MISSION CONCEPT FOR SPACE-BORNE GRAVIMETRY WITH COLD ATOMS INTERFEROMETRY

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THALES ALENIA SPACE

LIVING PLANET SYMPOSIUM 2022

BONN - MAY 26TH

ThalesAlenia Space

SPACE FOR LIFE ///

- Top manufacturer of telecommunications satellites
- World leader in satellite constellations

- Defense telecom satellites
- Very High Resolution optical/RF instruments
- Ground control systems

- Study Earth’s oceans
- Study Earth’s continents
- Forecast the weather
- Understand climate change

- Exploring our solar system
- Understanding our universe
- Living & working off Earth
- In-orbit services

Enabling location & map services
Ensuring the safety of travelers
Providing accuracy & reliability
Enabling the Internet of Things

MORE THAN

8,000 EMPLOYEES

17 SITES

WORLDWIDE

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ThalesAlenia Space

THALES ALENIA SPACE – SPACE TO EXPLORE (Domain of Exploration and Science – ITALIA)

EXPLORING OUR SOLAR SYSTEM

- CASSINI: Saturn
- BEPI-COLOMBO: Mercury
- EXOMARS 2020

UNDERSTANDING OUR UNIVERSE

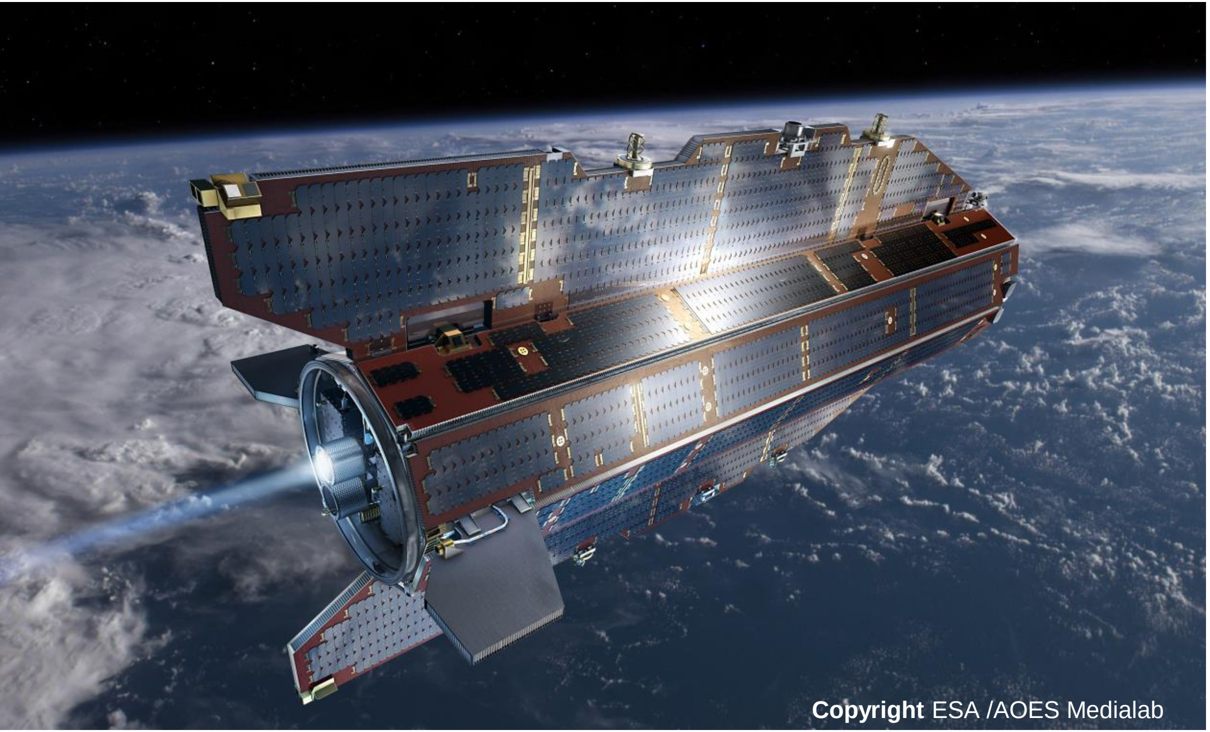
- ALMA: The origin of the Universe
- EUCLID: the dark matter
- ROSETTA: the comets
- HERSCHEL-PLANCK

