Cold Atom Interferometry

Towards a new Gravity Sensing Technology

CEOI Emerging Technology Challenge Workshop

Steve Maddox

1^{st}-2^{nd} May 2019

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Everywhereyoulook™

The Value we Bring

The Best Sensing Solutions for Your Needs

Space Qualified | Mil-Spec | Hybrid | COTS+ | Industrial

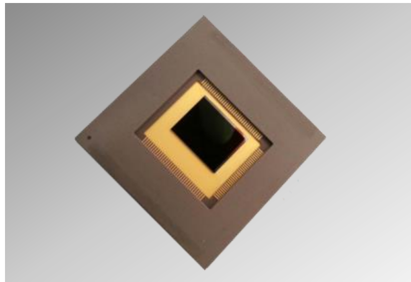
Detector | Camera | Quantum Sensing | Engineered System

Your Partner

COTS & Custom Sensors

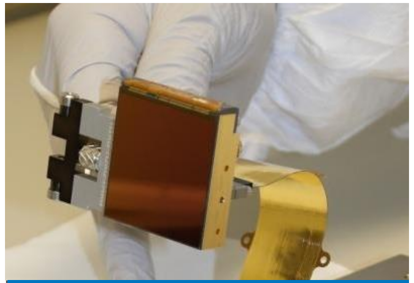
Engineered Detection Systems

Technical & Consultancy Services



CMOS

Leading the expansion of visible CMOS in space



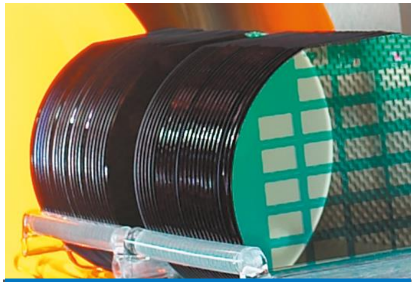
Infrared

MCT (2nd Gen)

Substrate Removed

InSb, InGaAs, etc.

Ultra-Low Light



CCD Foundries

X-Ray to NIR

Large Format FPAs

Quantum

Gravity Sensors (ground & space)

Time & frequency solutions

Components & services

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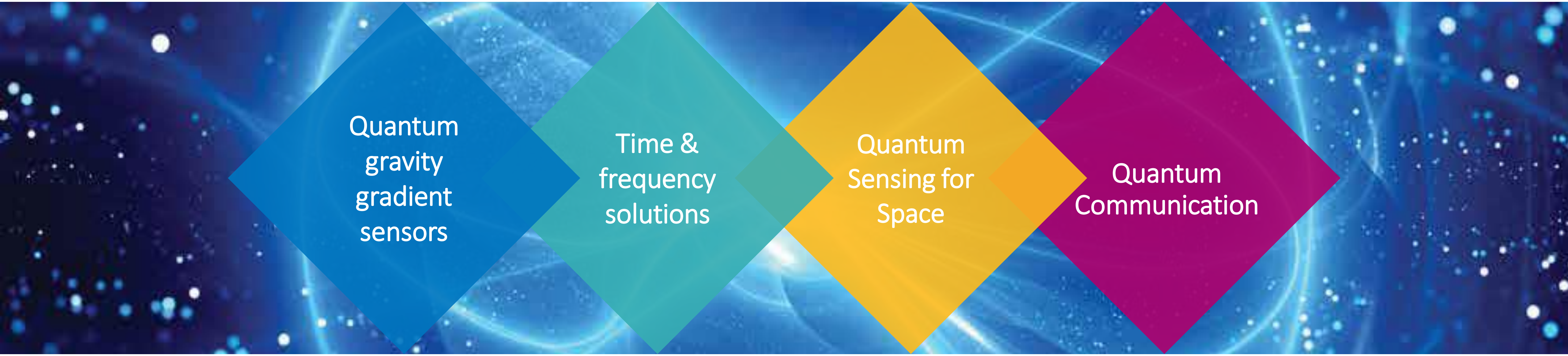
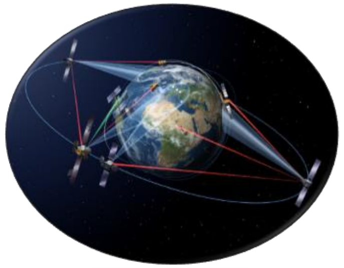
Commercialising Quantum Technologies of the Future

