Optical and Quantum Technologies for Earth Observation at the European Space Agency

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European Space Agency

Outline

- Introduction to the European Space Agency (ESA)
- European Centre for Space Applications and Telecommunications (ECSAT)
- Optoelectronics Section
- Earth Observation Missions
- Examples of Optical and Quantum Technologies
- Conclusions

ESA FACTS AND FIGURES

- Over 50 years of experience
- 20 Member States
- Eight sites/facilities in Europe, about 2200 staff
- 4.1 billion Euro budget (2014)
- Over 70 satellites designed, tested and operated in flight
- 18 scientific satellites in operation
- Six types of launcher developed
- 200th launch of Ariane celebrated in February 2011

50 YEARS OF EUROPEAN COOPERATION IN SPACE

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1964-2014

→ SERVING EUROPEAN COOPERATION AND INNOVATION

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- In 1964, Conventions of the precursors of ESA (ESRO & ELDO) entered into force.
- 2014 is dedicated to addressing the future in the light of these 50 years of unique achievements in space, which have put ESA among the leading space agencies of the world.
- 50 years of European cooperation in space is an anniversary for the whole space sector in Europe, which can be proud of its results and achievements.
- Testimony that, when Member States share challenging objectives and join forces, Europe can be at the leading edge of progress, innovation and growth, for the benefit of all its citizens.
- This has been, and continues to be, ESA's mission for the future.

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

20 MEMBER STATES AND GROWING

ESA has 20 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.

Eight other EU states have Cooperation Agreements with ESA: Estonia, Slovenia, Hungary, Cyprus, Latvia, Lithuania, Malta and the Slovak Republic. Bulgaria is negotiating a Cooperation Agreement. Discussions are ongoing with Croatia.

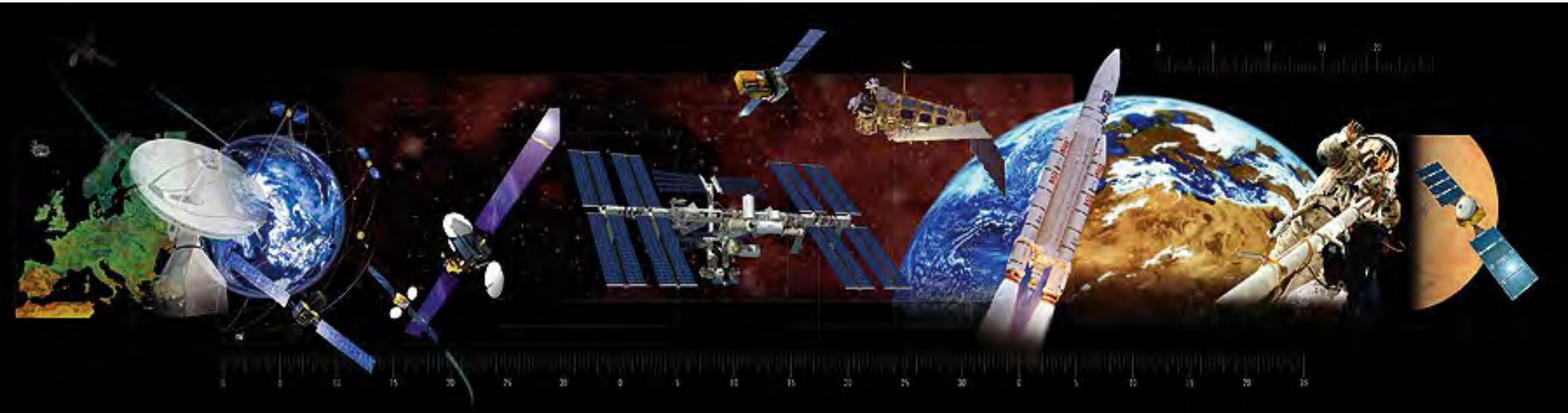
Canada takes part in some programmes under a long-standing Cooperation Agreement.

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

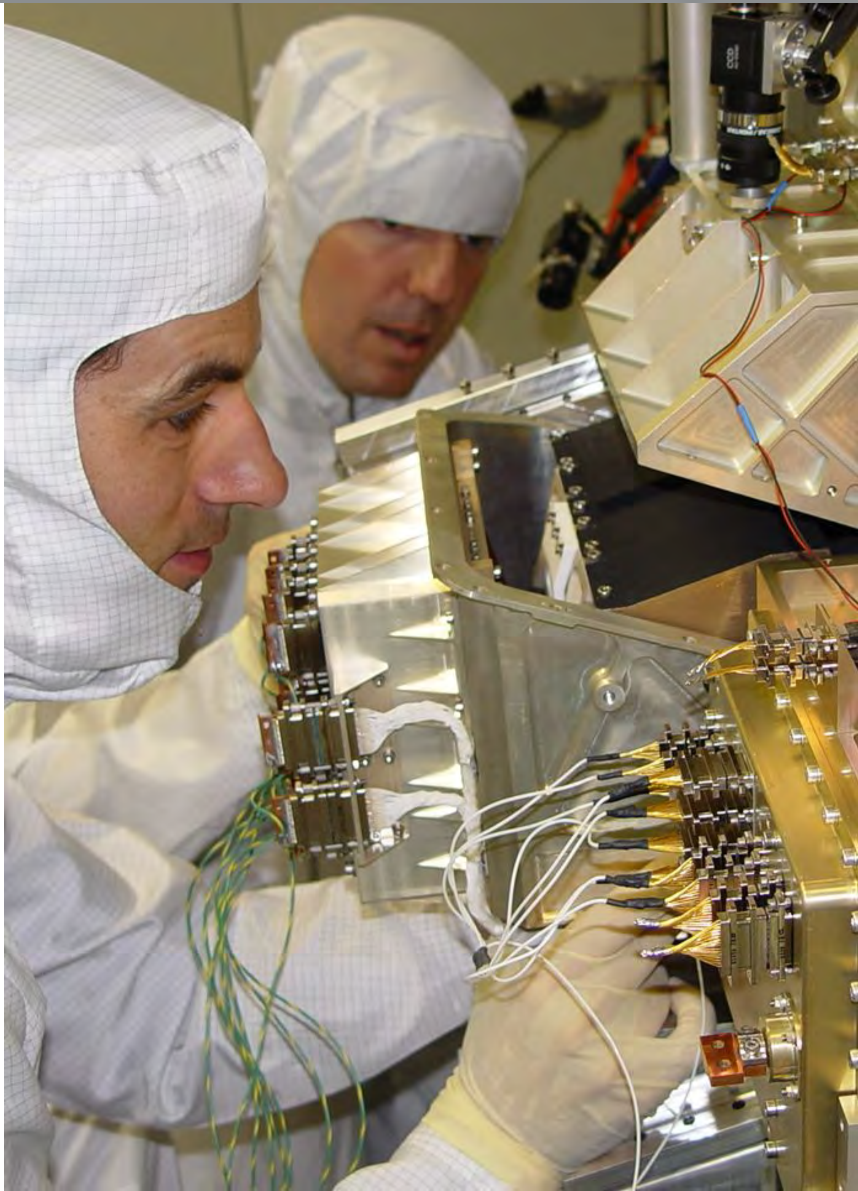


ESA's Industrial Policy

About 90% of ESA's budget is spent on contracts with European industry

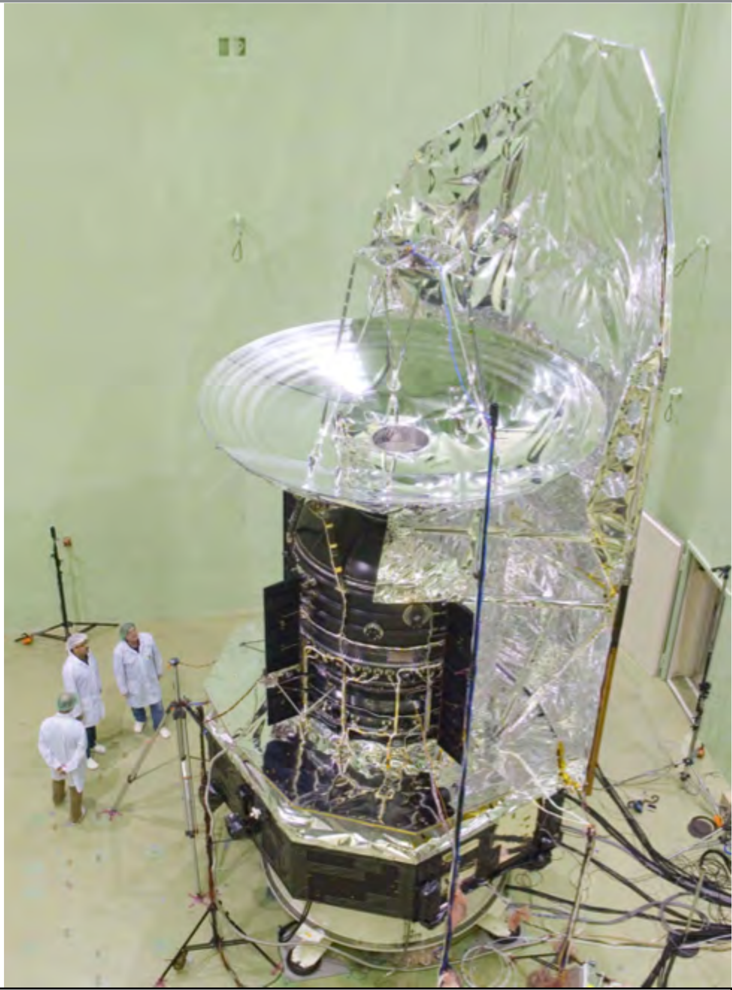
Industrial Policy:

- ensures that Member States get a fair return on their investment
- improves competitiveness of European industry
- maintains and develops space technology
- exploits the advantages of free competitive bidding, except where incompatible with objectives of the industrial policy



Space Technology

- R&D emphasis on:
  - Specific application / mission type
  - Ultimate performance
  - Harsh space environment
  - Mission lifetime operation
- Leading to:
  - Often one-off developments
  - Absence of mass production criteria
  - High unit cost
  - Space heritage considerations
  - Space (pre)qualification:
    - Mechanical & acoustic vibration tests
    - Vacuum tests: outgassing
    - Thermal cycling
    - Radiation tests



Herschel (launched May 2009) inside ESTEC LEAF facility

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 June 2015

Office space, conference meeting and services for 120 people

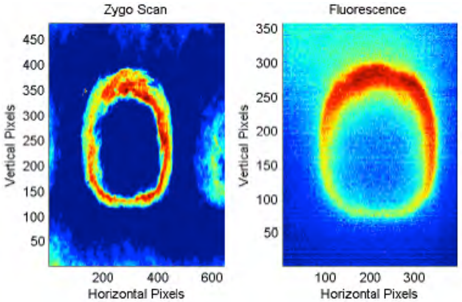
Environment-friendly

Optoelectronics Section

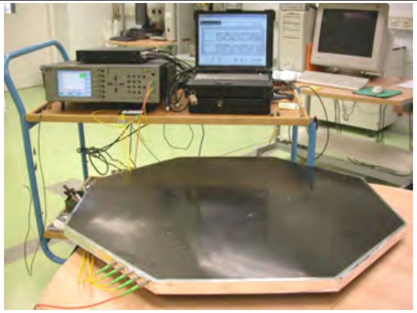
- Detectors
  - X-rays
  - UV, VIS, IR
  - FIR, THz, (sub)mm-wave
  - Superconducting technology
- Photonic devices
  - Fibres and sensors
  - Optical telecommunication
  - Photonic integrated circuits
- Lasers
  - Laser technology and components
  - Non-linear optics
  - Distance metrology
  - LIDAR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

Thinned Si wafer (courtesy IMEC)

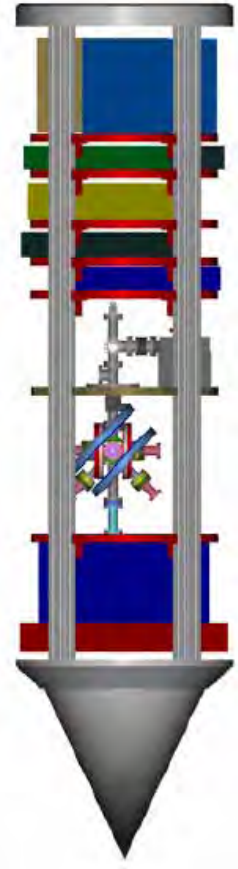
Laser-induced contamination tests



3D strain mapping in composite materials



BEC in Migrogravity (ZARM)



Photonics/Optoelectronic instruments

Instruments and sensors come in two flavours:

- Passive optical instruments
  - Imagers, Spectrometers, Photometers, Radiometers, gravity Gradiometers, Accelerometers, Attitude & Pointing (Star & Sun trackers), Interferometric Imagers, etc…
- Active optical instruments
  - Lidar (laser radar), Gravity Gradiometers and Accelerometers based on Laser-cooled Atom Interferometry, Laser Gyros, Laser Interferometers, Optical Frequency Standards, etc…

Application areas

Photonics/Optoelectronics is an enabling technology:

- Satellite payloads
  - Astronomy, Planetary Exploration, Fundamental Science Missions
  - Earth Observation Missions

Current trends:

- Telecoms: inter and intra satellite comms, transmission and routing
- Navigation: attitude control and inertial sensors
- Space transportation: next generation launchers


→EARTH OBSERVATION
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Pioneers in Earth Observation

Meteosat (1977–) ESA has been dedicated to observing Earth from space ever since the launch of its first meteorological mission.

ERS-1 (1991–2000) and **ERS-2** (1995–2011) providing a wealth of invaluable data about Earth, its climate and changing environment.

Envisat (2002–12) the largest satellite ever built to monitor the environment, it provided continuous observation of Earth's surface, atmosphere, oceans and ice caps.

Metereological Missions

Next-generation missions dedicated to weather and climate.

Meteosat Third Generation – taking over from Meteosat 11 in 2018/19, the last of four Meteosat Second Generation (MSG) satellites. MSG and MTG are joint projects between ESA and Eumetsat.

MetOp is a series of three satellites to monitor climate and improve weather forecasting, the space segment of Eumetsat's Polar System (EPS).

MetOp-A (2006–) Europe's first polar-orbiting satellite dedicated to operational meteorology.

MetOp-B launched in 2012.

MetOp-C follows in 2016.

Global Monitoring for a Safer World

Copernicus: an Earth observation programme for global monitoring for environment and security.

Led by the **European Commission** in partnership with ESA and the **European Environment Agency**, and responding to Europe's need for geo-spatial information services, it will provide autonomous and independent access to information for policy-makers, particularly for environment and security issues. ESA is implementing the space component: developing the **Sentinel** satellite series, its ground segment and coordinating data access.

ESA has started a **Climate Change Initiative**, for storage, production and assessment of essential climate data.

ESRIN

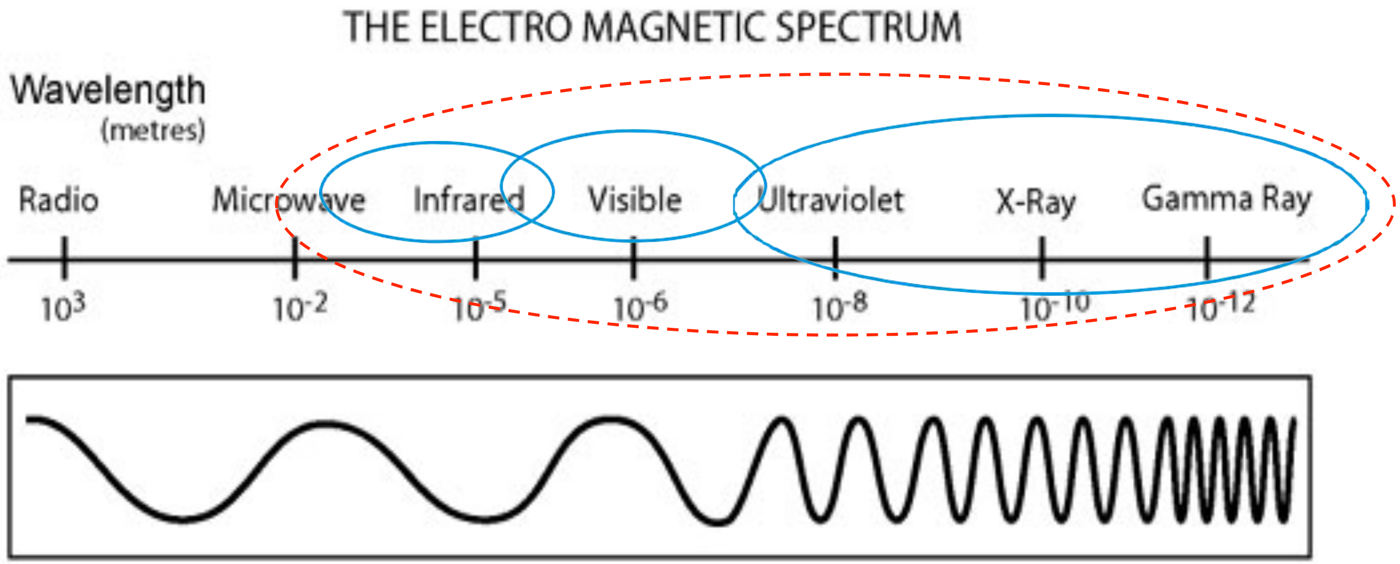
ESRIN, in Frascati, Italy, is ESA's centre for Earth Observation where operations and exploitation of Earth Observation satellites are managed.

