

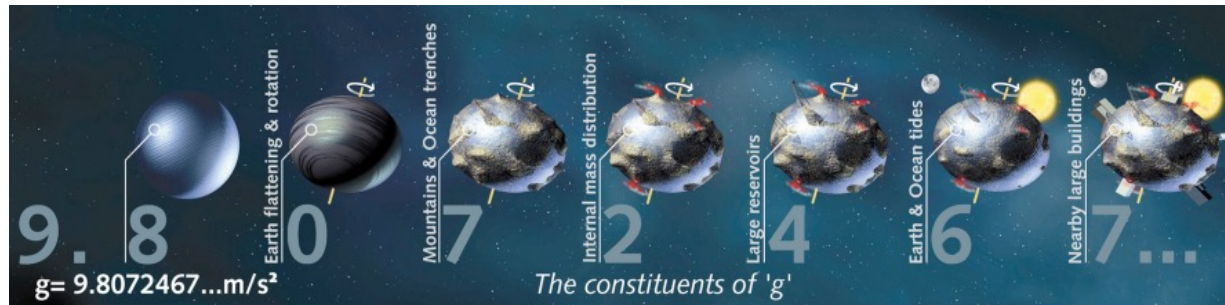
# ESA Activities and Perspectives on Quantum Space Gravimetry

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Massotti, Ilias Daras, Günther  
March, Arnaud Heliere, and  
Pierluigi Silvestrin

# Background: mass distribution and mass transport

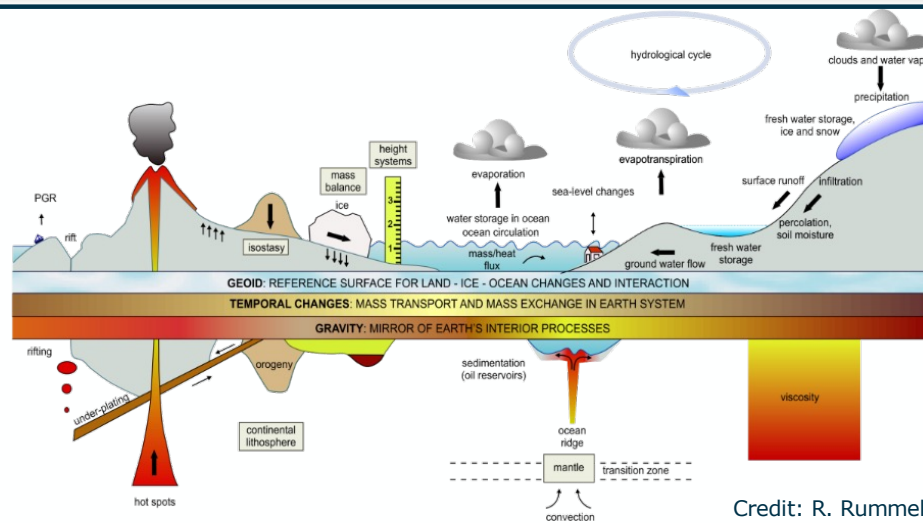
Gravity reflects the **mass distribution** of the Earth



© ESA

**Mass RE-distribution (=transport)** causes variations in the gravity field.

On short time scales, mass transport is mostly caused by water transport.