Next Generation Sensing and Control





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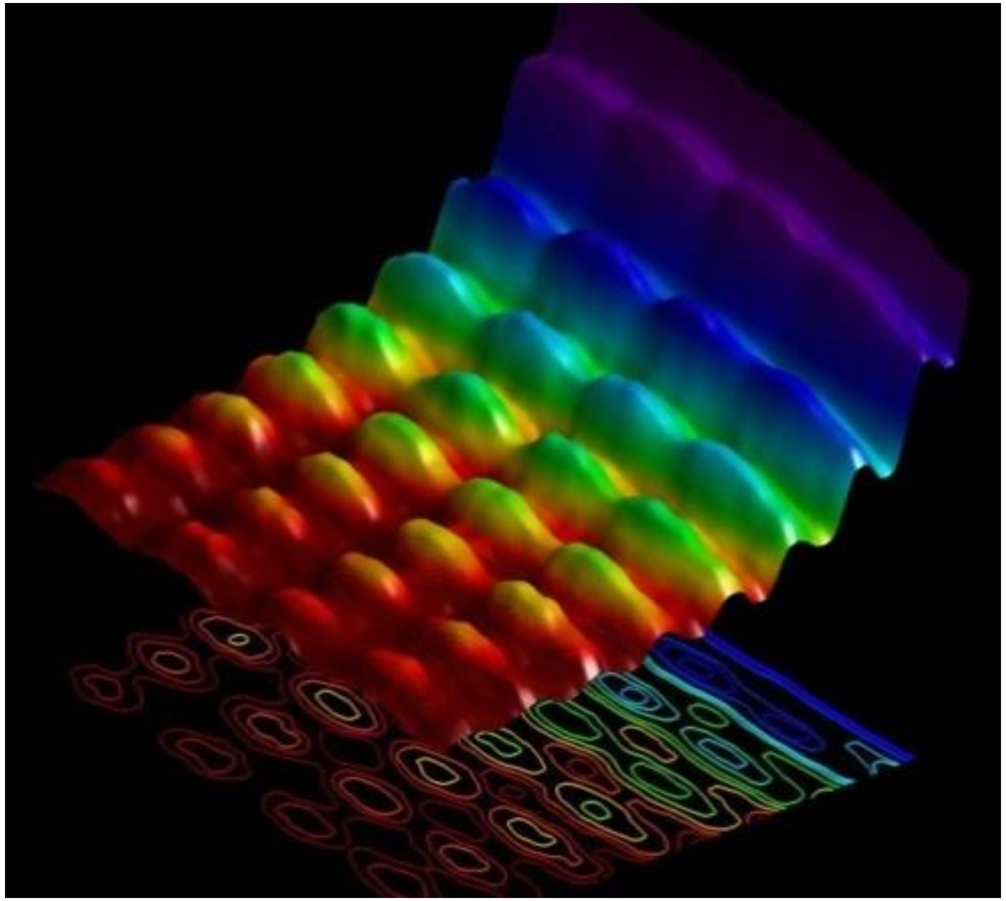
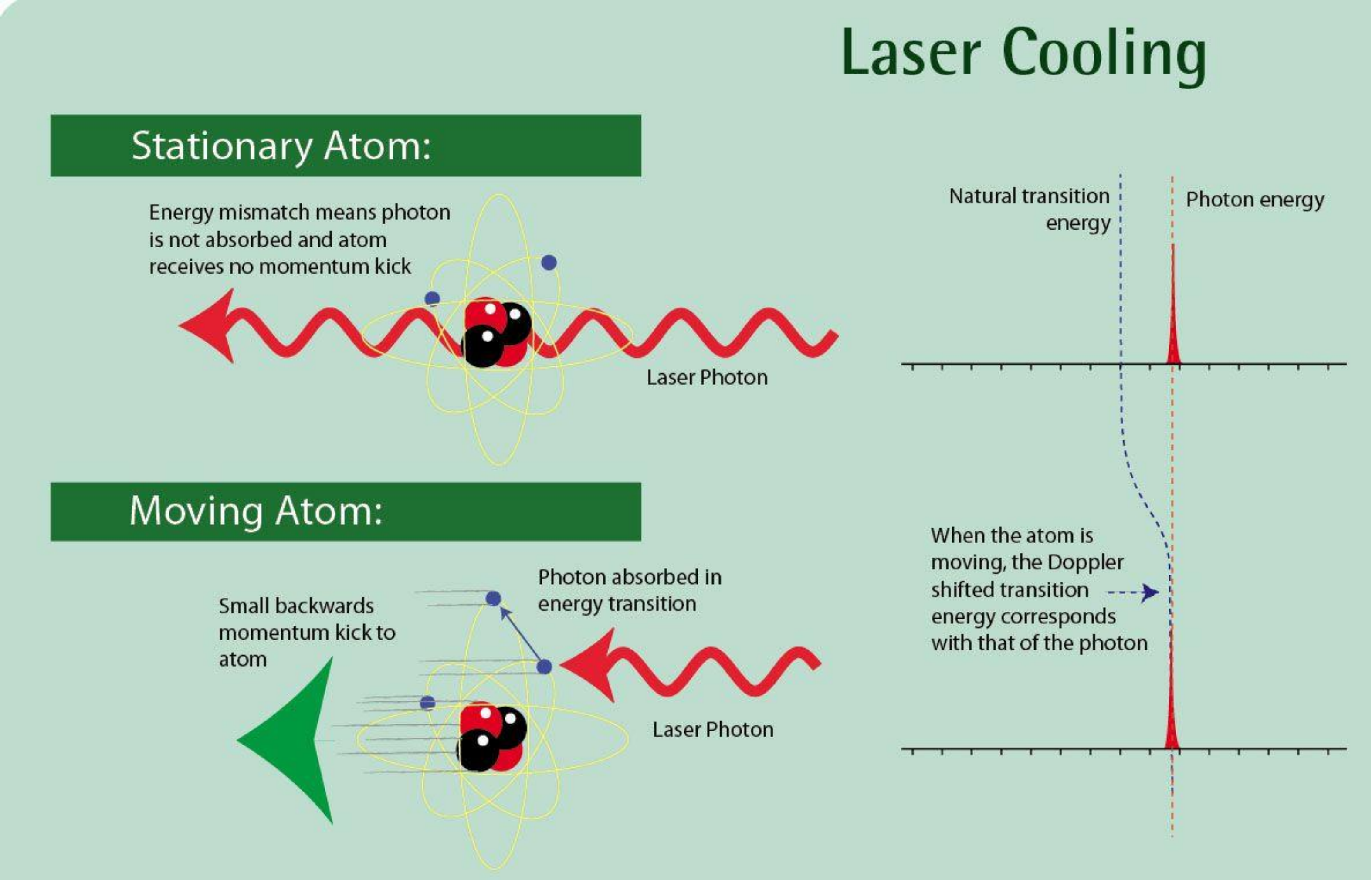
What is quantum sensing?

