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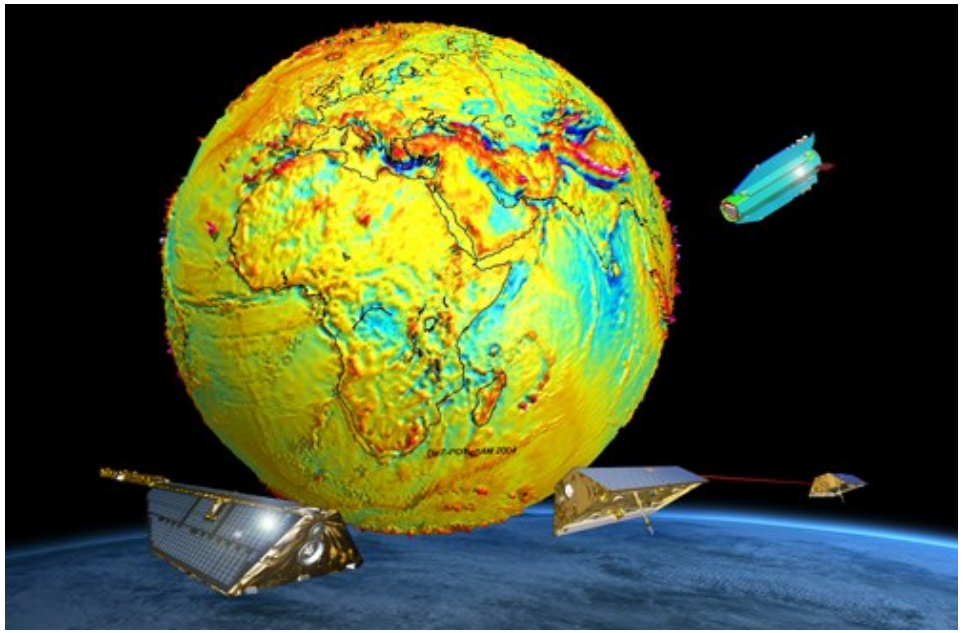
New Satellites for Gravity Field and Environmental Modelling – *Quantum Geodesy on the way*

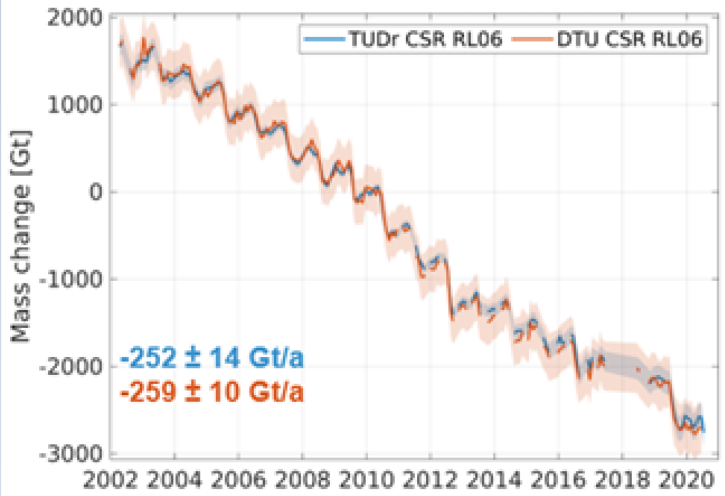
Rene Forsberg, rf@space.dtu.dk
DTU Space, Denmark



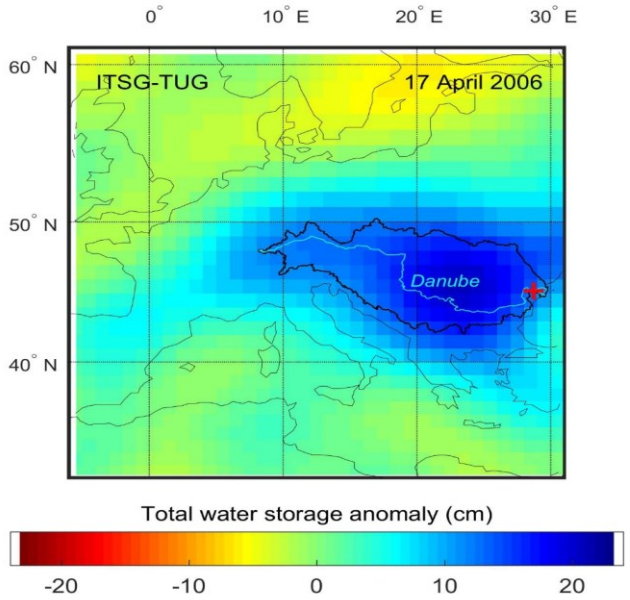
Climate change, satellites and role of geodesy

- Geodesy is everywhere – *but many scientists not aware*
- Ice sheet changes, land uplift: Geodesy important part of IPCC assessment on climate change effects
- Cryosphere ”geodetic methods” – direct measurements of changes (elevation changes from lidar, GNSS, radar altimetry, SAR interferometry, gravity – airborne and satellites
- ”Cryo” recognized as part of GGOS – Global Geodetic Observing System
- Space agencies (ESA, NASA, DLR, CNES, JAXA …) launch highly relevant satellite missions … *also for geodesy*

CryoSat-2, IceSat-2, GRACE-FO, GOCE, Sentinel-1, Sentinel-3, Topex/Poseidon, Jason .. and even ESA SMOS, SWARM relevant