LIVING & WORKING OFF EARTH

- ISS
- Lunar Platform
- Human spaceflight
- Reusable spacecraft

IN-ORBIT SERVICES

2009: GOCE (Gravity Field And Steady-state Ocean Circulation Explorer)

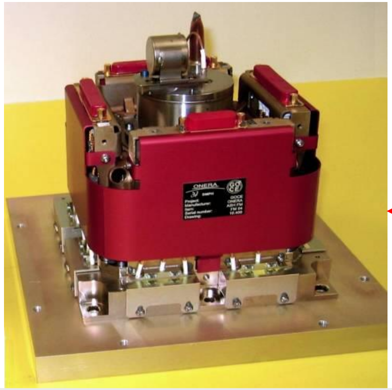


GOCE's Pillars

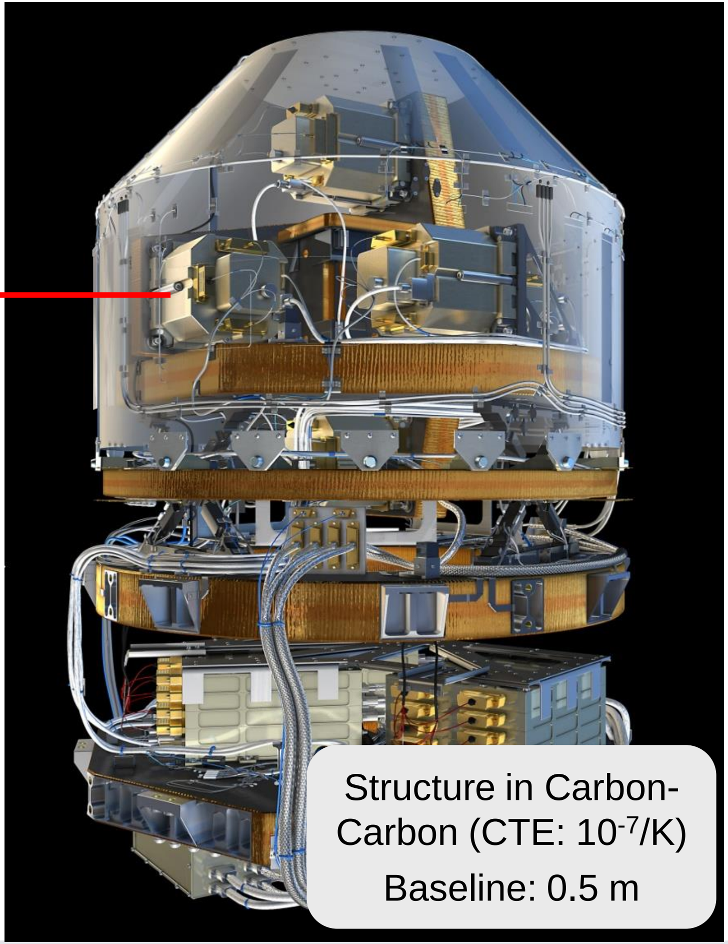
/// EGG Gradiometer with electrostatic accelerometers

/// DFACS Attitude Control

GOCE’S GRADIOMETER



Accelerometer



Geoid accuracy	2 cm
Resolution	100 km
Acceleration sensitivity	$2{\cdot}10^{-12}$ m/s^2
Gravity anomalies	0.6 mGal (1 mGal = 10^{-5} m/s^2)

Address Gravimetry from Space: Mission and Platform Contribution

Study environmental changes on a global scale → Measurement from space

Three fundamental features are typical objectives for gravity missions and platforms:

- Uninterrupted tracking in three spatial dimensions
- Measurement (or compensation) of non-gravitational forces (→ Drag Free Control System)
- Lowest possible orbital altitude (gravity field attenuates with the square of the distance) for the maximum sensitivity.