- Use atoms themselves as sensors – exploiting their quantum properties.
- Controlling and interacting with atoms using lasers (+magnetic and RF fields).
- Exploiting the wave-particle duality of atoms and photons.
- In order to use the atoms we first have to isolate, slow them down and confine them



Laser Cooling

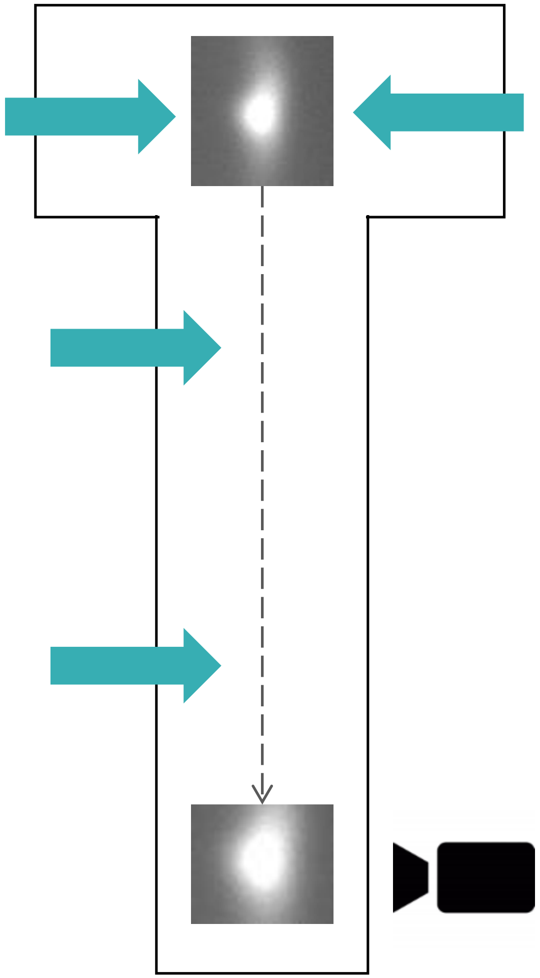
- Enabled by the ability to trap and cool atoms using lasers
- Nobel Prize for Physics in 1997
- Recent advances in laser technology have made this technology available outside the lab.



Using atoms to measure gravity

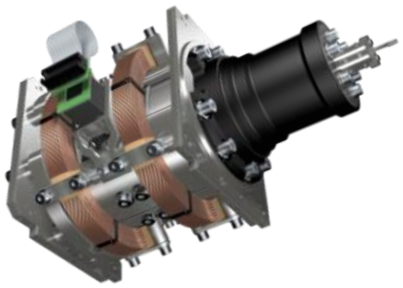
A few take home messages

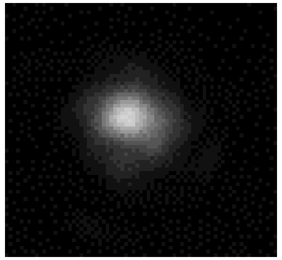
- Replace a traditional test mass with a ball of cold atoms
- Measure its behaviour under gravity using lasers to perform Atom Interferometry
- Equivalent to Optical Interferometry but replace the light wave with an matter wave and the mirrors with laser pulses

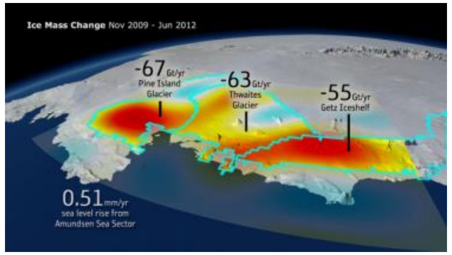


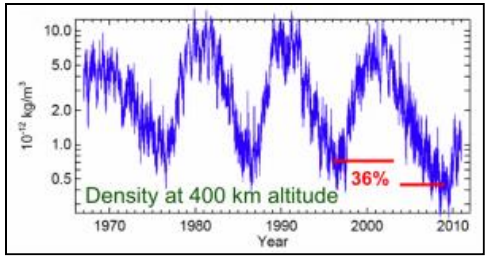
Cold Atoms – A new platform technology

- Gravity sensing
- Drag sensing
- Inertial navigation
- Attitude detection
- Timing references (atomic clocks)



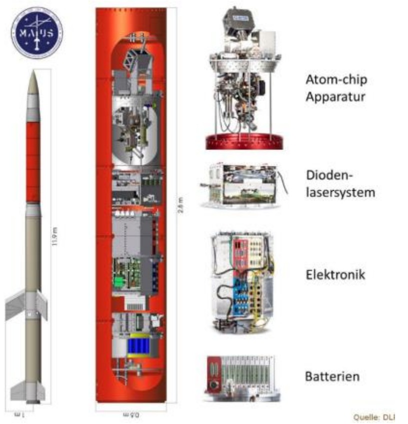






‘Current’ space cold atom systems

Organisation	Technology	Functionality	SWAP, Environment	When
NASA	Cold Atom Lab (CAL) on ISS	Dual species BEC - science	~370 litres Pressurised, a/c environment.	Launched in May 2018
China	Cold Atom Clock on Tiangong II	Ramsey fringe based Rb clock – GNSS and EO	SWAP unknown Pressurised, a/c environment.	Launched in September 2016
ZARM / Hannover / DLR	BEC on sounding rockets / drop tower	Dual species BEC - fundamental science (and EO?)	315kg, 300W 1400 litres 20g shock	First launch 2017



‘In development’ space cold atom systems

Organisation	Technology	Functionality	SWAP, Environment	When
ONERA / DTU	Cold Atom Gravimeter (GIRAFE)	Vibration Tolerant Gravity Sensor	Unknown SWAP Demonstrated in marine & airborne	Marine: 2015/2016 Airborne: 2017 (nothing published)
CNES/ESA	PHARAO cold atom clock	Ramsey fringe based Cs clock - science	~1000 litres Outside ISS	2020? (originally 2013)

