# Cold Atom Technologies at ESA

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# Outline

- Introduction to the European Space Agency (ESA)
- European Centre for Space Applications and Telecommunications (ECSAT)
- Optoelectronics Section
- Cold Atom Technologies
- Conclusions

# ESA FACTS AND FIGURES

- Over 50 years of experience
- 22 Member States
- Eight sites/facilities in Europe, about 2200 staff
- 4.4 billion Euro budget (2015)
- Over 80 satellites designed, tested and operated in flight
- 20 scientific satellites in operation
- Six types of launcher developed
- 200th launch of Ariane celebrated in February 2011

# PURPOSE OF ESA

"To provide for and promote, for exclusively peaceful purposes, cooperation among European states in **space research** and **technology** and their **space applications.**"

**Article 2 of ESA Convention**

# 22 MEMBER STATES AND GROWING

**ESA has 22 Member States: 18 states of the EU (AT, BE, CZ, DE, DK, ES, FI, FR, IT, GR, IE, LU, NL, PT, PL, RO, SE, UK) plus Norway and Switzerland. Estonia and Hungary will soon be part of ESA (2015)**

Seven other EU states have Cooperation Agreements with ESA: Bulgaria, Cyprus, Latvia, Lithuania, Malta, Slovakia and Slovenia. Discussions are ongoing with Croatia.

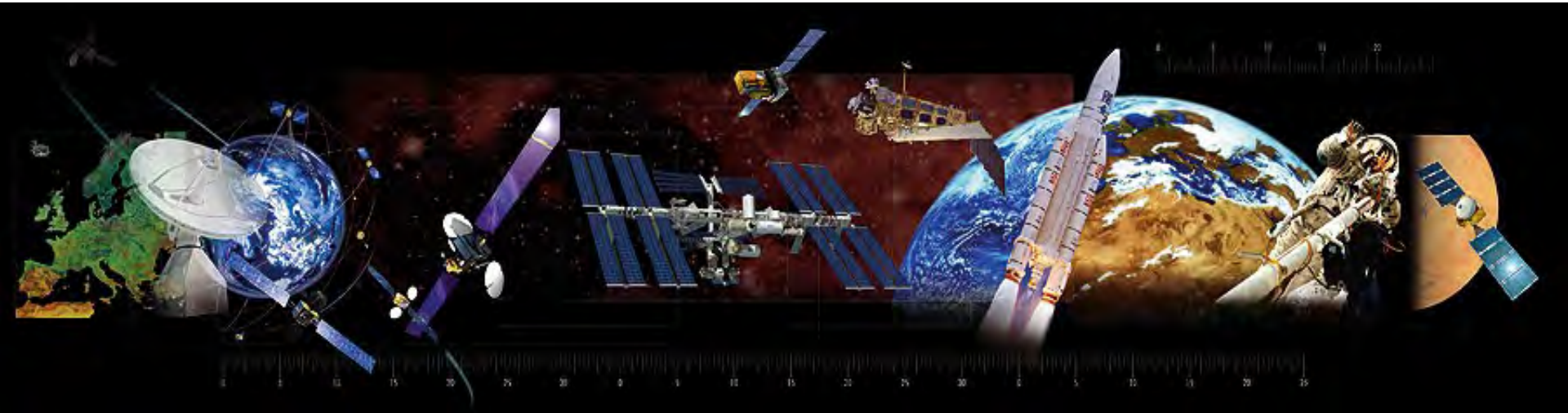
Canada takes part in some programmes under a long-standing Cooperation Agreement.

# ACTIVITIES

ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity.

- **Space science**
- **Human spaceflight**
- **Exploration**
- **Earth observation**
- **Launchers**
- **Navigation**
- **Telecommunications**
- **Technology**
- **Operations**

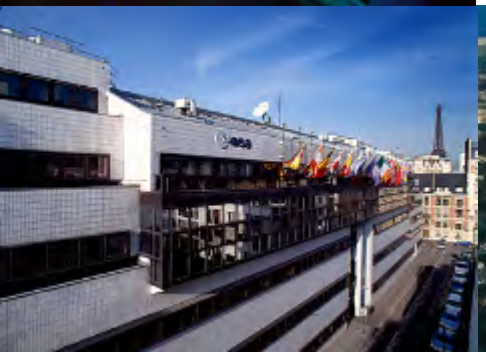
* Space science is a **Mandatory programme**, all Member States contribute to it according to GNP.
All other programmes are **Optional,** funded 'a la carte' by Participating States



# ESA Establishments and Centres in Europe

- **ESA-Headquarters**
  Paris
- **European Space Research & Tech. Centre**
  Noordwijk
- **European Space Operation Centre**
  Darmstadt
- **European Space Research Institute**
  Rome
- **European Astronauts Centre**
  Cologne
- **European Space Astronomy Centre**
  Madrid
- **ESA-Redu Centre**
  Redu

**European Centre for Space Applications and Telecommunications**
Harwell



# The ECSAT Roy Gibson Building


Completion scheduled in September 2015

Office space, conference meeting and services for 120 people

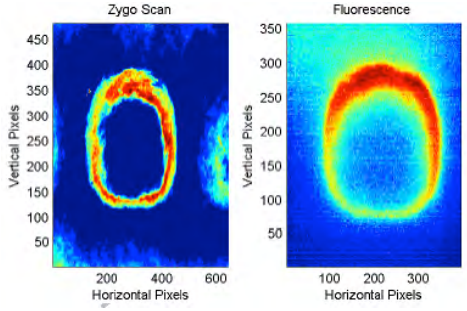
Environment-friendly

# Optoelectronics Section

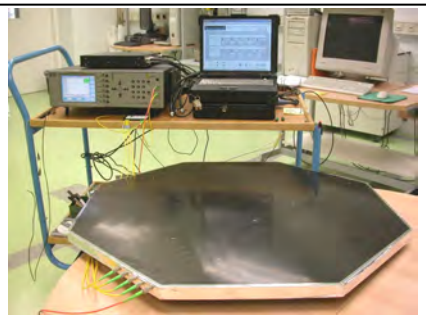
- Detectors
  - X-rays
  - UV, VIS, IR
  - FIR, THz, (sub)mm-wave
  - Superconducting technology
- Photonic devices
  - Fibres and sensors
  - Optical telecommunication
  - Photonic integrated circuits
- Lasers
  - Laser technology and components
  - Non-linear optics
  - Distance metrology
  - LIDAR
  - Optical frequency standards
  - Laser-cooled atom interferometry
  - Laser damage (laboratory)