Unfortunately, the lower is the orbit, the more is the air-drag the satellite experiences

Address Gravimetry with Quantum Accelerometers / Gyroscopes

❑ Principles and expected benefits

- Quantum states used as references
- State propagation to probe space

  → Orders of magnitude more sensitive, long term stability

❑ State of the art:

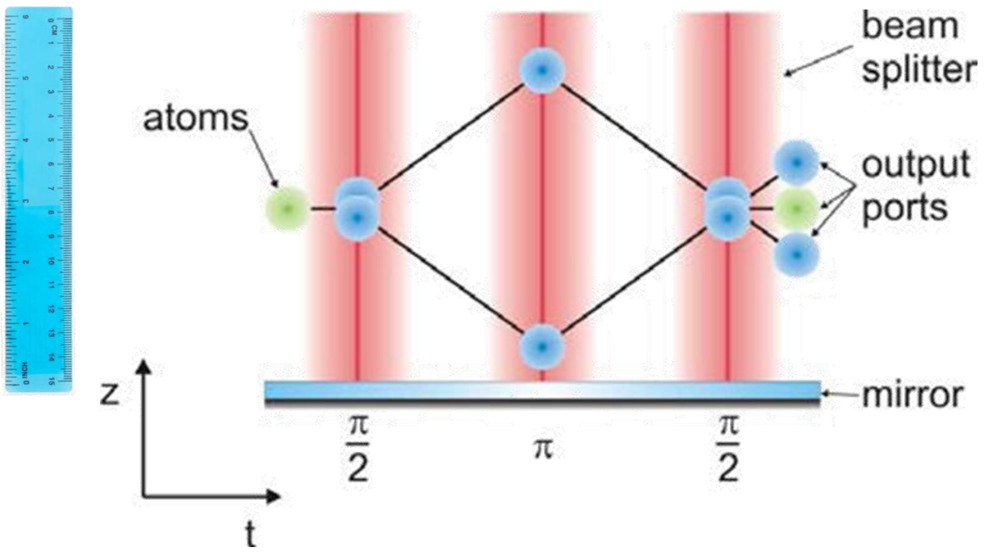
- On ground: up to commercial products
- In space: TRL from 3 to 6, according to specific subsystems

❑ What to explore

- Concepts compatibility with relevant environment
- SWaP compatibility (Size, Weight and Power)
- Benefits w.r.t. classical technology. Pure vs. Hybrid solutions

Accelerometer with a Quantum Mass: Cold Atom Interferometry

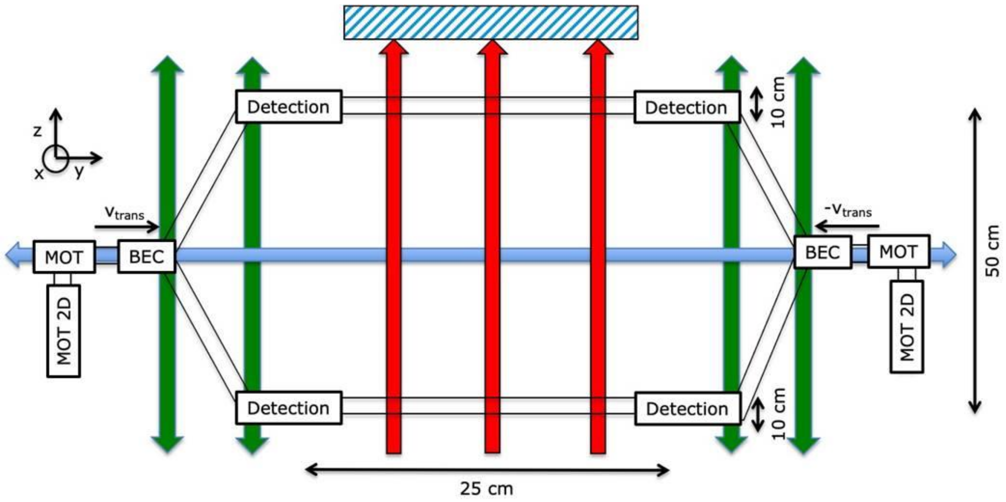
The laser acts as a ruler marking atoms position on their phase



Interferometer phase shift is proportional to the acceleration: $\Phi = k \cdot g \cdot T^2$

Gradiometry With Free Fall Cold Atoms

/// Simultaneous measurement of gravity gradient and rotation rate



/// At least one order of magnitude improvement in gravity gradient sensitivity, especially at very low frequencies

/// Rotation sensitivity at the level of 30 prad/s/√Hz

DFACS of New Generation

DFACS provides reduction of non-gravitational accelerations (due to atmosphere drag), angular and linear on three axes.

