ESA Activities and Perspectives on Quantum Space Gravimetry

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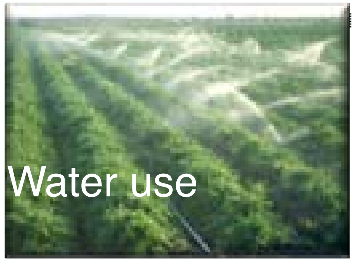
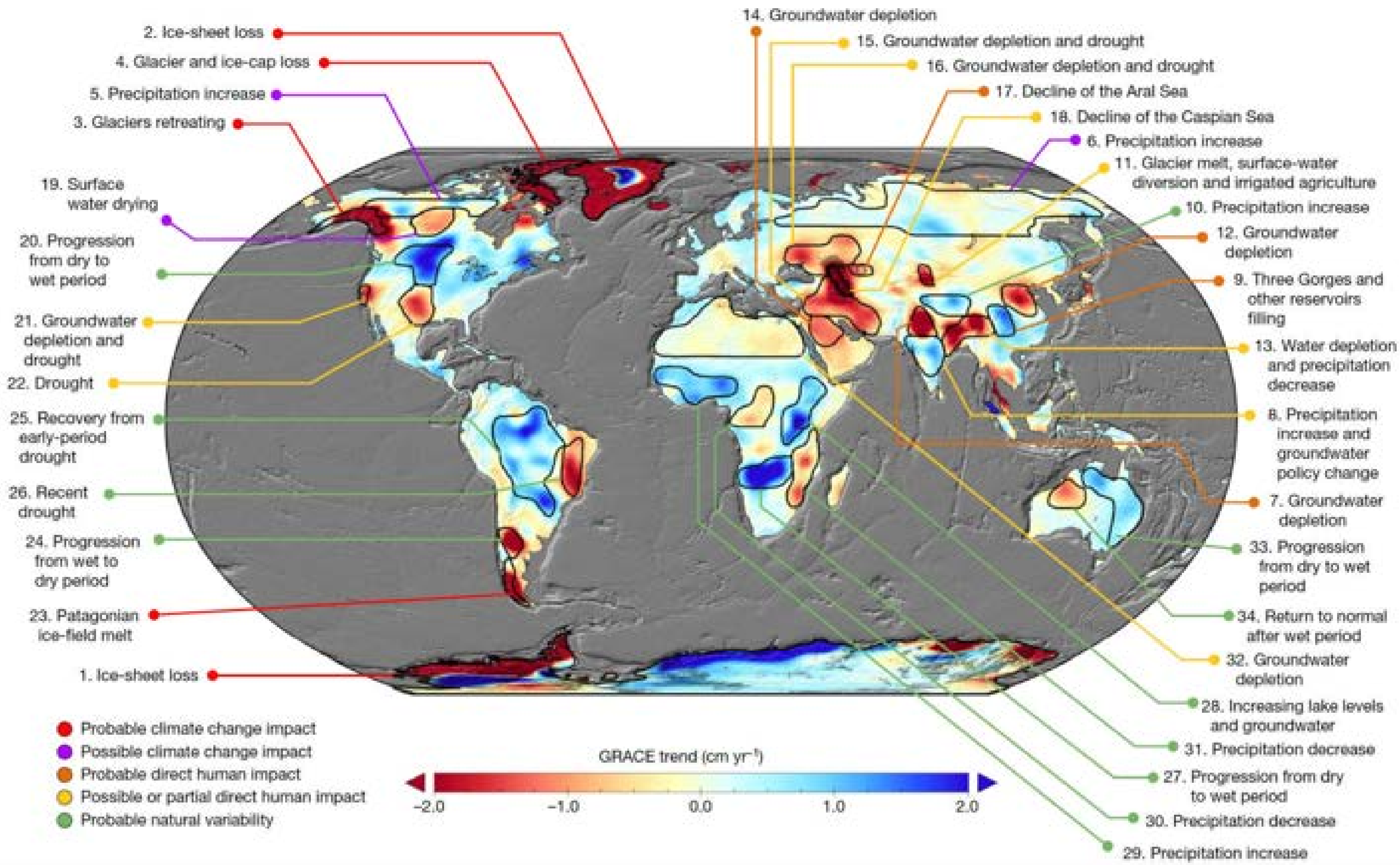
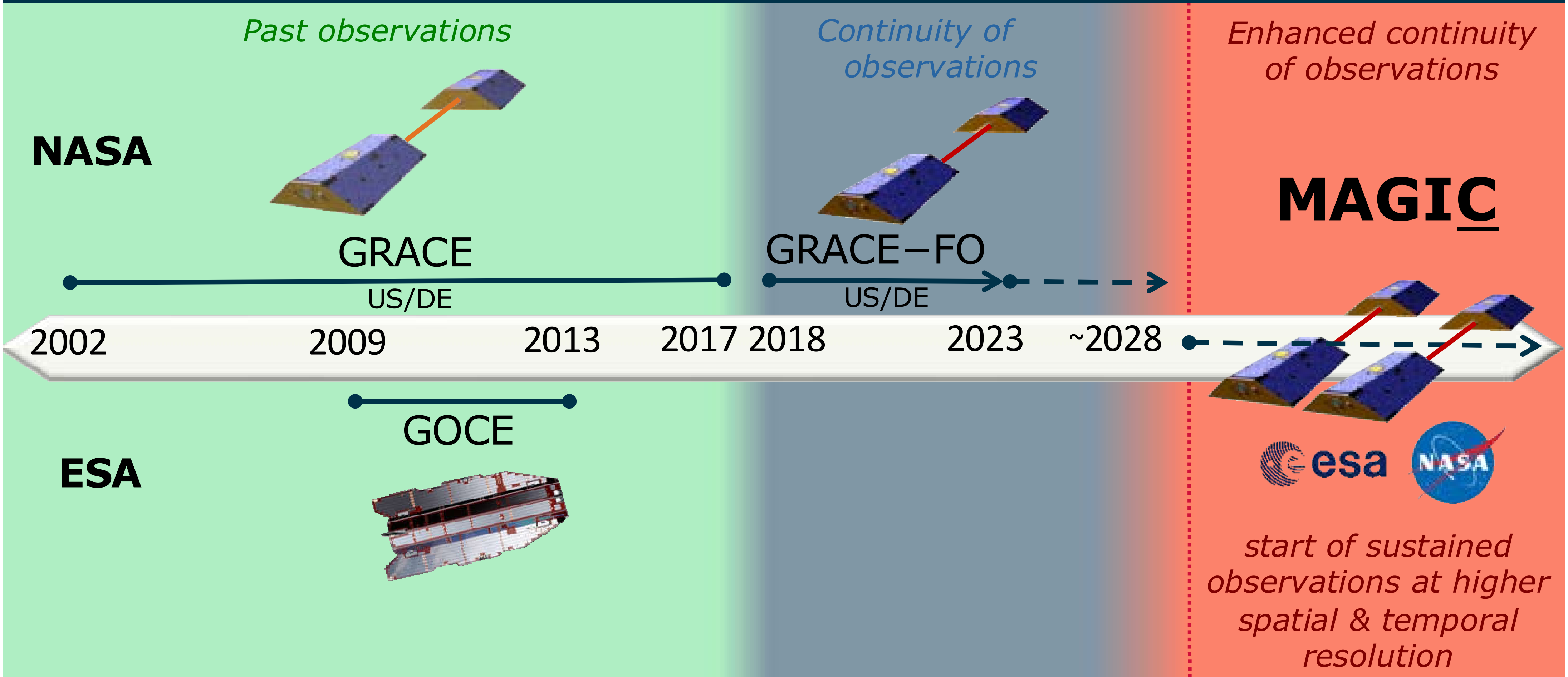
Mass change from gravity