The world's largest database of environmental data for both Europe and Africa is managed from ESRIN.

Earth Explorers

- These missions address critical and specific issues raised by the science community, while demonstrating the latest observing techniques.
- **GOCE** (2009–2013) studying Earth's gravity field (Gravity Gradiometry)
- **SMOS** (2009–) studying Earth's water cycle (Fiber signal distribution)
- **Swarm** (2013) three satellites studying Earth's magnetic field (Magnetometry, Accelerometry, Laser retro-reflector)
- **ADM-Aeolus** (2015) studying global winds (Lidar, Imaging)
- **EarthCARE** (2017) studying Earth's clouds, aerosols and radiation (ESA/JAXA) (Lidar, Imaging, Spectrometry)

Detection Spectra of Interest

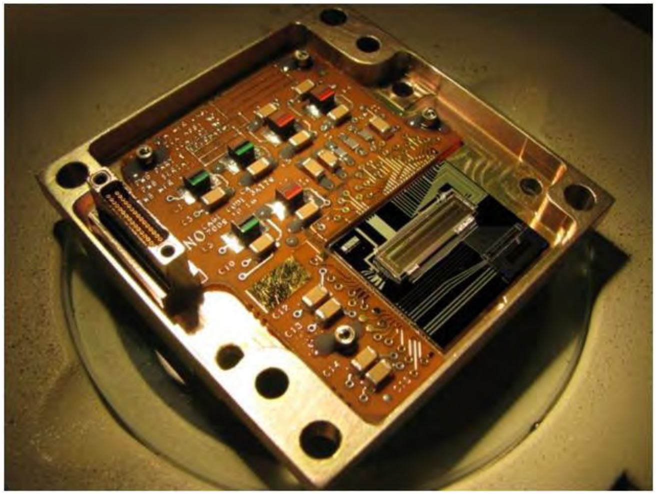


- FIR: 1000 to 15 µm
- LWIR: 15 to 8 µm
- MWIR: 8 to 3 µm
- SWIR: 3 to 1.4 µm
- NIR: 1.4 to 0.78 µm

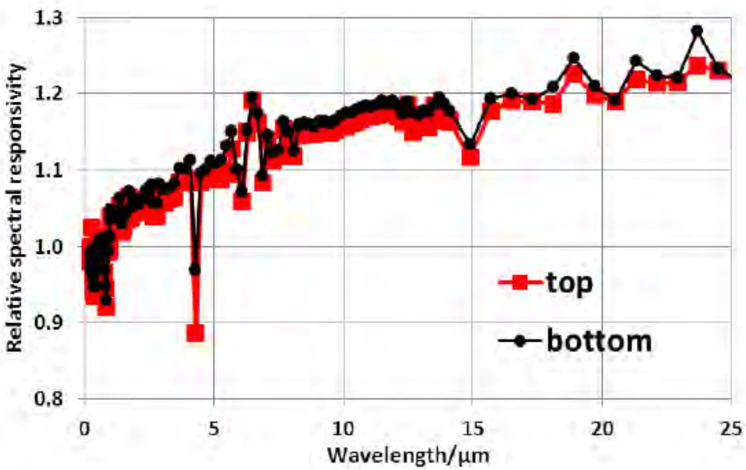
Example of Detector Technologies: Thermal Imaging

Infrared - Thermal detector development

- EarthCARE Broadband Radiometer (INO, Canada)
  - 32 pixel microbolometer with custom goldblack coating
  - 0.2 – 50 µm waveband



BBR Focal plane assembly

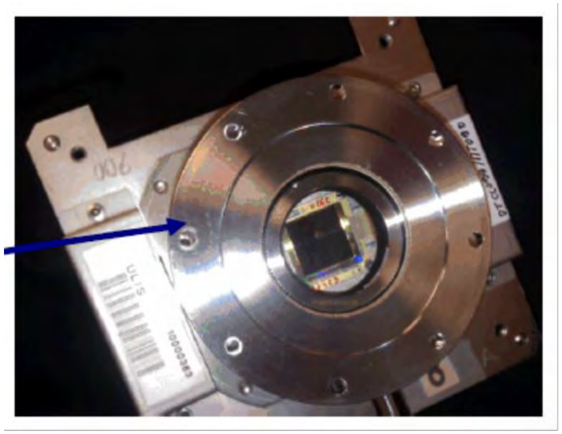


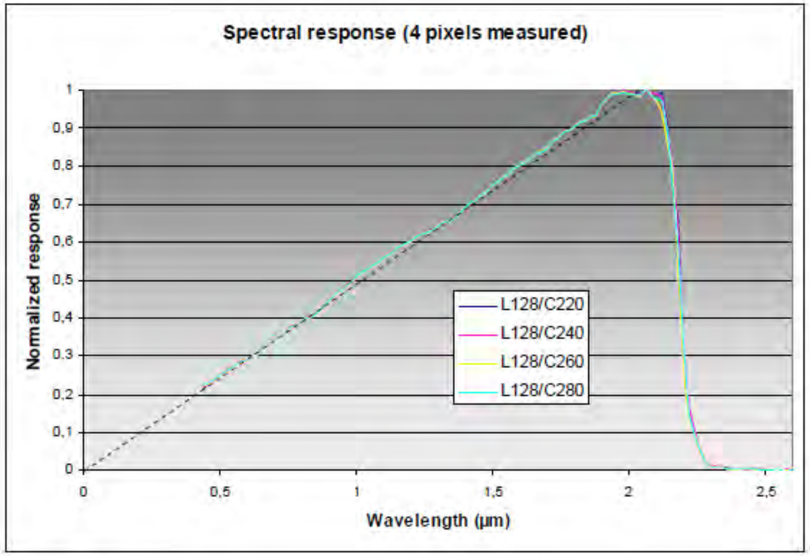
Relative spectral response measured from 0.2 – 25 µm

Example of Detector Technologies: Infrared #1

Infrared: SWIR

- Panchromatic MCT array development programme
  - Phase 1 – 500×256, 30μm pixel array
  - 0.4 – 2.2 μm
  - Phase 2 – Next Generation Panchromatic array ➔ EO Mission
  - 1k×1k, 15μm pixel array
  - 0.3 – 2.5 μm





Example of Detector Technologies: Infrared #2

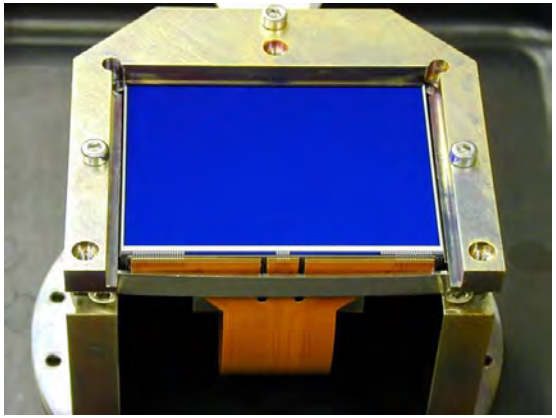
Infrared: MWIR to LWIR

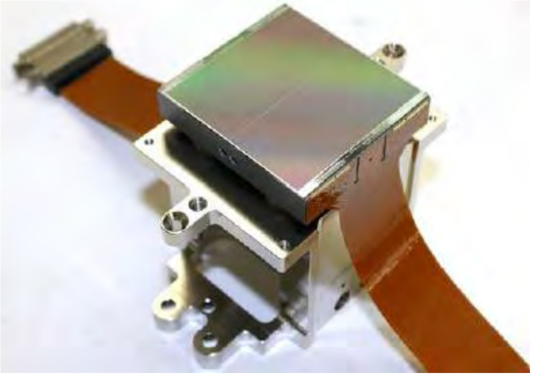
- Common aim for both Science and EO: reduction of Dark Current
  - ➔ Addressed by a dedicated roadmap: Low dark-current MWIR to VLWIR detectors development
  - Low Dark Current 2D LWIR/VLWIR MCT Detectors: exploration of state of the art MCT technologies for dark current reduction
    - “small” format (~ 256×256 pixels required)
    - LWIR band (11.5μm cut-off) and VLWIR band (14.5μm cut-off) explored
  - Low Dark Current MWIR/LWIR MCT detectors
    - Low dark-current and low noise detector development
  - Investigation of alternative technologies for LWIR/VLWIR detection: e.g. Type-2 Superlattice Structures

