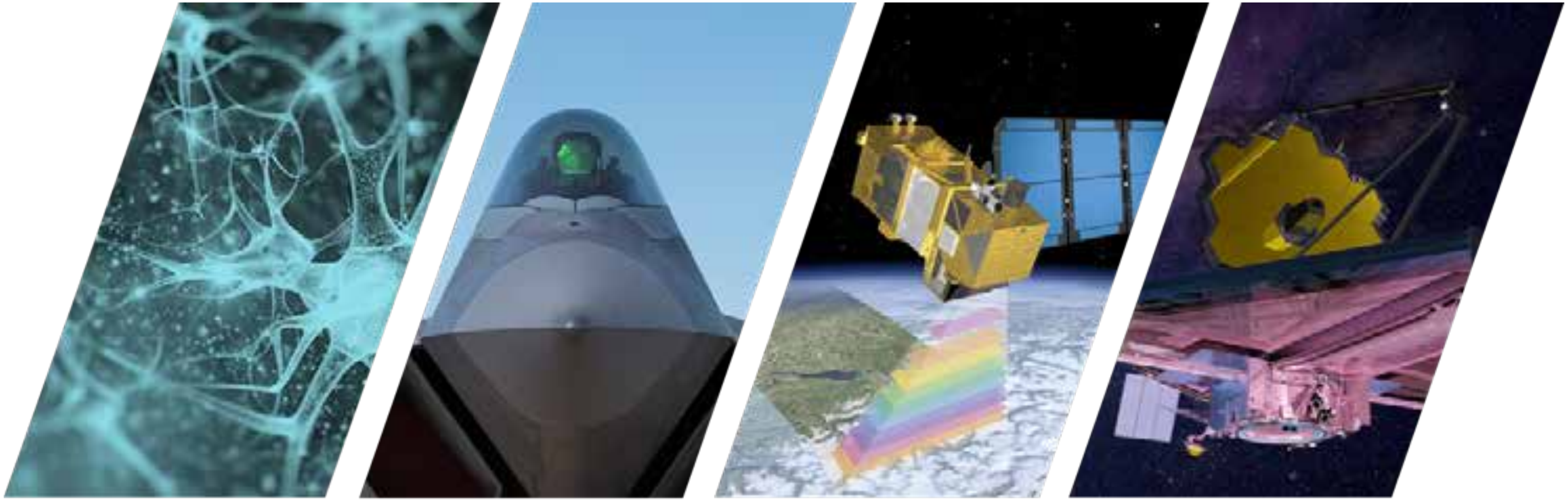

Cold Atom Accelerometry For Atmospheric Density Measurement

Steve Maddox
Product Development Manager
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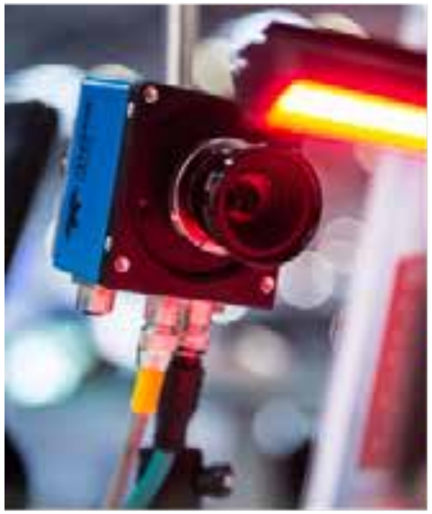
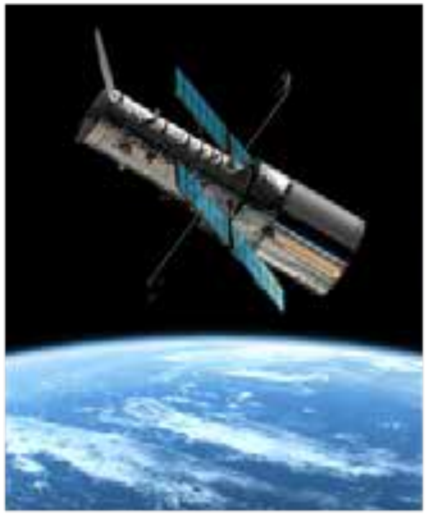
Teledyne Imaging

Focuses on the success of its customers by leveraging a remarkable portfolio of technology in sensing, signal generation and processing

