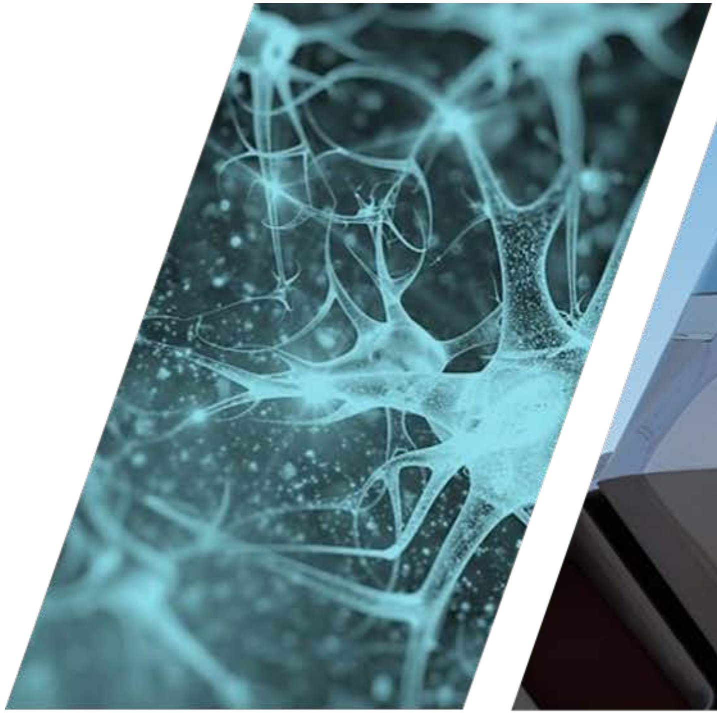
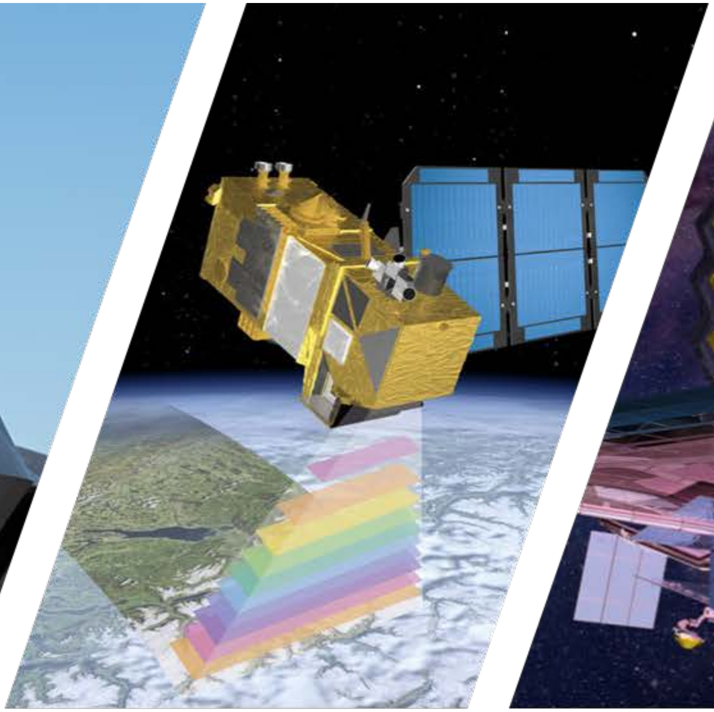
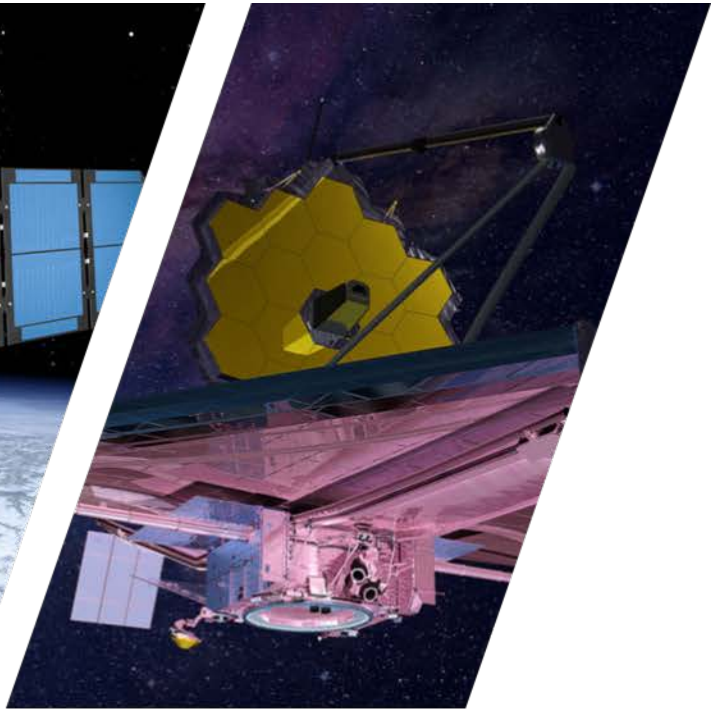


