CASPA Accelerometer: Development of a cold atom accelerometer for atmospheric drag measurement & Cold Atoms Gravity Explorer (CAGE)

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Commercialising Quantum Technologies of the Future

Shaping the future by designing the next generation of quantum technology solutions. Developing products and services that utilise the quantum properties of atoms.

Sensing
- Gravity gradient sensors for seeing underground

Timing
- Timing and Frequency solutions including GNSS holdover

Space
- Systems for Earth science, timing and navigation

Communications
- Quantum Key Distribution for ultra secure comms networks
What is Cold Atom Technology?

Atom Trapping and Cooling
State Preparation
Split and Recombine (3 interferometer pulses)
Detection

Image courtesy of Olivier Carraz, ESA
Applications in Space

- Frequency References (Clocks)
  - Next generation GNSS
  - Telecoms and Sensor synchronisation
  - Fundamental Physics e.g. Pharao/ACES
- Gravity
  - Gravity maps for ground-based navigation
  - Civil Engineering, prospecting
  - Earth science (ice sheets, ocean transport, climate change)
- Inertial Sensing
  - Acceleration & Rotation → Navigation
  - Acceleration → Atmospheric Density → Precise Orbit Determination, Gravity Waves

• Benefits:
  • High sensitivity
  • Absolute measurement - low drift
  • Repeatability – all 87Rb atoms are the same
  • No manufacturing variability / wear & tear
Cold Atom Space Payload (CASPA)

- Original CASPA programme funded by UK National Quantum Technology Programme (Innovate UK).
- 6U CubeSat, cold atom trapping only, no sensing functionality
- Focussed on miniaturisation and space readiness of key components and subsystems
ATMOSPHERIC DRAG MEASUREMENT

CASPA Accelerometer
Mission Concepts

Technology needs validation via an initial Pathfinder mission
• Cold Atom tech has flown on sounding rockets, the ISS, Tiangong 2 but only for scientific research and tech demo
• We want to fly the world’s first Cold Atom EO mission
• Follow on applications in gravity / navigation / timing
• Adjacent terrestrial applications

Two different mission concepts are currently being considered and look feasible:

CASPA-ADM (ESA Phase 0 Study)
• 16U CubeSat with 1 axis accelerometer

Q-ACE (UK NSIP Phase 0 Study)
• TAS SkimSat with 2 axis accelerometer
• Longer lifetime / higher performance

Measure small changes in velocity (acceleration) caused by changes in Atmospheric Density.
CASPA-ADM Mission Concept

The thermosphere
• Region between 90 and 1000 km altitude
• Characterized by large temperature variations
• Highly driven system
  • Solar flux
  • Geomagnetic activity
  • Gravity waves

Orbit prediction for active satellites and space debris
• Drag is dominant force and largest source of uncertainty below 600 km
• Lifetime predictions, collision risk assessment / avoidance

Very limited high-resolution, in-situ observations of thermosphere density
• 1970s and 1980s → Atmospheric Explorer missions
• Since 2000 → Missions of opportunity
CASPA-ADM Mission objectives

Demonstrate CAI technology with a science case
1. Verification of gas-surface interaction models
2. Observation of atmospheric waves
3. Observe cross-track accelerations (secondary)

Fill the present gap in density observations
1. Region below 400 km altitude
2. Fast LTAN progression
3. Medium-high solar activity

Mission concept
• 16U CubeSat
• 40 U² solar arrays
• Approximate initial altitude 400 km
• 40° – 76° inclination
• Approximate launch window 2022 – 2028

Note:
1 U = 10 cm x 10 cm x 10 cm
1 U² = 10 cm x 10 cm

Scientific objectives require a measurement accuracy of 1% for mass density
Key parameters in term of sensitivity

**Atom Trapping and Cooling**
- State Preparation
- Split and Recombine (3 interferometer pulses)
- Detection

**High signal**
- Maximise number of atoms detected
  - Number of atoms trapped
  - Temperature of the cloud
  - Efficiency of the detection
- Maximise phase shift in interferometer
  - Duration of the interferometer
  - Diffraction order

**Minimising noise**
- Rotations
- Magnetic fields
- Instrumental noise

**High repetition rate**
- Duration of the measurement cycle
- Interleaving

Image courtesy of Olivier Carraz, ESA
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Image courtesy of Olivier Carraz, ESA
CASPA-ADM Accelerometer Trade-offs

- Atom temperature:
  - Low temperatures enable longer integration times but take longer to prepare each sample → slower measurement rate and more instrument complexity

- Duration of the interferometer:
  - Longer interrogation times give lower noise but more sensitivity to satellite rotation
  - Atom loss due to non-zero temperature

- 20 nm/s² per shot is achieved for an interrogation time of 56 ms at 2μK, which can be achieved with the (relatively simple) molasses cooling

- Averaging over 4 shots within 10 s results in a precision of 10 nm/s²

- The time per shot includes:
  - Atom preparation time
  - Additional dead time of 1.2 s to limit the power consumption
Current CEOI Project – CASPA Accelerometer

Project Objectives

Develop the CASPA design into a compact cold atom accelerometer for atmospheric density missions.