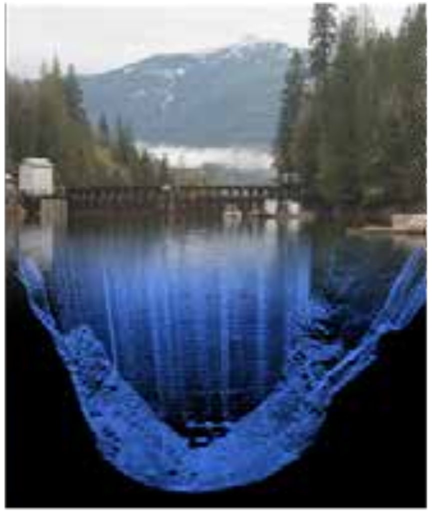


Machine Vision
DALSA | e2v | TS&I | ICM
Image sensors, cameras, processing hardware and software
Infrared, Visible, UV, X-Ray

Medical and Life Sciences
DALSA | e2v
Radiography detectors,
Radiotherapy generators



Aerospace & Defense
e2v | TS&I | DALSA
Sensors and systems for astronomy, earth science, and defense
High reliability chipsets & subsystems



Geospatial
Optech | CARIS
Lidar & Sonar 3D Surveying,
Geographic Information Systems
Software

Semiconductors
DALSA | e2v
MEMS foundry
CCD foundries
Packaging services

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

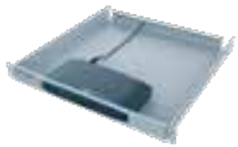
Timing and Frequency solutions including GNSS holdover