Example of Detector Technologies: Visible #1

Visible

- **CCD is workhorse detector**
  - Mature, reliable, very high performance
  - Low noise, low dark-current, high QE, relatively well controlled manufacture
  - Mainly mission specific developments but technology still evolving
  - Wafer scale devices – large area FPAs



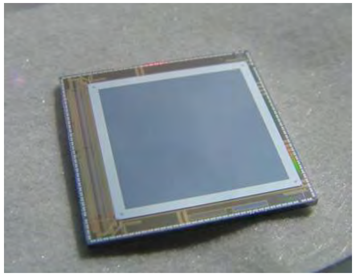


e.g. p-channel CCD evaluation, for improved radiation tolerance

Example of Detector Technologies: Visible #2

Visible

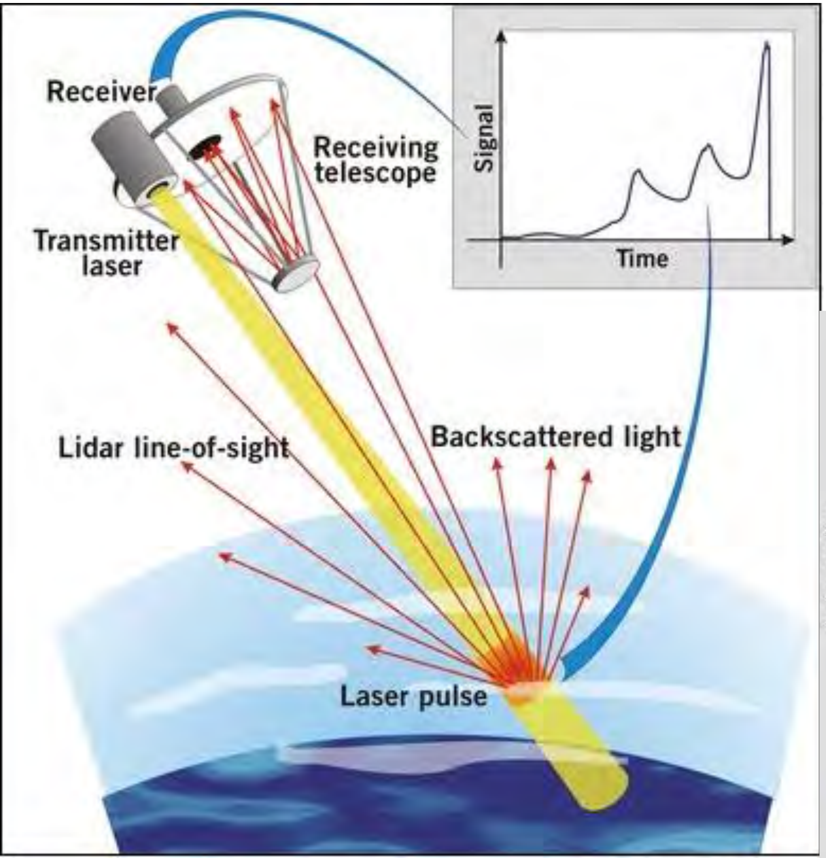
- **Challenger is CMOS Image Sensor (CIS)**
  - Promises operation that is fast, flexible, radiation hard, low-power and easy to interface
  - Strategic development roadmaps in place
  - ➔ Low noise, low dark-current, High QE, European supply
- **Back-thinned CIS development programme**
  - High-performance CIS (low dark-current, High QE) 1k x 1K pixel array.
  - Monolithic and hybrid approach

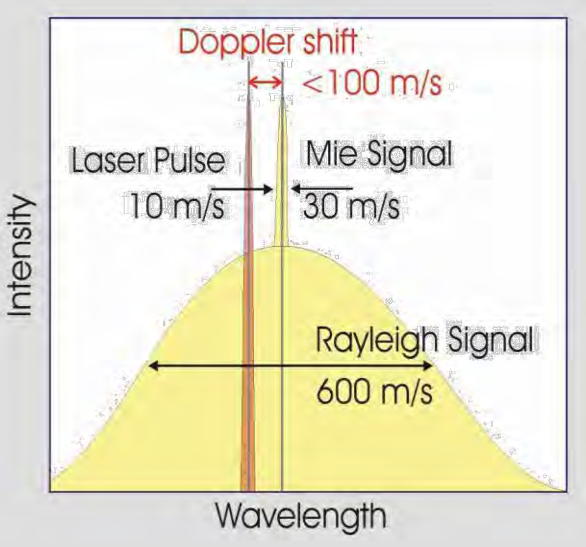


- **European CIS**
  - European CIS supply chain elaboration
  - Design + foundry + post-process
  - ➔ High-flux CIS development – EO applications
  - ➔ Low-flux CIS development – Science applications

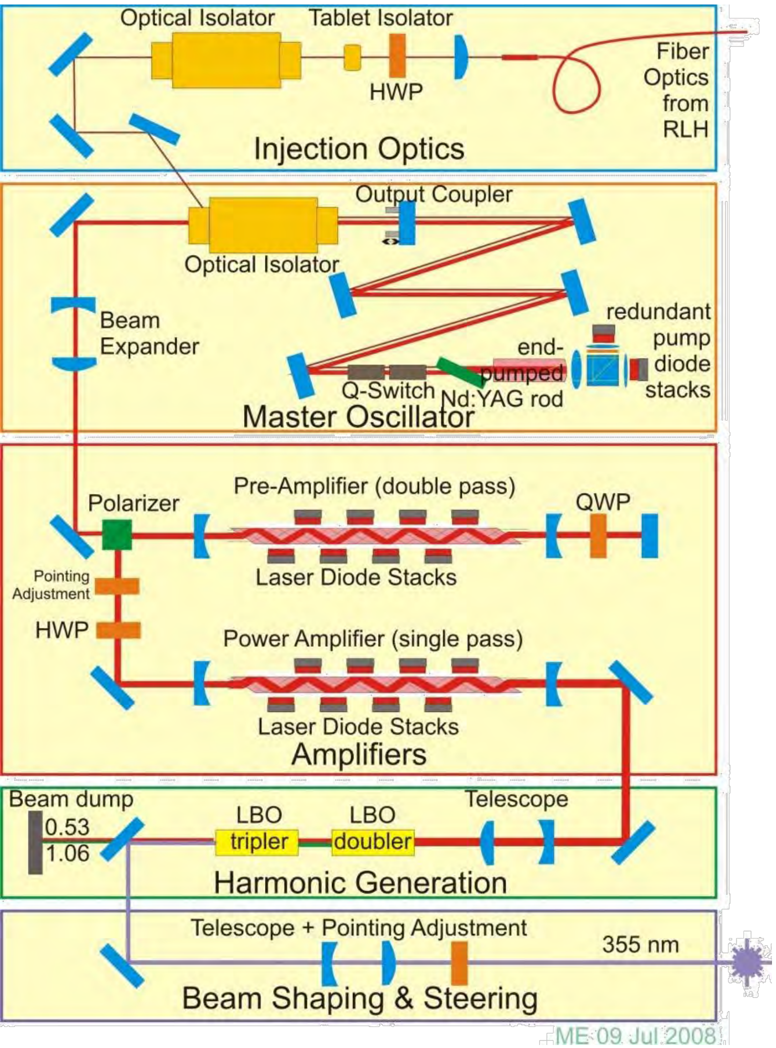
ADM-Aeolus: sensing the wind

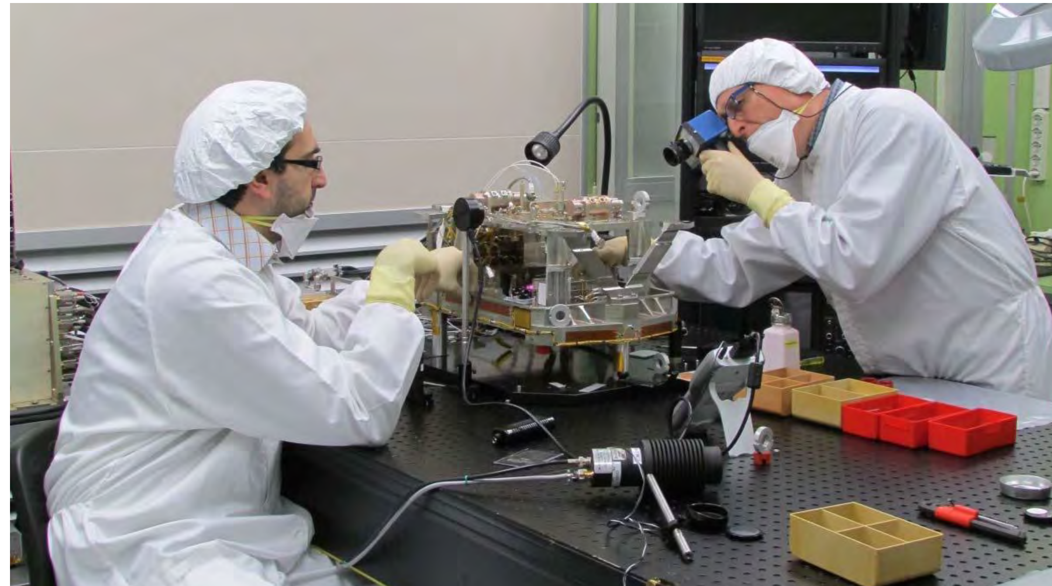
- Aladin Payload of the **ADM-AEOLUS** Earth Explorer Core mission of the ESA Living Planet Programme
- Mission goal: provide measurements of tropospheric wind profiles on a global scale, with high accuracy of 1m/s