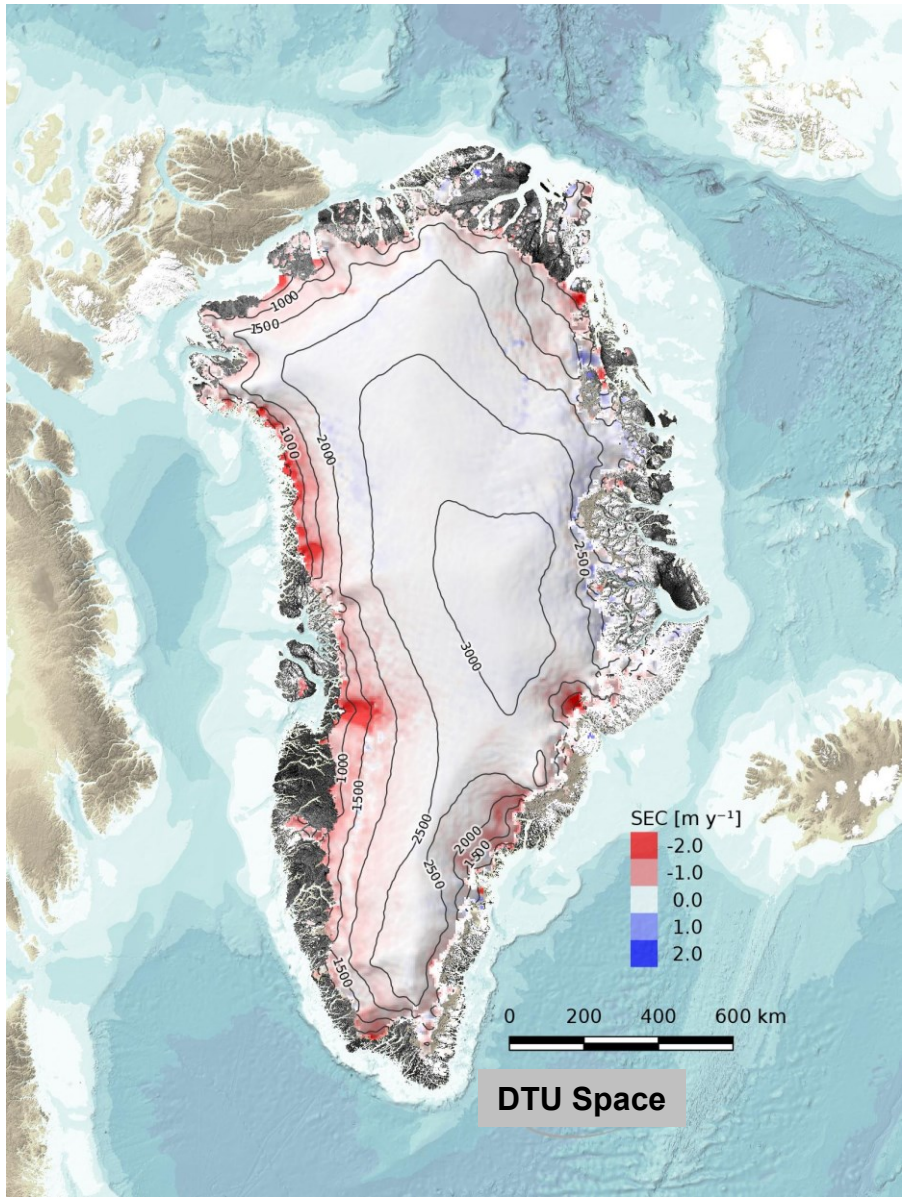


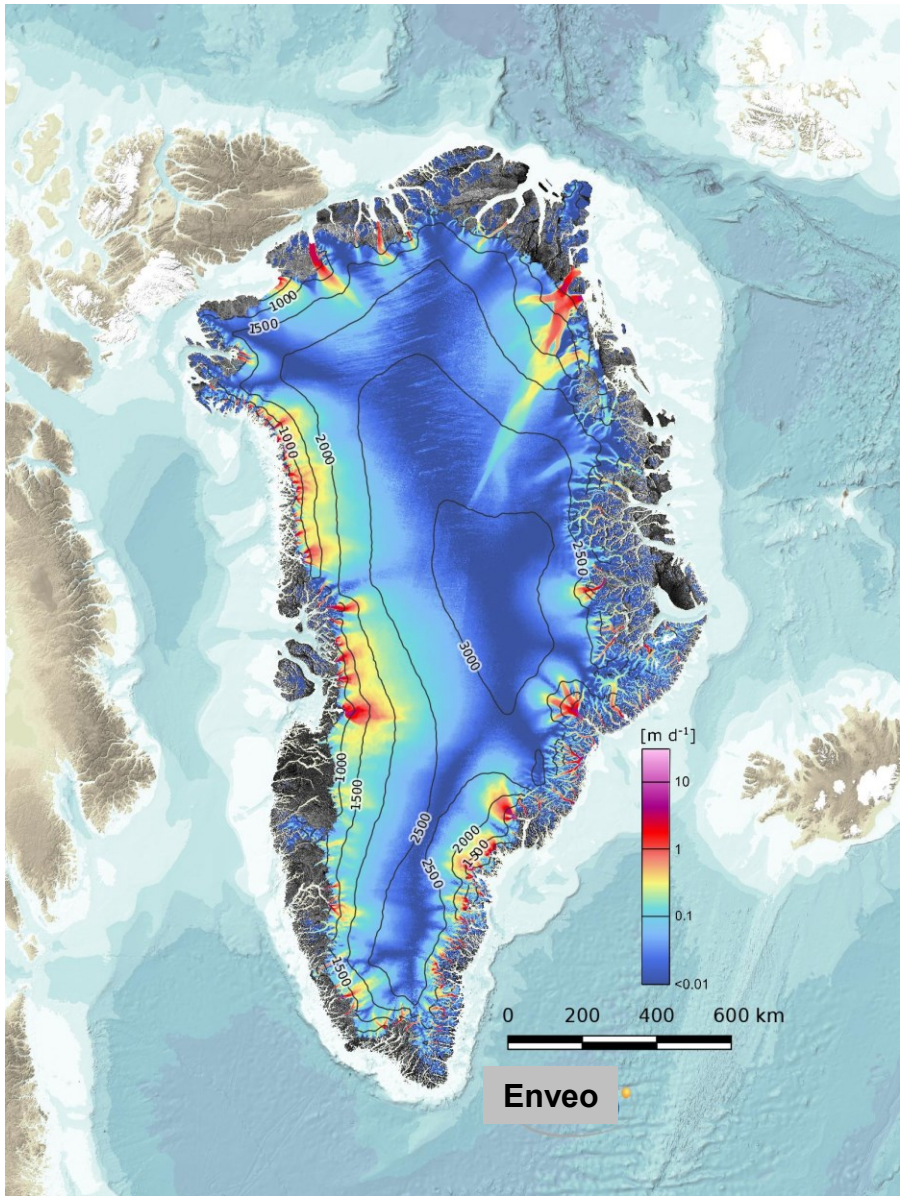
Mass change of the Greenland ice sheet (ESA CCI 2020)



Seasonally adjusted total water storage in the Danube basin, based on GRACE gravity change data (Goweleeuw et al., 2017)

CryoSat elevation changes and Sentinel-1 ice velocities – *routinely updated in ESA Ice Sheet CCI*