**Thinned Si wafer (courtesy IMEC)**

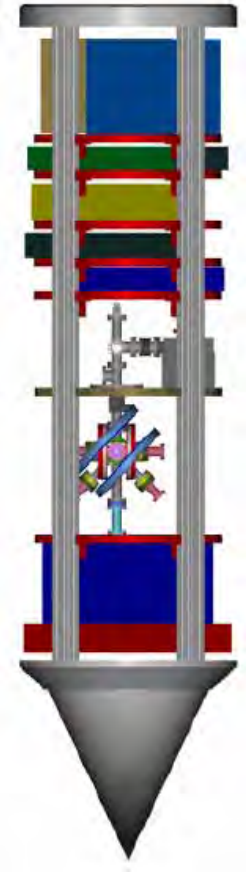
**Laser-induced contamination tests**




**3D strain mapping in composite materials**



**BEC in Migrogravity (ZARM)**



# Future Technologies

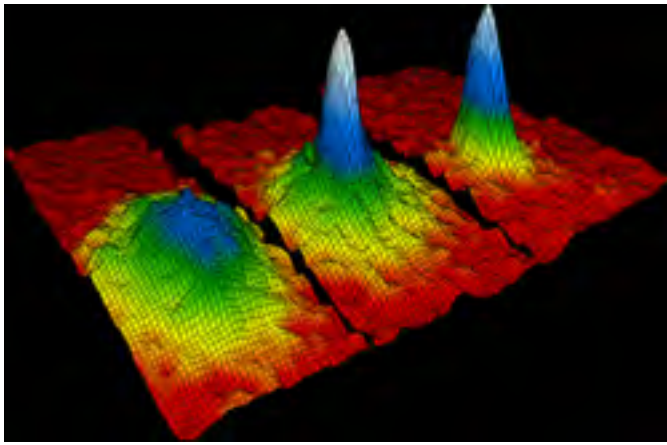
- ESA scientific advisory structure includes panel on future technologies:
  - External technology experts
  - Selected for broad technical knowledge
- Report to ESA Director of Technical and Quality Management
- 2012: analysed 64 enabling technologies
- Re-enforce R&D actions in two technology lines
  - Cold Atom Devices (CAI and OAFS)
  - Large Ultra-stable Structures
- Identified two technology challenges:
  - Radiation Protection
  - In-Space Propulsion

# Cold Atom Physics

- Why cold atoms?
  - Study/observe internal structure of free atoms (≠ solid state physics)
  - Atom waves potentially more interesting than electron or neutron waves (neutral + rich internal structure)
  - Interaction with external electric fields and gravity
- BUT: RT atom speeds ~ 300 m/s
  - Atom beams have low coherence ➔ difficult to handle as waves
  - Limited observation time (few ms) on a table-top experiment
- Low temperature physics
  - 4K (LHe) He thermal velocity ~ 90 m/s
  - Cryopump effect: condensation ➔ no gas phase
- Laser cooling techniques:
  - Magneto Optical Traps (MOT) < 10μK (100nK) ~ few cm/s (mm/s)
  - Adiabatic Expansion
  - Raman Cooling
  - Velocity Selective Coherent Population Trapping
  - Evaporative cooling in magnetic or optical traps ~ 100nK
  - Sympathetic cooling (involving more than one species)

$$\lambda_{dB} = \frac{h}{p}$$

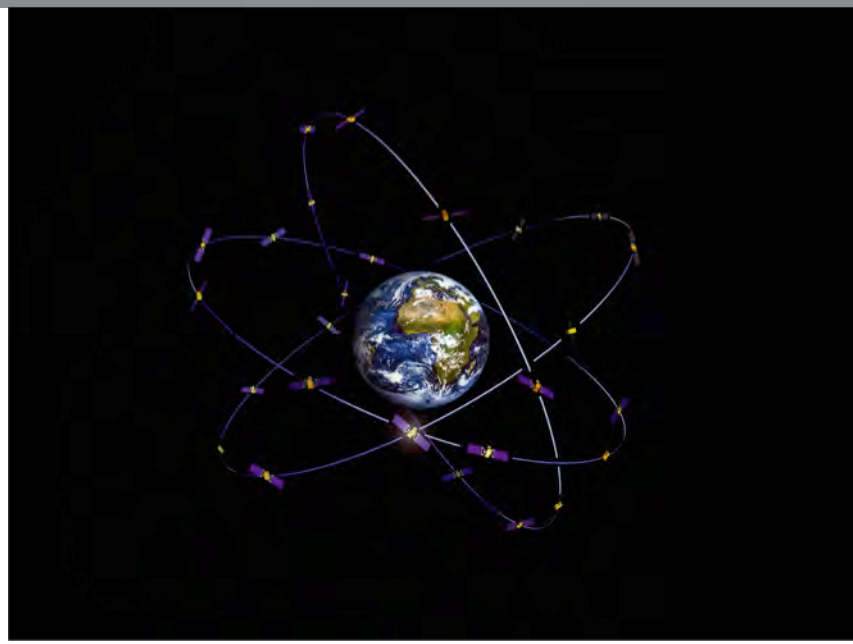
$$\Delta x \Delta p \sim \hbar$$

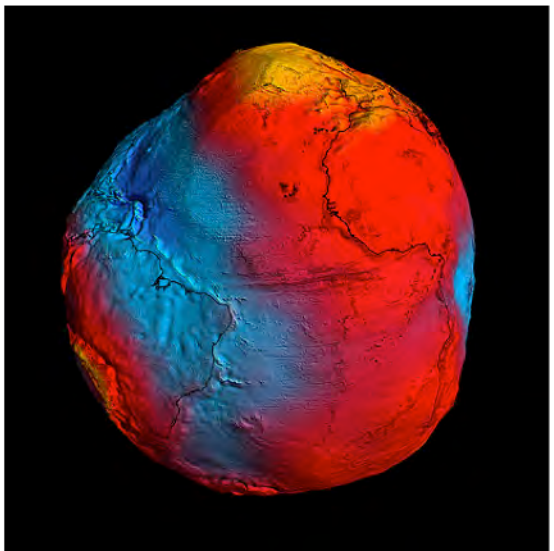


Velocity-distribution data of a gas of rubidium atoms, confirming the discovery of a new phase of matter, the Bose–Einstein condensate