Future Space Gravity Sensors

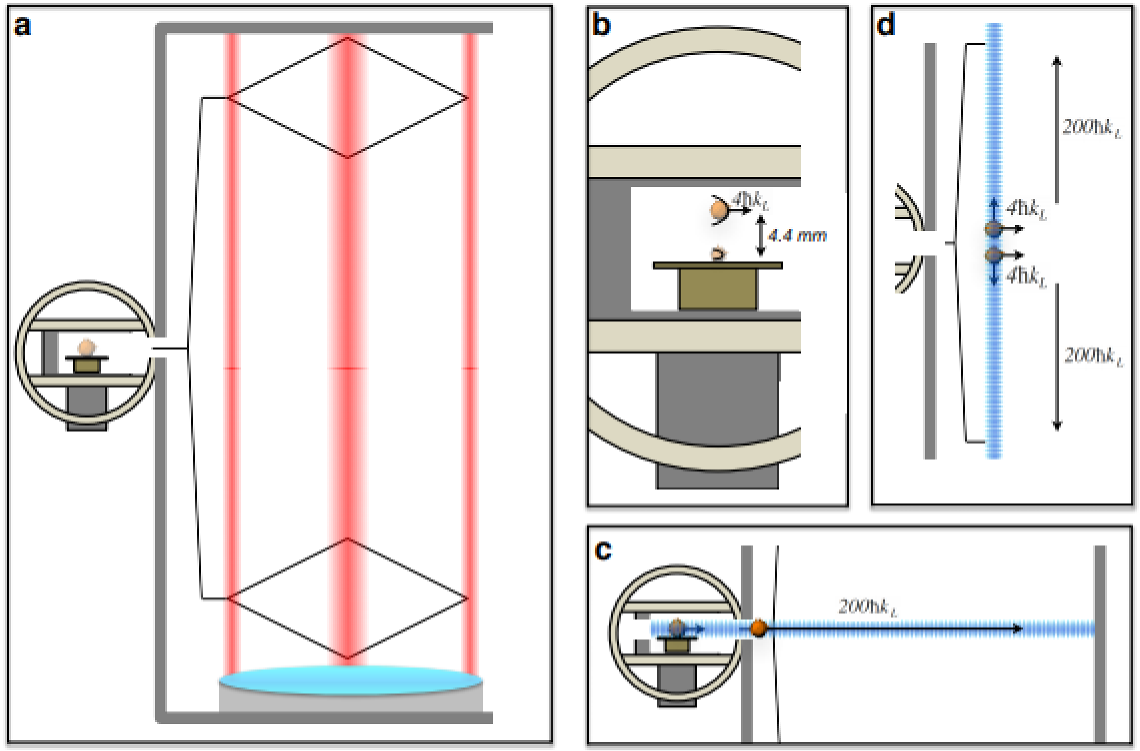
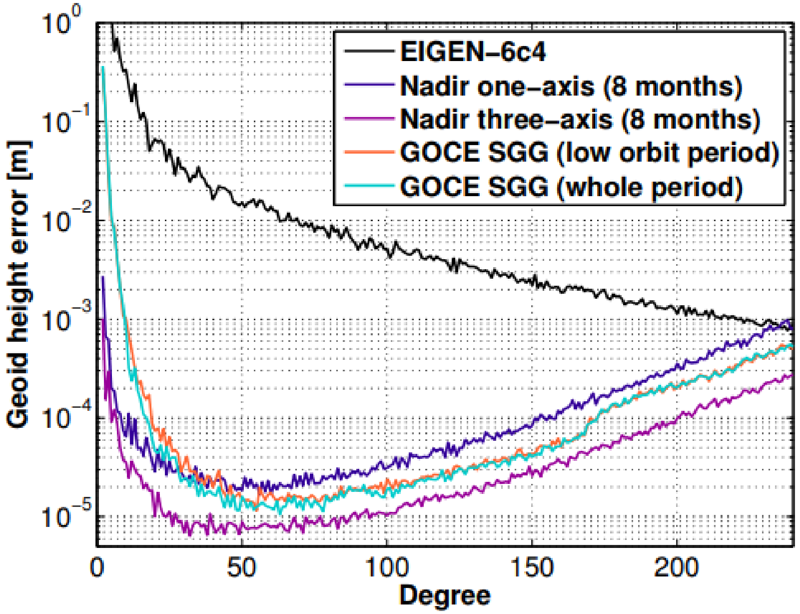


FIG. 1: (a) Scheme of the gravity gradiometer, based on differential accelerometry with two separated atom interferometers. (b) An initial BEC source of 10^6 atoms is magnetically evaporated, displaced and collimated in 1.1 s. (c) Horizontal transport step to the interferometry chamber (12 cm in 100 ms). (d) The BEC is split in two by the combination of a double Raman diffraction and a twin-lattice technique feeding both interferometers with ensembles at a horizontal velocity of 4 recoils.

Volume	1.78m^3
Mass	785 kg
Power Consumption	2940 W

(3-axis instrument including a 20% margin)



Concept study and preliminary design of a cold atom interferometer for space gravity gradiometry

A. Trimeche, B. Battelier, D. Becker, A. Bertoldi, P. Bouyer, C. Braxmaier, E. Charron, R. Corgier, M. Cornelius, K. Douch, N. Gaaloul, S. Herrmann, J. Müller, E. Rasel, C. Schubert, H. Wu, F. Pereira dos Santos

Proposals for Space Gravity Sensors

NASA /AO Sense development

NASA in collaboration with AO Sense have developed a terrestrial terrestrial proof-of-concept gravity gradiometer.

"It could be used…to obtain an extraordinary data set for understanding Earth's water cycle and its response to climate change. In fact, the sensor is a candidate for future NASA missions across a variety of scientific disciplines."

"With this new technology, we can measure the changes of Earth's gravity that come from melting ice caps, droughts, and draining underground water supplies, greatly improving on the pioneering GRACE mission."