Quantum Gravity Sensing in Space

Steve Maddox

NCEO AND CEOI EARTH OBSERVATION CONFERENCE
September 2019

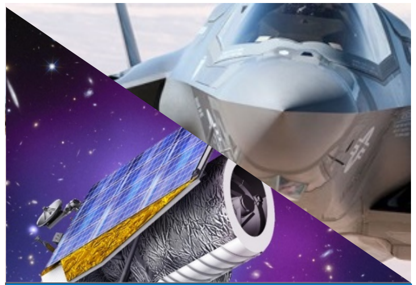
TELEDYNE IMAGING
Everywhereyoulook™

The Value we Bring

The Best Sensing Solutions for Your Needs

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

Detector | Camera | Quantum Sensing | Engineered System

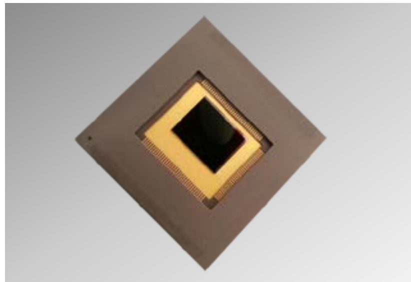


Your Partner

COTS & Custom Sensors

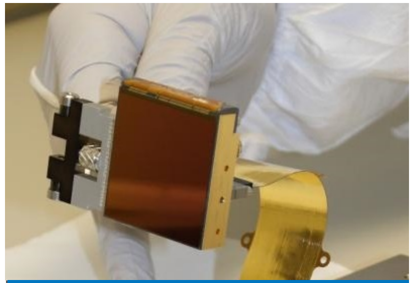
Engineered Detection Systems

Technical & Consultancy Services



CMOS

Leading the expansion of visible CMOS in space



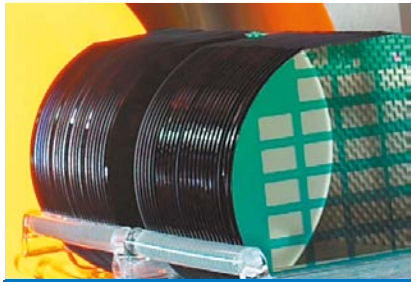
Infrared

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)

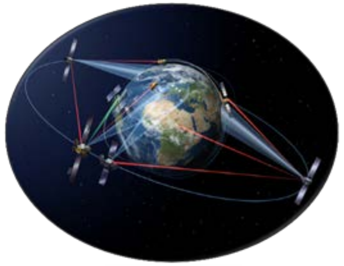
Time & frequency solutions

Components & services

Commercialising Quantum Technologies of the Future

Next Generation Sensing and Control

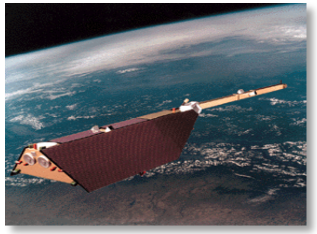
- Quantum gravity gradient sensors
- Time & frequency solutions
- Quantum Secure Communication
- Quantum Sensing for Space

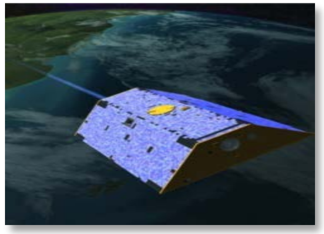


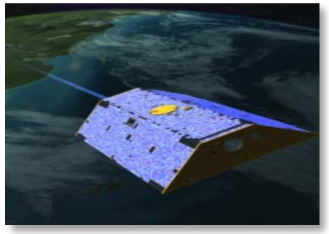
(Slide courtesy of Olivier Carraz, ESA)