- Produce a space suitable accelerometer physics package (Teledyne e2v)
- Develop an “atom chip” for producing magnetic fields local to the atoms in-vacuum (RAL Space)
- Build a space suitable seed laser system (RAL Space)
- Build a breadboard system capable of acceleration measurement (UoB and Teledyne e2v)
Preliminary Design

Physics Package
Compact form factor UHV chamber, high power vacuum feedthroughs, folded telescope design, upgrade path to include 2D MOT pre-cooling, magnetic field generation, ion pump, magnetic shielding, detection system.

Atom Chip
Second generation from RAL Space, bonding process in development, then component level testing to establish damage thresholds for current, temperature and vibration.

Seed Laser
Low-noise laser source in a CubeSat PC104 form factor, fully integrated module for wider experiment control system implementations, roadmap to high reliability applications.

Laser System
Implementation of demo laser system using a novel fibre Bragg grating approach to filter out unwanted frequencies.
EARTH GRAVITY MEASUREMENT

Cold Atom Gravity Explorer (CAGE)
Project Objectives

• Develop a strong, user driven science case for a cold atom gravity mission.

• Develop a concept design for a cold atom gravity sensor that will address the requirements of the defined science mission.

• Develop a strong and well-aligned UK consortium of partners including science user base, technology developers and platform providers.

• Strong focus on near term solutions using technology/performance assumptions that have already been demonstrated on the ground.
| Target Missions             | • NGGM  
|                          | • Future gravity missions  
<table>
<thead>
<tr>
<th></th>
<th>• Potential solutions for sustained observations</th>
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</table>
| Main Benefits             | • Cold atom gravity mission could lead to a two-fold improvement (over GOCE) on the gravity field recovery for degrees above 50°  
|                          | • Many applications and benefits of improved gravity field recovery  
|                          | • Proposed concepts require significant technology development, are high SWAP and require validation |
| CAGE Approach             | • CAGE set out to identify a pathfinder for a cold atom gravity mission  
|                          | • Not necessarily step change in performance but a stepping stone to a new technology domain |

* A. Trimeche et al 2019 Class. Quantum Grav. 36 215004 based on O. Carraz concept
Key parameters in term of sensitivity

Atom Trapping and Cooling

State Preparation

Split and Recombine (3 interferometer pulses)

Detection

High signal

• Maximise number of atoms detected
  • Number of atoms trapped
  • Temperature of the cloud
  • Efficiency of the detection

• Maximise phase shift in interferometer
  • Duration of the interferometer
  • Diffraction order

• Maximise differential phase shift
  • Baseline between sensors

High repetition rate

• Duration of the measurement cycle
• Interleaving

Minimising noise

• Rotations
• Magnetic fields
• Instrumental noise
Sensor Concept Development

Technology Constraints

- **No Interleaving**: Technology required for this is still low TRL and would significantly increase SWAP.

- **Limited Momentum Transfer**: Technology required for higher orders is still low TRL and would increase power requirements.

- **Single Axis Measurement**: Single axis measurement only to reduce complexity with gravity vector component calculation done in post processing.
Sensor Concept Development

Large Baseline Solution

- Baseline of the instrument needs to be increased beyond traditional sizes to achieve scientifically interesting results.

- Extendable booms explored for very large baseline but required stability and rigidity is difficult to achieve with current technology.

- Instrument concept is scalable beyond fairing limitations for future variants.
## Final Concept

### Operational Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometry Duration 2T (s)</td>
<td>8</td>
</tr>
<tr>
<td>Baseline (m)</td>
<td>4</td>
</tr>
<tr>
<td>Number of atoms</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Preparation Time (s)</td>
<td>2.7</td>
</tr>
<tr>
<td>Atom Temperature (nK)</td>
<td>1</td>
</tr>
<tr>
<td>Diffraction Order</td>
<td>2</td>
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<tr>
<td>Total Noise (E)</td>
<td>0.0485</td>
</tr>
</tbody>
</table>

![Full Sensor Diagram]
Performance and Technology Timeline

Technology Timeline

GOCE
- 10 mE/√Hz in 2 axis
- 20 mE/√Hz in radial direction

CASPA-ADM
- CAI Technology Demonstrator

CAGE
- 84 mE/√Hz

Future CAI
- 5 mE/√Hz*

* Based on numbers from A. Trimeche et al. Quantum Gravity, vol. 36, no. 21, 2019
Summary

• Cold Atom Technology will enable a host of new sensor capabilities well suited for space applications across EO (and with spin off applications in navigation, communications and terrestrial applications)

• The UK is leading at the compact, application-focussed cold atom systems

• A pathfinder mission to validate the technology in space is urgently required

• Feasible missions have been identified, studied and developed

• Breadboard, engineering model hardware is in development
Thank you

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