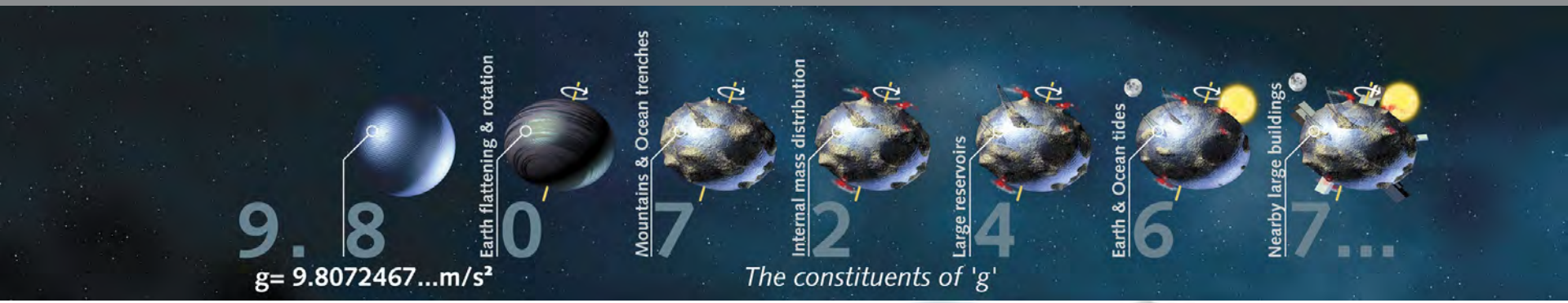
# Cold Atom Interferometry – Applications

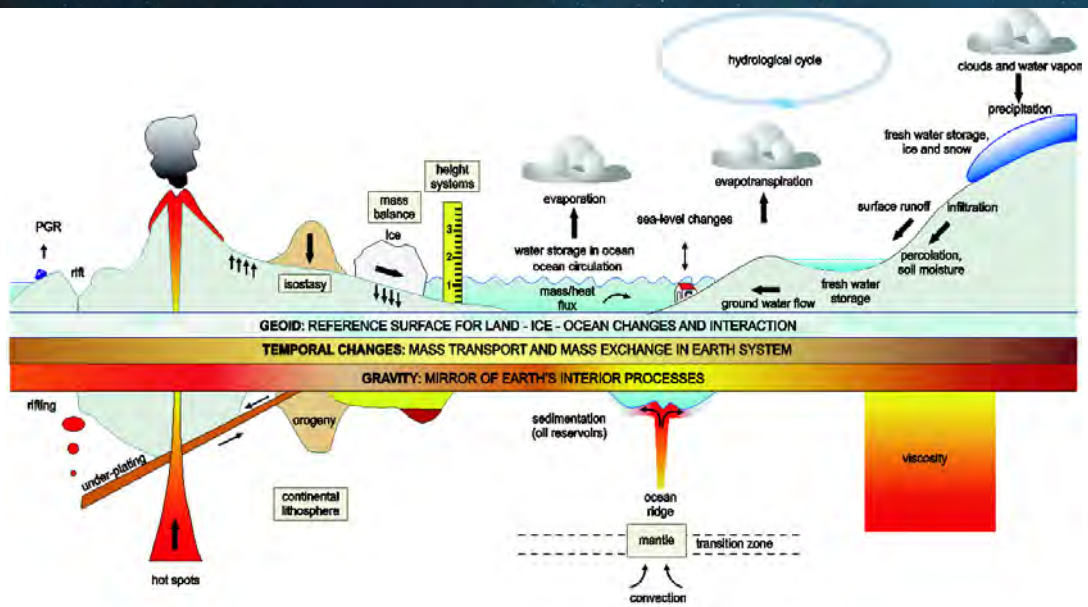
- Inertial Navigation
- Attitude Monitoring
- Accelerometers for Drag-Free Systems
- Deep Space Accelerometers
- Gravity Mapping
- Fundamental Physics:
  - Testing General Relativity
  - Short-Range Forces
  - Atom-Surface Interactions
  - Fundamental Constants
  - Electron Electric Dipole Moment
  - Spin-Gravity Coupling
  - Quantum Fluctuations
  - Decoherence