Past, present and future gravity missions

Past, present and planned







CHAMP

GRACE

GRACE FO

GOCE

2000 | 2010 | 2020 | 2030

Future constellation

Continuation of observations at lower resolution

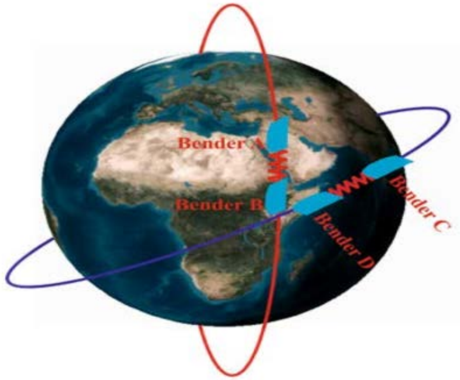
more accurate & better space/time resolution

GRACE II (US)

NGGM (Europe)

Start of sustained observations at high resolution

Simulation studies for ESA /NASA show that an international collaborative constellation will provide higher return than the sum of two missions



Key applications of Gravity Sensing

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

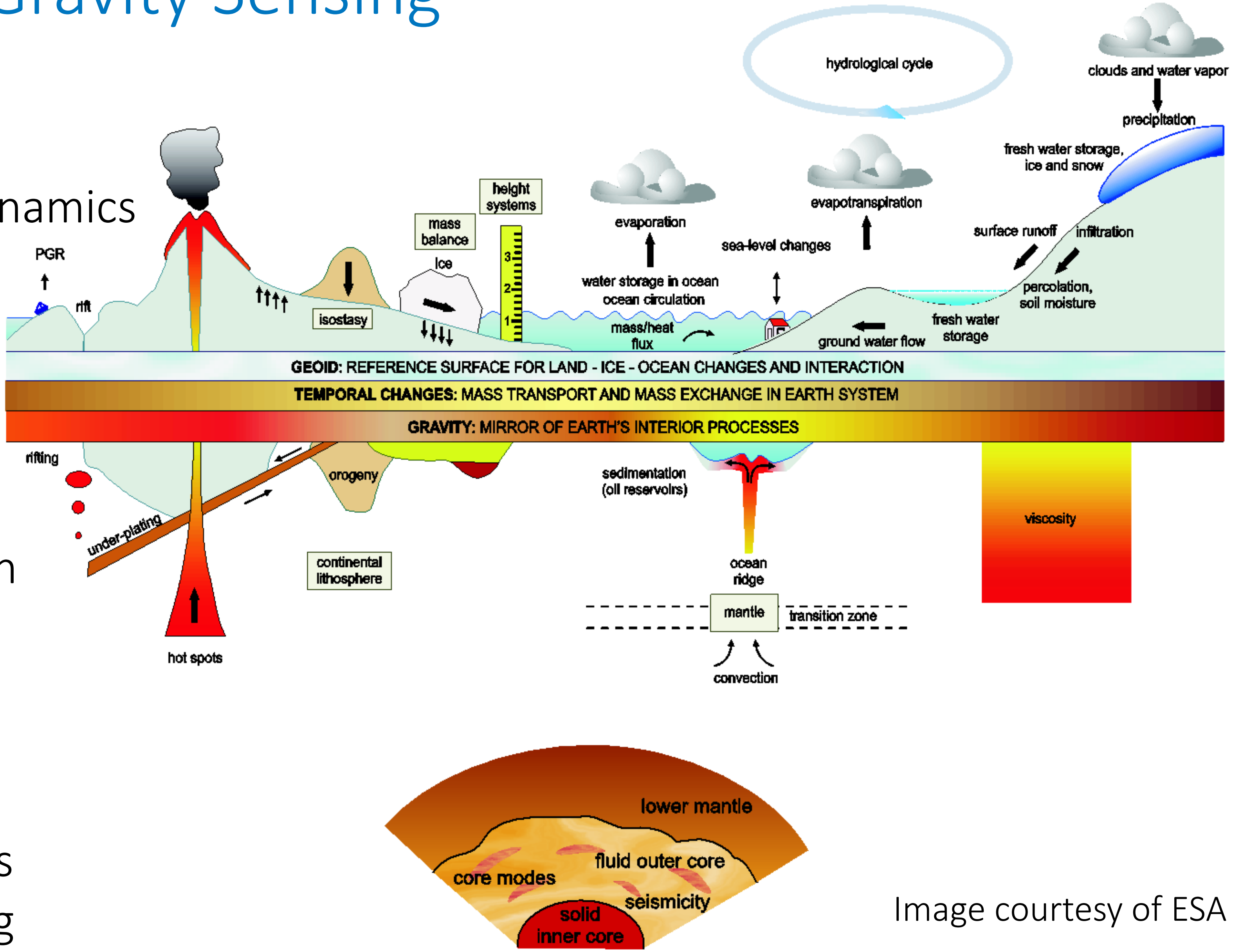
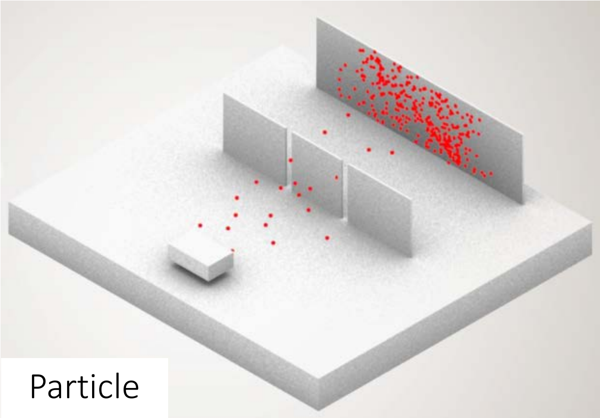