Rodell et al. (2018) ***Emerging trends in global freshwater availability*****.** Nature, 557:651–659

Background: ESA & NASA cooperation - Joint Mission



Clear way ahead for measurement priorities

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Satellite Gravimetry: A Review of Its Realization

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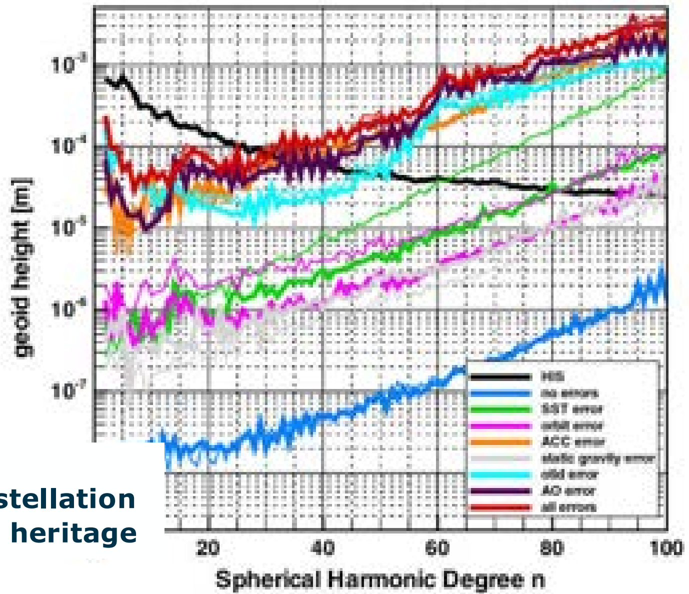


Fig. 10 Degree amplitudes in terms of geoid height error for May 2021 for different individual instrument and model errors (see legend). The *thin* and *bold lines* show the results obtained with MWI and LRI, respectively. The *blue curve* shows the numerical accuracy of the full-scale simulations (no errors applied) which is about 3 orders of magnitude below the current GRACE-FO error level. The *black line* depicts the monthly mean HIS signal

Data quality limited by:
- **under-sampling ➔ constellation**
- **accelerometer ➔ GOCE heritage**