esa CCI

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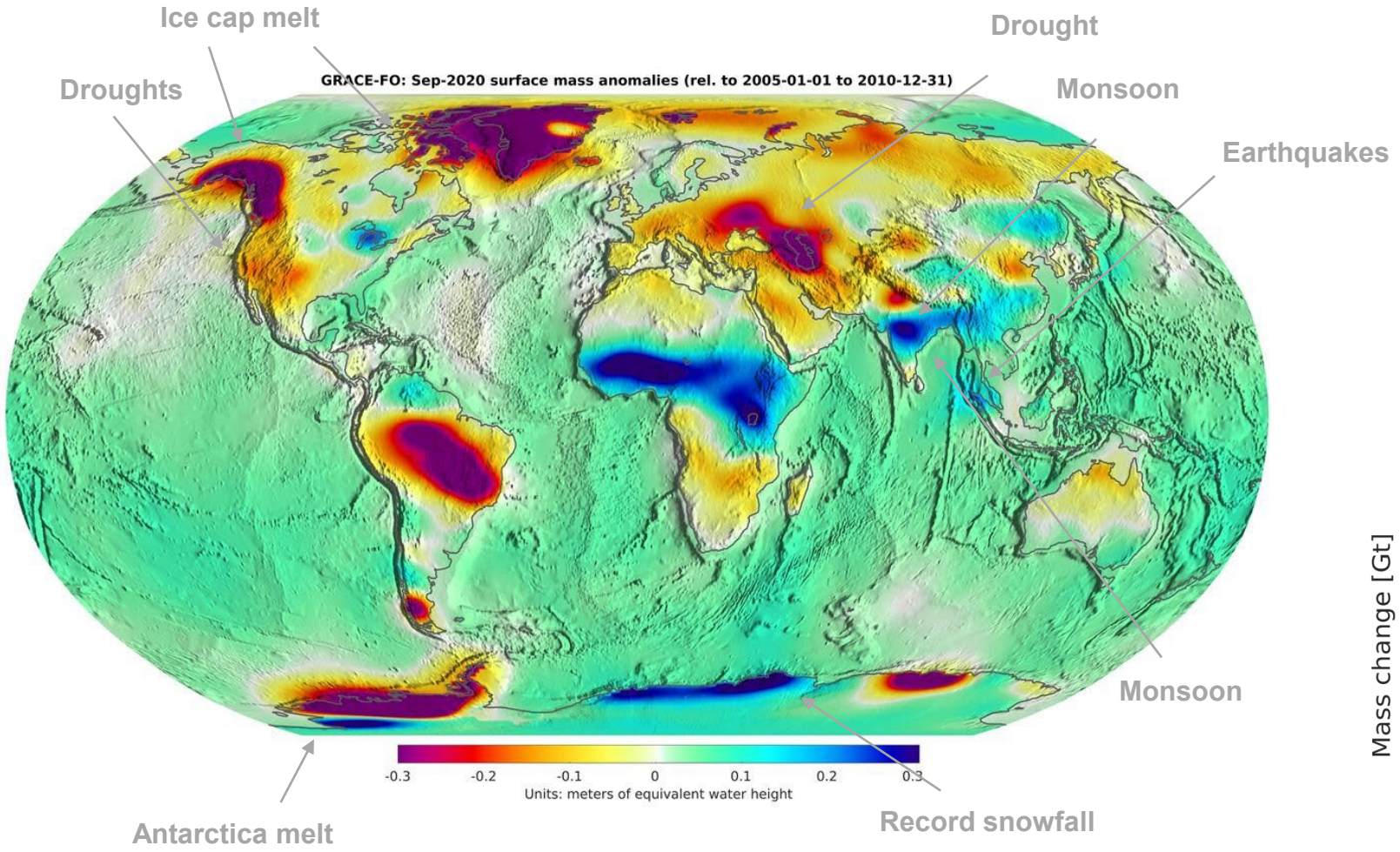
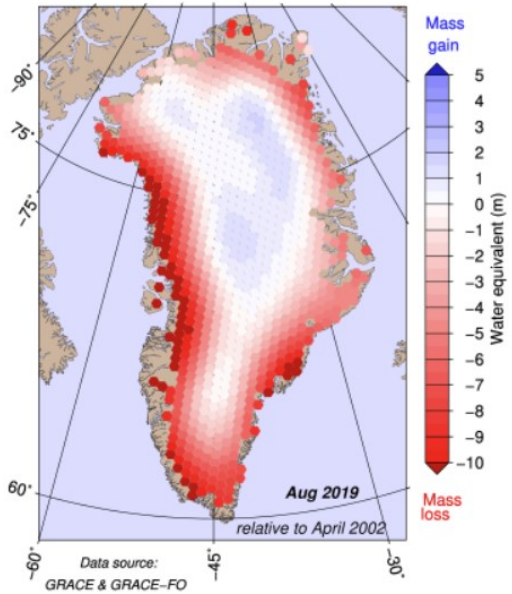
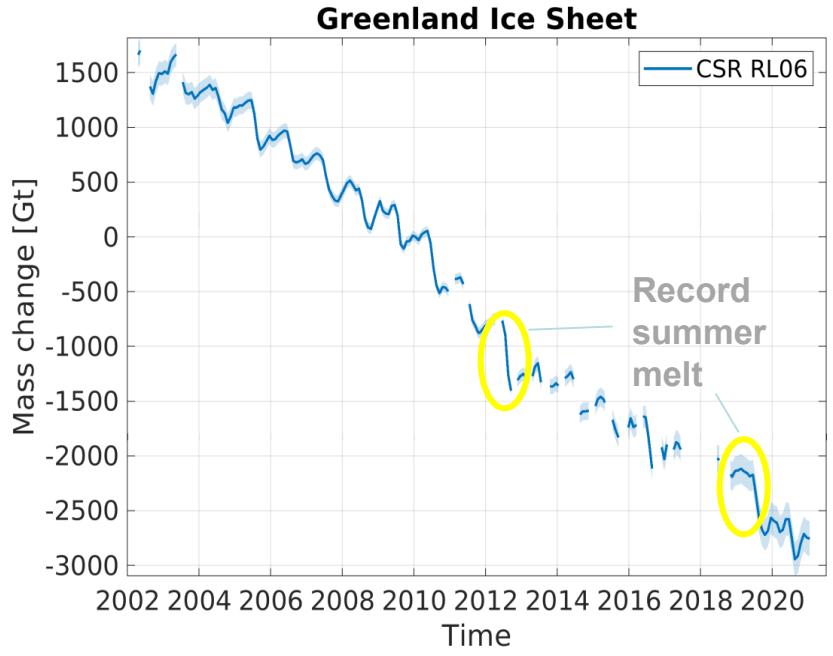
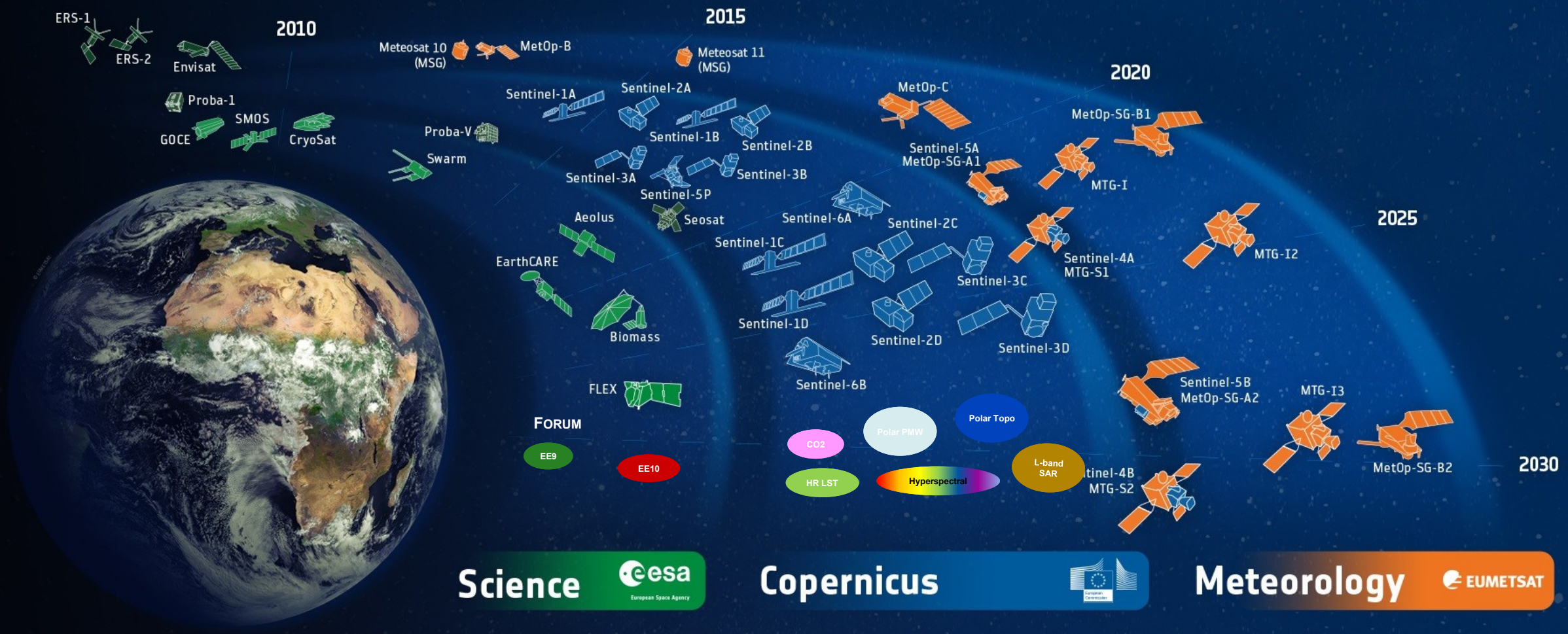
Global gravity field changes from GRACE / GRACE-FO (2002-17, 2018-)