AOCS sensors	– Accelerometer set – GNSS receivers – 2 star trackers – 2 CESS – 2 three-axis magnetometer – 2 three-axis coarse rate sensor
Actuators	– 3 magnetic torquers – 8 µRIT electric thrusters – 1 RIT electric thruster

Angular rates	$< 10^{-10}$ rad^2/s^2/Hz
Angular rates (Knowledge)	$< 10^{-8}$ rad/s/$\sqrt{Hz}$
Pointing stability	$< 10^{-4}$ rad
Linear acceleration	$< 10^{-9}$ m/s^2/Hz$^{1/2}$ @ 0.1 Hz

Quantum Sensing in Space – Recent studies

(ESA 2016 – 2018)

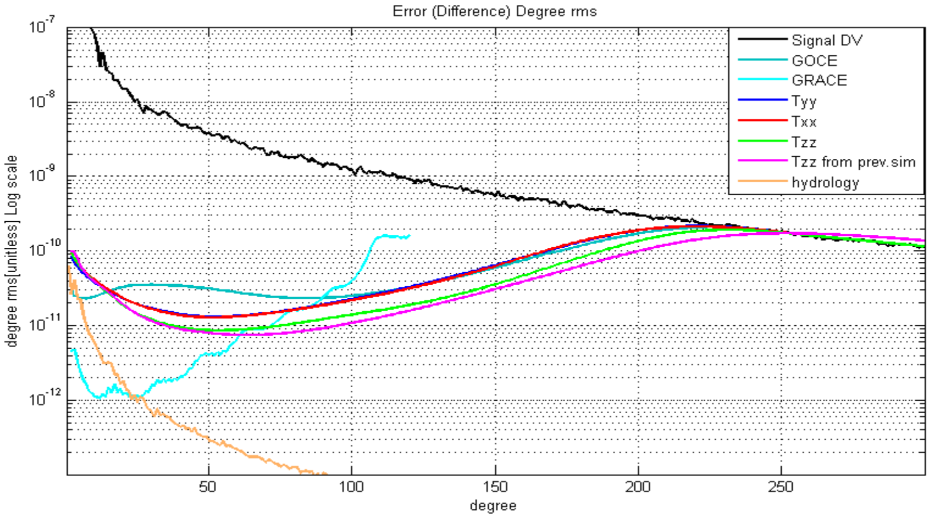
Study of a CAI mission scenario and evaluation of the potential performance compared to GOCE.

Partners: LENS (I), Marwan Technologies (I), Politecnico di Milano (I), TU Delft (NL)

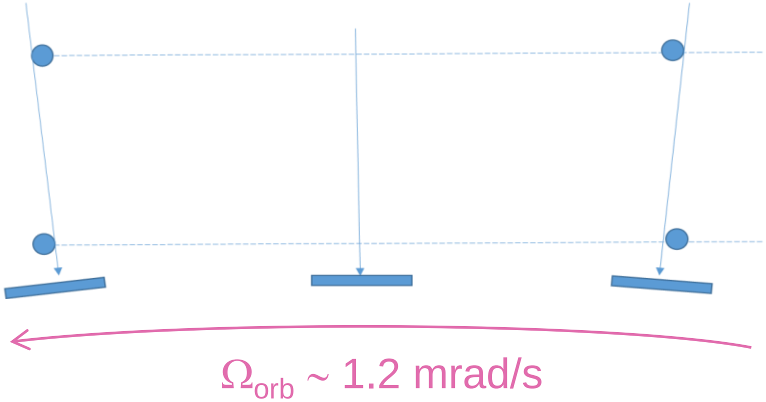
A tri-axial Cold Atom interferometer (based on rubidium) to be accommodated on a realistic platform, to be flown on a realistic orbit, addressing static gravity ought to improve on the performance of GOCE

