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

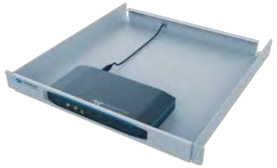
Shaping the future by designing the next generation of quantum technology solutions. Developing products and services that utilise the quantum properties of atoms.

Sensing

Gravity gradient sensors for seeing underground

Timing

Timing and Frequency solutions including GNSS holdover

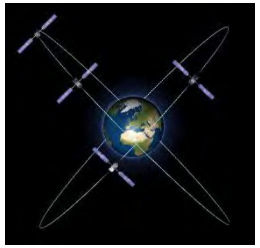


Space

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

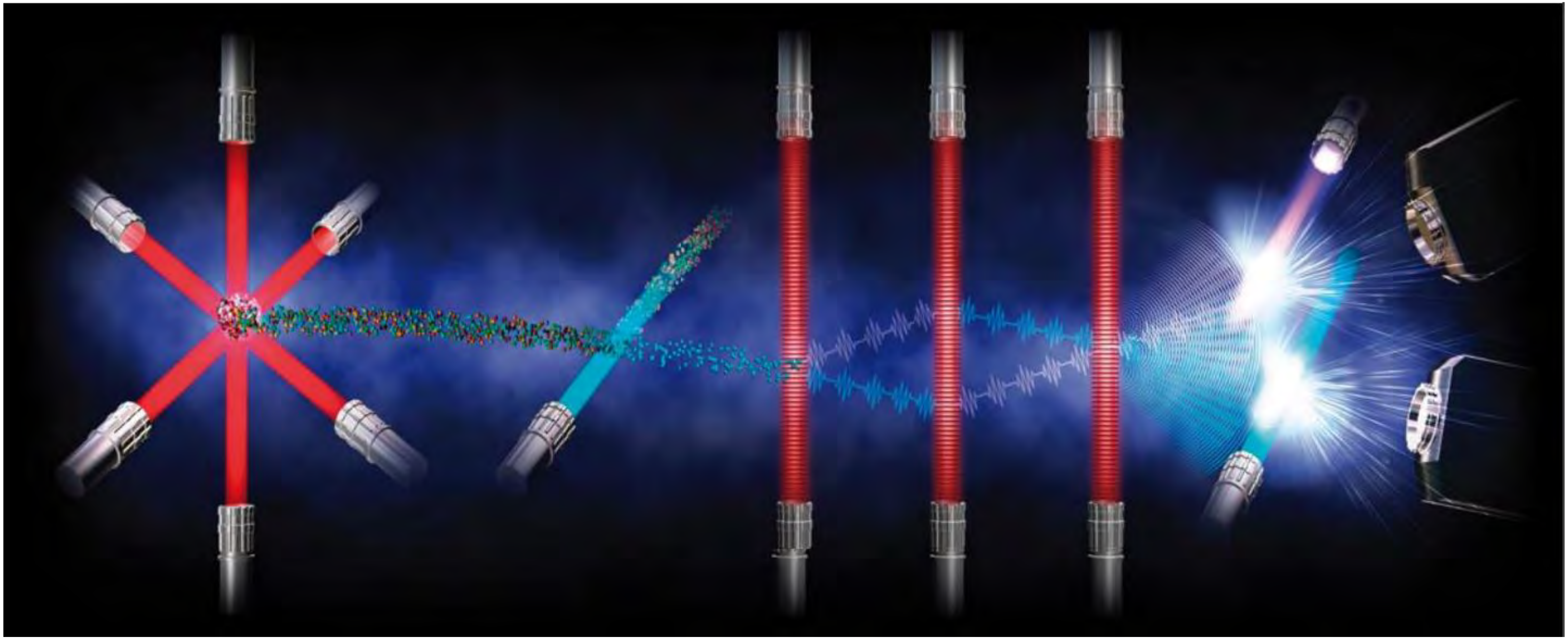
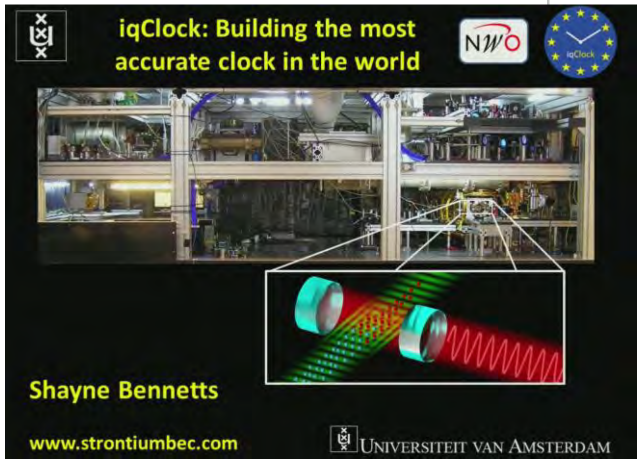


