Compact and Portable Atom Gravimeter

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ITU symposium on Quantum Information and Technology
• The Importance of gravity measurement

• Compact and potable atom gravimeter in USTC

• Calibration of USTC-AG02 and USTC-AG12 at NIM in 2019

• Outlook
The Earth Gravity

The constituents of 'g'

9.8072467\,\text{m/s}^2

Latitude
Altitude
Internal mass distribution
Oil & Gas field
Solid Tide
Ocean Tide & Air pressure
Why measure gravitational acceleration?

Satellite Configuration
Space-based geodesy

Seismic sensors

Autonomous navigation

Gravity field mapping

Equivalence Principle

Cosmology
Gravity Wave Detection

Oil & Gas

Newton's constant G

Measurement of h
& Definition of kg

Kibble balance
Outline

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The particle-wave duality makes the atoms ideal candidate for interferometry.

\[ \lambda_{dB} = \frac{h}{mv} \]

\[ \frac{\Delta \varphi_{atom}}{\Delta \varphi_{photon}} \sim \left( \frac{c}{v_{atom}} \right)^2 = 10^{11} \sim 10^{17} \]
Atom Gravimeter Working Process

Cold atom source  State prep.  3-pulse interferometer  Detection
Atom Interferometer

\[ \Phi(t) = \vec{k}_{eff} \vec{z}(t) = \vec{k}_{eff} \frac{\vec{g}}{2} t^2 \]

\[ \Phi_1 = \Phi_I \]

\[ \Phi_2^A = \Phi_{II} + \vec{k}_{eff} \vec{v}_{rec} T - \vec{k}_{eff} \frac{\vec{g}}{2} T^2 \]

\[ \Phi_2^B = \Phi_{II} - \vec{k}_{eff} \frac{\vec{g}}{2} T^2 \]

\[ \Phi_3 = \Phi_{III} + \vec{k}_{eff} \vec{v}_{rec} T - \vec{k}_{eff} \frac{\vec{g}}{2} (2T)^2 \]

\[ P_{|2>} = \frac{1}{2} (1 + \cos \Delta \Phi) \]

\[ \Delta \Phi = (\Phi_1 - \Phi_2^A) - (\Phi_2^B - \Phi_3) \]

\[ = -\vec{k}_{eff} \vec{g} T^2 + \Phi_I - 2 \Phi_{II} + \Phi_{III} \]

\[ = -\vec{k}_{eff} \vec{g} T^2 + \alpha T^2 \]
Development of Atom Gravimeters in USTC

- Running with free falling cold atoms
- Interrogation time, $T=80\text{ms}$
- Repetition rate: 3Hz

2015 -> Beginning, optical table based atom gravimeter
2016 -> Prototype of the portable atom gravimeter

Sensor

Controller

2017 -> The 1st generation of compact and portable atom gravimeter (USTC-AG01 & 02)

Controller

Sensor
Sensor Head

Volume: 0.30 × 0.30 × 0.65 m³
Mass: ~40 kg

Pump
Raman laser
Magnetic shield
MOT & Molasses
Interference zone
Detection zone

2018, USTC-AG11 & 12

谢宏泰等，一种原子布居数探测系统，ZL 2018 2 013804.2
杨胜军等，一种用于原子干涉重力仪探头的磁场系统，ZL 2018 2 0236129.6
陈帅等，一种适用于小型化原子干涉仪的真空结构，201711439186
Controller

Volume: $0.56 \times 0.68 \times 0.72 \, \text{m}^3$
Mass: $\sim 80 \, \text{kg}$

Laser system (Two lasers)
- Cooling
- Repumper
- Pump
- Blowing
- Raman
- Probe
- ...