Example of laser technology: ADM Tx – most complex space laser design ever built



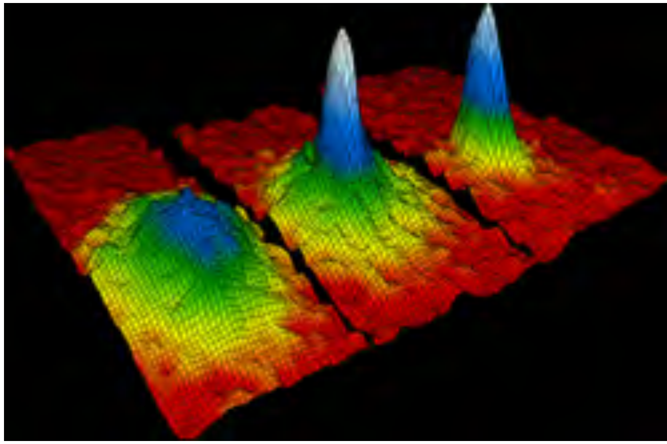


Example of Laser Technology: Cold Atom Physics

- 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)

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

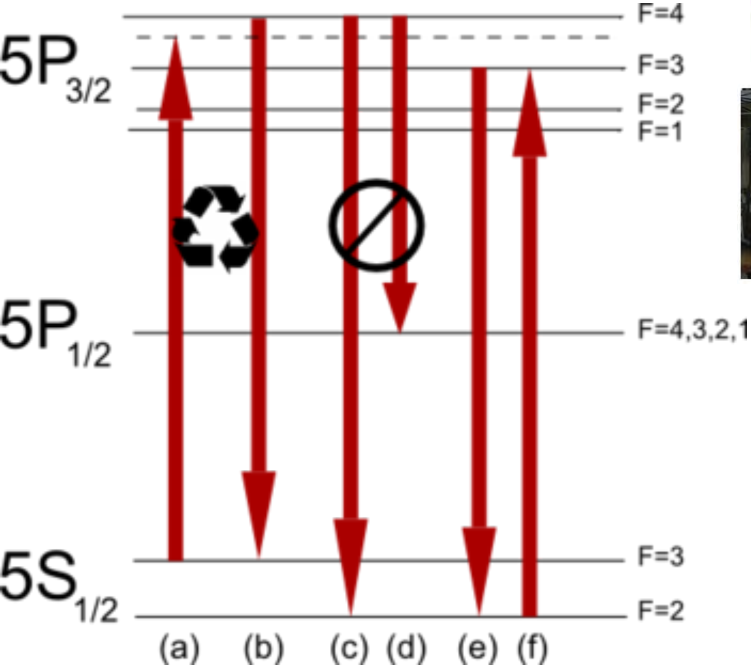
$$\Delta x \Delta p \sim \hbar$$

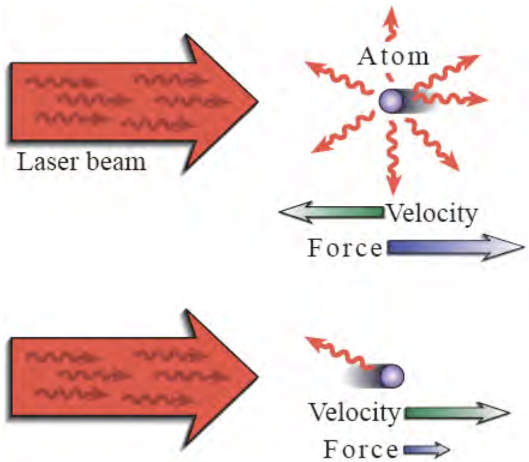


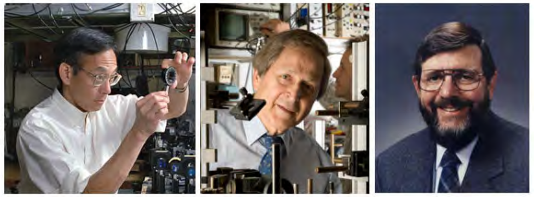
Velocity-distribution data of a gas of rubidium atoms, confirming the discovery of a new phase of matter, the Bose–Einstein condensate

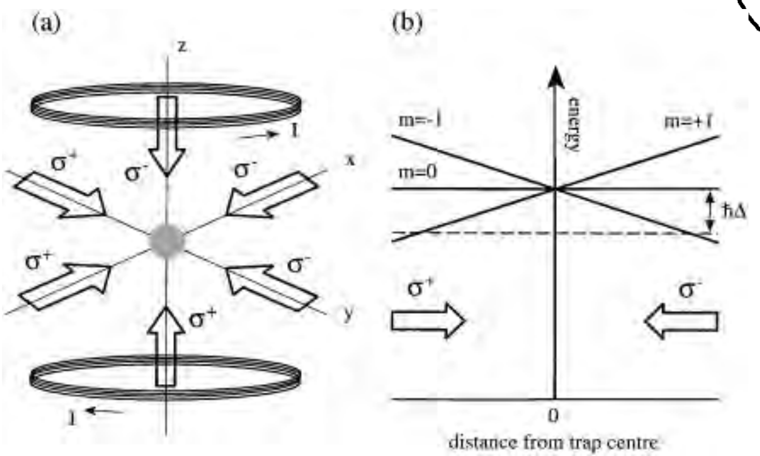
Magneto-Optical Traps (MOT)

- Doppler cooling
- Optical Molasses (3D)
- Zeeman cooling
- MOT (Nobel Prize 1997)
- Sisyphus cooling discovery

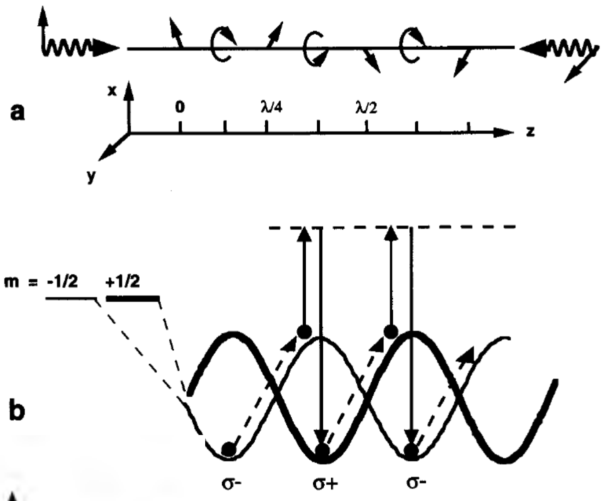






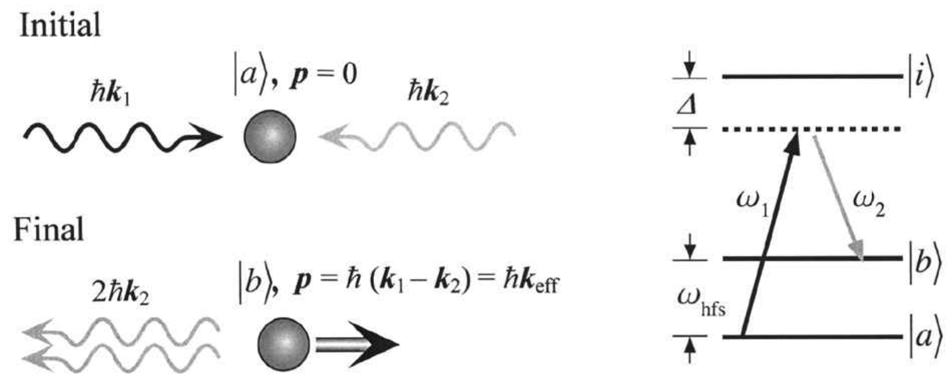


(a) Interfering, counter-propagating beams having orthogonal, linear polarizations create a polarization gradient. (b) The different Zeeman sublevels are shifted differently in light fields with different polarizations; optical pumping tends to put atomic population on the lowest energy level, but non-adiabatic motion results in "Sisyphus" cooling.