# Background: ESA & NASA cooperation - Joint Mission

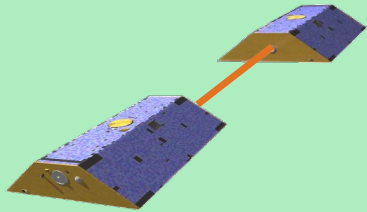


*Past observations*

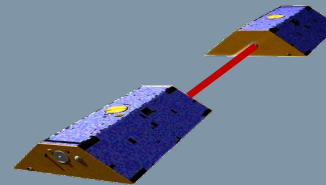
*Continuity of observations*

*Enhanced continuity of observations*

**NASA**



GRACE  
US/DE



GRACE-FO  
US/DE

**MAGIC**

2002

2009

2013

2017

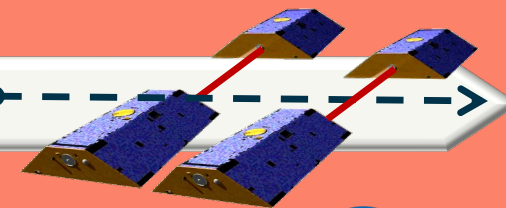
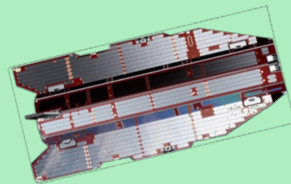
2018