Image courtesy of Olivier Carraz, ESA

Applications in Space

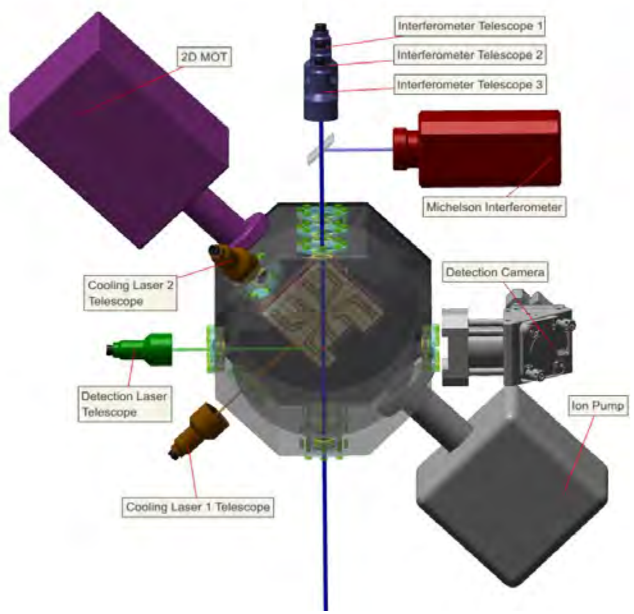
- Frequency References (Clocks)
  - Next generation GNSS
  - Telecoms and Sensor synchronisation
  - Fundamental Physics e.g. Pharao/ACES
- Gravity
  - Gravity maps for ground-based navigation
  - Civil Engineering, prospecting
  - Earth science (ice sheets, ocean transport, climate change)
- Inertial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

IUK MINAC Clock



H2020 IQClock Project

- **Benefits:**
  - High sensitivity
  - Absolute measurement - low drift
  - Repeatability – all 87Rb atoms are the same
  - No manufacturing variability / wear & tear



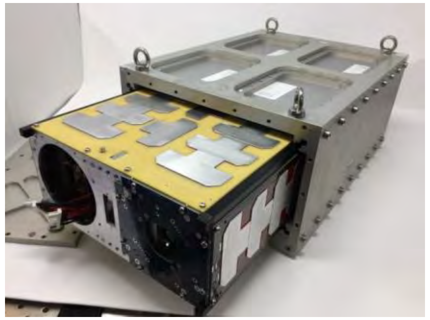
CEOI Cold Atom Gravity Explorer (CAGE)

Cold Atom Space Payload (CASPA)

Innovate UK

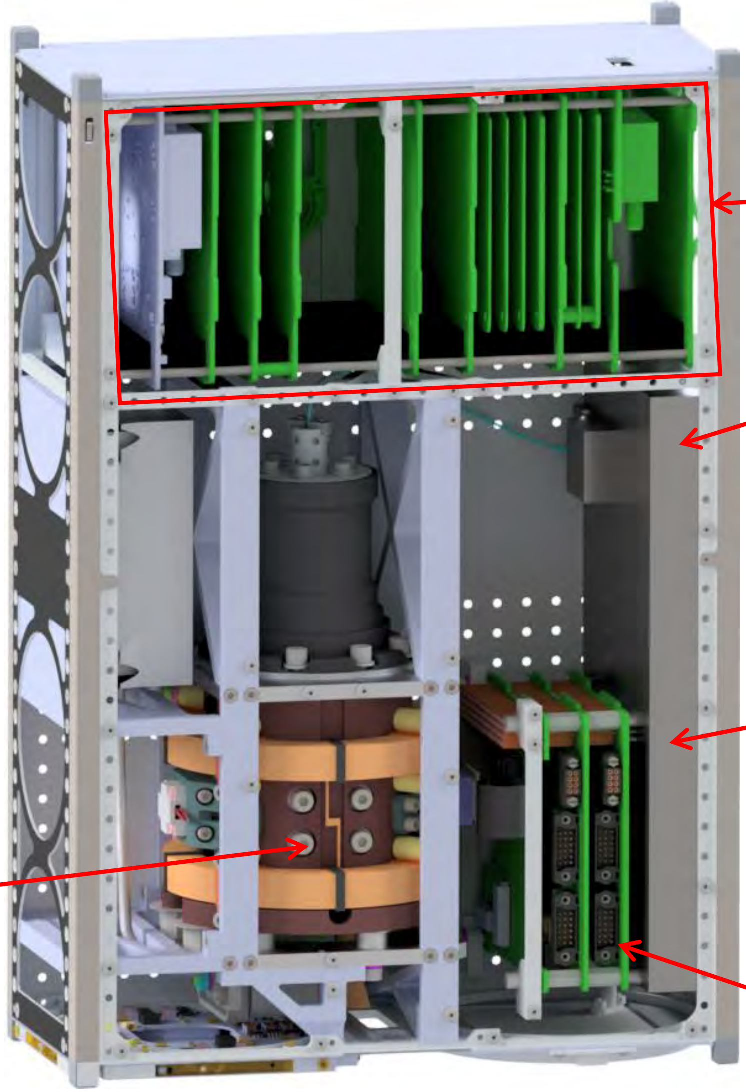
UNIVERSITY OF BIRMINGHAM

- 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



Physics package: Vacuum assembly

TELEDYNE e2V
Everywhereyoulook™



Platform: Avionics & structure

CLYDE SPACE

Optical subsystem: Frequency Doubler

UNIVERSITY OF Southampton

covesion

Optical subsystem: Laser System

G&H
ENABLING PHOTONIC TECHNOLOGIES

Electronics subsystem: Imager and experiment control

XCAM

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.