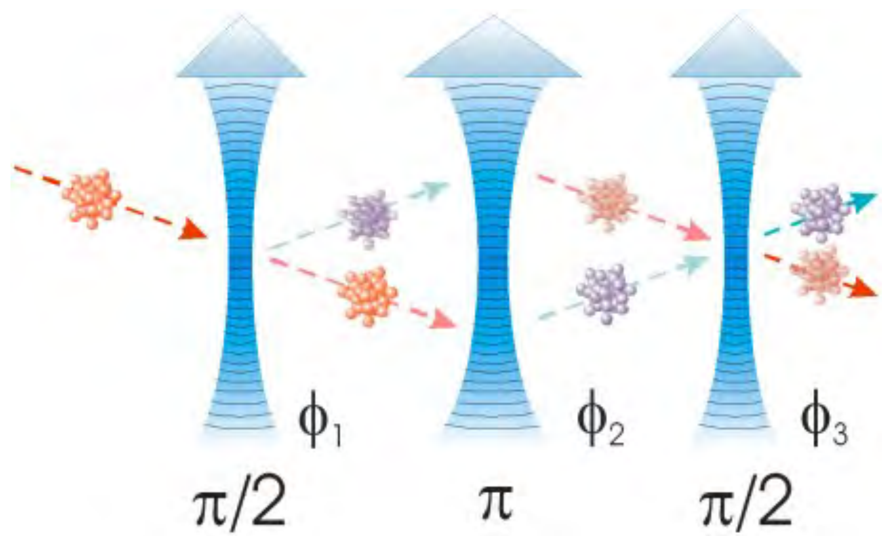


Atom Optics

- What is needed:
  - Coherent mechanism providing the equivalent of mirrors, beam splitters and lenses for cold atoms beams
- Stimulated Raman transitions
  - Two counter-propagating laser beams stimulate Raman transitions between hyperfine ground states
  - Provides a recoil from the two photons (absorbed + emitted)
  - Large detuning, Δ, reduces probability of excited state $|i\rangle$ becoming populated
  - Depending on how long they are applied, stimulated Raman transitions act as mirrors (π pulse) or beam splitters (π/2 pulse)



An atom undergoes a stimulated Raman transition. It absorbs a photon of frequency ω_1 and emits another one (via a stimulated emission) of frequency ω_2. As both photons carry momentum, and because momentum has to be conserved in the process, the atom receives a recoil momentum kick. *Metrologia*, 2001, **38**, 25-61



Atom Interferometry

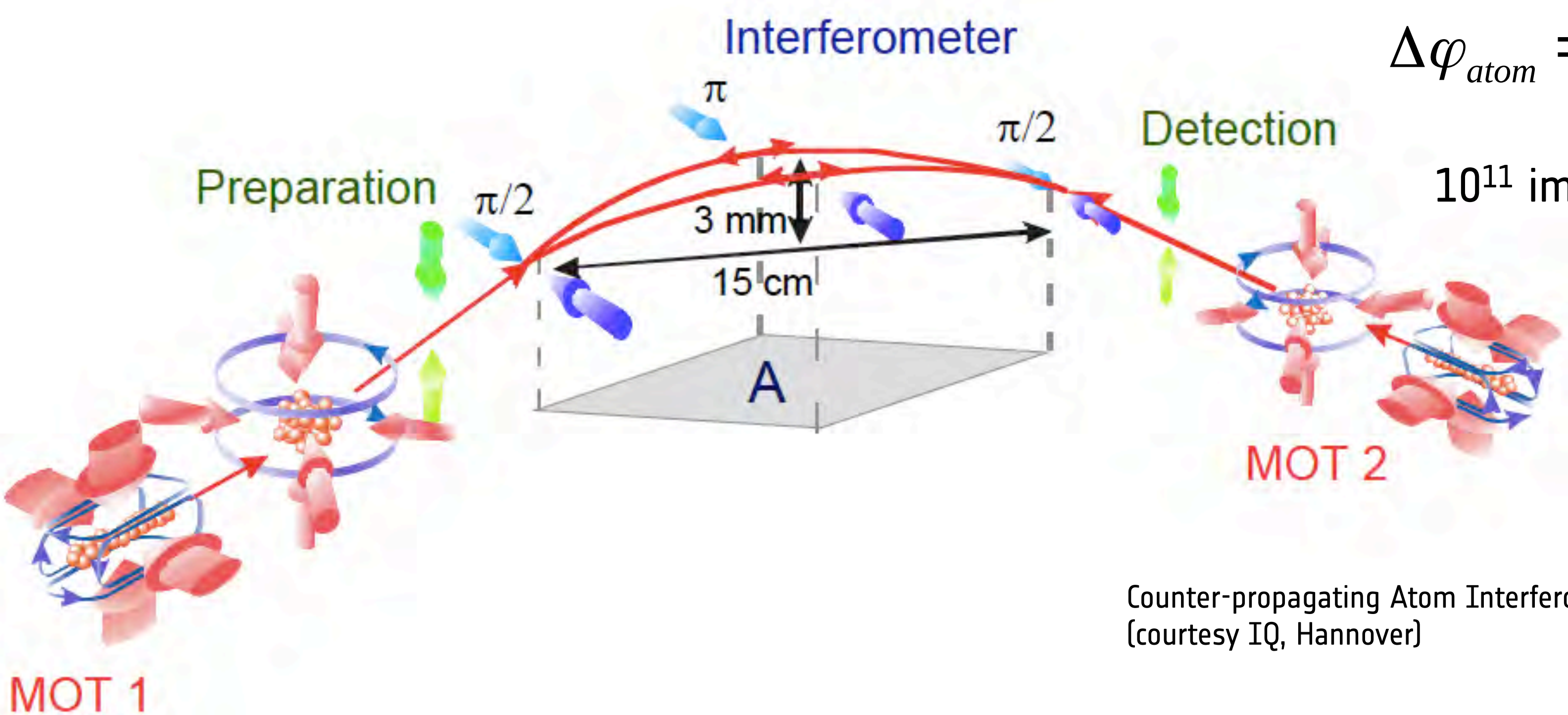
- 2D MOT loads 3D MOT with high flux ~ 10^9 atoms/s
- 3D MOT cools atom clouds ~ 10^8 ^{87}Rb atoms <10μK
- Atomic state preparation for atom optics sequence
- Raman π/2–π–π/2 sequence
- Detection by fluorescence

$$\Delta\varphi_{light} = \frac{4\pi}{\lambda c}\vec{\Omega}\cdot\vec{A}$$

$$\Delta\varphi_{atom} = \frac{4\pi}{\lambda_{dB} v}\vec{\Omega}\cdot\vec{A}$$

$$\Delta\varphi_{atom} = \frac{mc^2}{\hbar\omega}\Delta\varphi_{light}$$

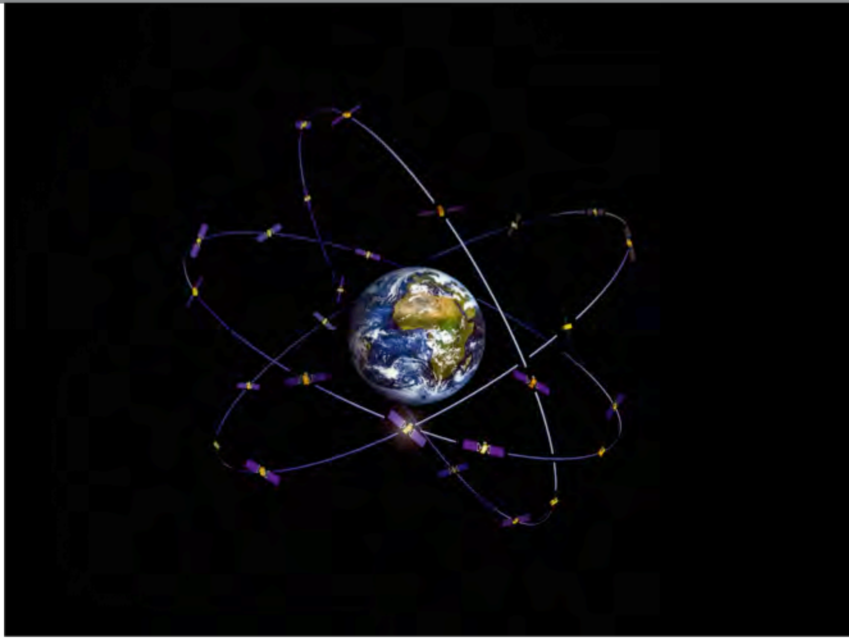
10^{11} improvement!