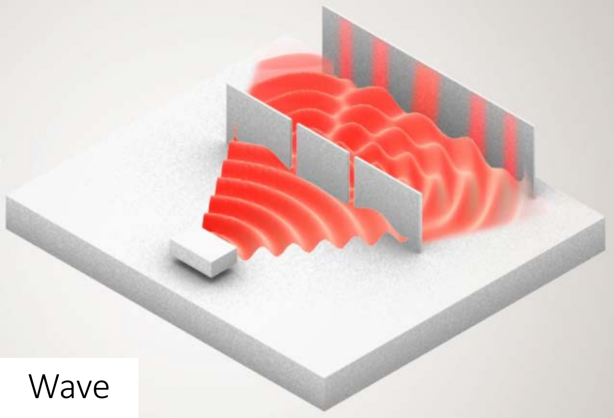
Image courtesy of ESA

What is Quantum sensing?

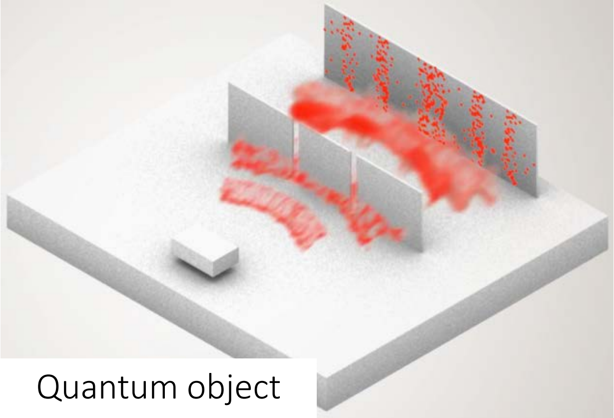
- Use clouds of atoms in vacuum as sensors
- Confined and measured using very precise lasers
- Exploits the wave-particle duality of atoms to create an atom interferometer
- Benefits:
  - High sensitivity
  - Low drift



Particle



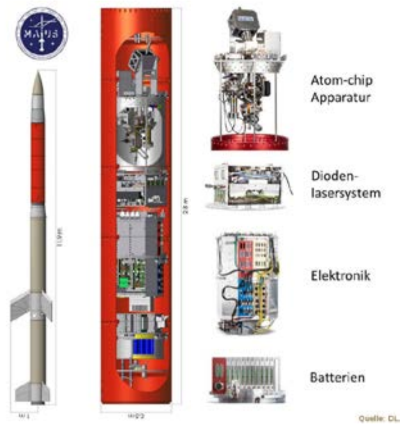
Wave



Quantum object

‘Current’ space cold atom systems

Organisation	Technology	Application	SWAP, Environment	When
NASA	Cold Atom Lab (CAL) on ISS	Fundamental Science	~370 litres Pressurised, a/c environment.	Launched in May 2018
China	Cold Atom Clock on Tiangong II	GNSS Clock/EO Technology Demonstrator	SWAP unknown Pressurised, a/c environment.	Launched in September 2016
ZARM / Hannover / DLR	BEC on sounding rockets / drop tower	Fundamental science	315kg, 300W 1400 litres 20g shock	First launch 2017