3 Future Planning

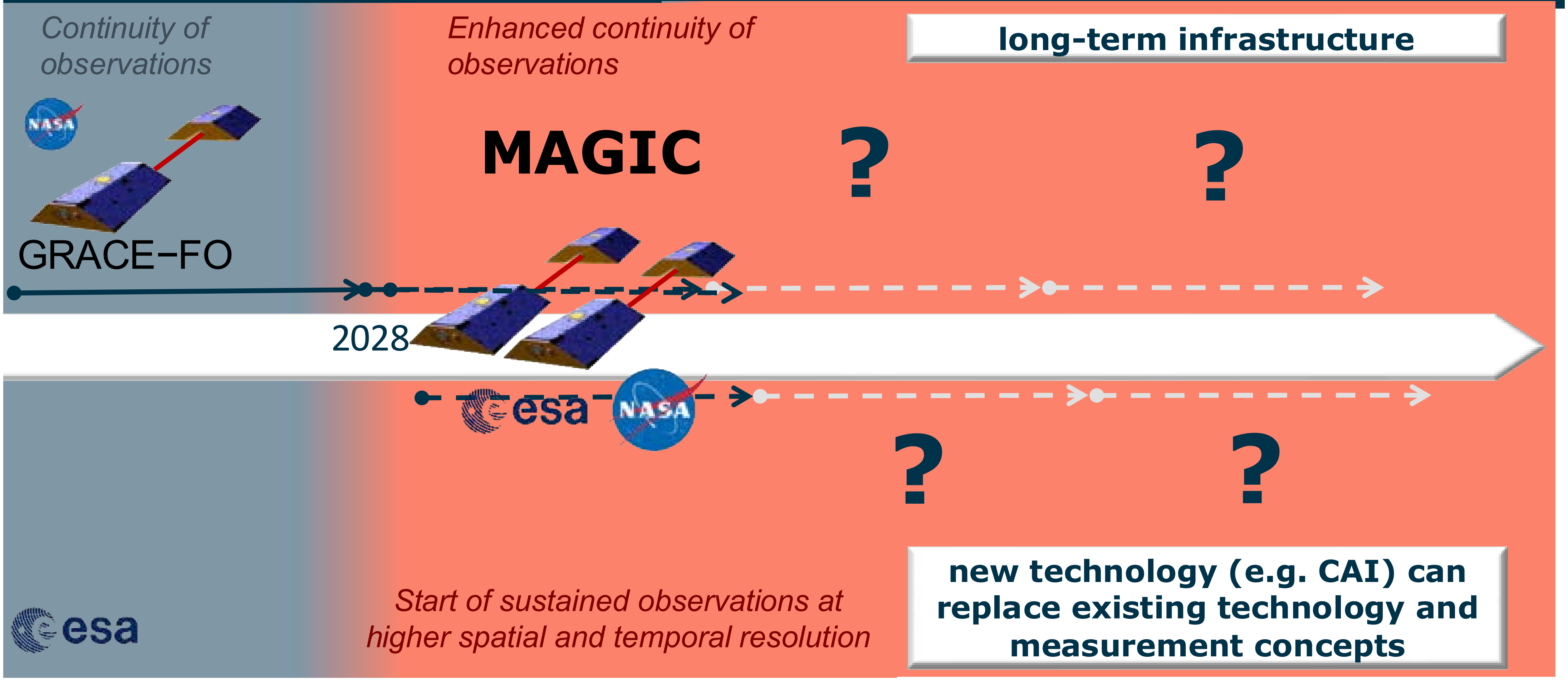
A disadvantage of the current GRACE concept is that only one satellite pair is flown in a nearly polar orbit with an 89° inclination. Thus, GRACE and now GRACE-FO observe the variations of the gravity field signal essentially only in flight direction on orbits from the North to the South Pole. This non-uniform mapping of the Earth's gravity field (anisotropy) results in stripes in the derived gravity field maps. These disturbances can be corrected by post-processing, but at the same time additional errors are generated and the signal is attenuated. Therefore, the GRACE concept makes it difficult to significantly improve the spatial and temporal resolution despite the successful operation of the LRI on GRACE-FO (Flechtner et al. 2016).

A significant improvement will only be possible by so-called Next Generation Gravity Missions (NGGM). The current NASA Earth Science Decadal Survey Report (National Academies of Sciences 2018) has listed mass transport observations as one of the five main priorities of Earth observation for the next decade. To this end, studies are currently being carried out at NASA, but also at ESA, CNES and DLR/GFZ, to determine which mission concept would best improve the spatial and temporal resolution of gravity field maps but also to secure continuity of data. In order to overcome the anisotropy, it is proposed, for example, to launch a second pair of satellites in addition to the one flying over the polar regions with an inclination of only about 70°. Both pairs of satellites could be equipped with a LRI successfully tested on GRACE-FO. This so-called Bender constellation (after Peter Bender, who first investigated this constellation (Bender et al. 2008)) has been investigated in various simulation studies (e.g. Bender et. al. 2008; Wiese et al. 2009, 2011; Elsaka et al. 2014). It could be shown that the combination of the measurement data of these two satellite pairs using a much lower orbit of about 320 km could improve the accuracy of the gravity field models by a factor of 10 and at the same time increase the spatial resolution from 400 to 150 km. Of particular importance in this context is the improved observation of the non-gravitational perturbation accelerations acting on the satellite, which are not caused by the gravity field but mainly by the air drag-drag and the radiation pressure of the Sun. For GRACE and GRACE-FO these are directly measured with a high-precision accelerometer. However, the accuracy of this accelerometer would have to be further improved. Finally, the models for the correction of tidal and non-tidal