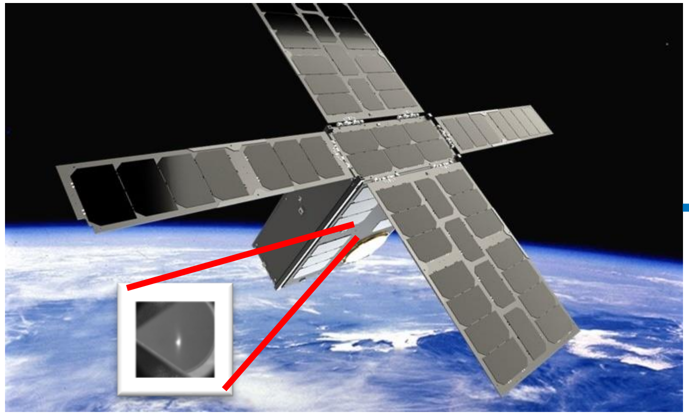
The Goddard-AOSense terrestrial proof-of-concept gravity gradiometer.
Credits: AOSense, Inc

Teledyne e2v development plan

- Develop interferometry capability and design
- Terrestrial product in its own right

REVEAL Ground Based Gradiometer

- Adapt key technology for space
- Miniaturisation, power reduction, robustness, material suitability



Cold Atom Space Payload

Cold Atom Space Instrument

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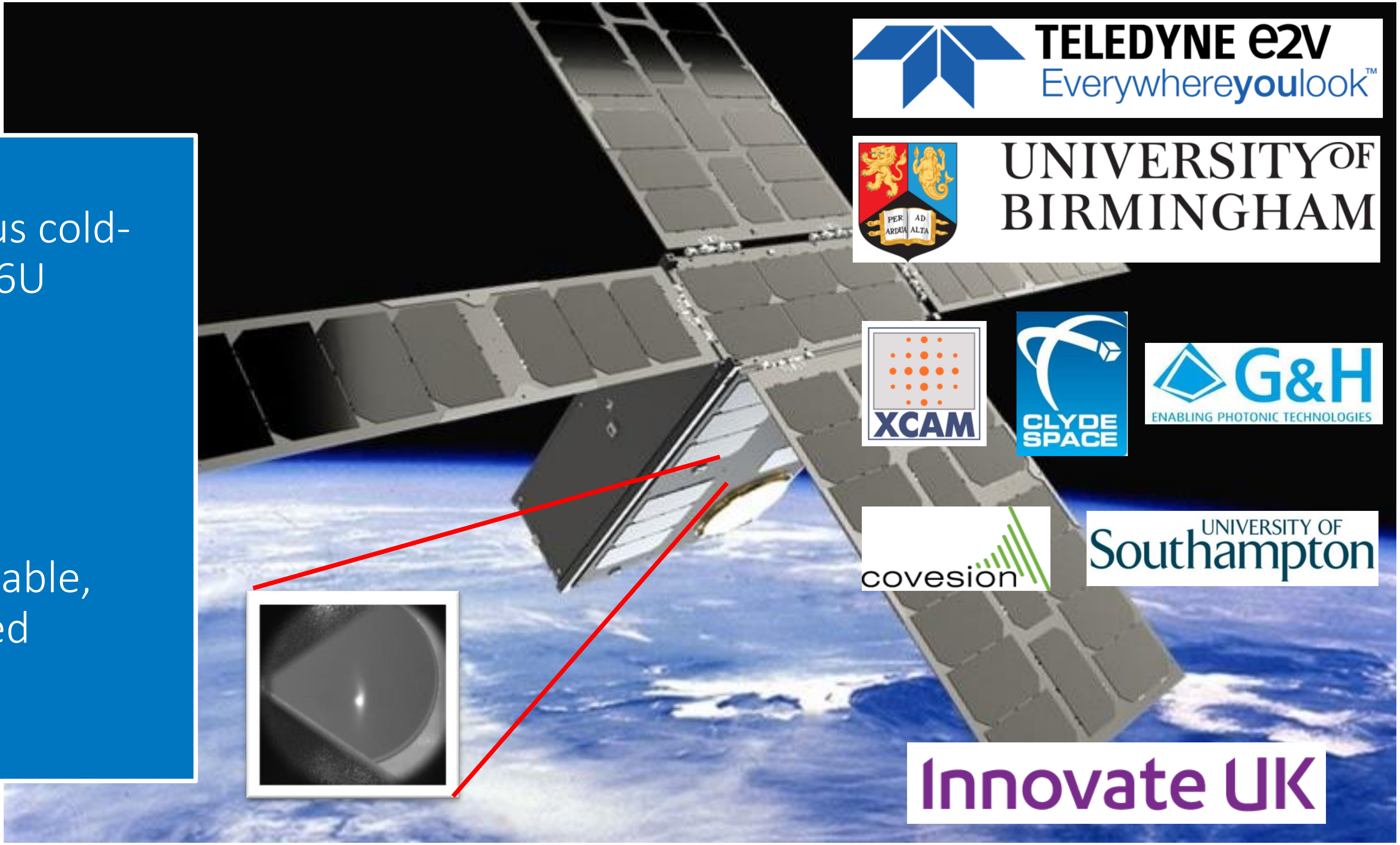
CASPA: Cold Atom Space PAyload

Mission

- Deliver autonomous cold-atom cooling on a 6U CubeSat

Objectives

- Increase TRL
- Develop space-suitable, properly engineered solutions
- Reduce SWAP