2023

~2028

GOCE

**ESA**



*Start of sustained observations at higher spatial & temporal resolutions*

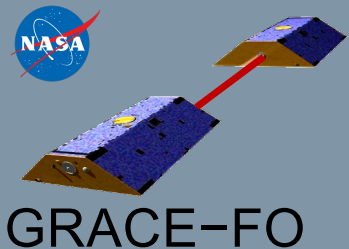


# Opportunities for Quantum Gravimetry: long-term

*Continuity of observations*

*Enhanced continuity of observations*

**long-term infrastructure**

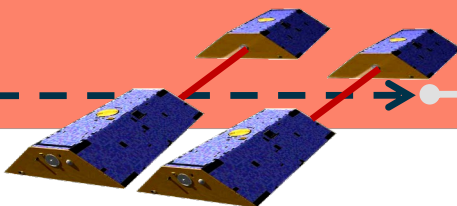


GRACE-FO

**MAGIC**



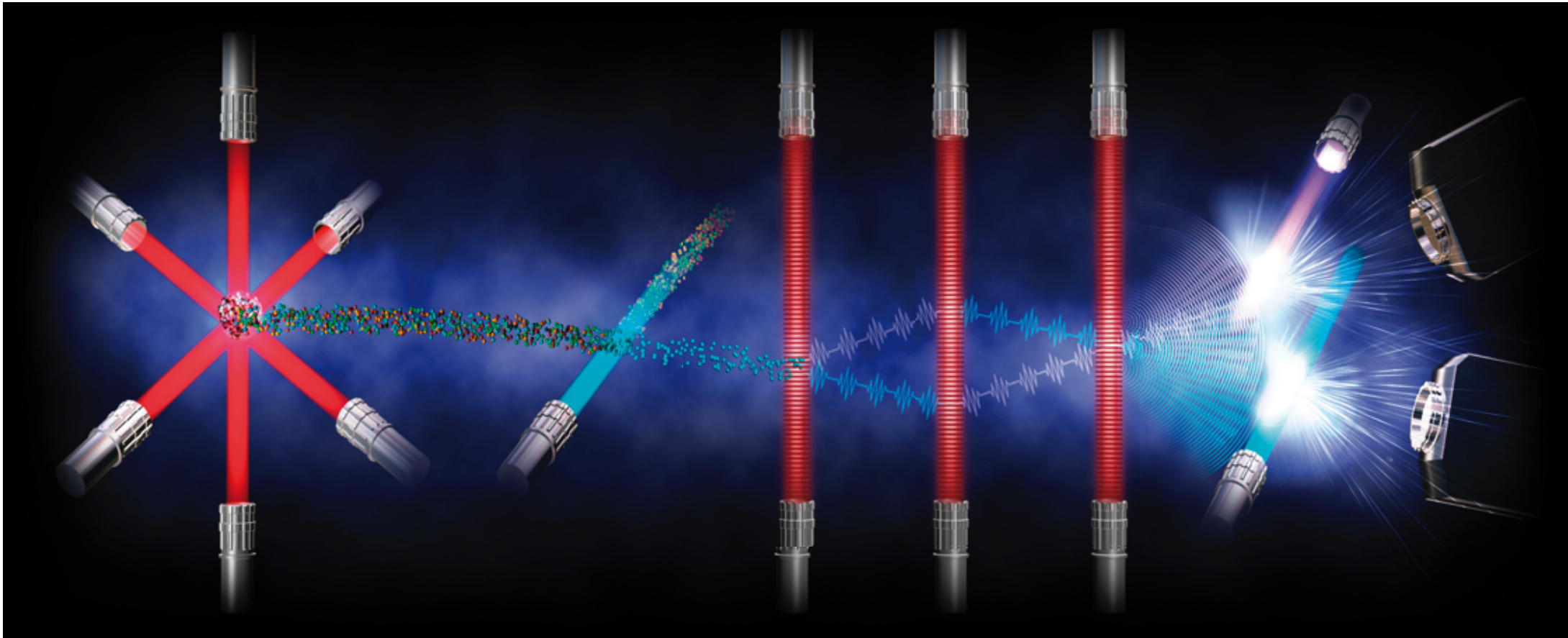
~ 2028



*Start of sustained observations at higher spatial and temporal resolutions*

**new technology (e.g. CAI) can augment existing technology and measurement concepts**

# Principle of a CAI inertial sensor



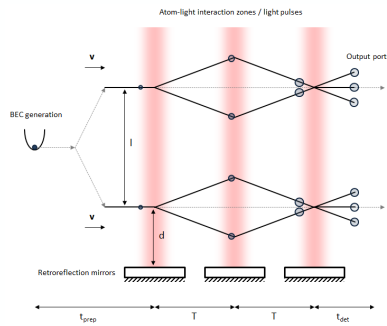
Credit: LP2N



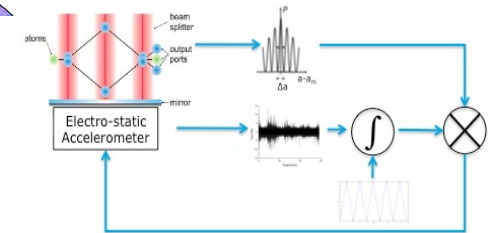
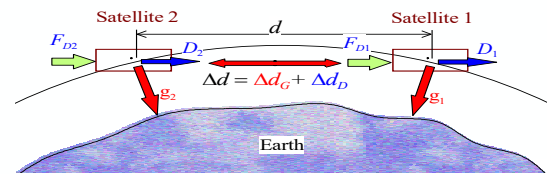
# Space Quantum Gravimetry

- Absolute measurements based on fundamental quantum physics
- No drifts, no mechanisms
- In space: long atom interferometry time, but cannot be tested on ground → need in-orbit experiment

## 1. Cold Atom Interferometer (CAI) interleaved quantum gravity gradiometer (QGG)



## 2. Hybridization classical accelerometers/CAI for SST



GOCE mission evolution goals:

- one order of magnitude lower error in gradients
- no drag compensation necessary

- improve “classical” space accelerometers at low frequencies (no drifts in principle)
- raise ‘hybrid accelerometer’ performance to match that of laser interferometer for much better gravimetry data
- Can be implemented as add-on to existing accelerometer