MAGIC baseline implementation scenario

- **Two-pair "Bender" constellation** acting as precursor of future operational system (first realisation early in next decade, to be later enhanced by a third satellite pair replacing the first one)
- **First satellite pair (P1)** implemented via a DE-USA fast-paced cooperation programme with some potential ESA in-kind contributions, maximising synergy with GRACE-FO to ensure continuity of observations
- **Second satellite pair (P2)** implemented via a Europe-USA cooperation programme with some potential NASA in-kind contributions with target launch date such as to maintain 4 years of combined operations
- **Potential demonstration of technologies** to be implemented in subsequent pairs to reach full operational performance
- Gravity data retrieved from: inter-satellite ranging + non-gravitational acceleration measurements
- Inter-satellite ranging improvement by >100 with the laser interferometer tested in GRACE-FO
- However, to achieve pre-operational performance, likewise improvement is needed for accelerations ➔ improved MicroSTAR accelerometer based on GOCE / Microscope technologies
- Roadmap for technologies including also quantum (cold atom interferometry) sensing in the longer term

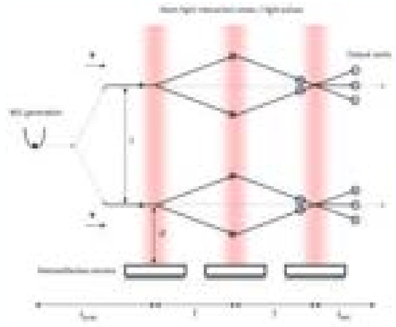
Opportunities for Quantum Gravimetry: long-term



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)

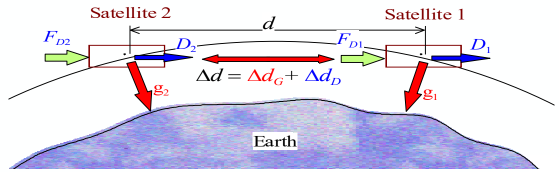


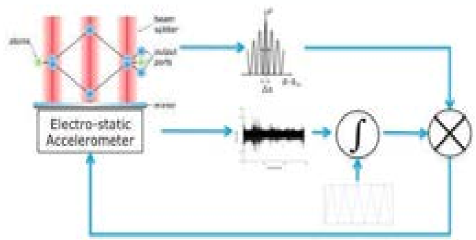
GOCE mission evolution goals:

- one order of magnitude lower error in gradients

- no drag compensation necessary

2. Hybridization classical accelerometers/CAI for SST



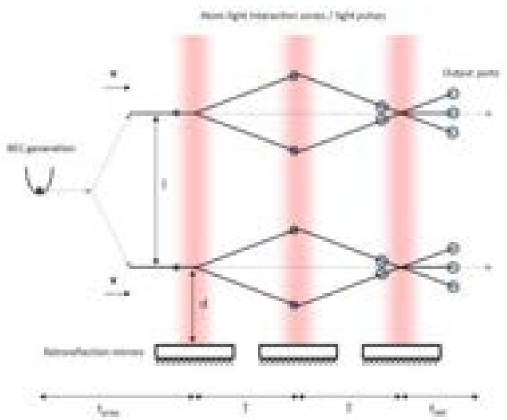


- improve "classical" space accelerometers at low frequencies (no drifts in principle)
- raise 'hybrid accelerometer' performance to match that of laser interferometer for much better gravimetry data
- Can be implemented as add-on to existing accelerometer

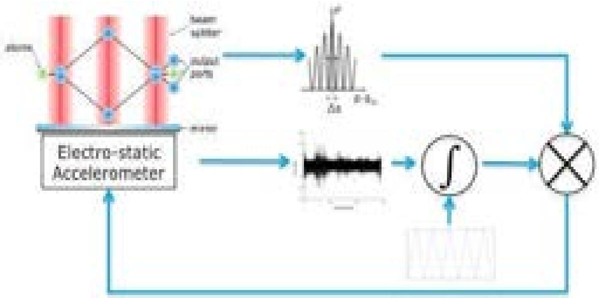
Cold Atom Interferometer Activities for EO