Space Quantum Gravity Sensors

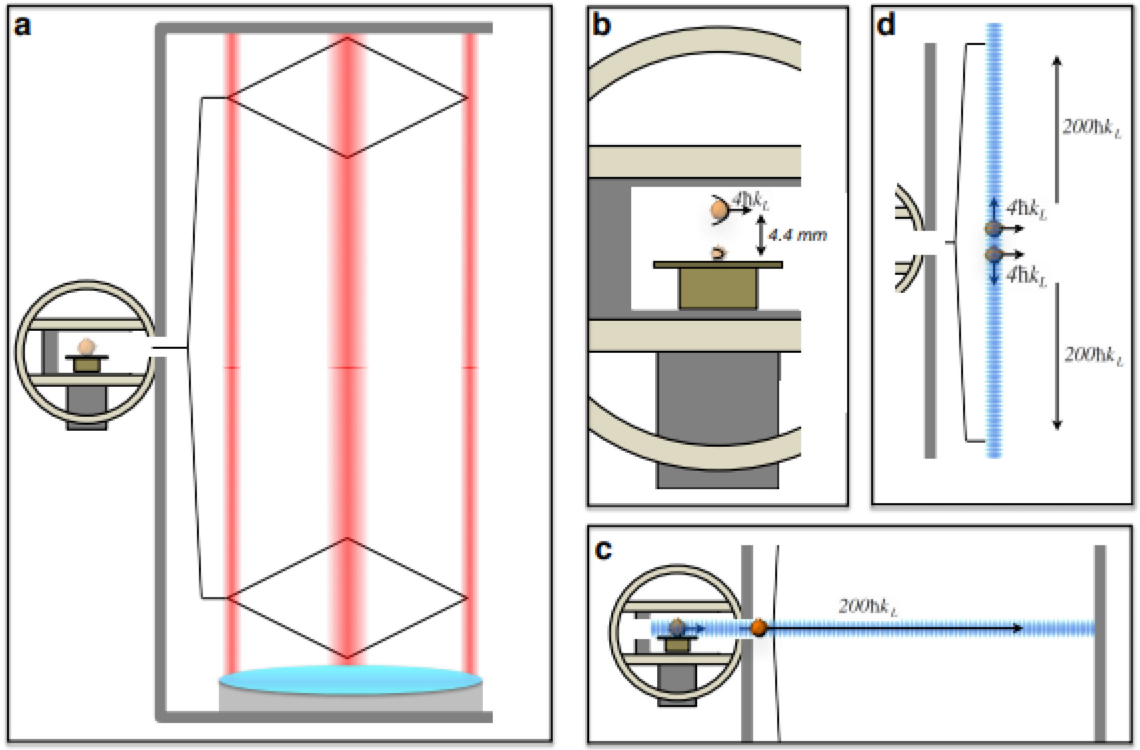
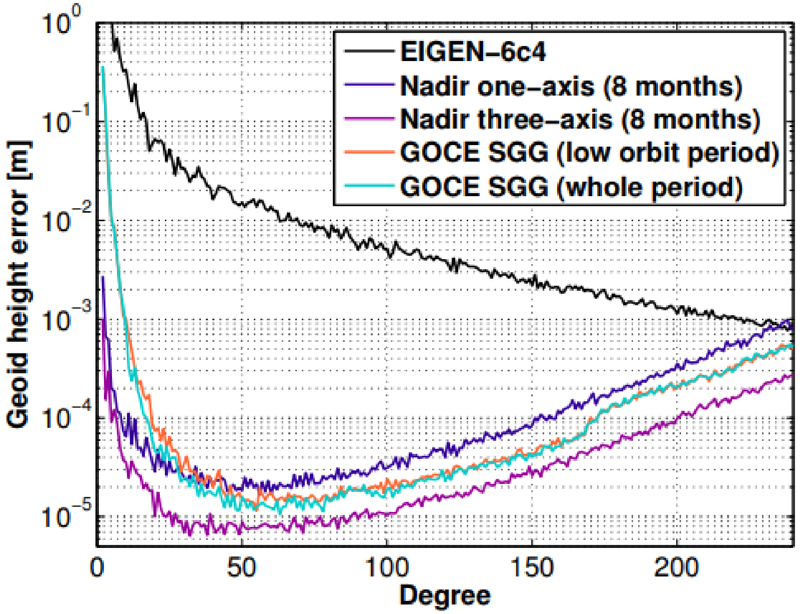


FIG. 1: (a) Scheme of the gravity gradiometer, based on differential accelerometry with two separated atom interferometers. (b) An initial BEC source of 10^6 atoms is magnetically evaporated, displaced and collimated in 1.1 s. (c) Horizontal transport step to the interferometry chamber (12 cm in 100 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