Mission and Platform contribution to CAI

- Full-fledged DFACS control (3-axis linear and angular acceleration control using ultra-high accuracy accelerometer and proportional micro-newton thrusters) as the one currently proposed for “classical” missions such as NGGM/MAGIC, provides drag-free environment at GOCE-like altitude (<300 km) compatible with the scientific performance
- Only nadir-pointing platforms can be designed for such performance at such altitude
- DFACS requires acceleration measurements at 10 Hz, which cannot be provided by current CAI technology. Measurements for drag free are based on GOCE-like accelerometer .
- Estimate of the angular rate provided by the controller (for centrifugal acceleration correction)
- Single-axis CAI instrument plus GOCE-like full tensor gradiometer, the CAI providing the low-bandwidth extension and reference, would require strongly miniaturized solution



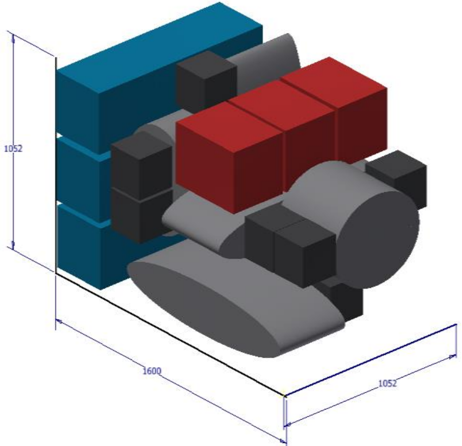
Orbital Rate Degrades Performance



- The rotation of the effective wave vector with respect to the atom clouds reduces contrast
- Tilted mirrors are introduced to compensate for average rate (spherical Earth approximation). Additional compensation of slow rate modulation at orbital frequency
- Tilted mirrors prevent gyro-mode. Angular rate shall be provided by AOCS/DFACS for centrifugal acceleration correction
- Angular rate estimate provided by the controller (or by a top-level gyro) is not yet adequate to reach the expected reconstruction

How big is a triaxial Cold Atom Gradiometer?

Instrument Volume.



The estimated payload size is: (**1052** × **1052** × **1600**) mm

- 3 x single axis instrument: (1052 × 444 × 805) mm
- 3 x laser system: approx. (300 × 300 × 400) mm
- 3 x electronic system: approx. (300 × 300 × 1000) mm
- 9 x ion getter pump: approx. (200 × 200 × 200) mm

Data provided by ESA, developed by a separated consortium

GOCE EGG

(H 1350, Ø 830)

How ‘hungry’ is a triaxial Cold Atom Gradiometer?

Instrument Mass and Power budgets.

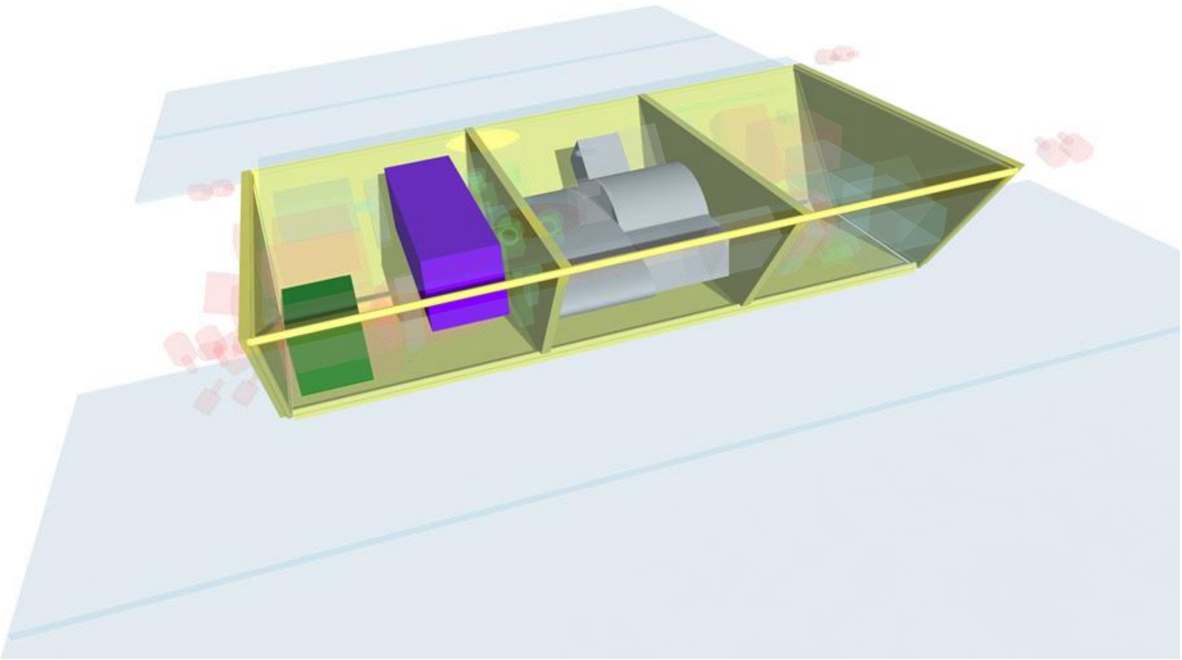
GOCE	Mas [kg]	Power [W] (science mode)
Platform	866.1	617.1
Gradiometer	180.7	114.9
Satellite	1060.8	876.0