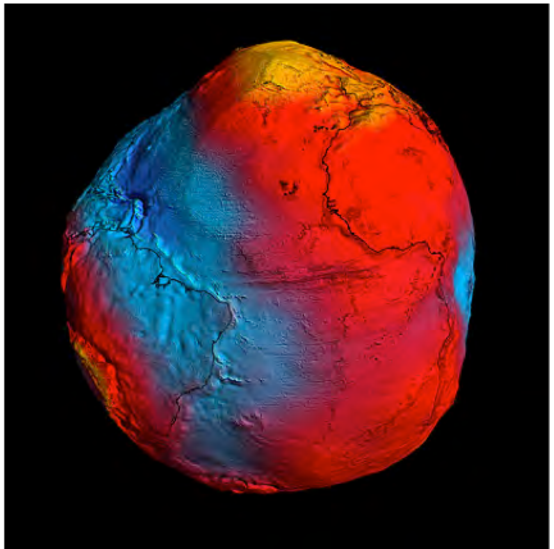


Counter-propagating Atom Interferometers scheme
(courtesy IQ, Hannover)

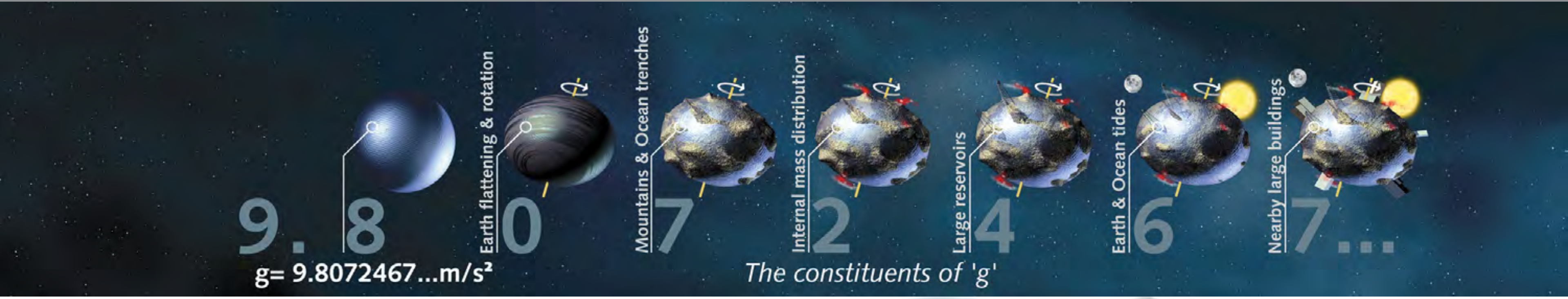
Applications

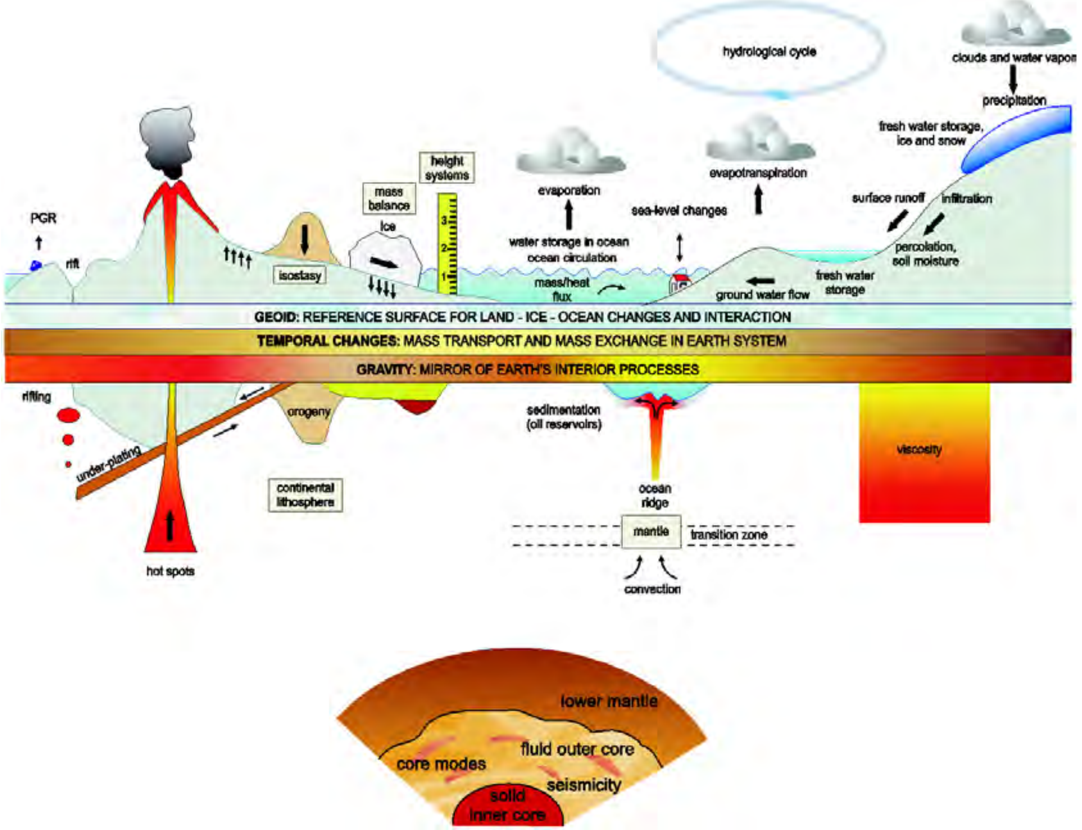
- Inertial Navigation
- Attitude Monitoring
- Accelerometers for Drag-Free Systems
- Deep Space Accelerometers
- Gravity Mapping
- Fundamental Physics:
  - Testing General Relativity
  - Short-Range Forces
  - Atom-Surface Interactions
  - Fundamental Constants
  - Electron Electric Dipole Moment
  -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