Concepts for Earth Geodesy

1. CAI interleaved gravity gradiometer

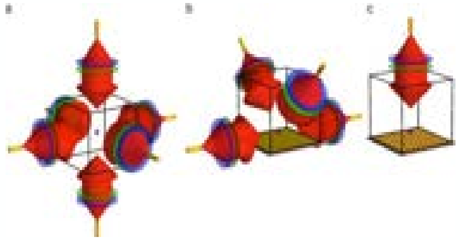


2. Hybridization classical accelerometers/CAI

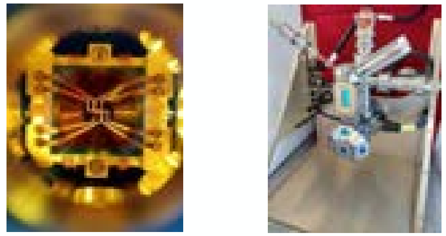


Hardware developments

1. Grating Magneto Optical Trap (MOT)



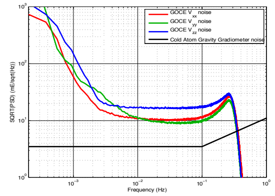
2. Compact Vacuum Chamber for BEC

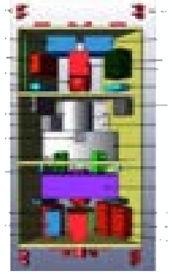


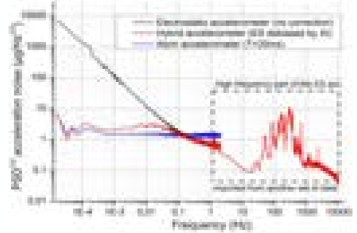
3. Agile and compact laser system for CAI