ESA Developed Earth Observation Missions



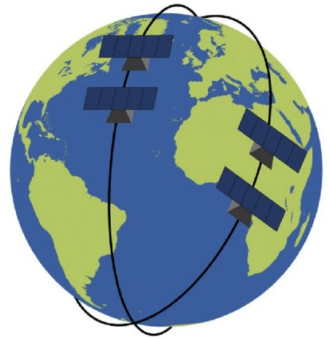
New ESA initiatives – missions of special geodetic relevance:

MAGIC / NGGM gravity mission

- Next Generation Gravity Mission – international cooperation (NASA)

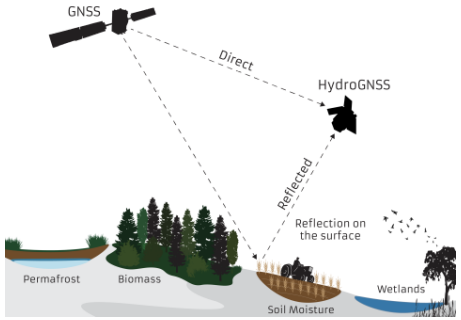
  … missing clear NASA support (NASA-DLR GRACE-I mission)

- Quantum parthfinder mission in preparation (EU-DEFIS/ESA)



Small satellitle missions:

- SCOUTS: 3-year from proposal to lauch small missions: HydroGNSS contract
- ICeye contributing mission (SAR constellation mission), GNSS reflectometry

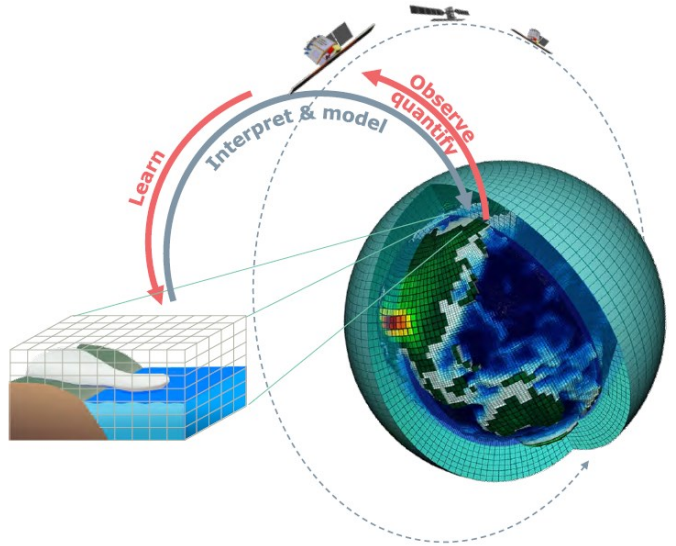


”Boost Future-EO”

- New strategy process initiated for 2024-
- Society use and relevance, Digitial Twin Earth, New Space …
- ESA-CLIMATE … new name for CCI initiative 2024-
- Feedback from Review of EOEP5/Future EO-1

HARMONY – EE10, next earth-explorer ..

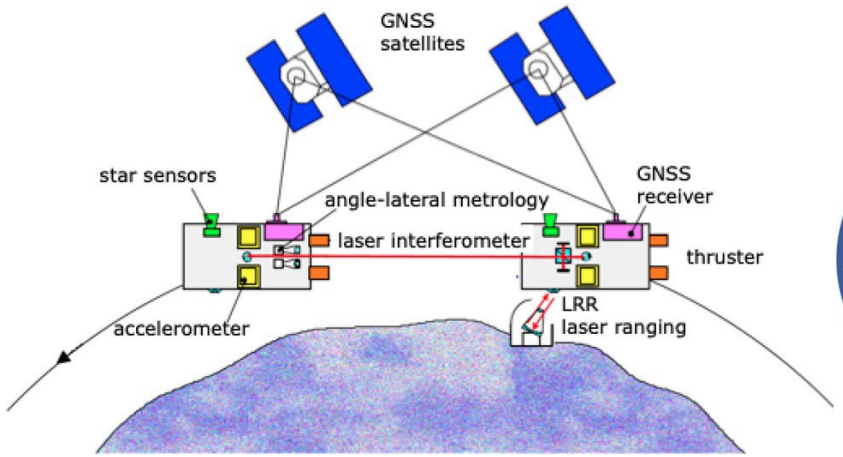
- Companion satellites to S-1: coastal oceanography, clouds, cryosphere, geodynamics, DEMs, ...