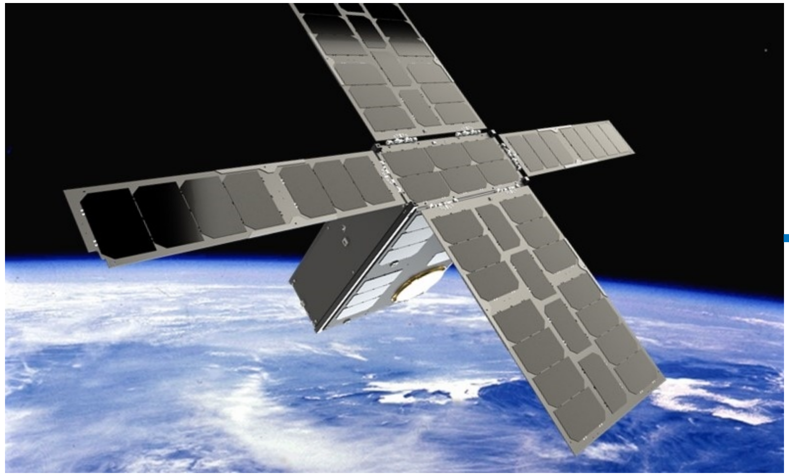
A. Trimeche, B. Battelier, D. Becker, A. Bertoldi, P. Bouyer, C. Braxmaier, E. Charron, R. Corgier, M. Cornelius, K. Douch, N. Gaaloul, S. Herrmann, J. Müller, E. Rasel, C. Schubert, H. Wu, F. Pereira dos Santos

Development plan

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

REVEAL Ground Based Gradiometer (IUK)

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



Cold Atom Space Payload (IUK)

Cold Atom Space Instrument

Cold Atom Gravity Explorer (CEOI)

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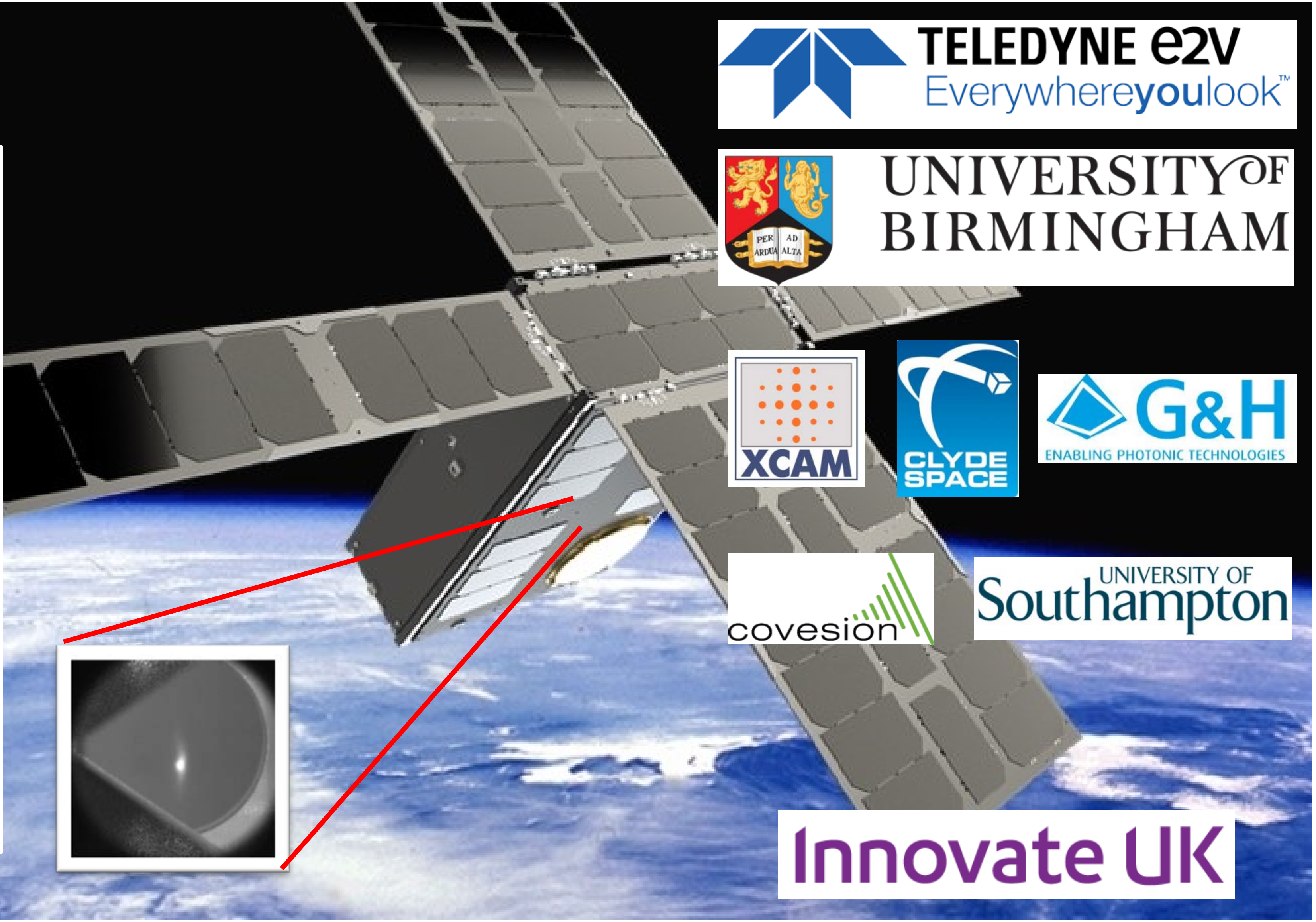
CASPA: Cold Atom Space PAyload