# From classical to quantum gravimetry

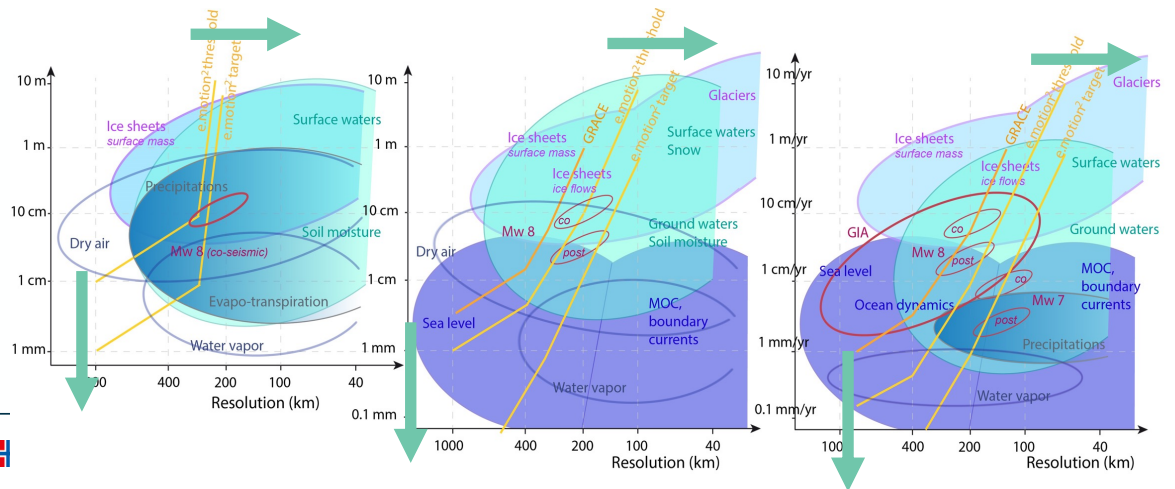
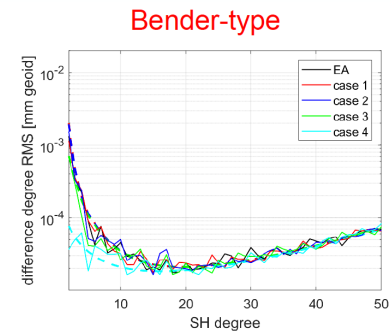
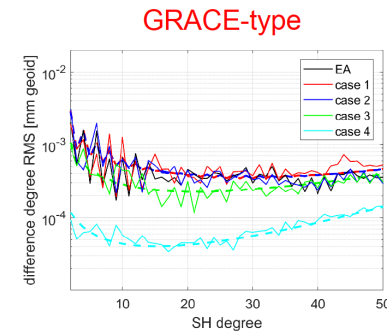
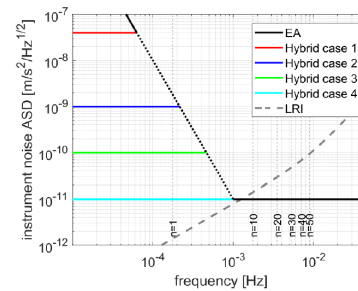
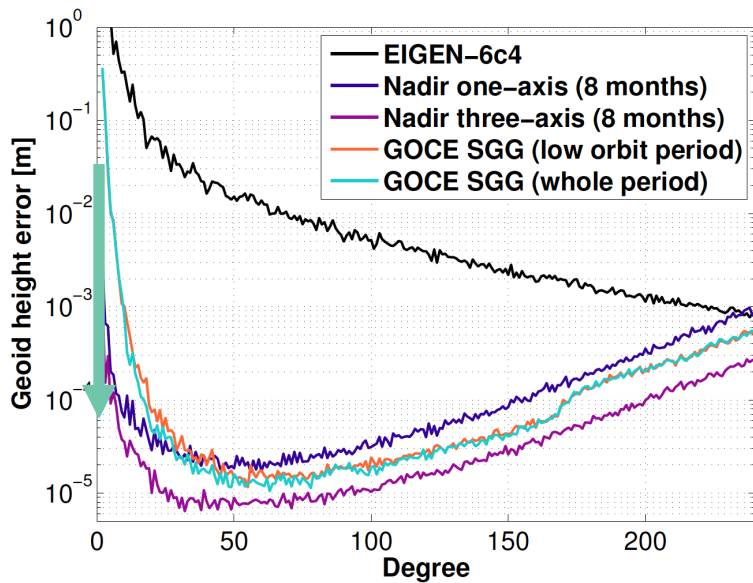


## 1. Cold Atom Interferometer (CAI) interleaved quantum gravity gradiometer (QGG)

- Static field already improved in 8 months mission (Lifetime for GOCE: 3 years)
- Time variable: Needs 1-2 orders magnitude improvement (Sensitivity enhancement, multiple S/C)