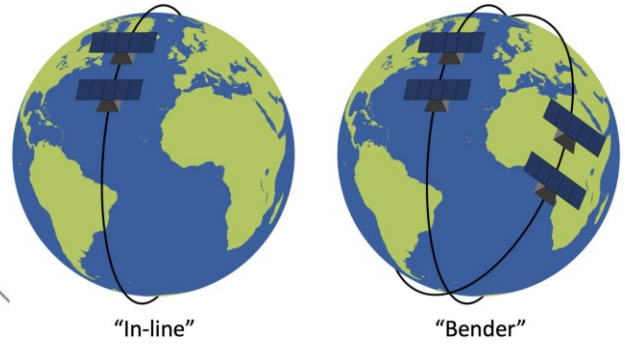


Planned gravity field missions:

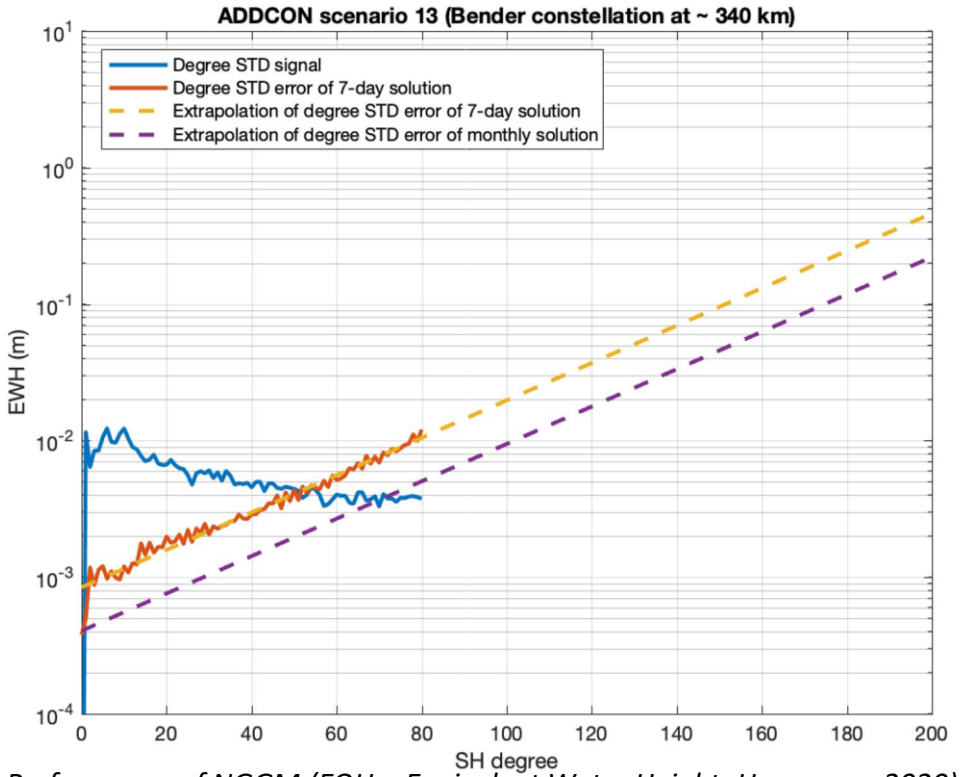
ESA NGGM / MAGIC (2029-2031) … laser interferometry

NASA/DLR GRACE-I … ”GRACE2” + *birds tracking* + *quantum?*





Measurement principle of
NGGM (Silvestrin et al., 2015)



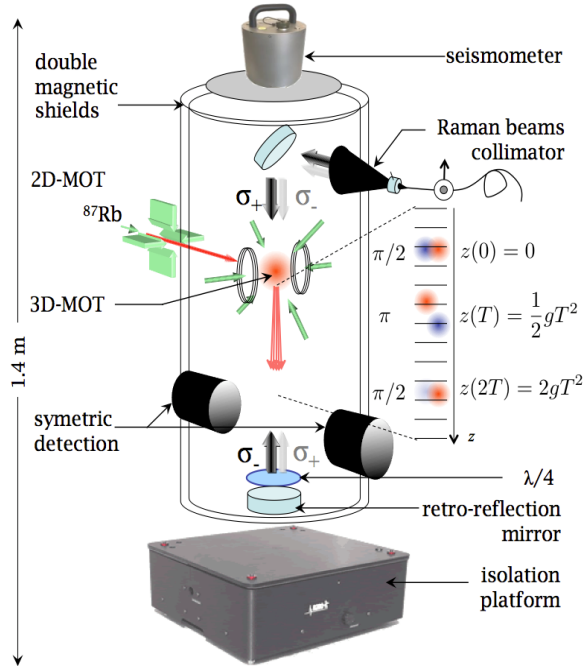
Performance of NGGM (EQH = Equivalent Water Height; Haagmans 2020)

Note: planetary missions could also be obvious targets for mature cold atom gravity missions, especially for the Moon and Mars

Limitations of space gravimetry missions – *Quantum*

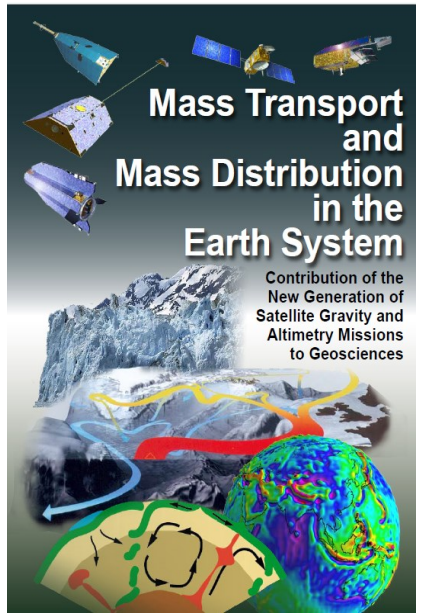
- Orbit heights … need to be low (300-350 km? lowest GOCE orbit @ 224 km)
- Orbit height limitations imply need for airborne and in-situ data. Combination solutions have long heritage in geodesy
- CAI instrumentation proven in-situ and in marine/airborne campaigns (ONERA-GIRAFE)
- Global framework for gravimetry sensors being build-up (GGOS = Global Geodetic Observing System – satellite observations integral part of this

Cold atom instruments already commercially availaible (quantum absolute gravimeter, IXBlue)



Challenges for Cold Atom Interferometry (CAI) accuracy in space:

- Accelerometer better than ~ 10^{-10} m/s^2 for CHAMP-like pathfinder mission (measurement range of ±10^{-4} m/s^2)
- Gradiometer ~ broadband accuracy better than 10^{-12} m/s^2 (GOCE-like mission)
- Constellation mission vision 2035+: frequent repeats in time and space, providing near-real time warnings … floods, earthquakes, climate events ..