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

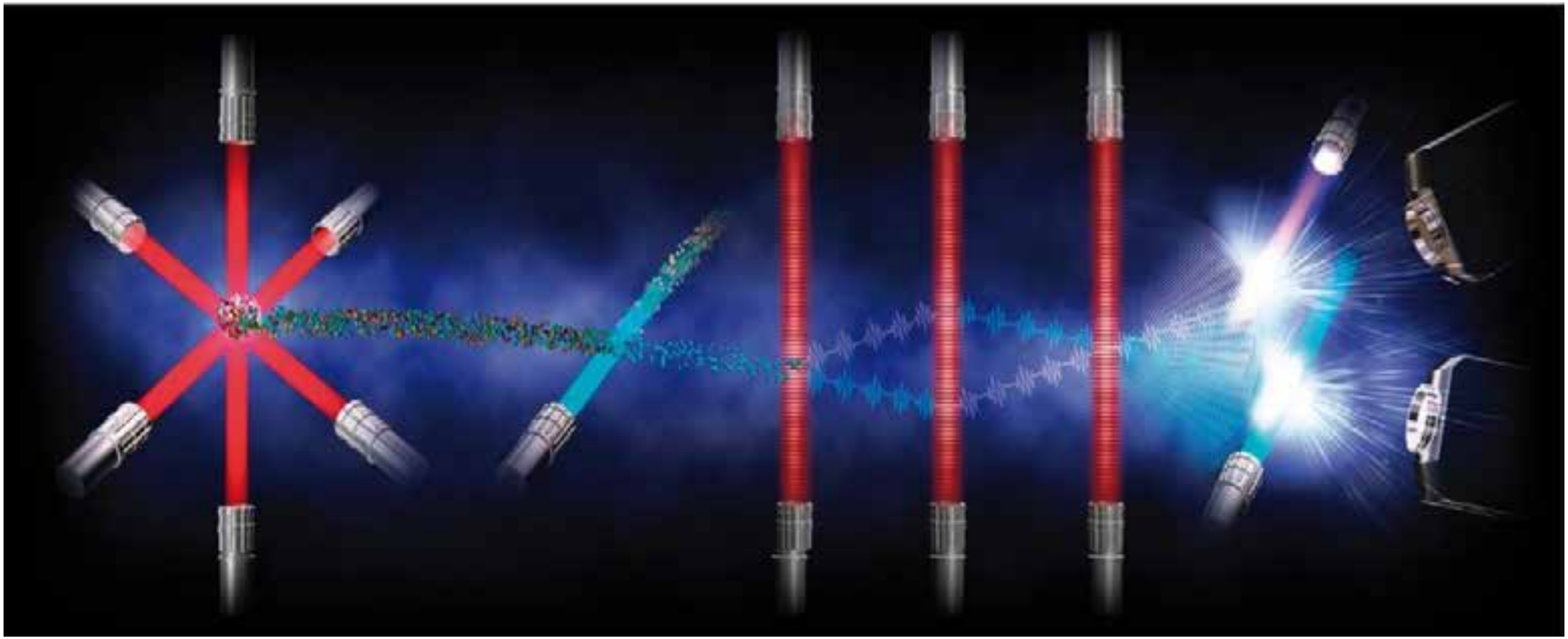


Image courtesy of Olivier Carraz, ESA

Classical compared to Quantum Sensors

Example of the Atomic Clock

Wrist watch

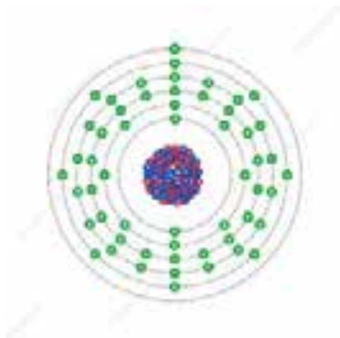
Frequency reference:
Quartz oscillator

Resonance frequency:
32kHz

Off every month by
15 seconds

How well can you manufacture it

Atomic Clock



Frequency reference:
Caesium atom

Resonance frequency:
9.2GHz

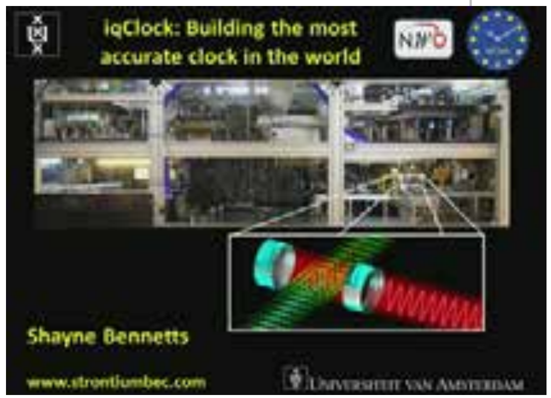
Off every month by
0.1 micro seconds

How well can you read out the atoms
(and shield them from the environment)

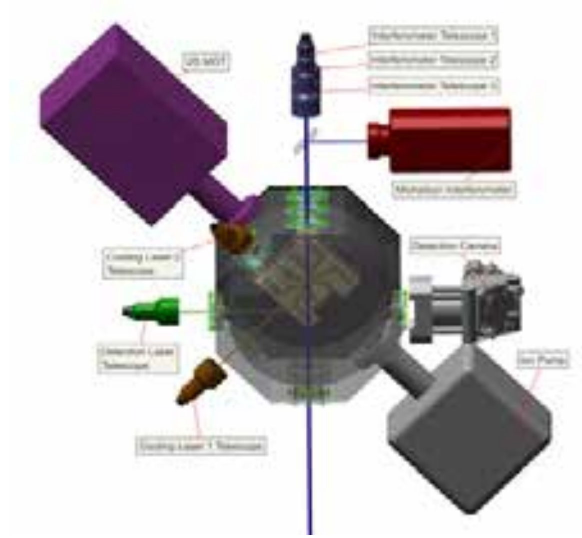
Applications in Space

- Frequency References (Clocks)
  - Next generation GNSS
  - Telecoms
  - Sensor synchronisation
  - Fundamental Physics e.g. Pharao/ACES
- Gravity
  - Candidate technology for future gravity missions
  - Gravity maps for navigation
  - Civil Engineering, prospecting
  - Earth science (ice sheets, ocean transport, climate change)
- Accelerometers
  - Navigation
  - Atmospheric Density
  - Precise Orbit Determination
  - Gravitational Waves
- Rotation Sensing
  - Navigation