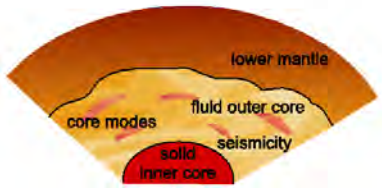




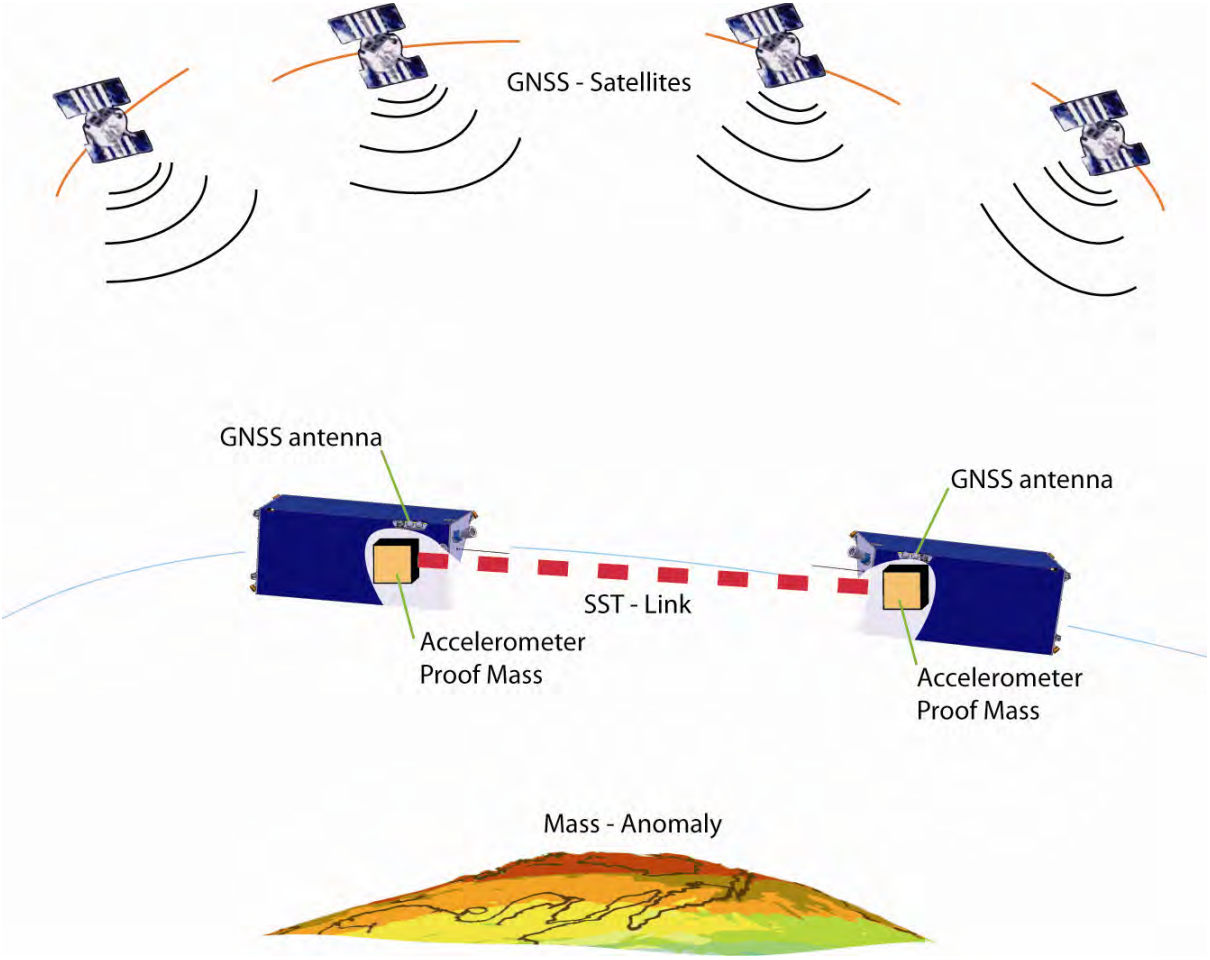
# Earth Gravity Field



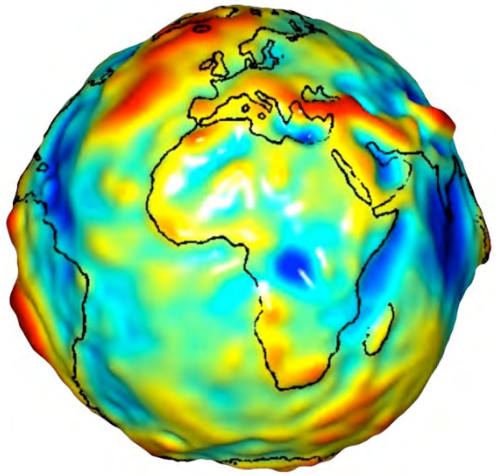



# Two-satellites ranging LOW-LOW SST



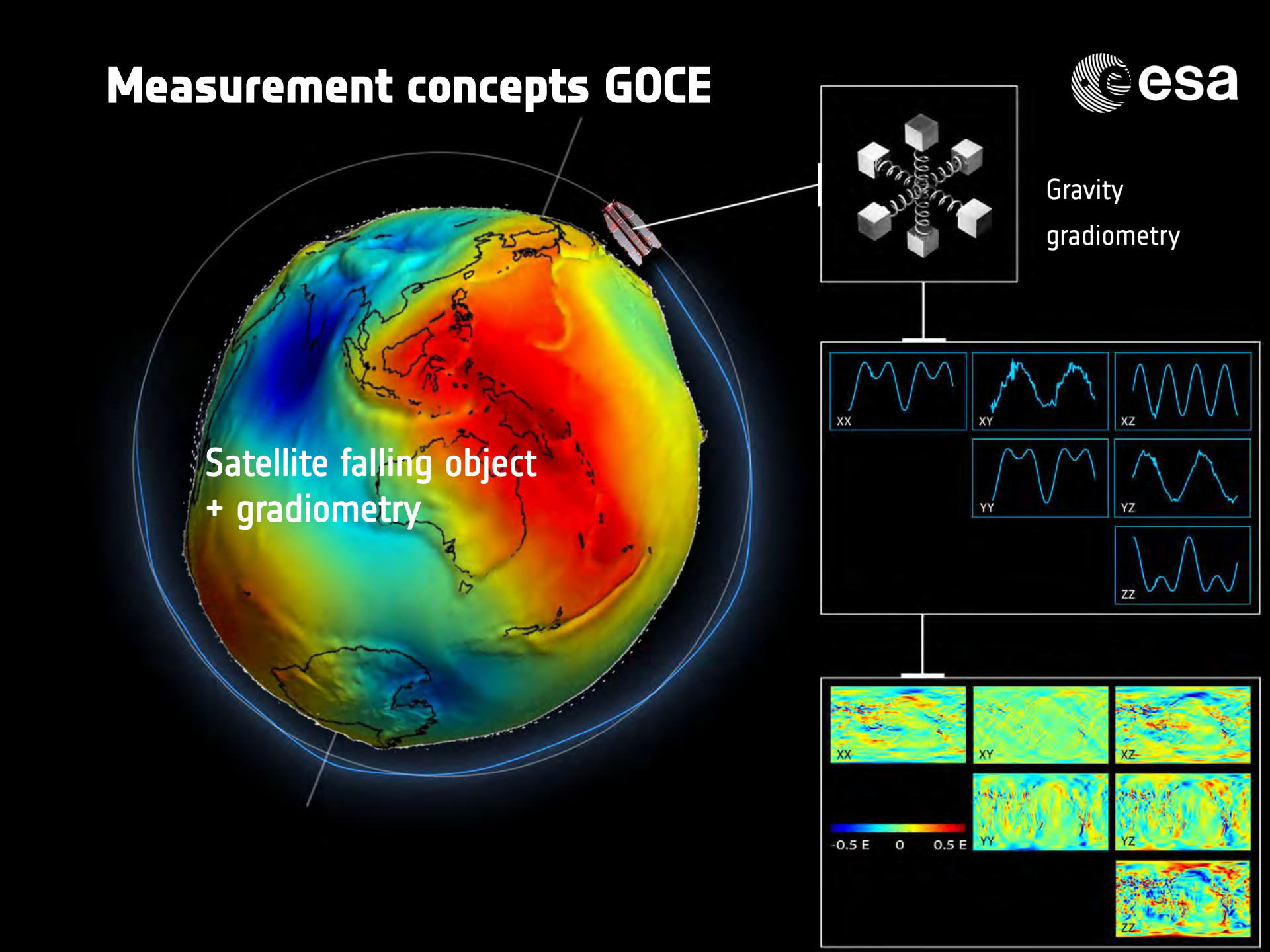

GRACE 1 pair of satellites



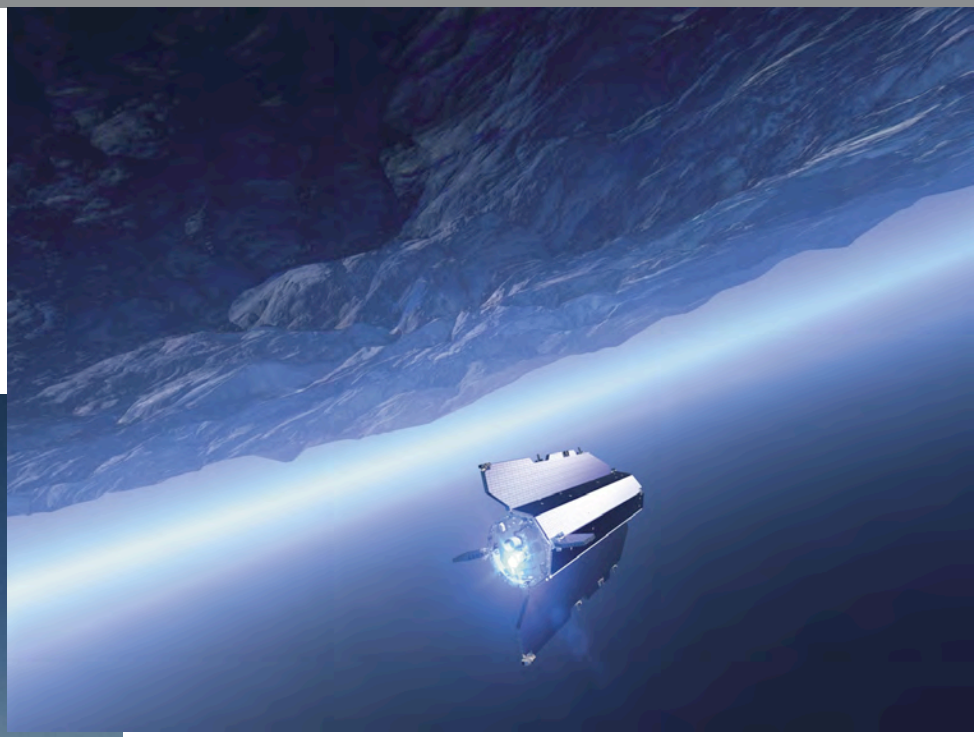
One accelerometer per satellite for non-gravitational effects