EU-DEFIS quantum initiative 2020-

Sep 2020: **EU-DEFIS – Working group** / user needs / roadmap (DE, FR, IT, DK, GR scientists + ESA/ESTEC)

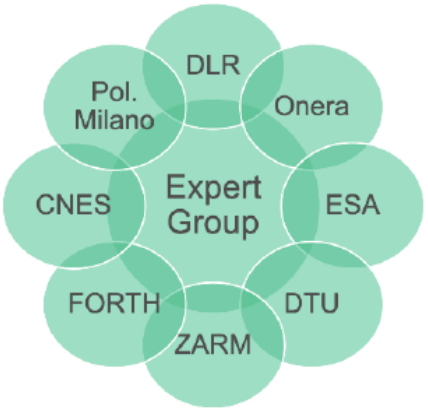
Jan 2021: **WG report** – Quantum gravimetry
- Pathfinder mission (5 år) *or*
- Full-scale mission (7 år) */ BEC*

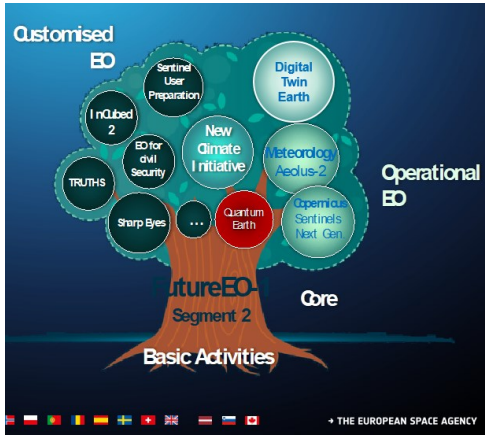
Apr 2021: **ESA "Future EO**" with quantum initiative …

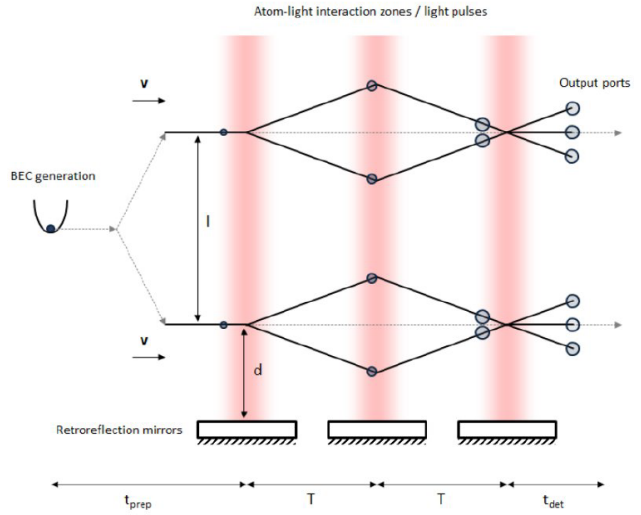
Maj 2021: Telecon – 1st **Consultation Platform**

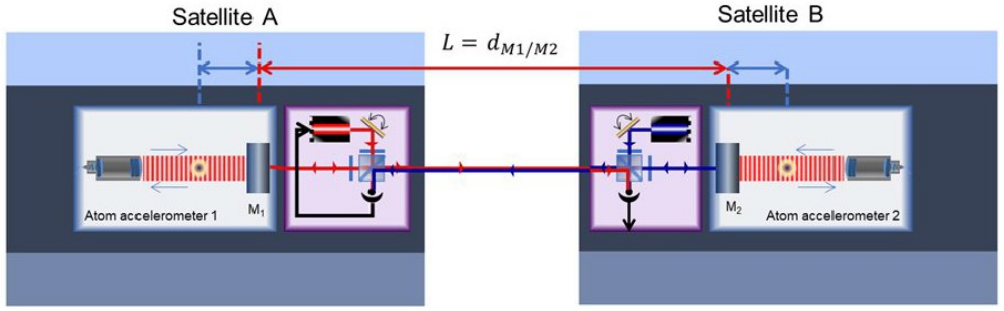
Fall 2021/Spring 2022: **EU HE Call** + **EDF project** – "Quantum gravimetry" (17 MEuro) and "Quantum Sensing"

EU motivation: "quantum supremacy"







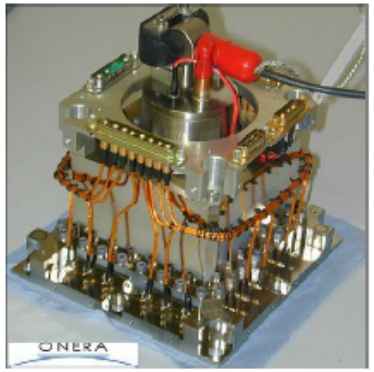


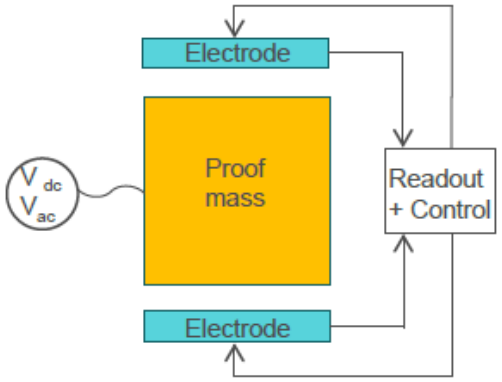
Quantum vs classical sensors

Classical accelerometer

- High maturity
- High resolution and bandwidth
- **Drift and bias**
- **Calibration = loss of continuity and measurement time**

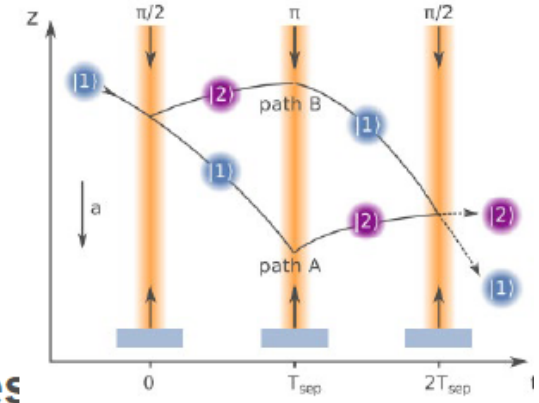
GOCE single accelero-meter head

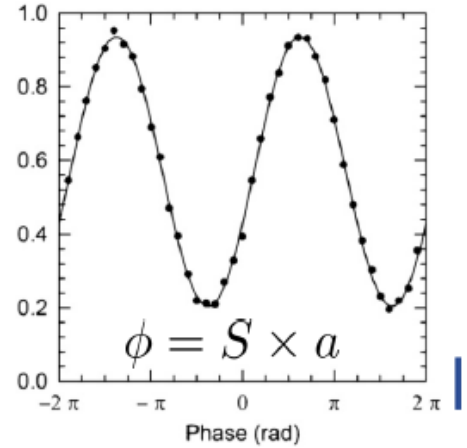




Quantum accelerometer

- High stability (no drift)
- High accuracy (no bias)
- High resolution
- Scalable dynamic range
- **Low bandwidth, dead times**
- **Phase ambiguity**

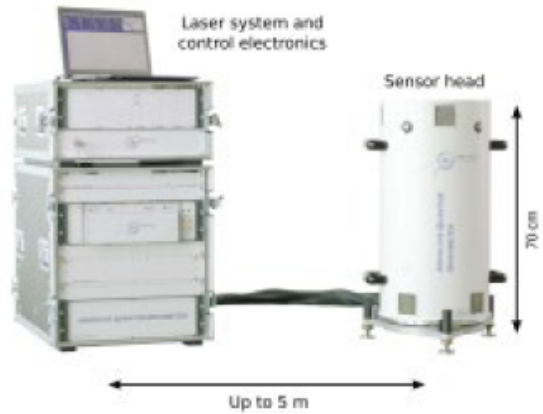




Matter wave source: cold or ultra-cold atoms ?