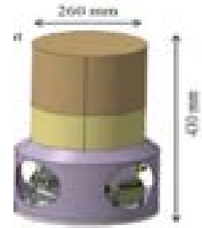
Results

1. Mission and instrument concepts validated



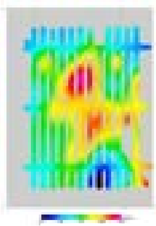






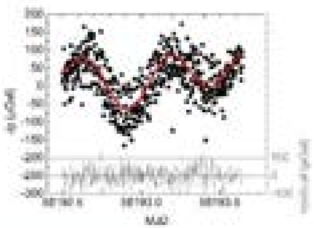
2. On-ground validation

CAI

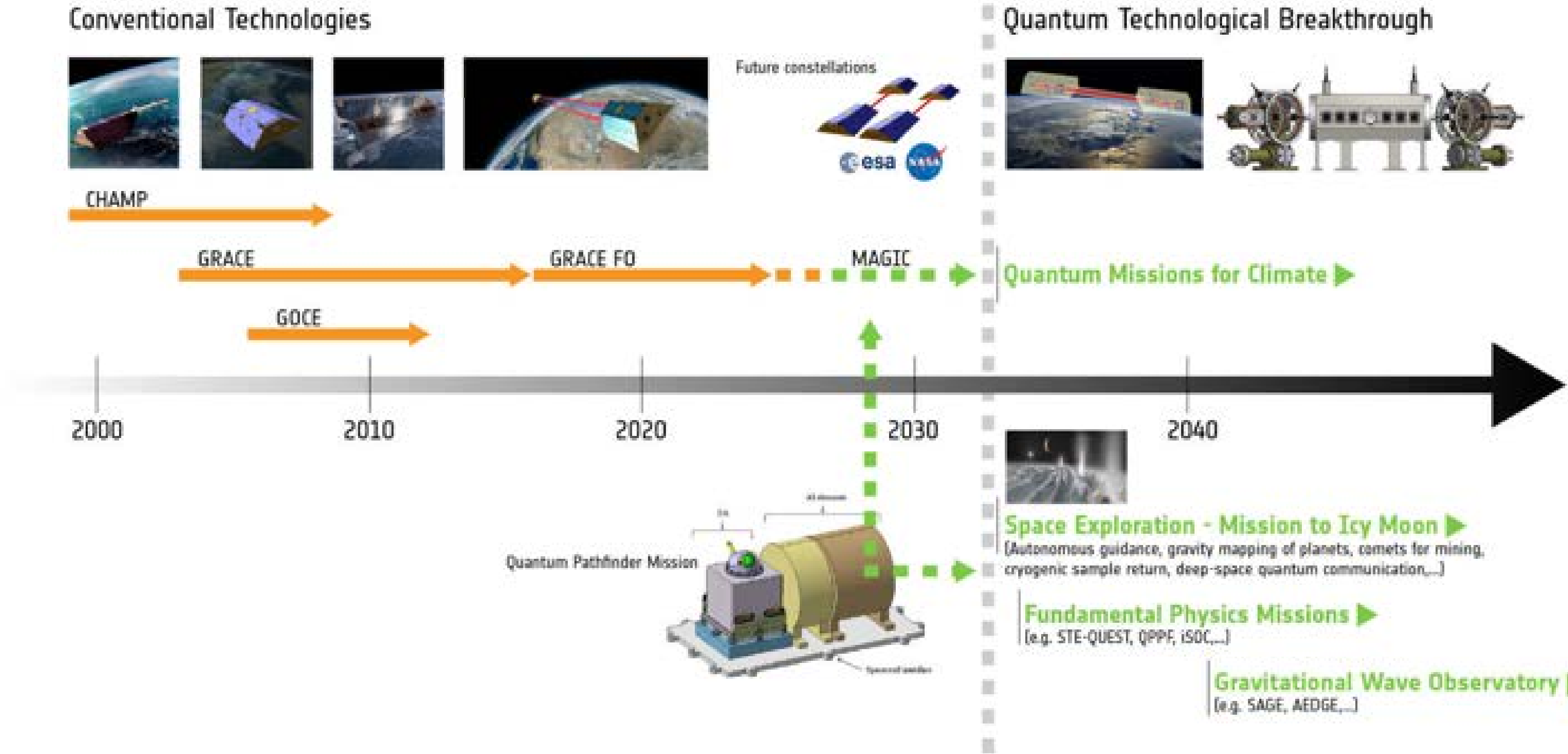


Classical

Laser System



Airborne campaign


Conventional Technologies
Quantum Technological Breakthrough
Future constellations
esa
CHAMP
GRACE
GRACE FO
MAGIC
GOCE
Quantum Missions for Climate
2000
2010
2020
2030
2040
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,...)

From Quantum Pathfinder Mission towards Quantum Space Gravimetry

- COM Horizon Call 2021 under evaluation:
    - First quantum accelerometry measurement in space
    - EM instrument development about to start in 2022
    - Next steps TBC by COM

- MAGIC/NGGM opportunity:
    - Science oriented (Gravimetry Data). Accommodation of CAI instrument (not necessarily BEC-based) is under assessment for Pair 2 or later (e.g. > 2031)

- Quantum Space Gravimetry for Earth Mass Transport (QSG4EMT): Dedicated science study to explore the feasibility of QSG user requirements with candidate mission architectures.

ESA Space Gravimetry proposals for CMIN22

- **Magic/NGGM**
  - For MAGIC/NGGM, the first Mission of Opportunity in the FutureEO programme, the framework of joint constellation with NASA (MAGIC), based on satellite-to-satellite tracking by means of Laser Interferometer instrument and MicroSTAR Accelerometer family incorporated in two pairs of satellites
  - MAGIC/NGGM is EO priority at CM22
  - 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
  - A Quantum (gravimetry) Mission for Climate is key part of the «Space for a Green Future» Accelerator
  - Development of the baseline concept for BEC-based 3D hybrid accelerometer to advance on QSG definition
  - After CM22, initial preparatory steps for the QSG development linked to the specific Accelerator **(«Space for a Green Future»)**