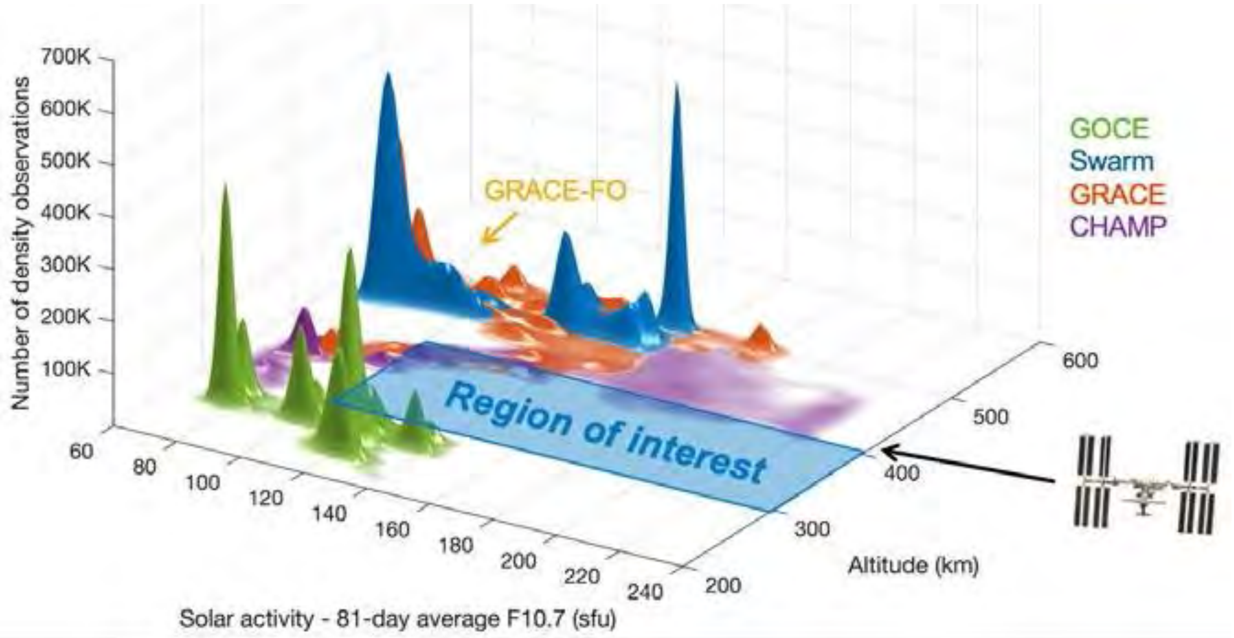
CASPA-ADM Mission Concept

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



Distribution of density observations with respect to altitude and solar activity showing observational gap. Credit: Christian Siemes, TU Delft

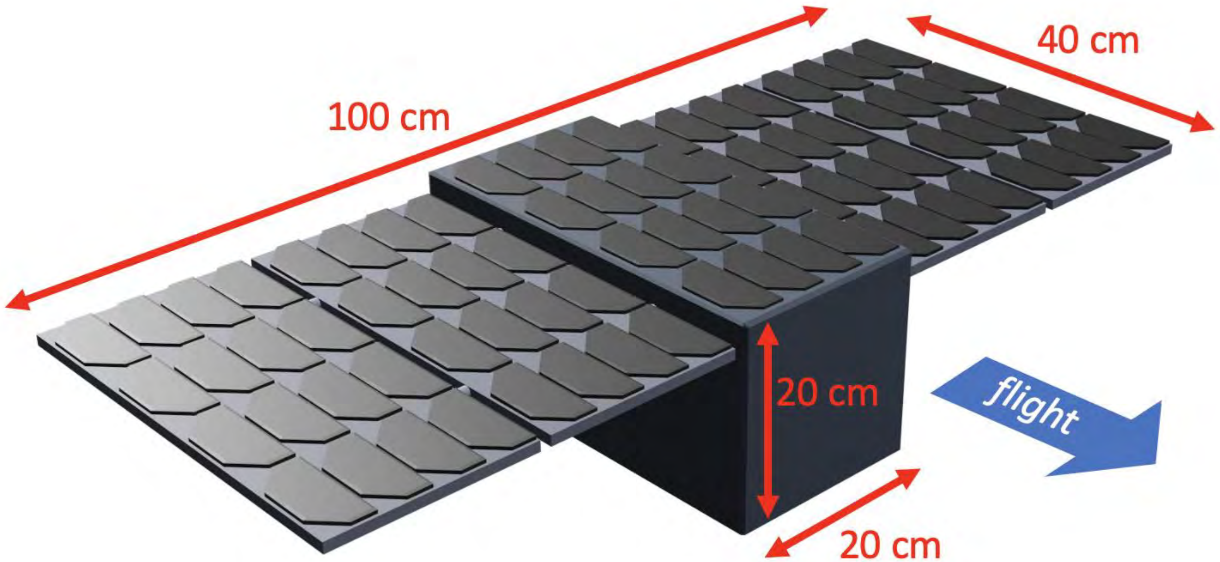
Very limited high-resolution, in-situ observations of thermosphere density

- 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 U^2 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 U^2 = 10 cm x 10 cm