## 2. Hybridization classical accelerometers/CAI for SST

- Drag compensation relaxation
- Low degree improvement (also in Bender configuration)

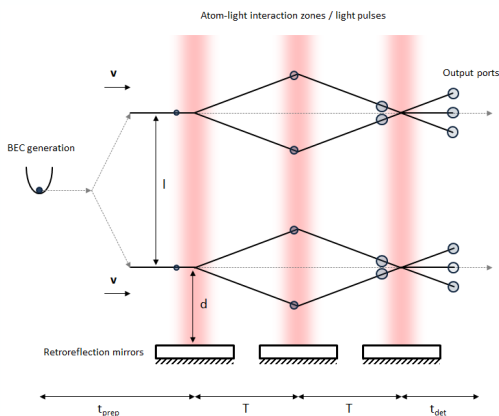


# Cold Atom Interferometer Activities for EO

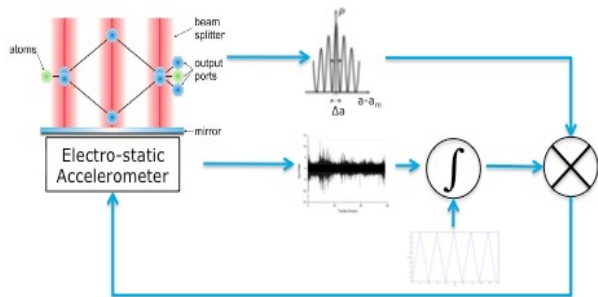


## Concepts for Earth Geodesy

### 1. CAI interleaved gravity gradiometer

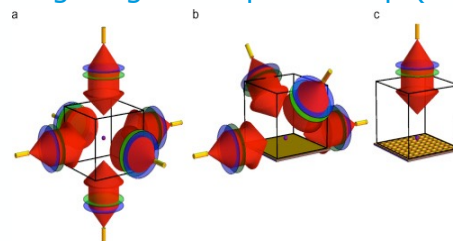


### 2. Hybridization classical accelerometers/CAI

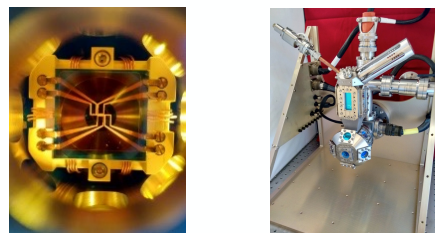


## Hardware developments

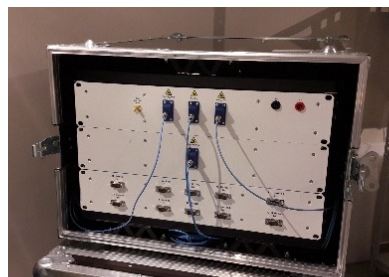
### 1. Grating Magneto Optical Trap (MOT)