Preliminary budget overview				
	Mass (kg)	Mass + 20 % component margin (kg)	Power (W)	Power + 20 % component margin (W)
Instrument with tiptilt mirror	206.1	247.2	664.0	796.8
Instrument with tiptilt mirror	206.1	247.2	664.0	796.8
Instrument without tip/tilt mirror	199.6	239.5	610.0	732.0
Total	**611.8**	**733.9**	**1938.0**	**2325.6**
Total + 20 % system margin	**733.9**	**880.7**	**2325.6**	**2790.7**

Data provided by ESA, developed by a separated consortium

Realistic accommodation of a single axis gradiometer

On a platform adequate for a gravimetric mission around the Earth



Quantum Sensing in Space – Recent studies

(ASI 2020-2021)

MOCAST + Feasibility study for a mission based on CAI technology integrated with an atomic clock, to study the Earth gravity field

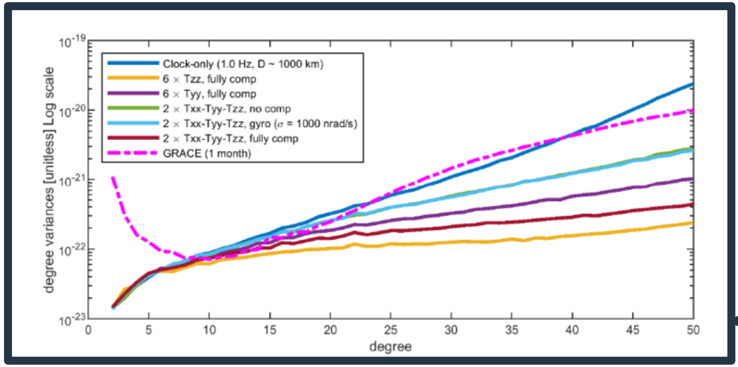
Partners: Politecnico di Milano (I), Atom Sensors (I), Università di Trieste(I), Università di Trento (I)

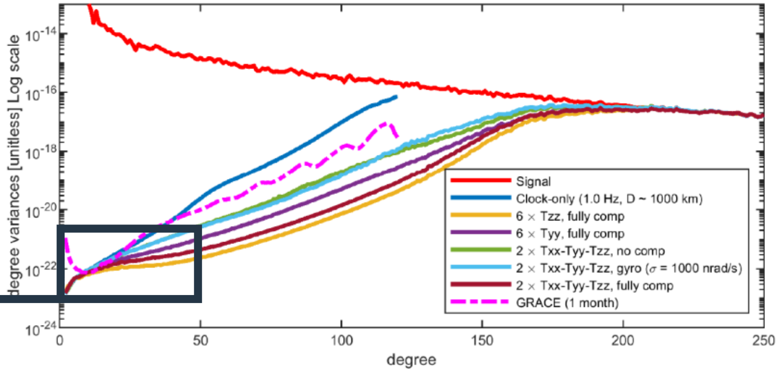
A QSG mission in formation flying (Bender constellation, with two or three satellites per orbit) with an "enhanced" quantum payload consisting of:

- **Cold Atom Interferometer** (^{88}Sr atoms), providing observations of gravitational gradients (low sensitivity to magnetic fields, high isotopic abundance),
- **Atomic clock** (^{87}Sr atoms) for optical frequency measurements using an ultra-stable laser providing time observations, hence observations of differences of the gravitational potential.