Cold atoms (µK) = Optical Molasses

-> laser cooling



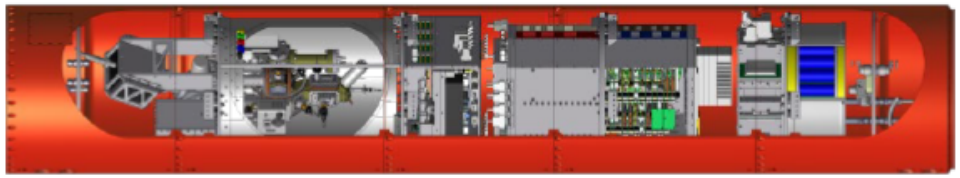
Example:
µQuans gravimeter

Interferometry with cold atoms (molasses) (100 kg, 250 W)

Ultra-cold atoms (nK, pK) = BEC

-> laser cooling + evaporative cooling + lensing

Example: *MAIUS sounding rocket (300 kg, 300 W)*
BEC production + proof of priciple interferometer



- **Ground** performance, demonstrated with **cold atoms** and **T << 1 s**: **10^{-8} m s^{-2} $Hz^{-1/2}$**
- **Space** performance, **projected** with **ultra-cold atoms** and **T > 1 s**: **$10^{-10..-12}$ m s^{-2} $Hz^{-1/2}$**
- BEC = more complex, increased SWAP, lower TRL for interferometry

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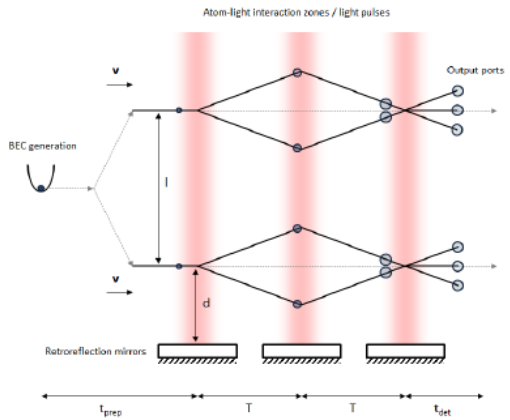
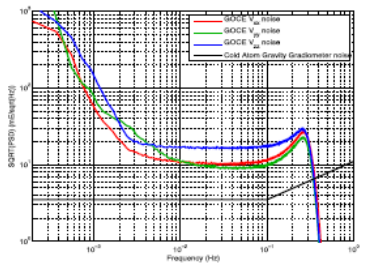
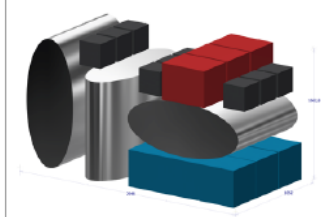
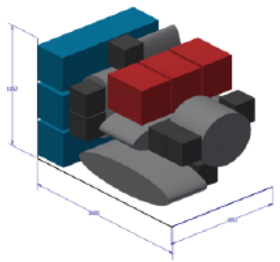
Concepts for future geodetic missions

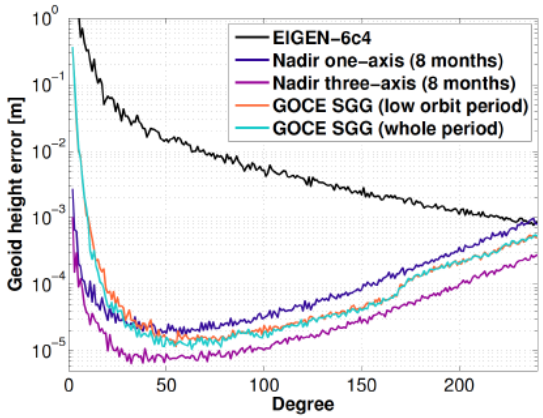
GOCE-like (Gravity Gradiometer) concept

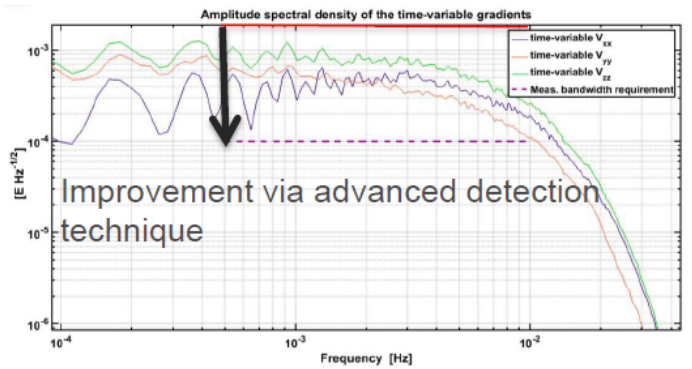


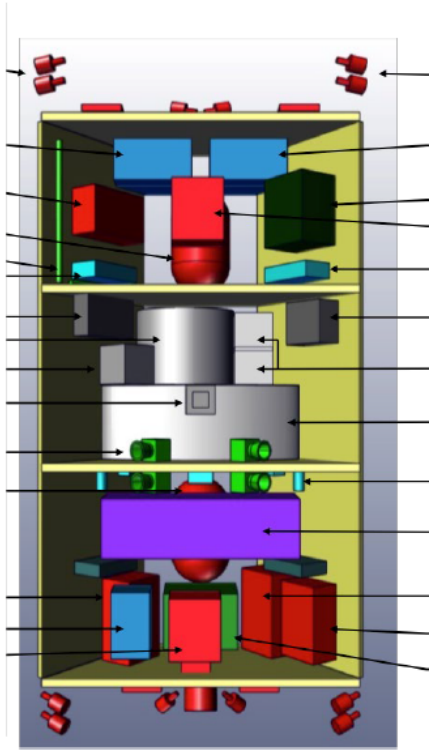


$$\sigma_\Gamma = \frac{1}{\sqrt{N}} \cdot \frac{\sqrt{2}}{d k_{eff}} \cdot \frac{1}{T^{3/2}} \sqrt{T_{cycle}}$$

Elliptical shield	Elliptical shield
	
(1052 x 1052 x 1600)mm	(1052 x 1063 x 2048)mm







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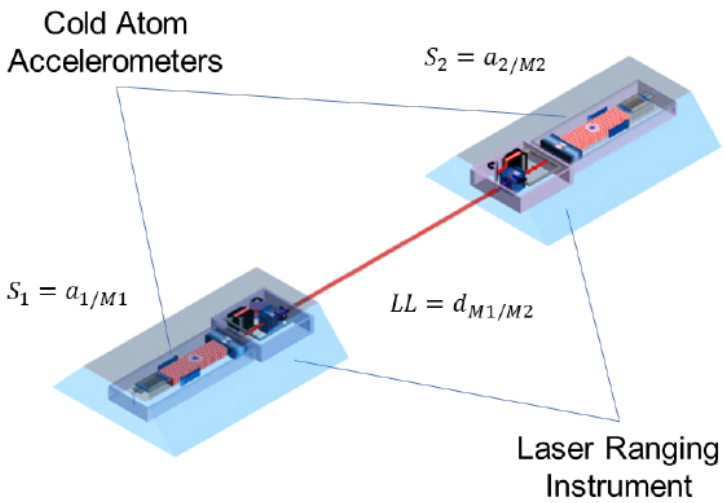
A. Trimeche et al, Concept study and preliminary design of a cold atom interferometer for space gravity gradiometry, Classical Quant. Grav. 36,215004 (2019).