Mission

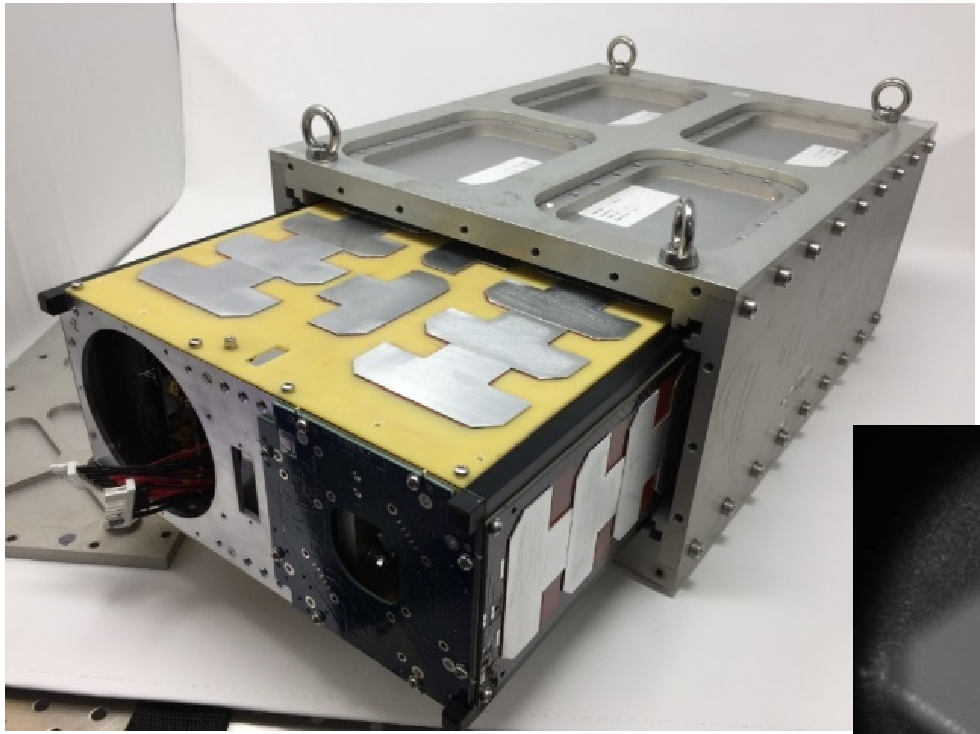
- Deliver autonomous cold-atom cooling on a 6U CubeSat

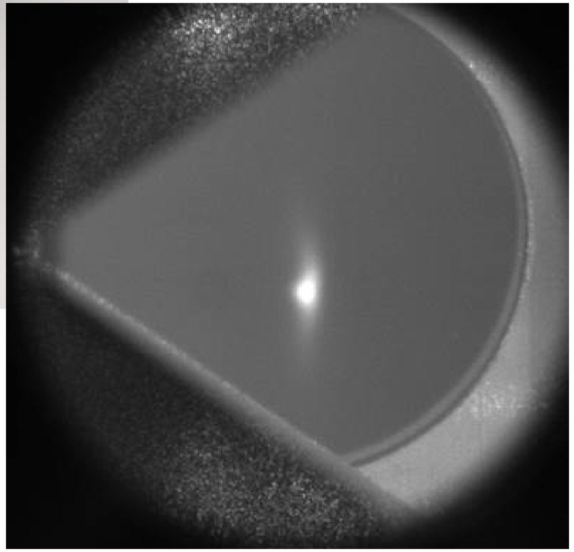
Objectives

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



Engineering Model Testing Complete





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Cold Atom Gravity Explorer (CAGE)