Scientific objectives require a measurement accuracy of 1% for mass density

TUDelft RAL Space

TELEDYNE e2V Everywhereyoulook™ Part of the Teledyne Imaging Group

Key parameters in term of sensitivity

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

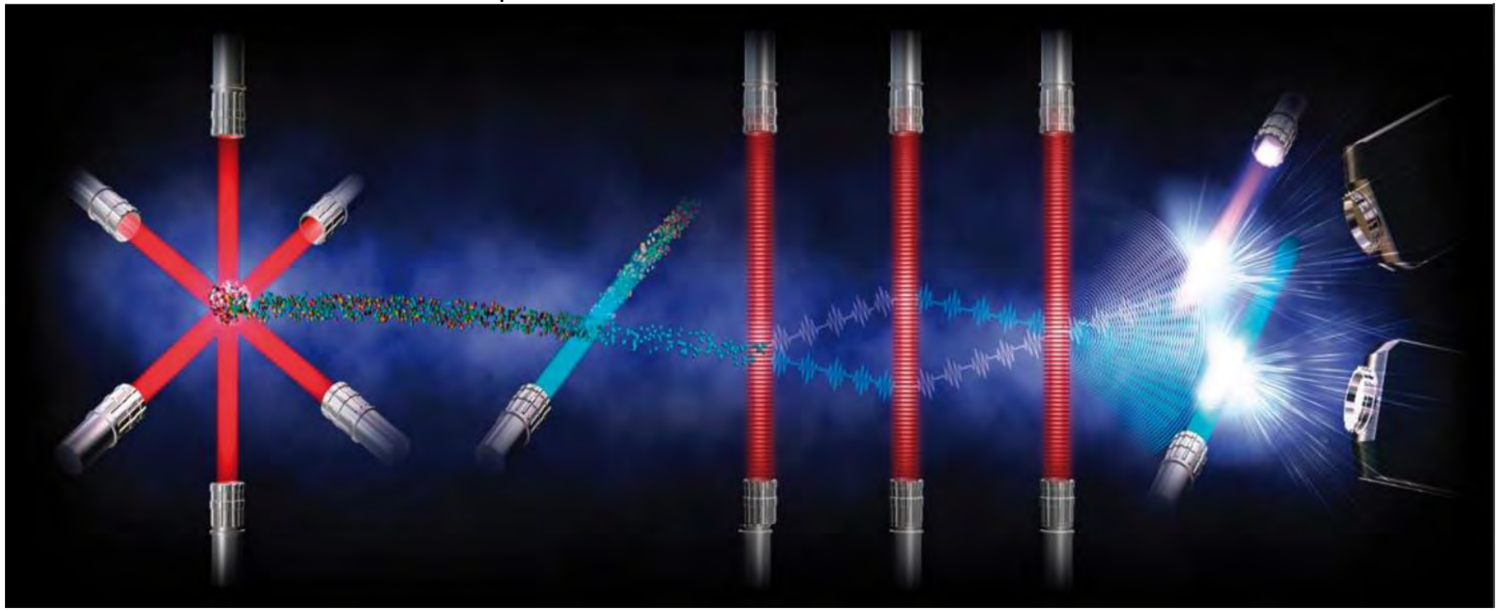


Image courtesy of Olivier Carraz, ESA