Credit: EADS Astrium

# Measurement concepts GOCE



# GOCE reenters atmosphere



European Space Agency

# Goce gravity boost to geothermal hunt

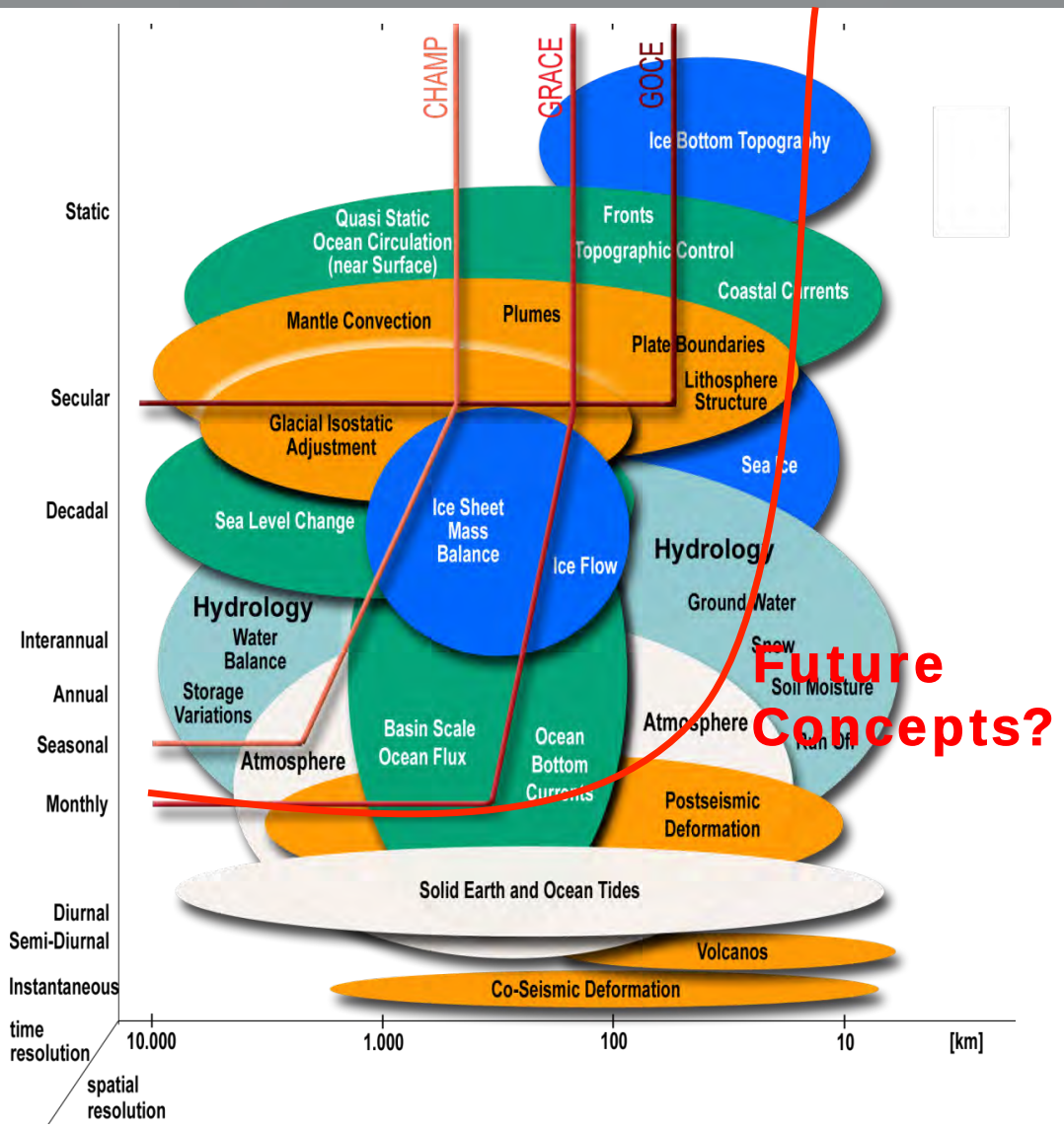
By Jonathan Amos
BBC Science Correspondent, Vienna

16 April 2015 | Science & Environment


Iceland is famous for its geothermal power stations, but the resource globally is under-developed