Electronic system (magnetic field & optical control, power supplies)

Control and Data acquisition system

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龙金宝等，一种适用于冷原子干涉精密测量的双激光器系统，201711439114.7
Continuous Measurement of g @Shanghai

Gravimeter
USTC-AG12

32s /each g value

Sensitivity: 100 μGal/√Hz
Stability: 3.2 μGal@2000s

Overall

At night

Sensitivity: 60 μGal/√Hz
Stability: 2.5 μGal@2000s

Shanghai Lab, USTC
2018-09-23 to 10-09

(1 μGal = 10^{-8} m/s^2)
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Two transportable atom gravimeters in one IVECO truck

January 7, 2019
Calibrate Atom Gravimeters in 3D active vibration isolator

Measure g in Building 21, NIM@Changping (重力精测实验室II)

Sensor
Controller
Sensor
USTC-AG12
USTC-AG02
3D active vibration isolator
Continuous Measurement of g @NIM

Gravimeter USTC-AG12

- Sensitivity: 42 μGal/√Hz
- Stability: 1.3 μGal@1000s

Gravimeter USTC-AG02

- Sensitivity: 35 μGal/√Hz
- Stability: 0.9 μGal@1000s

8s /each g value

32s /each g value
### Systematic Errors Overall

<table>
<thead>
<tr>
<th>Gravimeter</th>
<th>USTC-AG12</th>
<th></th>
<th>Gravimeter</th>
<th>USTC-AG02</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Systematic effect</strong></td>
<td><strong>Bias /μGal</strong></td>
<td><strong>Uncertainty /μGal</strong></td>
<td><strong>Systematic effect</strong></td>
<td><strong>Bias /μGal</strong></td>
<td><strong>Uncertainty /μGal</strong></td>
</tr>
<tr>
<td>$k_{\text{eff}}$ independent</td>
<td>0</td>
<td>1.4</td>
<td>$k_{\text{eff}}$ independent</td>
<td>0</td>
<td>1.8</td>
</tr>
<tr>
<td>Tilt</td>
<td>0</td>
<td>0.5</td>
<td>Tilt</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Two-photon light shift</td>
<td>66.2</td>
<td>2.6</td>
<td>Two-photon light shift</td>
<td>84.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Coriolis</td>
<td>13.2</td>
<td>3.9</td>
<td>Coriolis</td>
<td>-17.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Self gravity</td>
<td>-0.1</td>
<td>0.1</td>
<td>Self gravity</td>
<td>-0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Laser frequency</td>
<td>0</td>
<td>0.026</td>
<td>Laser frequency</td>
<td>0</td>
<td>0.026</td>
</tr>
<tr>
<td>Wave front</td>
<td>0</td>
<td>6</td>
<td>Wave front</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>79.3</td>
<td>7.7</td>
<td><strong>Total</strong></td>
<td>67.2</td>
<td>8.6</td>
</tr>
</tbody>
</table>

## Corrected Calibration Result

<table>
<thead>
<tr>
<th>Gravimeter</th>
<th>Time (UTC+8)</th>
<th>Result (μGal)</th>
<th>Uncertainty (μGal)</th>
<th>Height (m)</th>
<th>Reference Value (μGal)</th>
<th>Difference (μGal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USTC-AG12</td>
<td>2019-01-17 00:00</td>
<td>Reported value</td>
<td>980121269.9</td>
<td>15.4</td>
<td>980121385.9</td>
<td>-116</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corrected value</td>
<td>980121371.3</td>
<td>0.957</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USTC-AG02</td>
<td></td>
<td>Reported value</td>
<td>980121268.5</td>
<td>17.0</td>
<td>980121365.5</td>
<td>-97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corrected value</td>
<td>980121369.9</td>
<td>1.027</td>
<td></td>
<td>4.4</td>
</tr>
</tbody>
</table>

- The results with the correction of $k_{eff}$ and environmental effects were the corrected values.
- The reference values of $g$ were provided by NIM.
中国计量科学研究院

校 准 证 书

证书编号 LSJ2019-0031

客户名称 中国科学技术大学
器具名称 全探针干涉仪
型号规格 自研干涉仪
出厂编号 UTSC-AG12 / UTSC-AG02
生产厂商 中国计量科学研究院
客户地址 上海市浦东新区秀浦路90号
校准日期 2019-01-17

批准人：

地址：北京市丰台区18号
电话：610-6125074
网址：http://www.imc.ac.cn
Outlook

- **Performance improvement**
  - Decrease noise for *higher sensitivity*
  - Decrease drift for *better stability*
  - Further evaluate systematic error to *reduce uncertainty*
  - Build more robust system to *improve reproducibility*

- **Engineering improvement**
  - Reduce *size*
  - Decrease *weight*
  - Lower *power consumption*
  - Make it *easy to use*
Thanks for your attention!