High repetition rate

- Duration of the measurement cycle
- Interleaving

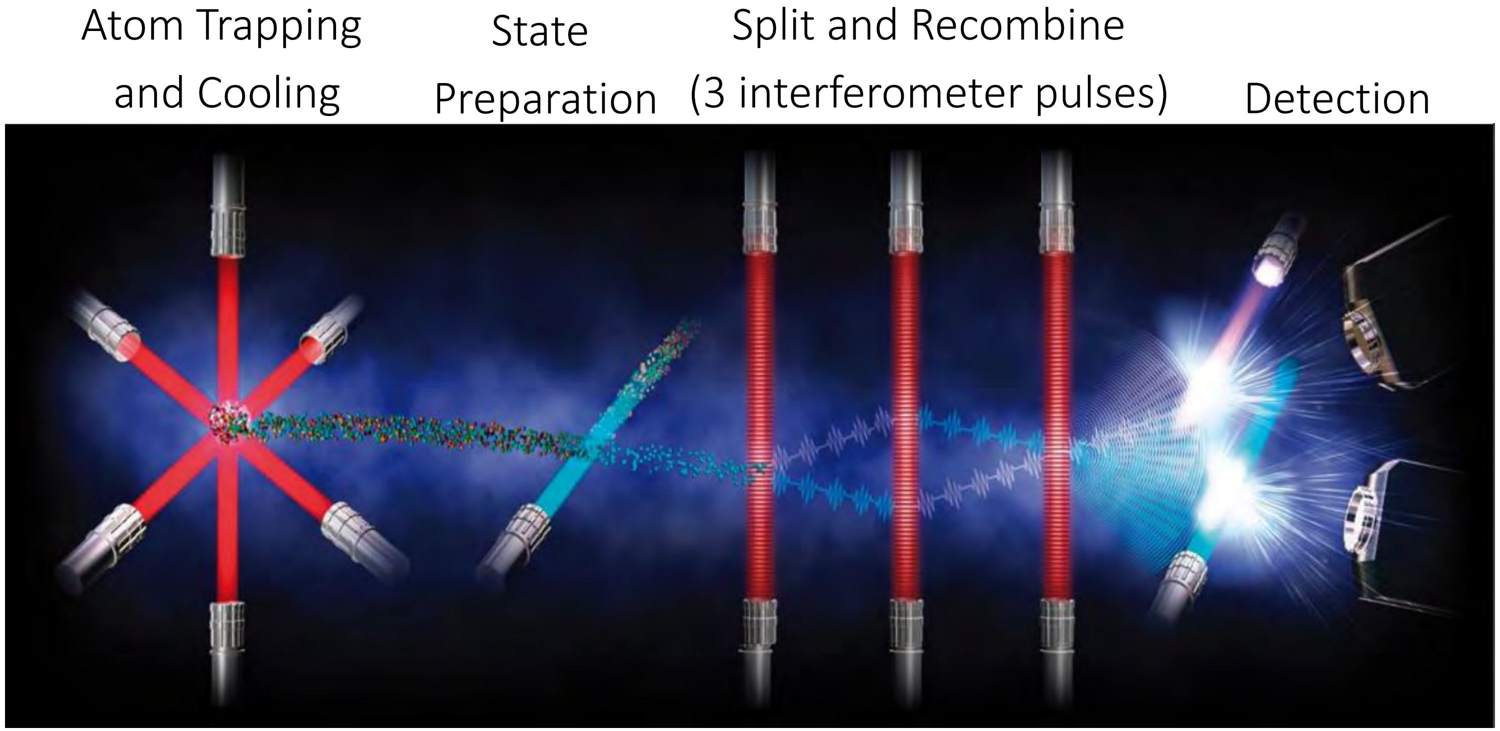
High signal

- 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

Key parameters in term of sensitivity



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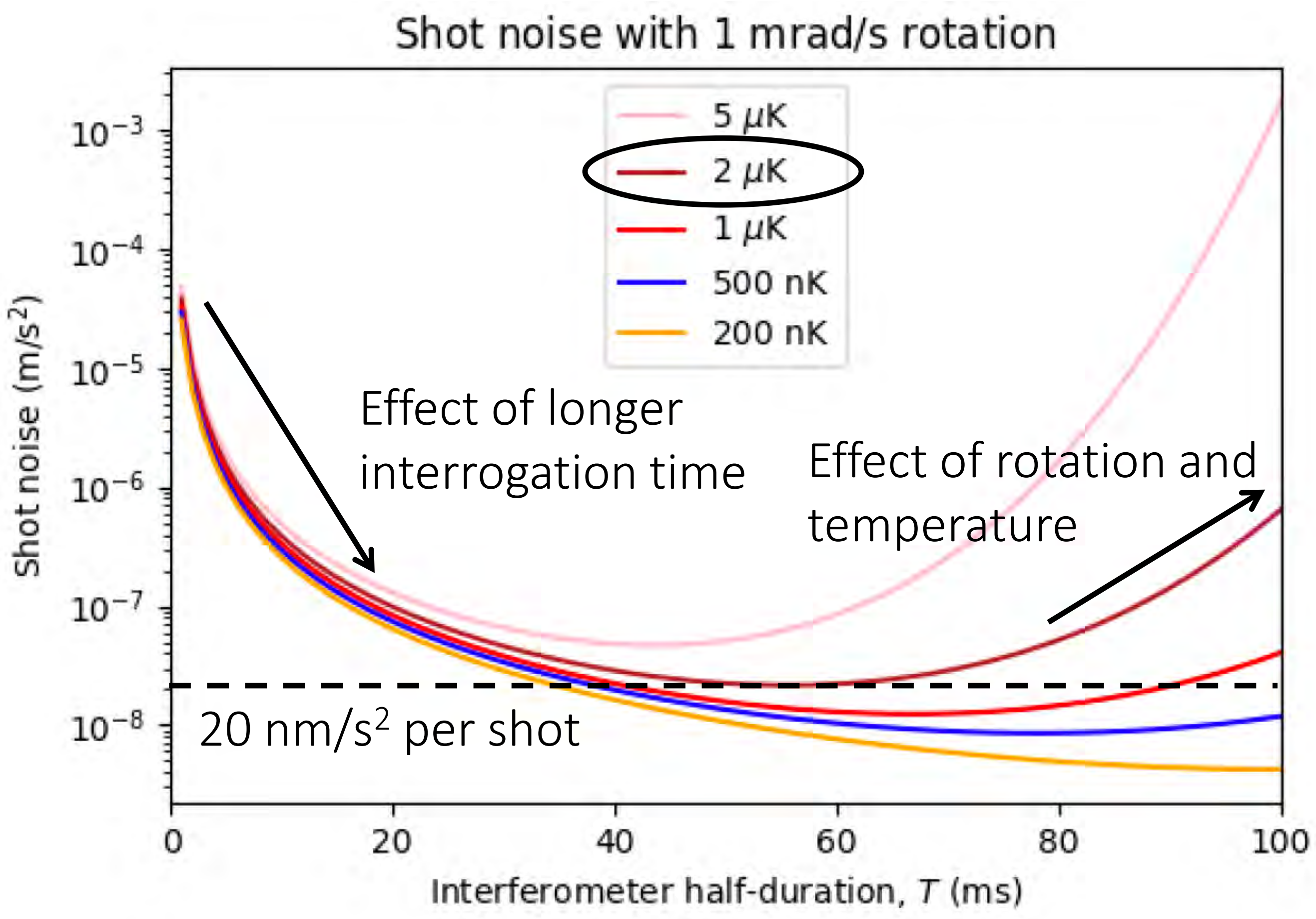
CASPA-ADM Accelerometer Trade-offs