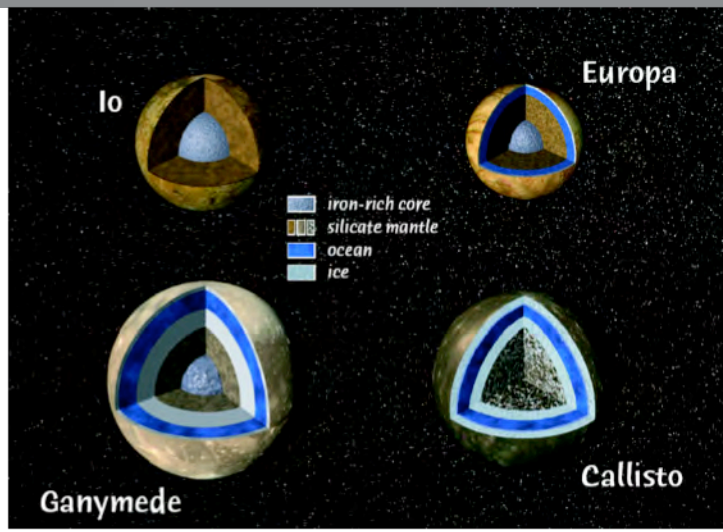
**The hunt for sources of geothermal energy is getting a boost from new observations of the Earth made from space.**

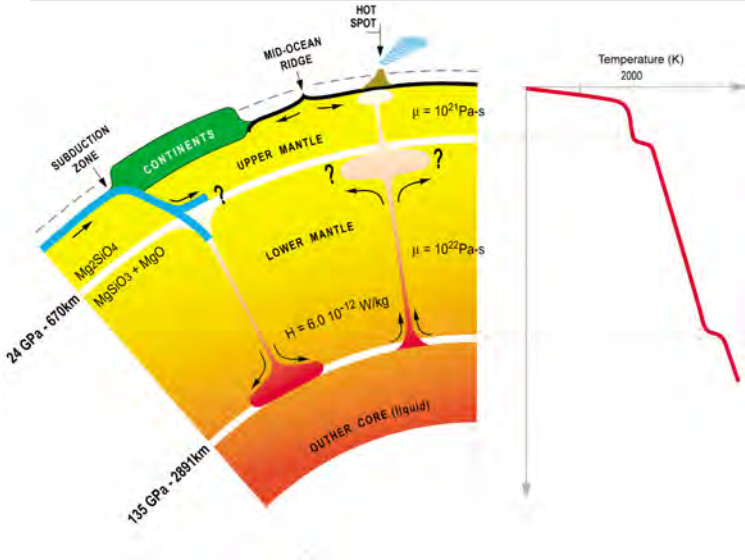
# What is needed in the near future?



# Earth and Planetary Applications

- EOP – Enabling Observation Techniques for Future Solid Earth Missions (Prime: EADS Astrium)
  - Satellite Gravity Gradiometry (SGG)
  - Observables: diagonal gravity gradient tensor components, Txx, Tyy, Tzz
  - Required accuracy: down to 0.1 mE/√Hz
  - Measurement band: 0.1 to 100 mHz
- GOCE gradiometer performance
  - Goal: 100mE/√Hz @ 5mHz, 18mE/√Hz @ 10mHz, 11mE/√Hz from 20 to 100mHz
  - Actual: Tzz & Txz noise level ~ 2 × specs, causes unknown
- GSP – Gravity Gradient Sensor Technology for Future Planetary Missions (Prime: University of Twente)
  - Accommodation: ~10 kg
  - Required accuracy: 1 mE/√Hz

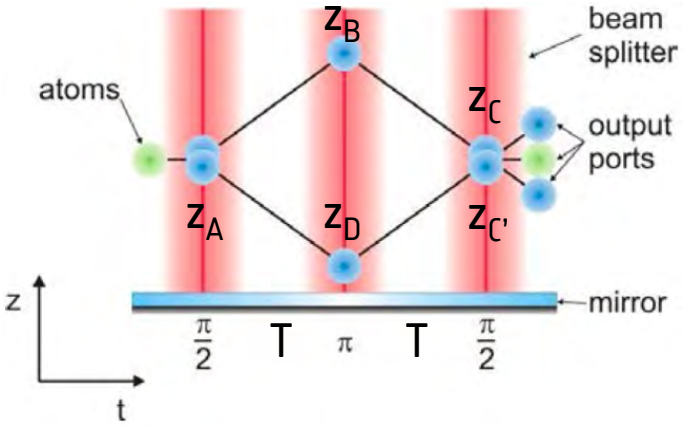


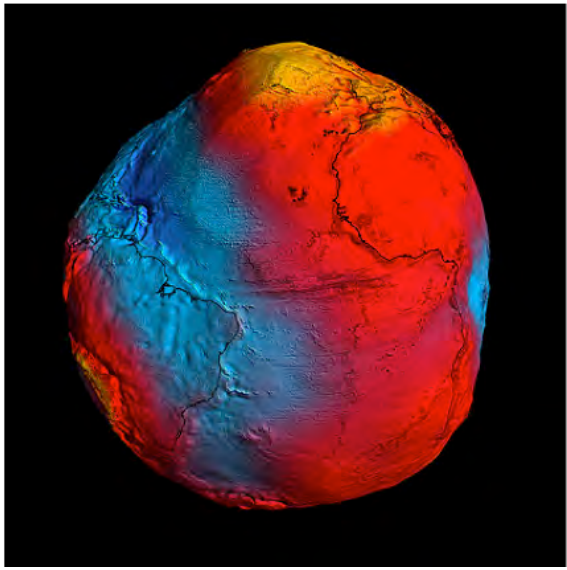




1 E = 1 Eötvös = $10^{-9}$ $s^{-2}$

# Future Gravity Mission Concept

- Cold Atom Interferometry technology requirements for EO
- EO Future Missions elaborated gradiometer/gyroscope concept
  - Gradiometer performance:
  - 3.5 (goal 1.0) mE/√Hz (0.1 – 100 mHz)
  - Gyroscope performance:
  - 35 prad/s/√Hz (0.1 – 100 mHz)