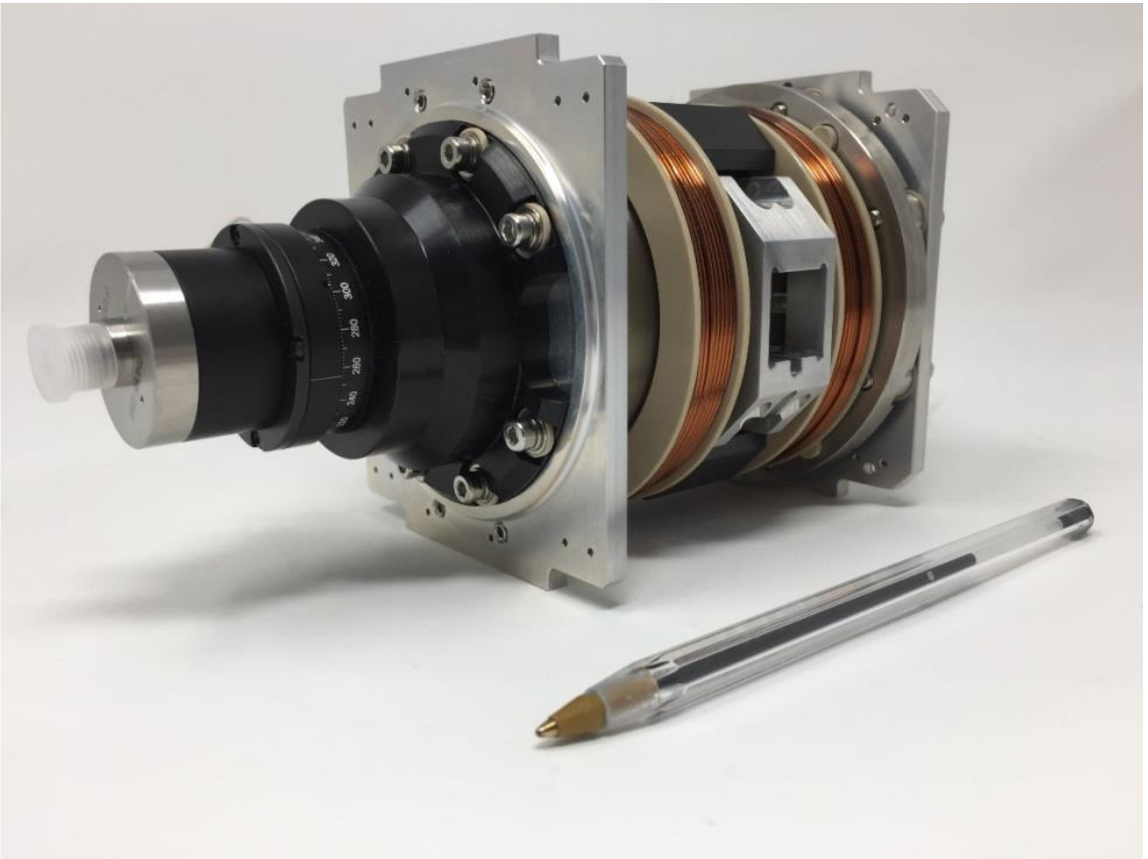


Physics Package Development

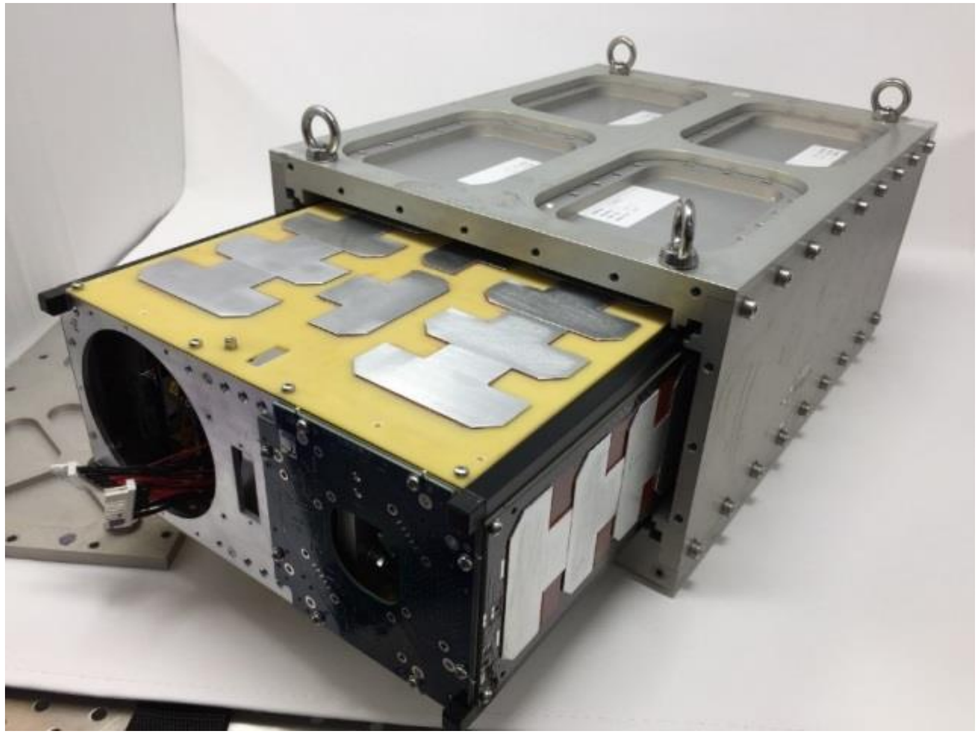
- Integrated physics package inc:
  - Titanium alloy UHV chamber
  - Ion pump
  - Atom Source
  - Magnetic Field Generation
  - Magnetic Shielding
  - Optical delivery

- Space suitable materials

- Designed for launch shock and vibration conditions



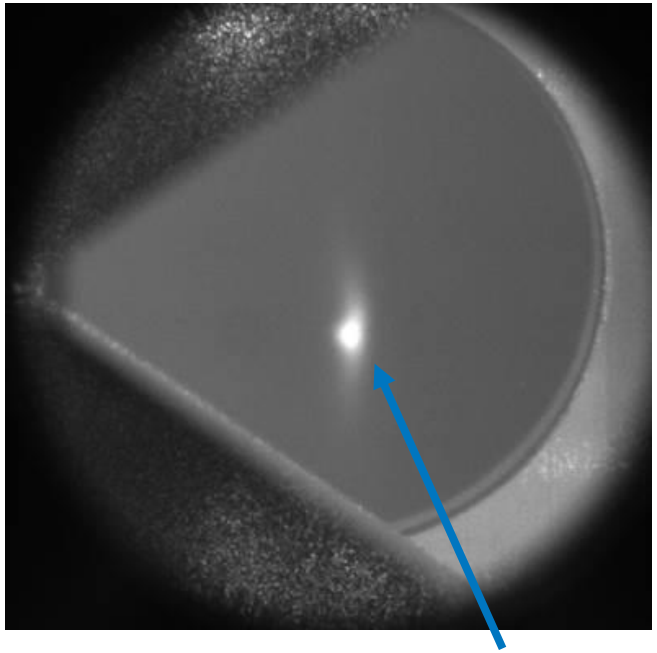
Engineering Model Integrated



Status

- Automated power up sequence, laser locking and MOT imaging implemented
- Environmental testing phase