IUK MINAC Clock



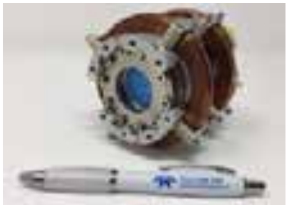
H2020 IQClock Project



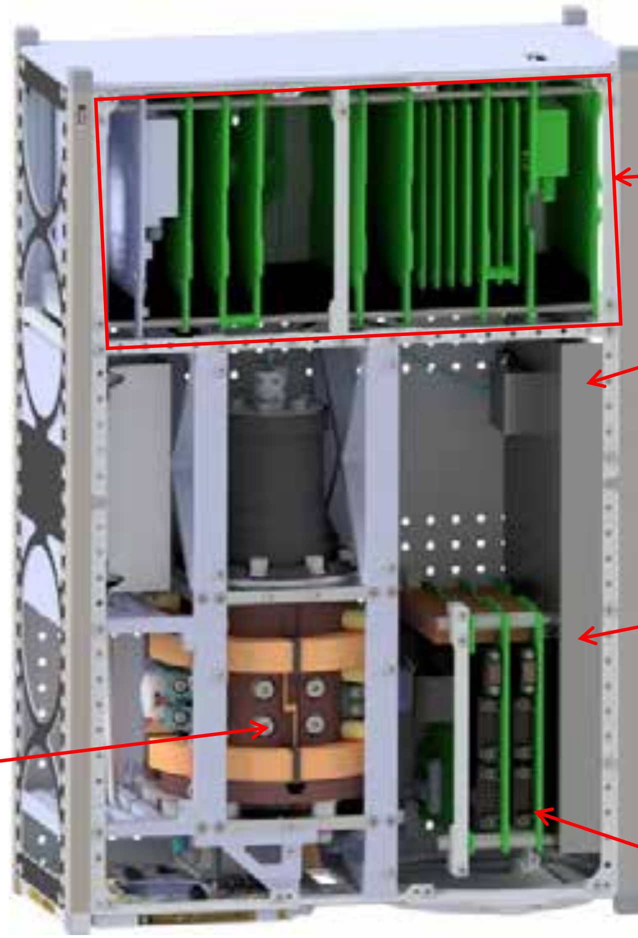
CEOI Cold Atom Gravity Explorer (CAGE)

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



Physics package: Vacuum assembly



Platform: Avionics & structure

Optical subsystem: Frequency Doubler

Optical subsystem: Laser System

Electronics subsystem: Imager and experiment control

Target Missions and Main Benefits

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

CASPA-ADM (ESA Phase 0 Study)

- 16U CubeSat with 1 axis accelerometer
- Verification of gas-surface interaction models, Atmospheric Waves, Cross-track accelerations
- Lifetime predictions, collision risk assessment/avoidance

Q-ACE (UK NSIP Phase 0 Study)

- TAS SkimSat with 2 axis accelerometer
- Longer lifetime / lower altitude
- Investigate climate change effects on atmospheric density

Pathfinder for world first Cold Atom EO mission

Enabled by precise and stable cold atom instrument

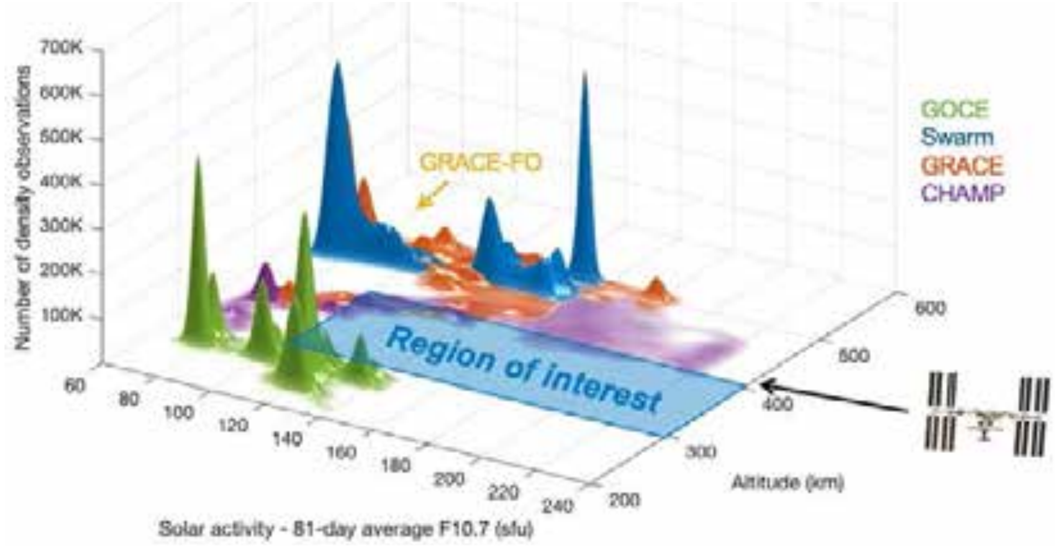
Follow on applications in gravity / navigation / timing