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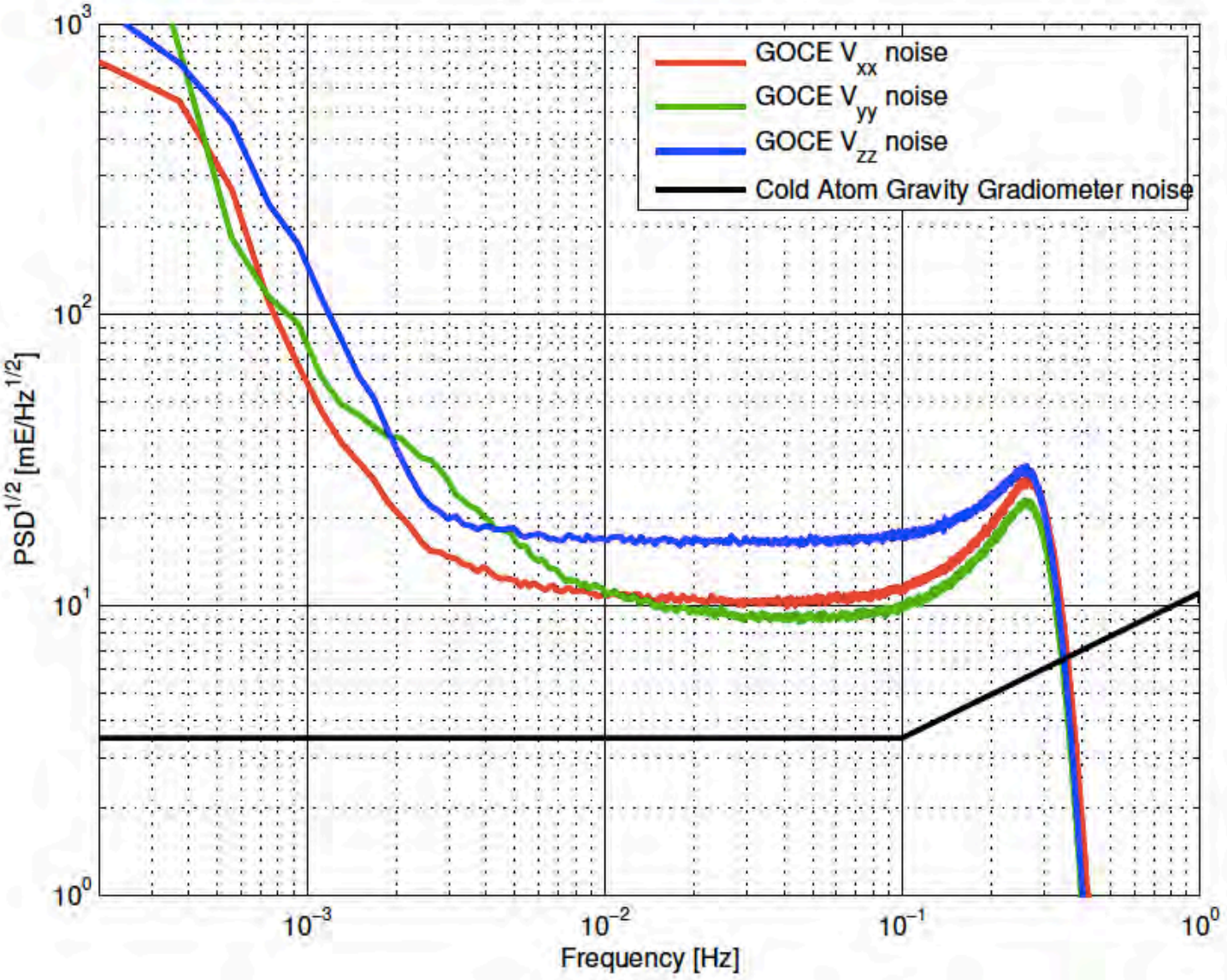
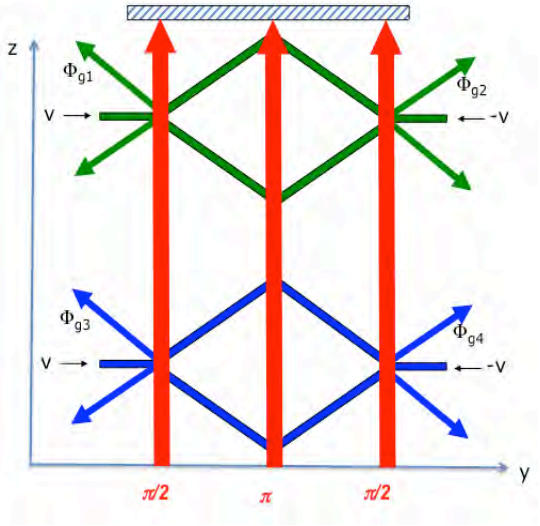
# Cold Atom Interferometer us. GOCE

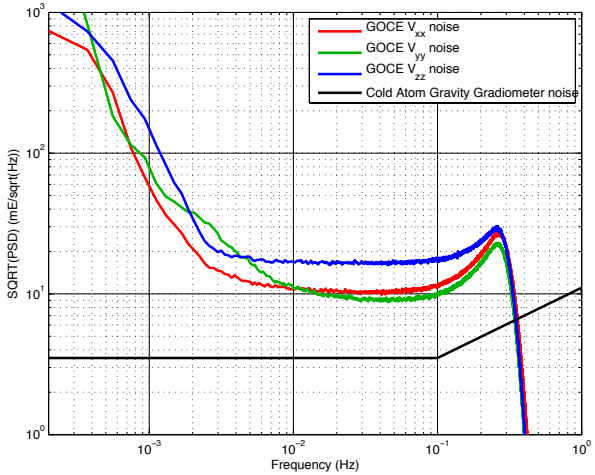



Courtesy of ESA EOP-SF

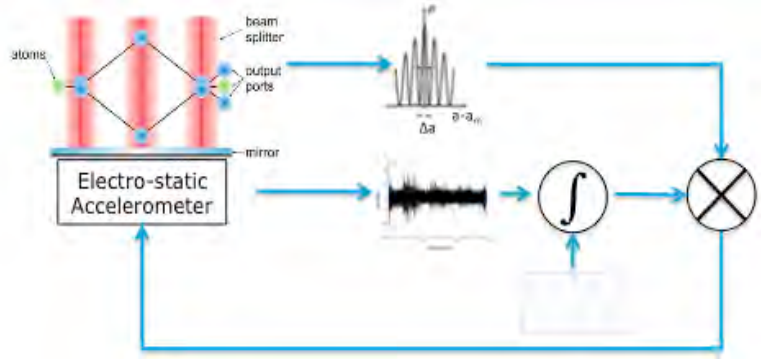
# CAI concepts for measuring Earth gravity field