Parameter	Target	Actual
Size	4U Envelope	4U Envelope
Weight	4.00kg	3.57kg
Power	40W peak power	~25W



10^7 atoms at microkelvin temperatures

Key applications

- Ice Sheets and Glaciers
- Terrestrial Water Storage
  - Groundwater depletion
- Sea Level Change and Ocean Dynamics
- Climate Service Applications
  - Drought and flood prediction
- Commercial
  - Water reserves for mining
  - Oil and gas exploration
  - Geothermal energy sources
  - Ocean currents for shipping

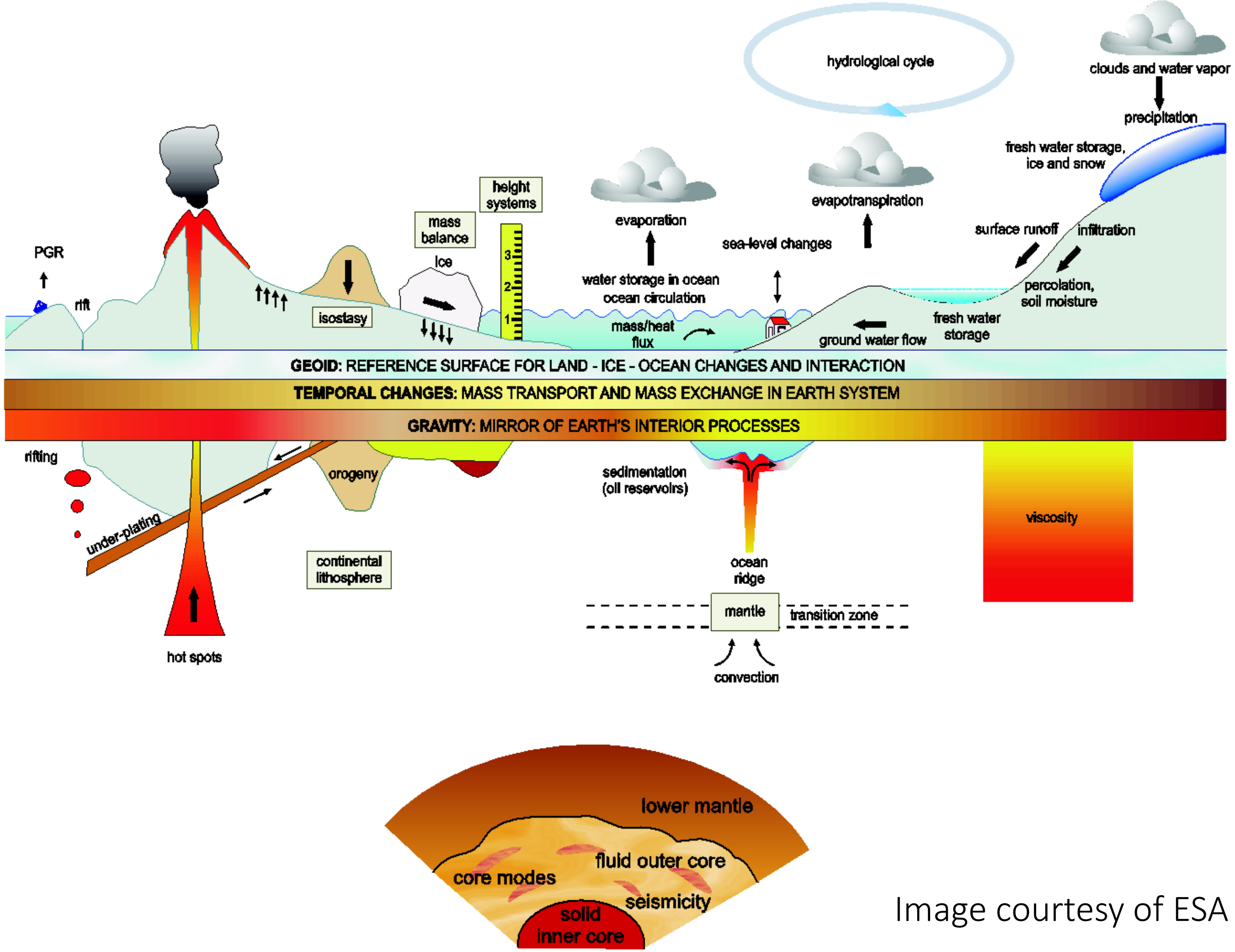


Image courtesy of ESA

Key applications – longer term

- Key technology for future gravity missions
  - Enhanced performance – enabling new science and commercial applications
  - Same or "good enough" performance but at much lower cost, potentially enabling constellations