- 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 gives lower noise but more sensitivity to satellite rotation
    - Atom loss due to non-zero temperature
- 20 nm/s^2 per shot is achieved for an interrogation time of 56 ms at 2 μK, which can be achieved with the (relatively simple) molasses cooling
- Averaging over 4 shots within 10 s results in a precision of 10 nm/s^2
- 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

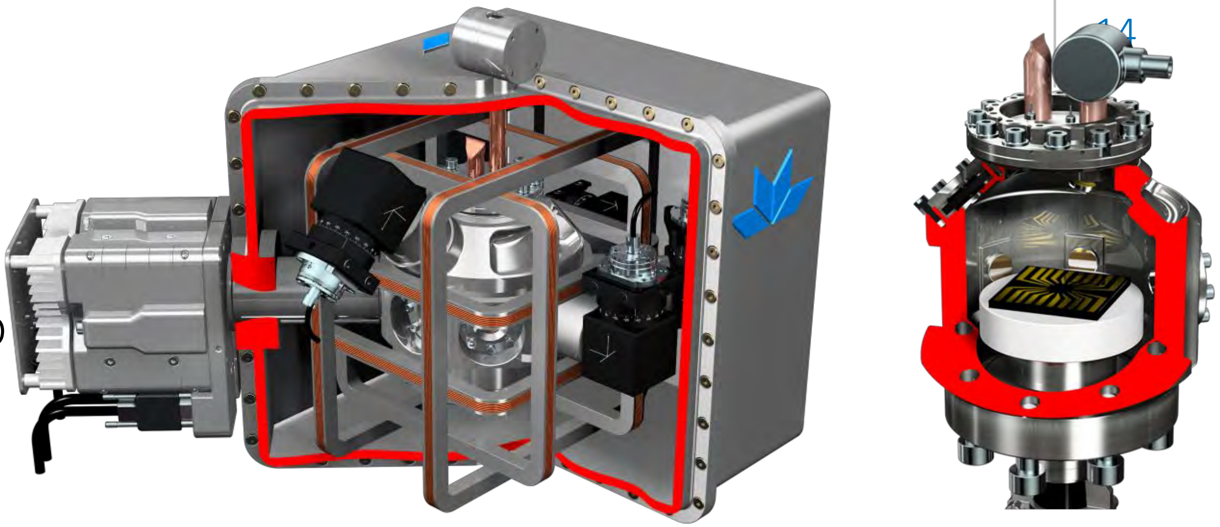
Second generation from RAL Space, bonding process in development, then component level testing to establish damage thresholds for current, temperature and vibration.

Seed Laser

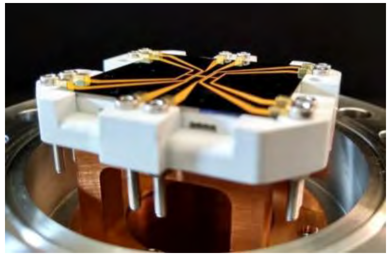
Low-noise laser source in a CubeSat PC104 form factor, fully integrated module for wider experiment control system implementations, roadmap to high reliability applications.

Laser System

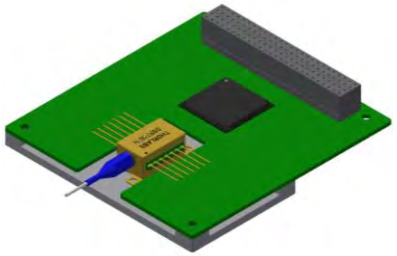
Implementation of demo laser system using a novel fibre Bragg grating approach to filter out unwanted frequencies.



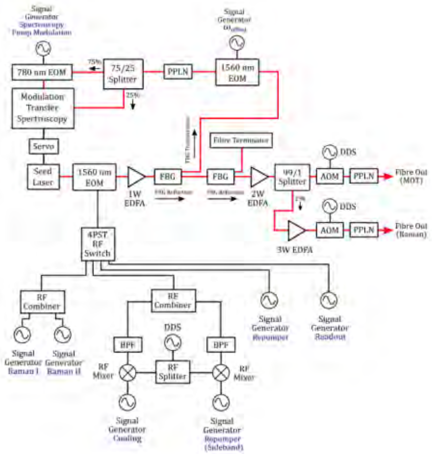
Credit: Teledyne e2v
(2D MOT Cold Quanta)



Credit: RAL Space



Credit: RAL Space



Credit: University of Birmingham; *"Optical frequency generation using fiber Bragg grating filters for applications in portable quantum sensing"* – C. D. Macrae