Mission and Platform contribution to MOCAST+

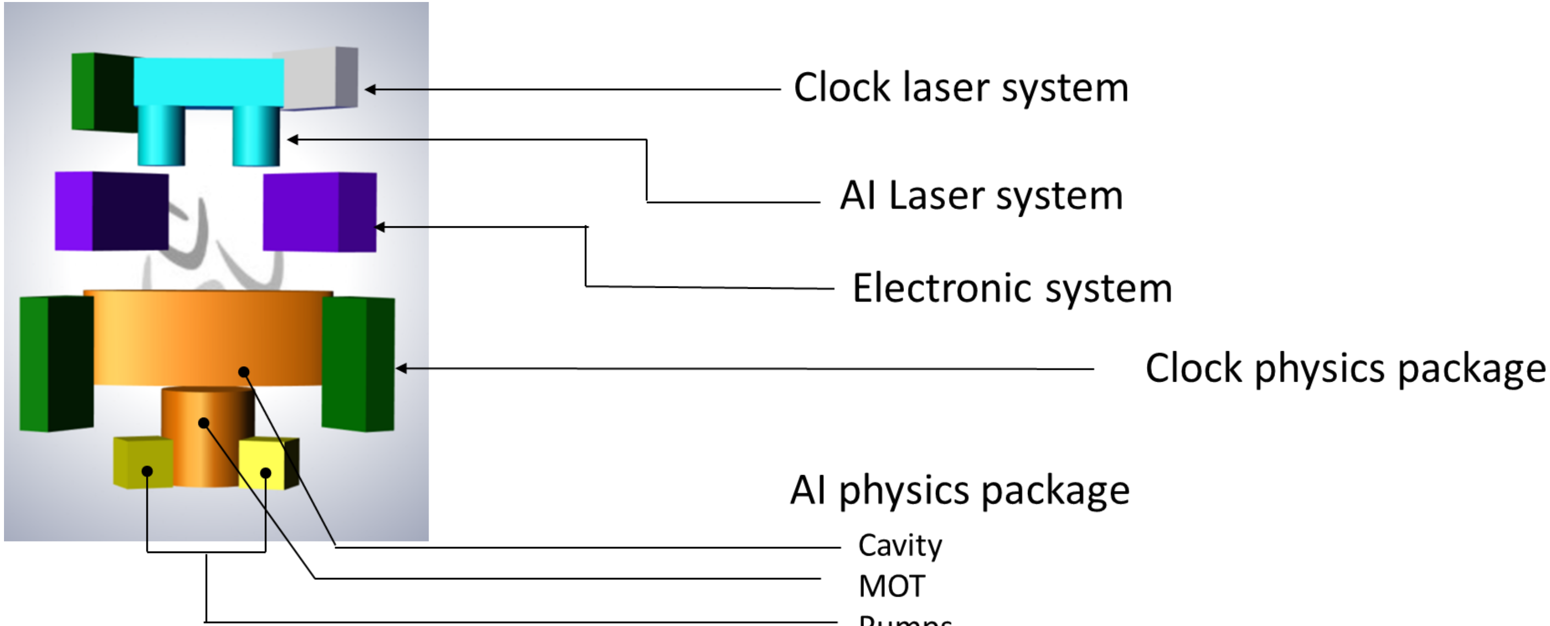
- Angular rotations, through the centrifugal term, put again a serious limitation to the measurement of the gravity gradient
- MOCAST+ could improve the current knowledge of the Earth gravity field and its time variation, at the price of higher mission and platform complexity (but no showstoppers today):
  - longer inter-satellite distances (~ 1000 km)
  - Inter-satellite laser link
  - Bender formation with three satellites per orbit
  - Improvement of angular rate measurement





Realistic accommodation of a single axis gradiometer + clock

On a platform adequate for a gravimetric mission around the Earth



ASI Agenzia Spaziale Italiana · POLITECNICO MILANO 1863 · AtomSensors · ThalesAlenia Space · UNIVERSITÀ DEGLI STUDI DI TRIESTE · UNIVERSITÀ DI TRENTO