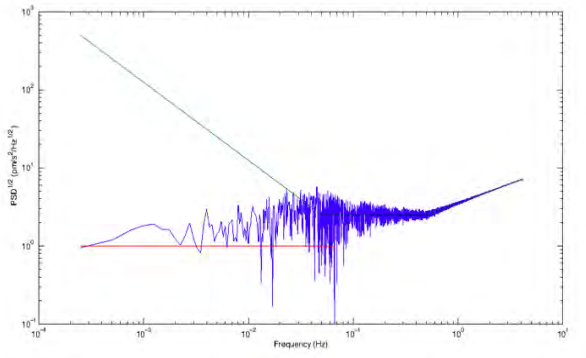
- CAI gravity gradiometer + gyroscope




- Hybridization classical accelerometers/AI for SST



# CAI GG Concept – studies and R&D

## Running studies and R&D activities

- Compact Vacuum chamber for an Earth Gravity Gradiometer based on Laser-Cooled Atom Interferometry (2014)
- Study of a Cold-Atom interferometry gravity gradiometer sensor and mission concept (2015)
- Hybrid Atom Electrostatic System for Satellite Geodesy (2015)

## Planned technology development activities

- Development of Cooling/Raman Laser source with enhanced operational features (~ mid 2015)
- Development of phase and frequency modulators for atom sensor systems

# Optical Atomic Clocks – What and Why

- Based on narrow optical transitions in laser-cooled atoms or ions
- Frequencies ~$10^5$ times higher than microwave frequencies
- Q-factor ~$10^{15}$ (or even higher)
- Better time resolution (clock "ticks" faster)
- Better stabilities than microwave clocks

$$\text{instability } \sigma \propto \frac{\Delta f}{f} \frac{1}{(S/N)}$$

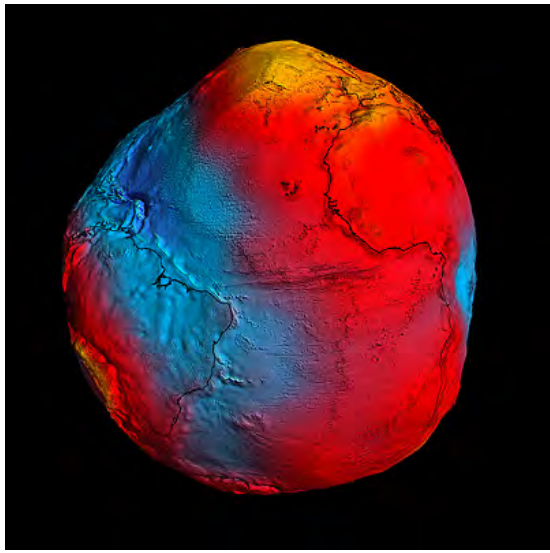

Single ion Optical Atomic Clock reference

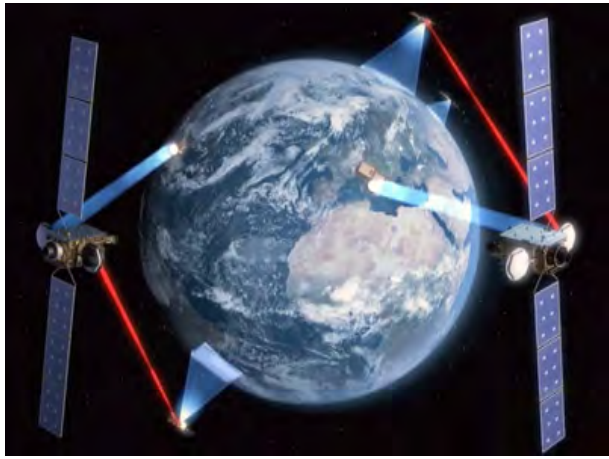
Improved capability from Optical Atomic Clocks will benefit from evolving remote high-accuracy optical clock frequency comparison techniques:

- e.g. satellite – ground: enhanced microwave, optical links
- ground techniques: optical fibre transfer

# Optical Atomic Clocks

- UK heritage and excellence in time keeping (NPL)
  - First Atomic Clock (Caesium I) in 1955 (Louis Essen)
  - Most accurate Cs clock to date
- Potential of optical atomic clocks in space:
  - Optical master clock at GEO
    - Reduced local gravitation potential variations
    - No reliance on ground clock corrections
    - Improved data synchronisation
    - Improved position determination (navigation)
  - European Data Relay System (EDRS)
    - Continuous, high-data rate links: satellite-GEO-ground
    - Frequency comparison for gravity field determination
  - Direct measurement of the earth's geoid (with ground-based OAC and spaceborne clock comparison techniques)
    - Civil engineering, oil and gas exploration, etc.
    - CCI (ice sheets, ocean transport, seasonal effects)





European Space Agency

# Generic Technology Programmes

**Technology Research Programme (TRP)**
http://www.esa.int/Our_Activities/Technology/About_the_Basic_Technology_Research_Programme_TRP

**General Support Technology Programme (GSTP)**
http://www.esa.int/Our_Activities/Technology/About_the_General_Support_Technology_Programme_GSTP

**Technology Transfer Programme (TTP)**
http://www.esa.int/Our_Activities/Technology/Technology_Transfer_Programme_TTP

**European Components Initiative (ECI)**
http://www.esa.int/Our_Activities/Technology/European_Component_Initiative_ECI

**Network Partnering Initiative (NPI)**
http://www.esa.int/Our_Activities/Technology/Networking_Partnering_Initiative

**Innovation Triangle Initiative (ITI)**
http://www.esa.int/Our_Activities/Technology/Technology_Business_Opportunities/Overview2

**StarTiger**
http://www.esa.int/Our_Activities/Technology/Technology_Business_Opportunities/Approach

# Domain-specific Technology Programmes

**Earth Observation Envelope Programme (EOEP)**
http://www.esa.int/Our_Activities/Technology/About_the_Earth_Observation_Envelope_Programme_EOEP

**Science Core Technology Programme (CTP)**
http://www.esa.int/Our_Activities/Technology/Science_Core_Technology_Programme_CTP

**European Transportation and Human Exploration Preparatory activities (ETHEP)**
http://www.esa.int/Our_Activities/Human_Spaceflight/Exploration/Exploring_together_The_Global_Exploration_Strategy

**Mars Robotic Exploration Preparation Programme (MREP)**
http://www.esa.int/Our_Activities/Technology/Mars_Robotic_Exploration_Preparation_Programme_MREP

**Advanced Research in Telecommunications Systems (ARTES 3-4 & 5)**
http://www.esa.int/Our_Activities/Technology/ARTES_3-4_5

**European GNSS Evolution Programme (EGEP)**
http://www.esa.int/Our_Activities/Navigation/GNSS_Evolution/About_the_European_GNSS_Evolution_Programme

**European Programme for Life and Physical Sciences (ELIPS)**
http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/Taking_the_ISS_to_the_next_level_ISS_exploitation_and_ELIPS

***EMITS – ESA Invitation to Tender System***
http://emits.esa.int/emits/owa/emits.main

# Acknowledgements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