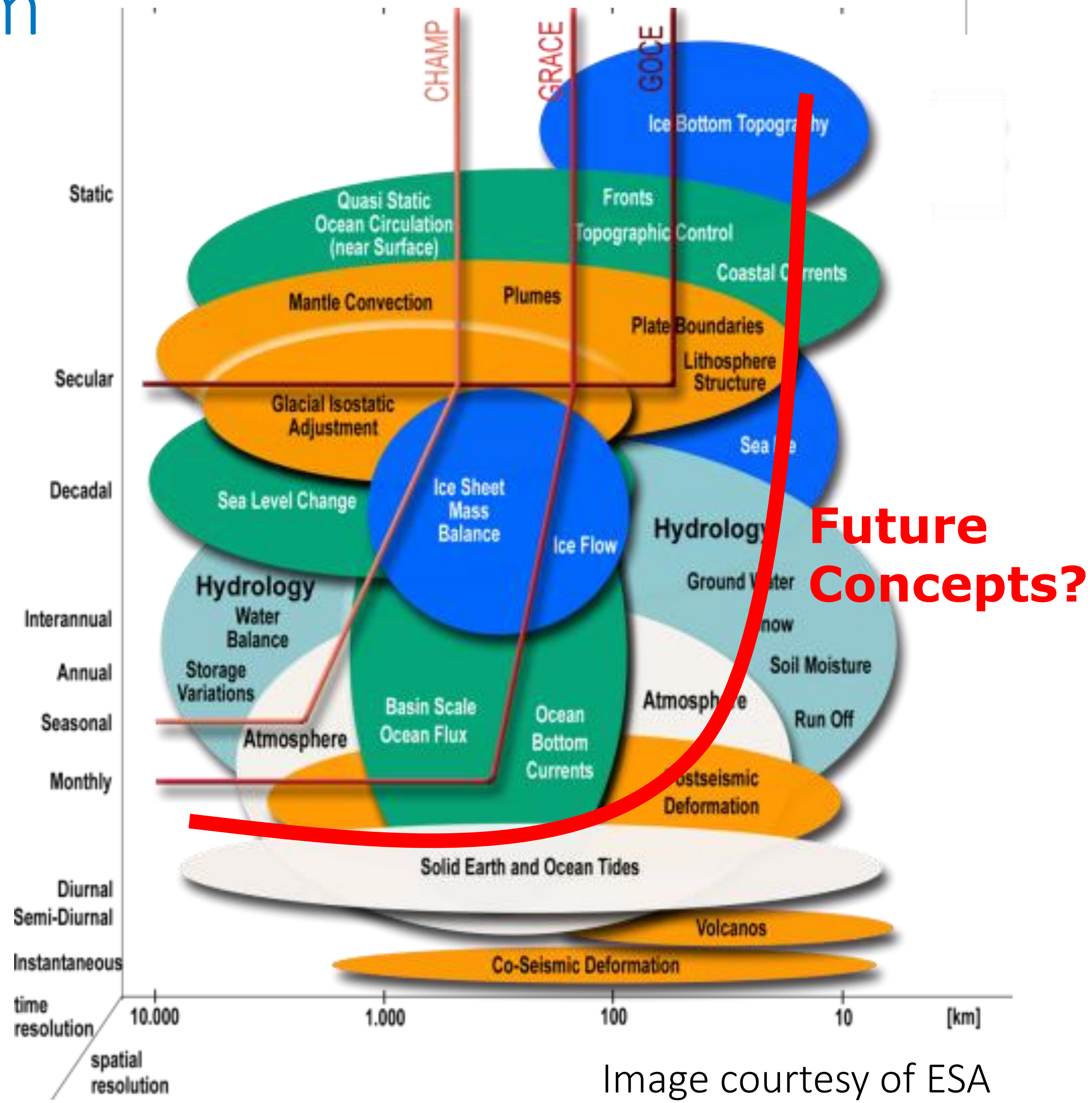
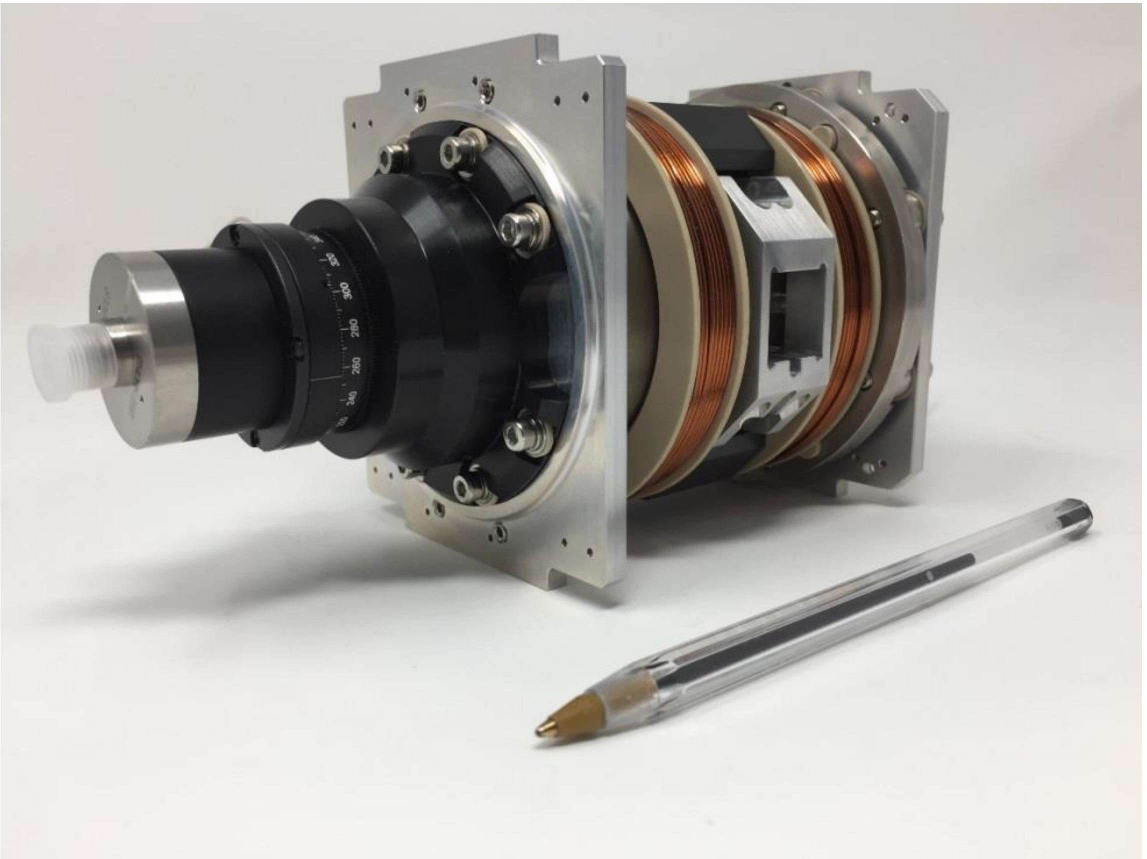


Image courtesy of ESA

Summary

- CAI is ready for space implementations
- CAI will bring performance improvements
- Substantial international investments and flight programmes
- UK is a latecomer but now leading in cost and miniaturisation
- Need to get “something” into space as soon as possible – a pathfinder with a science case
- Commercial applications will follow



Thanks for listening

We’re also interested in exploring new collaborations – please get in touch.

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