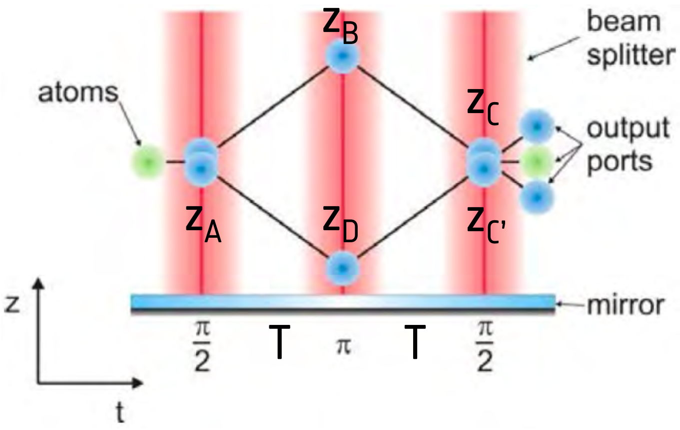
Earth Gravity Field

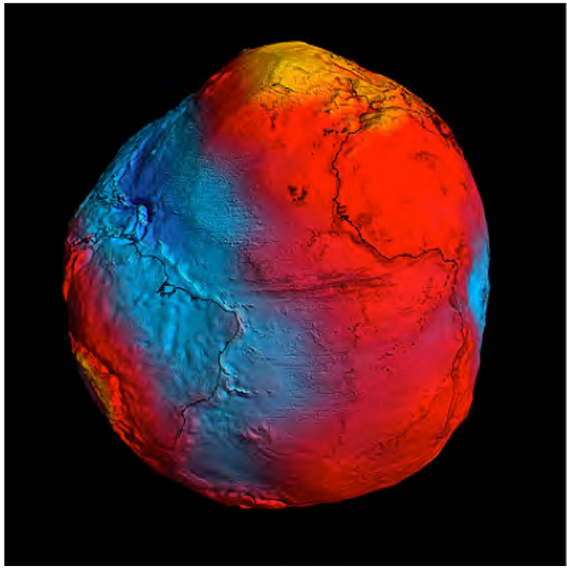




Future Gravity Mission Concept

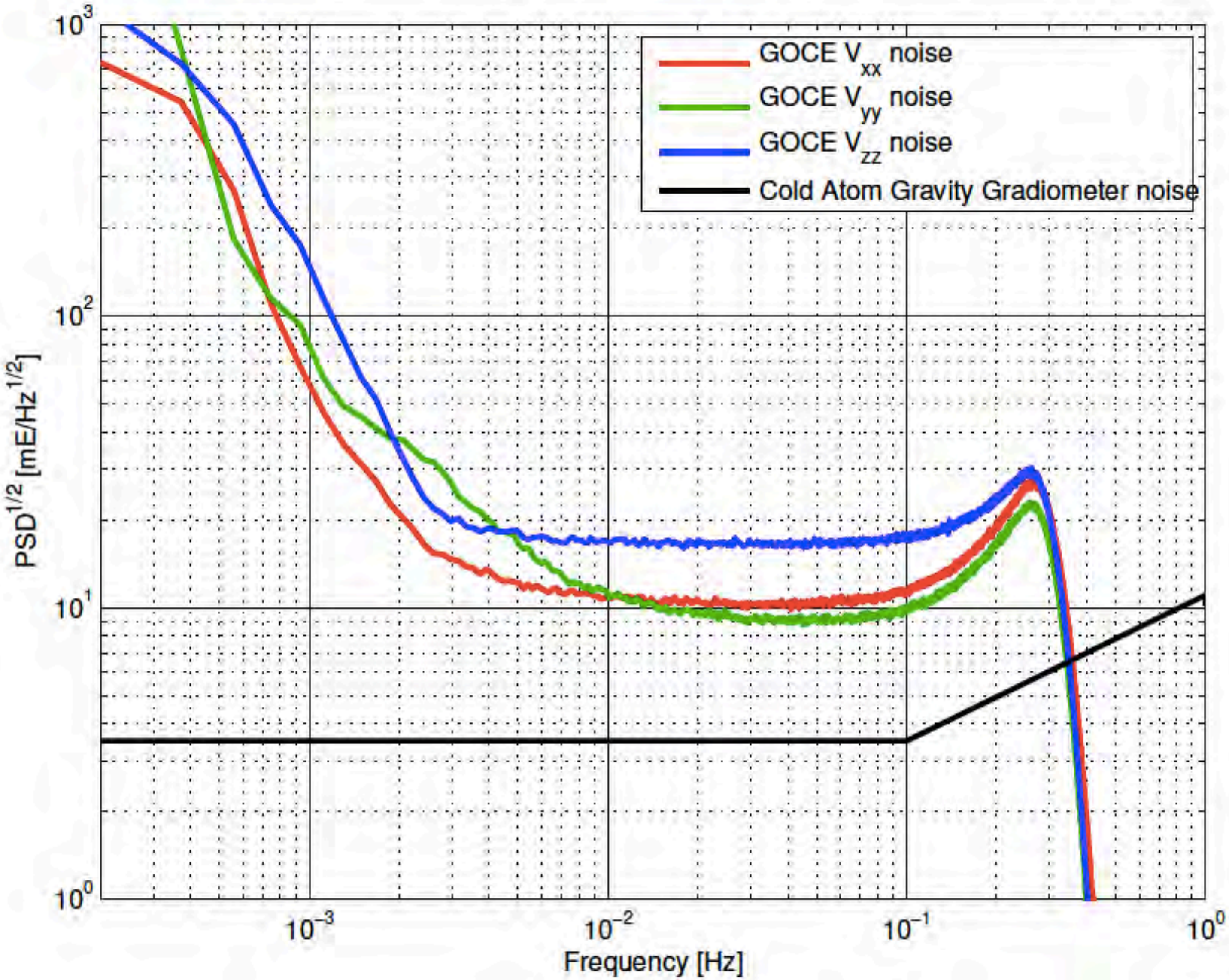
- Cold Atom Interferometry technology requirements for EO
- EO Future Missions elaborated gradiometer/gyroscope concept
  - Gradiometer performance:
  - 3.5 (goal 1.0) mE/√Hz (0.1 – 100 mHz)
  - Gyroscope performance:
  - 35 prad/s/√Hz (0.1 – 100 mHz)





European Space Agency

Cold Atom Interferometer vs. GOCE



Courtesy of ESA EOP-SF

Conclusions

ESA is fostering optoelectronics technologies with major impact on European Competitiveness and market perspectives

- **Remote Sensing**: new advanced instrumentation (lidar, cold-atom interferometry) will give Europe the edge on weather forecasting, geodesy and environmental monitoring
- **Optoelectronics** is leading to major advances in Space observation, as well as in Satellite development and operations in terms of performance, functions, resources & accommodation.

Details on programs and developments on

www.esa.int

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

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

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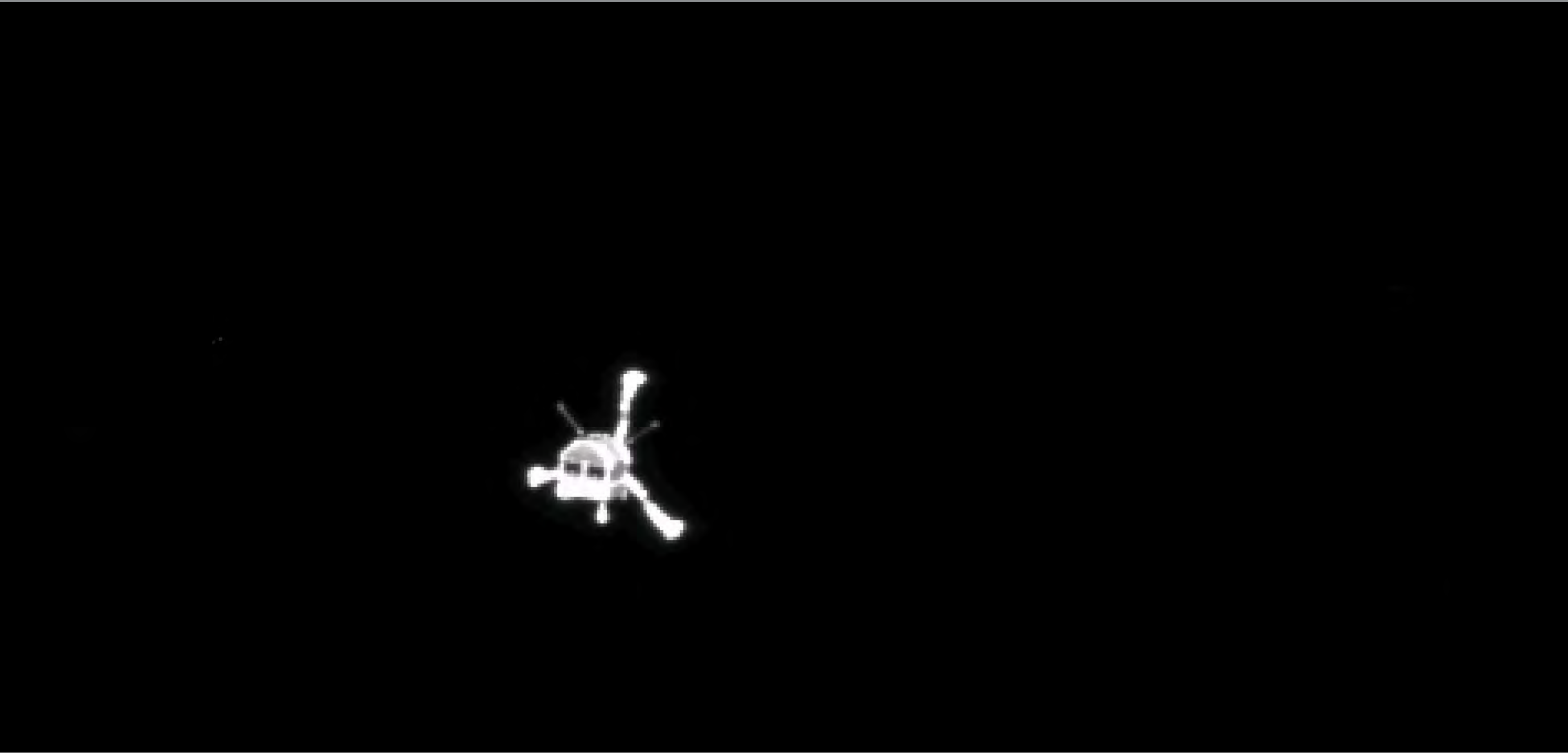
Farewell Philae



Title Farewell Philae - narrow-angle view

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European Space Agency

Description Rosetta's OSIRIS narrow-angle camera captured this parting shot of the Philae lander after separation