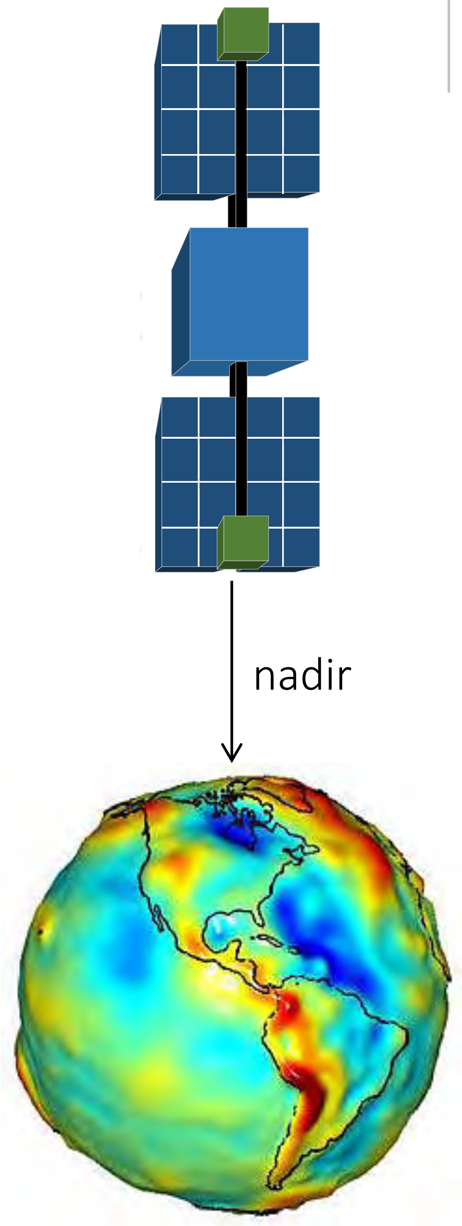
UNIVERSITY OF BIRMINGHAM RAL Space

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 and Main Benefits

Target Missions

- NGGM
- Future gravity missions
- Potential solutions for sustained observations