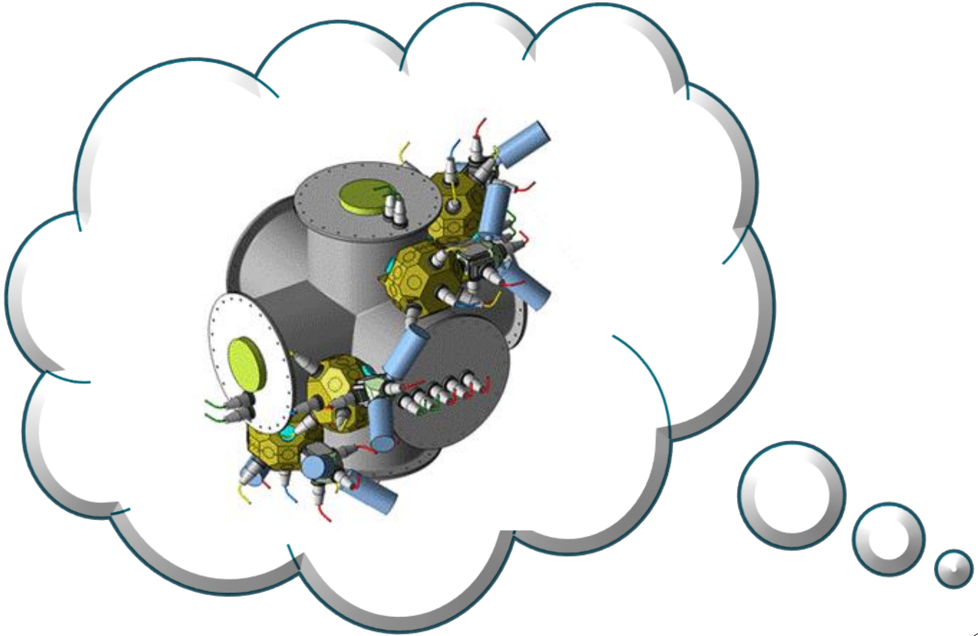
A Cold Atom Gradiometer Today?

- Quantum Cold Atoms gradiometer in a GOCE-like mission is promising for theoretical performances.
- New generation drag free control at low altitude (250 km) is adequate, but ion propulsion technology development is desirable
- CAI mission still needs electrostatic accelerometers to implement DFACS (CAI data rate is still far from being adequate)
- Reduction of instrument footprint (Size, Weight, Power) is necessary, although feasibility studies have shown compatibility of real platforms with single axis instruments
- Synergy with atomic clocks provides improvement at very low harmonics, but very long baseline constellations (>> 100 km) require dedicated studies

ESA and EU support in-orbit-demonstration and pathfinder missions in the next decade.

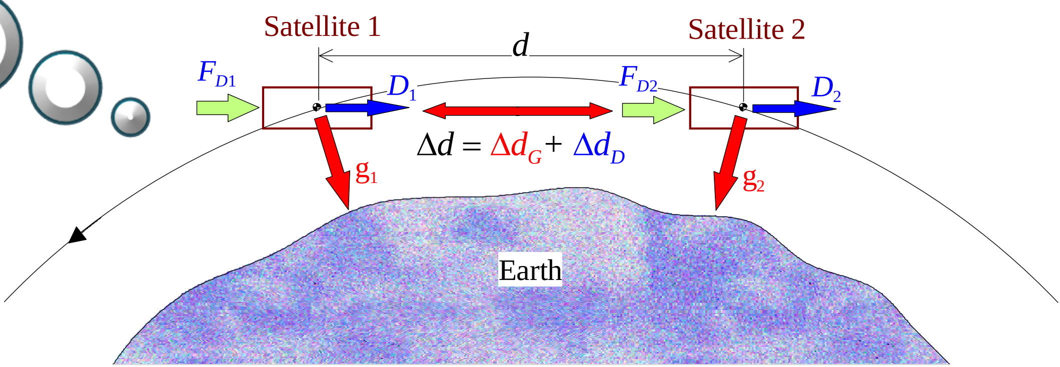
Space industry is ready to take the challenge

Waiting for Quantum Gradiometry



/// NEXT GENERATION GRAVITY MISSION (MAGIC)

- Gravity field recovered from measuring (with a laser ranging system) the distance variation (Δd) induced between the satellites;
- Non-gravitational effects produced by atmospheric drag (Δd_g) separately measured by accelerometers and accounted for in the data processing.



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