### 2. Compact Vacuum Chamber for BEC

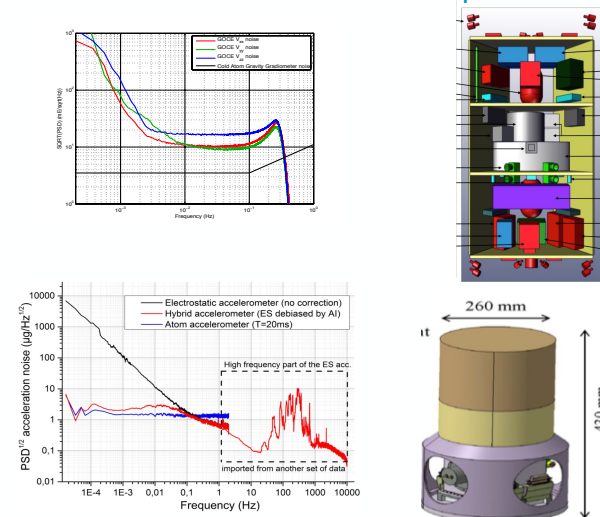


### 3. Agile and compact laser system for CAI

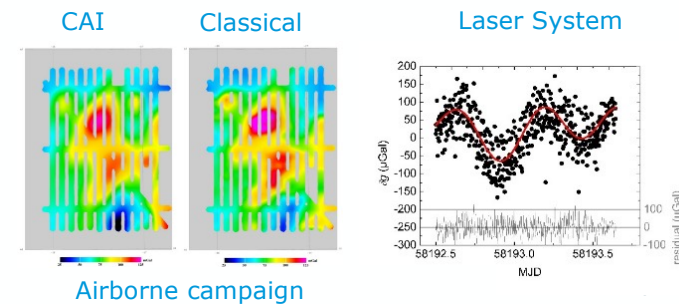


## Results

### 1. Mission and instrument concepts validated



### 2. On-ground validation

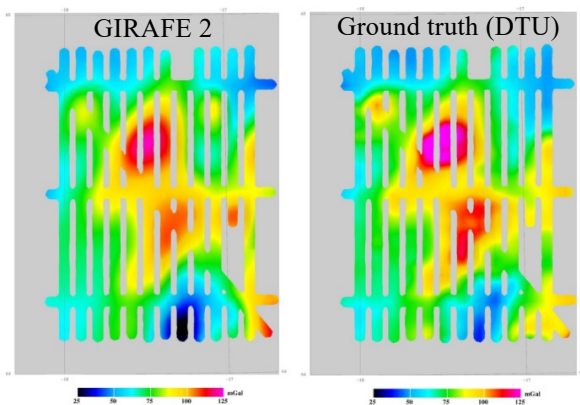
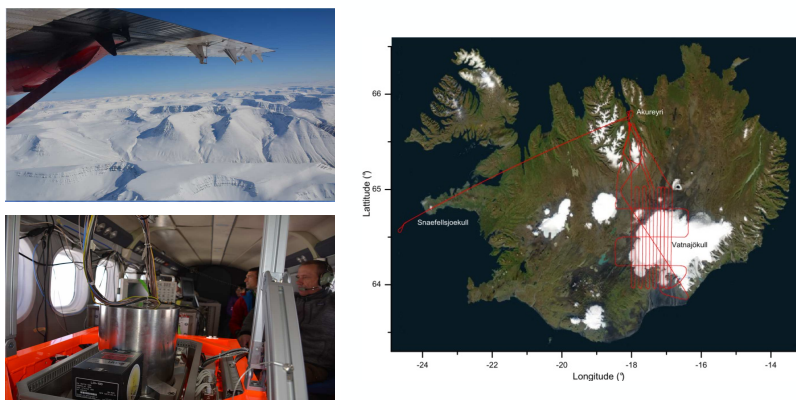


→ THE EUROPEAN SPACE AGENCY

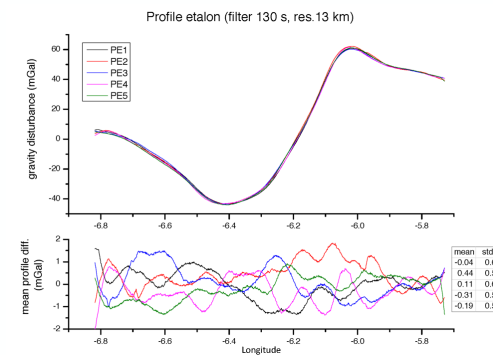
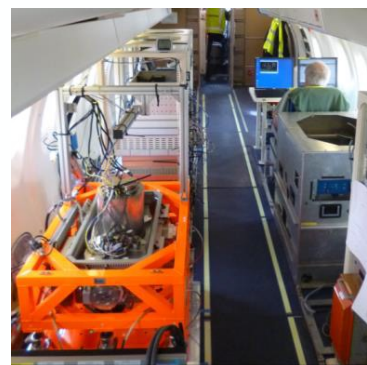
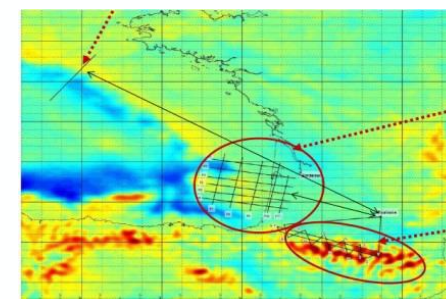


