T_{xx}T_{xx}^2 \Omega_y \delta\Omega T^6)</td>
<td>(-1.84 \times 10^{-4})</td>
</tr>
<tr>
<td>9 (-444Lk_{\text{eff}}T_{xx}^2 \Omega_y^2 \delta\Omega T^6)</td>
<td>(-1.84 \times 10^{-4})</td>
</tr>
<tr>
<td>10 (15k_{\text{eff}}T_{xx}\Omega_y^2 \delta v_z T^4)</td>
<td>(+9.62 \times 10^{-5})</td>
</tr>
<tr>
<td>11 (\frac{225L^2}{2H} k_{\text{eff}} T_{xx} \Omega_y^2 \delta\Omega T^5)</td>
<td>(-8.25 \times 10^{-5})</td>
</tr>
<tr>
<td>12 (\frac{225L^2}{4H} k_{\text{eff}} T_{xx}^2 \Omega_y \delta\Omega T^5)</td>
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<tr>
<td>13 (-\frac{225L^2}{3H} k_{\text{eff}} T_{xx} \Omega_y^2 \delta\Omega T^5)</td>
<td>(-4.12 \times 10^{-5})</td>
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<tr>
<td>14 (-\frac{225L^2}{3H} k_{\text{eff}} T_{xx}^2 \delta\Omega T^5)</td>
<td>(-2.06 \times 10^{-5})</td>
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<tr>
<td>15 (\frac{30L^2}{R^2} k_{\text{eff}} T_{xx} \Omega_y \delta\Omega T^4)</td>
<td>(-1.95 \times 10^{-5})</td>
</tr>
<tr>
<td>16 (-\frac{45}{2} k_{\text{eff}} \Omega_y^4 \delta x T^4)</td>
<td>(-1.67 \times 10^{-5})</td>
</tr>
<tr>
<td>17 (15k_{\text{eff}}T_{xx} \Omega_y^2 \delta x T^4)</td>
<td>(+1.11 \times 10^{-5})</td>
</tr>
</tbody>
</table>

Error model to understand sensitivity to atom velocity and laser beam pointing jitter.
Wavefront distortion: temporal variations

Time varying wavefront inhomogeneities will lead to non-common phase shifts between distant clouds of atoms

- High spatial frequencies diffract out of the laser beam as the beam propagates between atom clouds

- Limit for temporal stability of wavefronts determined by stability of final telescope mirror

Mirror: Be at 300K
Atom cloud kinematic constraints

Shot-to-shot jitter in the position of the atom cloud with respect to the satellite/laser beams constrains static wavefront curvature

Wavefront error vs. spatical frequency, assuming 10 nm/Hz$^{1/2}$ position jitter
Terrestrial Sensor

1 km vertical shaft at, e.g., Homestake mine.
Seismic fluctuations give rise to Newtonian gravitational fluctuations which perturb atom trajectories.

Seismic noise induced strain analysis for LIGO (Thorne and Hughes, PRD 58)

Primary disturbances are surface waves. Suggests location in underground facility.

Also, atmospheric fluctuations.
References analyzing GW detection using AI

Satellite/LEO; Full analysis of wavefront errors

Satellite; Terrestrial

General Relativity using Atom Interferometers
Laboratory Instrument
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