Adjacent terrestrial applications

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



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

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

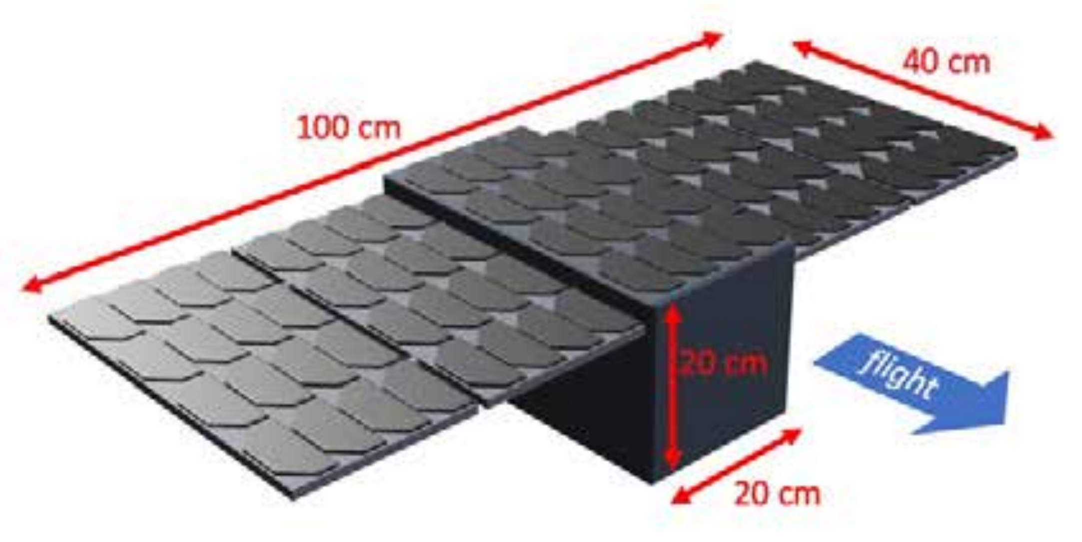
Very limited high-resolution, in-situ observations of thermosphere density

- 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 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

CASPA-ADM Accelerometer Performance

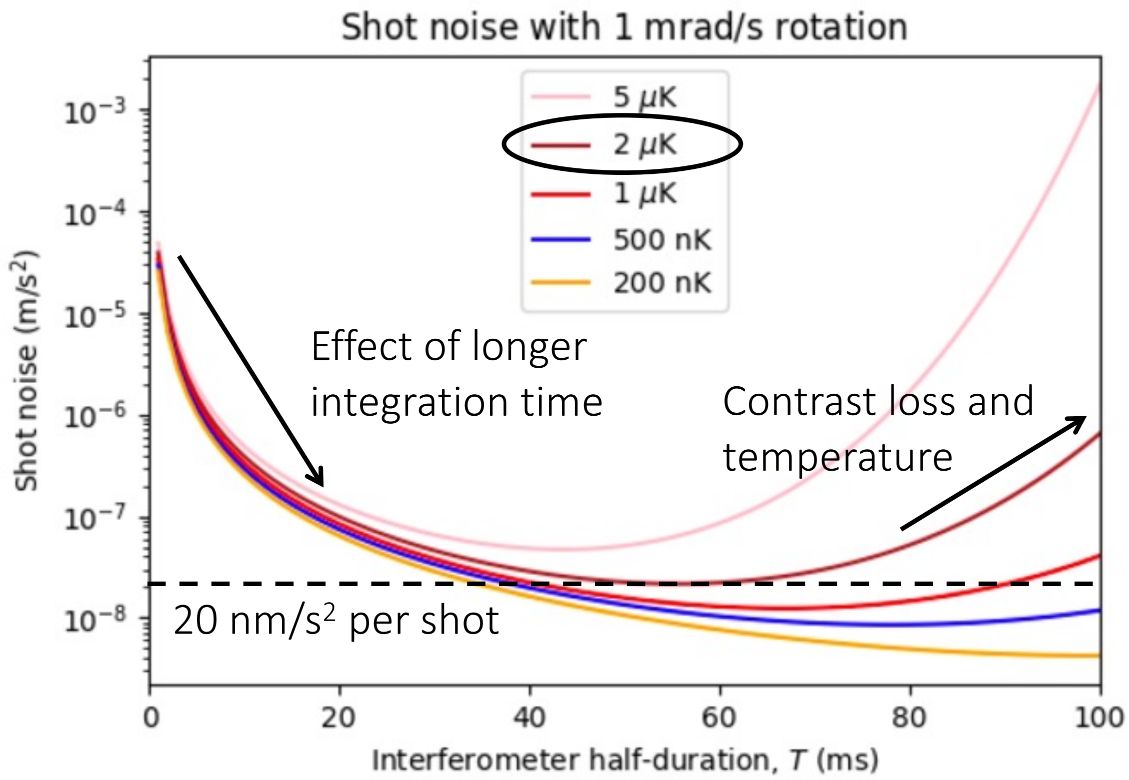
The figure shows the estimated measurement accuracy (based on commonly achieved performance in research labs) and taking into account:

- contrast loss due to satellite rotation
- atom loss due to non-zero temperature

A precision of 20 nm/s^2 per shot is achieved for an interrogation time of 56 ms when atoms are cooled to 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



CASPA-ADM Accelerometer Specification

Accuracy defining parameter	Value
Starting atoms (in MOT)	2×10^8
Atom temperature	$2\ \mu$K
Atoms detected	2×10^6
Time between interferometer measurements	2.5 s
Averaging time	10 s
Shot noise	2×10^{-8} m/s^2
Noise after averaging	1×10^{-8} m/s^2

Model of the vacuum chamber with the atom chip

Other noise sources	Mitigation strategy
Vibration	Minimise moving parts, model full system, consider hybrid sensor
Magnetic fields	Passive shields, detailed model, consider active shielding
Instrumental noise	Careful design and accounting for systematics

Current CEOI Project – CASPA Accelerometer

Project Objectives

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

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

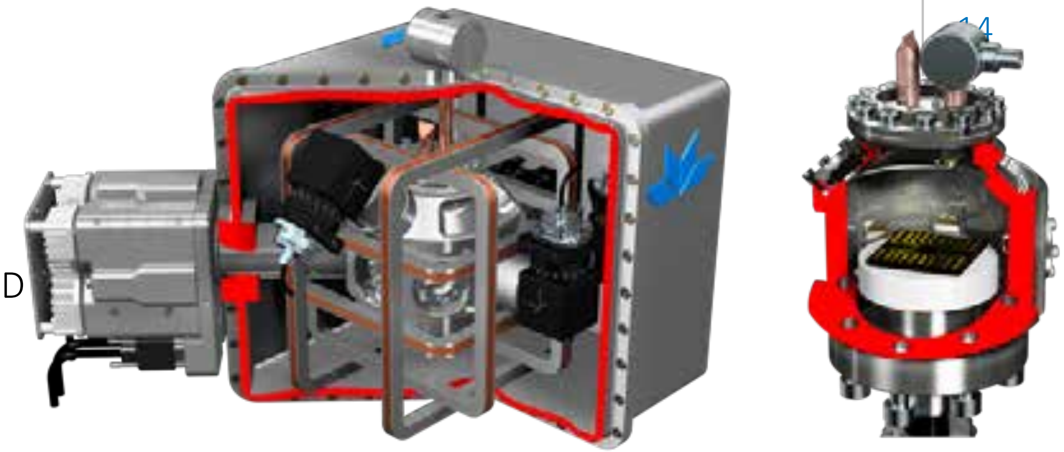
Second generation from RAL Space, bonding process in development, then component level testing to establish damage thresholds for current, temperature and vibration.

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.

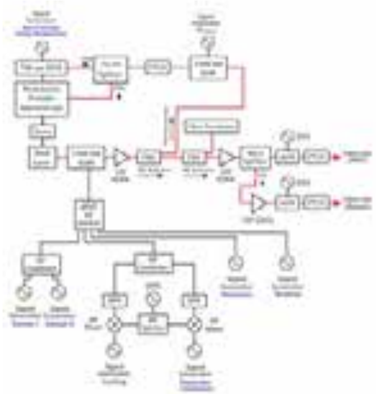
Laser System

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

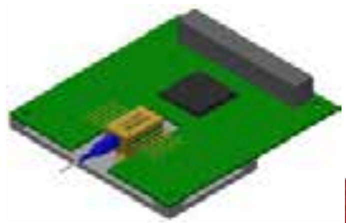


Credit: Teledyne e2v

Credit: RAL Space



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



Credit: RAL Space

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, simple, application-focussed end of the market
- 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