# EOP Campaigns

1. CryoVex/KAREN 2017 Campaign:  
First successful airborne survey of a matter wave gravimeter



2. Airgravi Campaign:  
Reaching state of the art of standard campaign



# Quantum Space Gravimetry Mission



- CARIOQA PMP selected for COM Horizon Call 2021 (European Commission Call):
  - First quantum accelerometry measurement in space
  - EM instrument development started in December 2022
  
- MAGIC/NGGM opportunity:
  - Science oriented (Gravimetry Data). Accommodation of CAI instrument is under assessment for Pair 3 or later (e.g. > 2032)
  
- Quantum Space Gravimetry for Earth Mass Transport (QSG4EMT): Dedicated science study to explore the feasibility of COM-ESA QSG user requirements with candidate mission architectures (e.g. constellation of SST and/or Gravity gradiometer instruments).



# Quantum Space Gravimetry for Earth Mass Transport (QSG4EMT)



<https://www.asg.ed.tum.de/iapg/qsg4emt/>

Startseite	
Kontakt	
Mitarbeiter	+
Lehre	+
Publikationen	+
Forschung	+
ESA Baltic+ Project - Theme 5	+
ESA Project MAGIC/Science	+
<b>ESA Project QSG4EMT</b>	-
Team	
Publications and Presentations	
Documents	
Data	
Internal Area	
Contact	
DFG Research Unit NEROGRAV	+
DFG Research Training Group UPLIFT	+

Startseite > ESA Project QSG4EMT



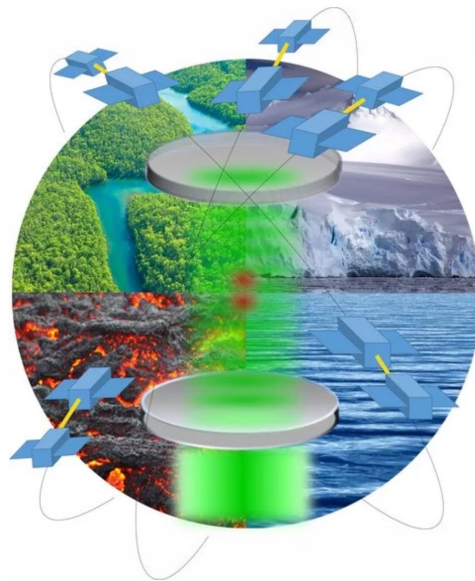
## Quantum Space Gravimetry for monitoring Earth's Mass Transport Processes (QSG4EMT)

Gravity field observations are a unique measurement technique to observe and monitor mass and mass transport in the Earth's system. Sustained gravity field observation from space contributes significantly to a number of Essential Climate Variables (ECVs) as defined by GCOS, and directly measures changes of the newly adopted ECV "Total water storage".

Next Generation Gravity Missions are expected to enhance our knowledge of mass transport processes in the Earth system, establishing their products applicable to new scientific fields and serving societal needs.

Compared to the current situation (GRACE Follow-On), a significant step forward to increase spatial and temporal resolution can be achieved by new mission concepts such as the joint NASA/ESA mission concept Mass change And Geosciences International Constellation (MAGIC).

As core component of ESA's Accelerator "Space for a Green Future", a quantum gravity mission constellation has the high potential to further to acquire unprecedented data on key Earth processes, to enhance climate monitoring, and to cope with impacts on water cycle (groundwater changes, droughts, floods, extreme weather events) and sea level rise.