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

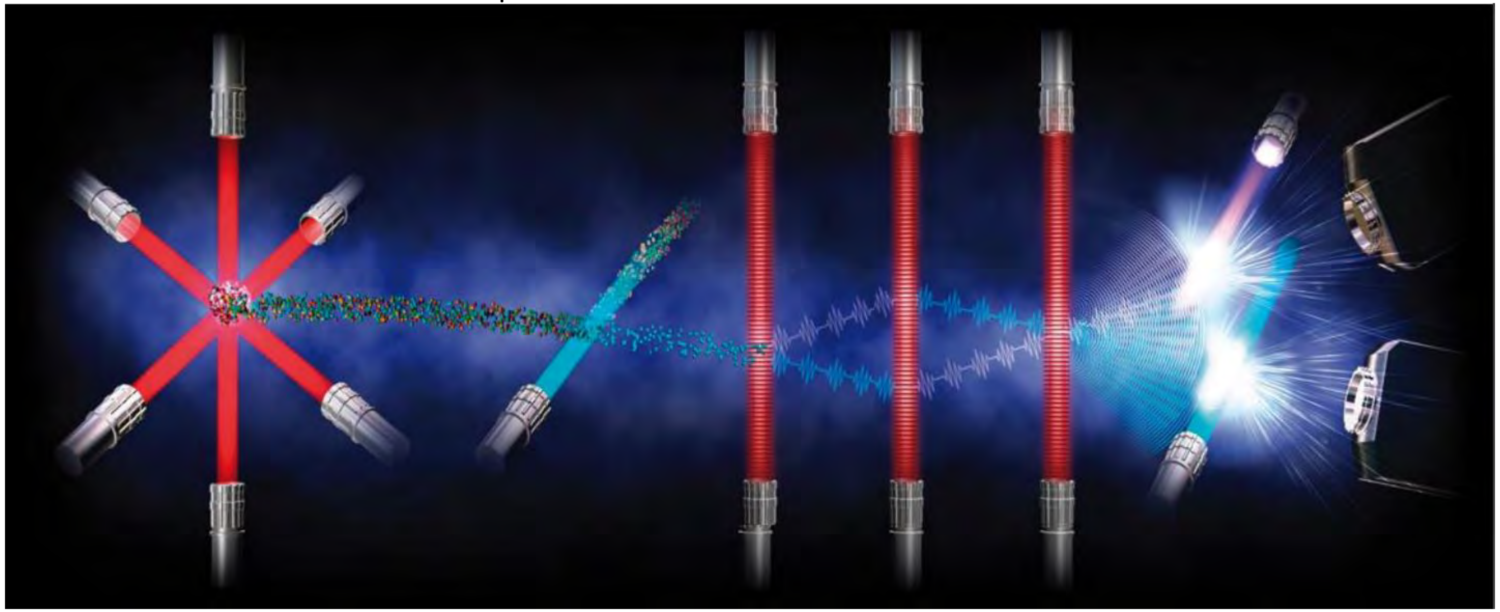


Image courtesy of Olivier Carraz, ESA

High repetition rate

- Duration of the measurement cycle
- Interleaving

Minimising noise

- Rotations
- Magnetic fields
- Instrumental noise

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

Sensor Concept Development

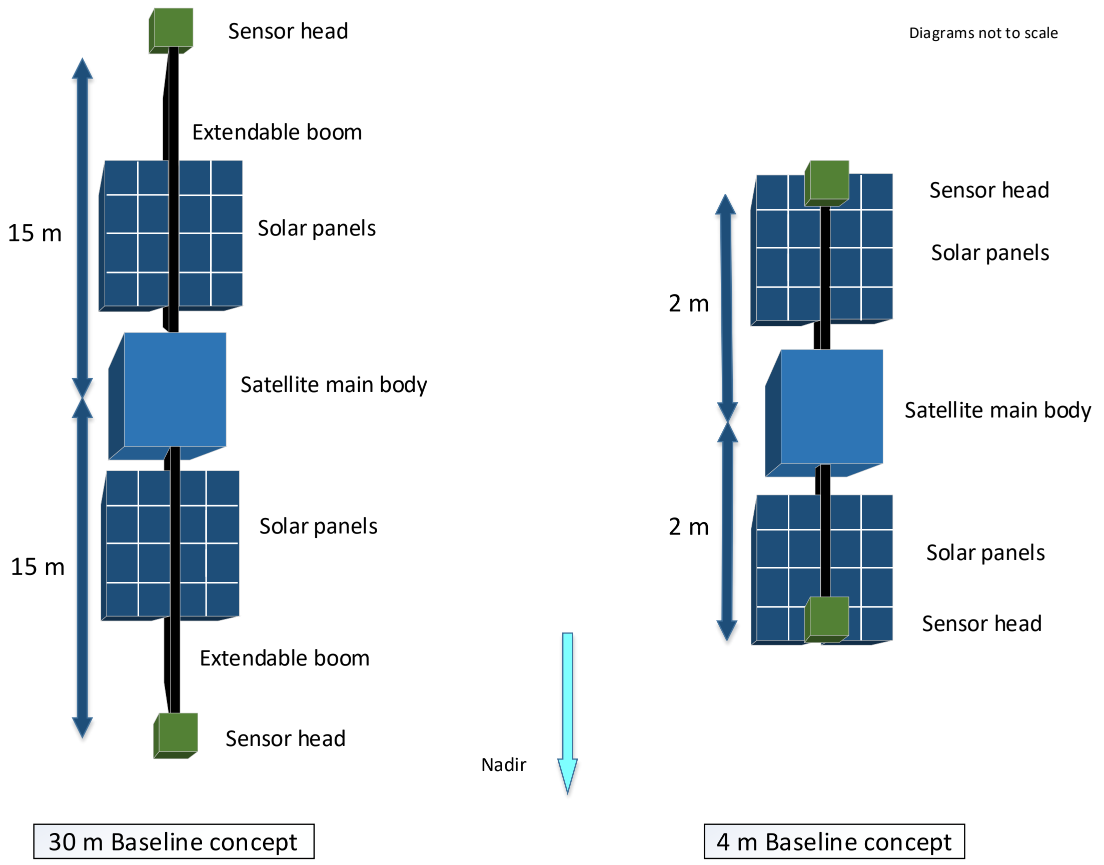
Technology Constraints

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

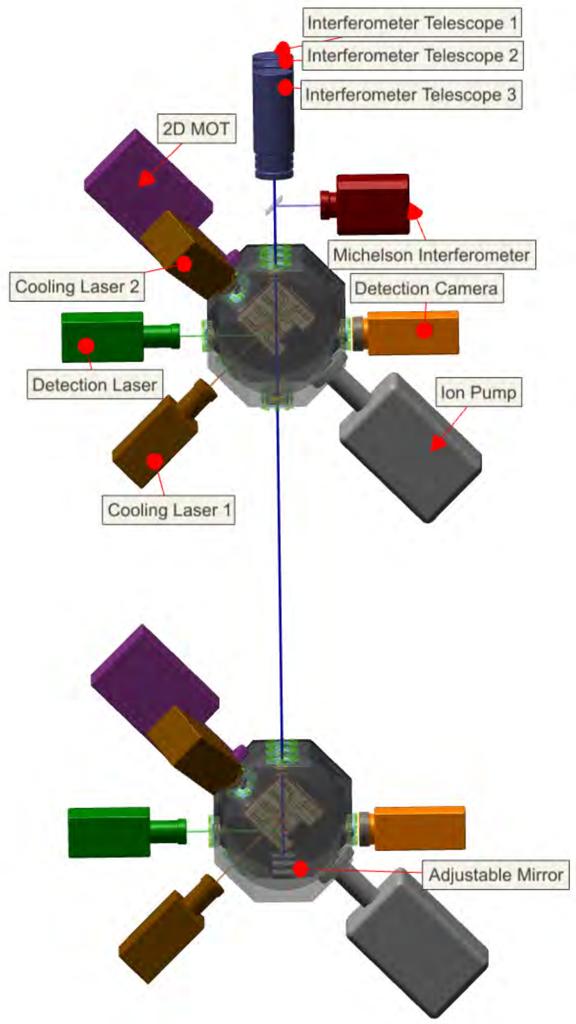


Final Concept

Operational Parameters

Parameters	Values
Interferometry Duration 2T (s)	8
Baseline (m)	4
Number of atoms	10^3
Preparation Time (s)	2.7
Atom Temperature (nK)	1
Diffraction Order	2
Total Noise (E)	0.0485

Full Sensor



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 Class. 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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