Centre for EO Instrumentation

UK SPACE AGENCY

Objectives:

- Identify a concept for a pathfinder mission with a science case to enable a longer term mission.
- Build concept payload design, science case and mission definition

The University of Nottingham UNITED KINGDOM · CHINA · MALAYSIA

UNIVERSITY OF BIRMINGHAM

University of Reading

British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL

University of BRISTOL

Newcastle University

STFC RAL Space

ThalesAlenia Space A Thales / Finmeccanica Company

Summary

- Quantum sensors are a promising new technology for gravity sensing
- UK is a latecomer but is catching up with a focus on cost reduction and miniaturisation
- For the UK to be credible we need to rapidly launch a pathfinder mission with a credible science case
- Opportunity for commercial applications to follow

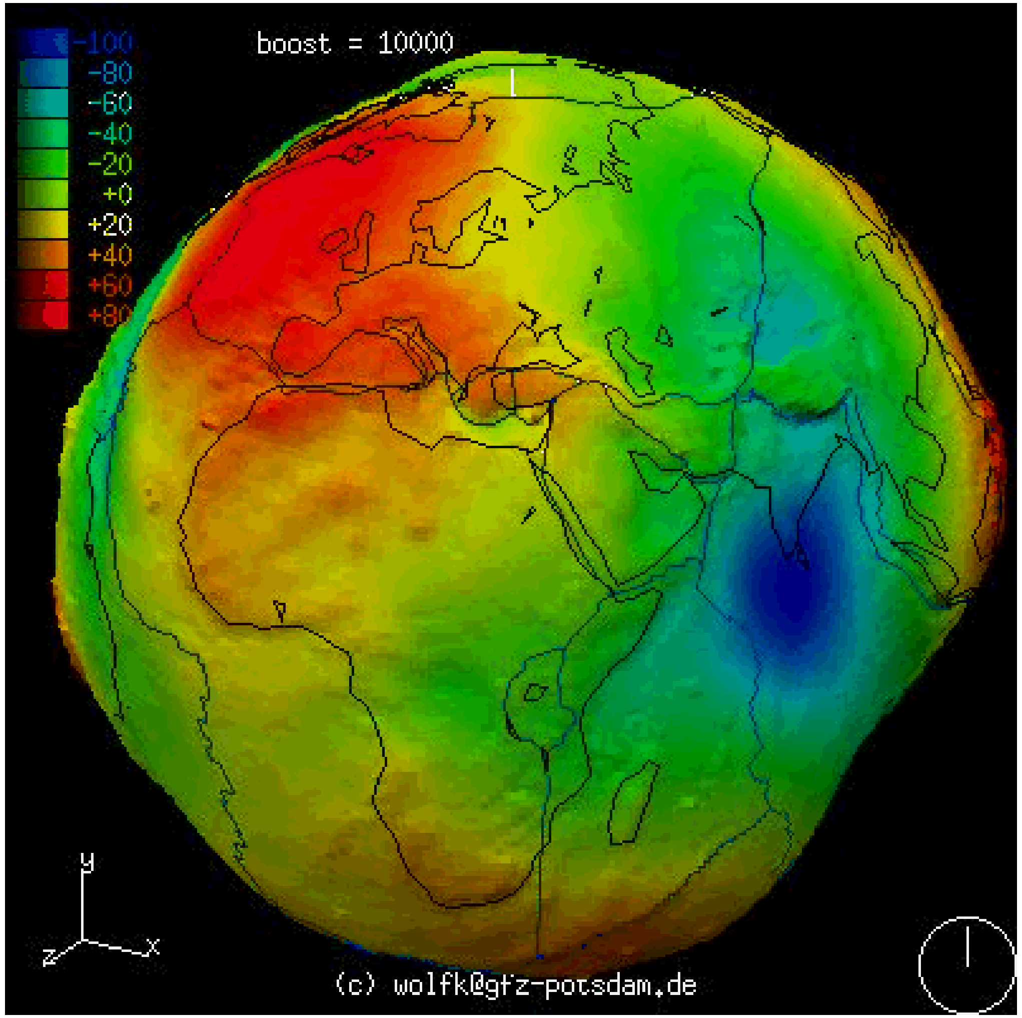

Image courtesy of ESA