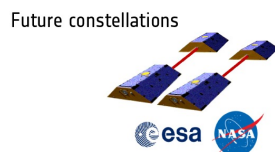
EGU23-14264 **ECS Highlight**

**Future satellite gravity field missions - Impact of quantum sensors and extended satellite constellations**

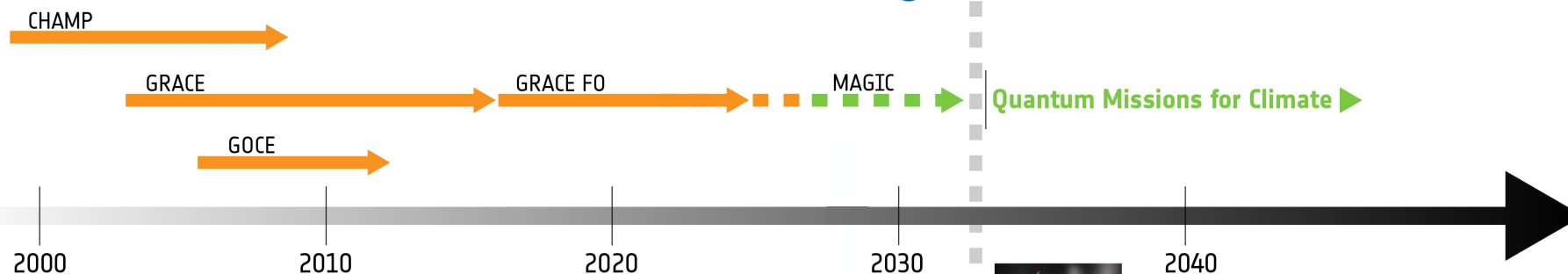
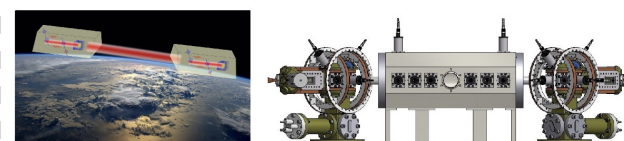
- Sensitivity analysis of scientific instrument performance
- Added value of QSG for current and planned mission concepts
- Mission architectures LL-SST with 3D hybrid accelerometer
- Mission architectures for quantum/hybrid gradiometry
- User requirements for QSG missions



## Conventional Technologies



## Quantum Technological Breakthrough



Quantum Pathfinder Mission



**Space Exploration - Mission to Icy Moon**

Autonomous guidance, gravity mapping of planets, comets for mining, cryogenic sample return, deep-space quantum communication,...]

**Fundamental Physics Missions**

[e.g. STE-QUEST, QPPF, iSOC,...]

**Gravitational Wave Observatory**

[e.g. SAGE, AEDGE,...]



# ESA Space Gravimetry at CMIN22



- **Magic/NGGM**

- Resolution at CMIN 22 (ESA/C-M/CCCXIII/Res. 4) NOTES that FutureEO-1 Segment 2 will inter alia include (...) the start of the development of the NGGM/MAGIC mission in cooperation with NASA;
- To be well noted: without a constellation approach, the reason to pursue better instrumentation is extremely weak, as the first challenge is to overcome geophysical signal sampling issues of GRACE (FO)

- **Quantum Missions for Climate:**

- FutureEO to include resources to prepare more quantum-based accelerometer/IMU Technologies
- Development of the baseline concept for BEC-based 3D hybrid accelerometer to advance on QSG definition
- After CM22, initial development of QSG Instrument sub-units.



# Conclusion on QSG



Absolute measurement with no drifts → enhance gravity gradiometry and sat-to-sat tracking techniques

- In particular using Cold Atom Interferometry (CAI) – sensitivity increased under nano-gravity by the ability of Long interrogation times
- shared objective (improved performance) with MAGIC/NGGM

EC and ESA has developed a roadmap for a European QSG Pathfinder mission for the next decade

Workshop on User Requirements for SQG – in Nov-2021 at ESTEC

- Led to requirements for the QSG4EMT activity

Planned future activities (2023-2025):

- CAI accelerometers on Bose-Einstein Condensates (BEC)
- Critical element of Laser package
- Airborne campaign