Concepts for future geodetic missions

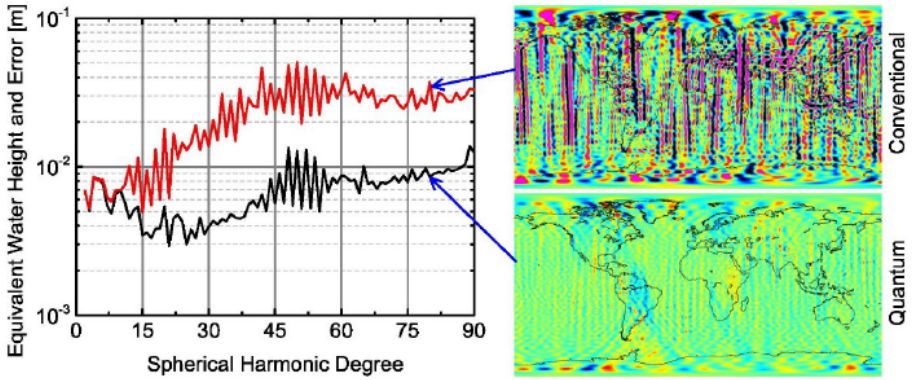
GRACE-like (or twin-satellite) concept



- Gravity field mapping with laser correlated quantum accelerometers in space
- **Instrument:** **Dual-satellite long baseline atom gradiometer**
- **Sensitivity:** **~10 µE.Hz-1/2**
- **Altitude:** 370 km
- **Intersatellite distance:** 100 km
- **Developement:** 10 years
- **Mission lifetime:** 5 years

Impact of quantum performances on space gravimetry:

Resolution: The performances of atomic sensors can contribute to improve **the resolution of the gravity maps** produced by gravimetry space missions[1].



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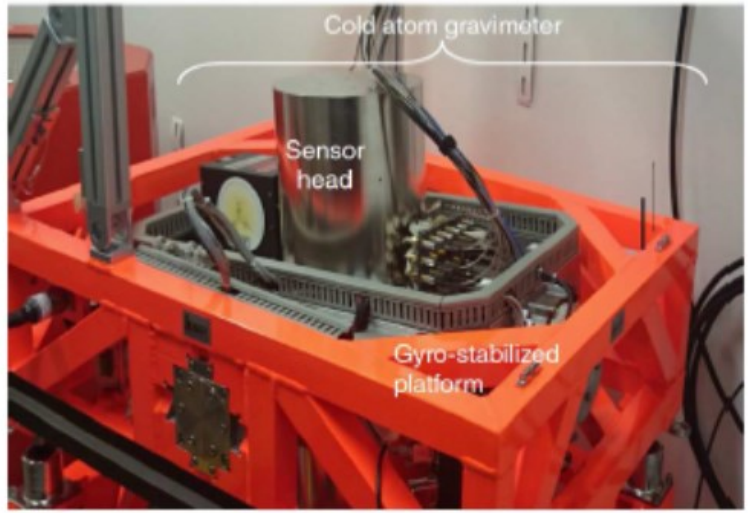
[1] *T. Lévèque et al, « Gravity Field Mapping Using Laser Coupled Quantum Accelerometers in Space », Journal of Geodesy, Accepted for publication, arXiv:2011.03382 (2020).*

Airborne Quantum Gravimetry campaigns 2017-19



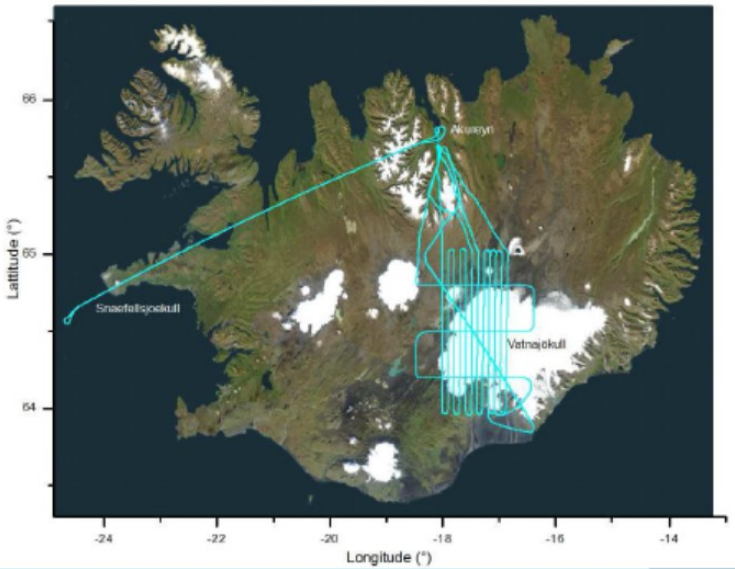
Flight campaign ONERA ”GIRAFFE”: Iceland 2017 / Toulouse: Bay of Biscay, Pyrenees 2019

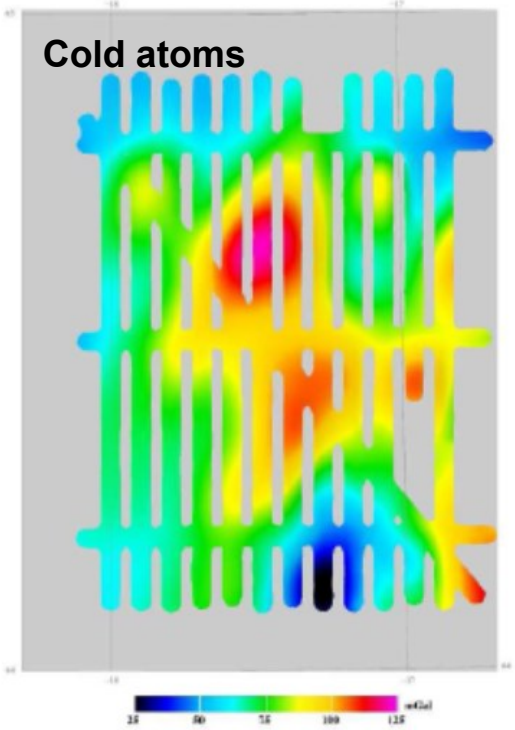
Validation: state-of-the-art strapdown IMU gravimeter / upward continued ground gravity

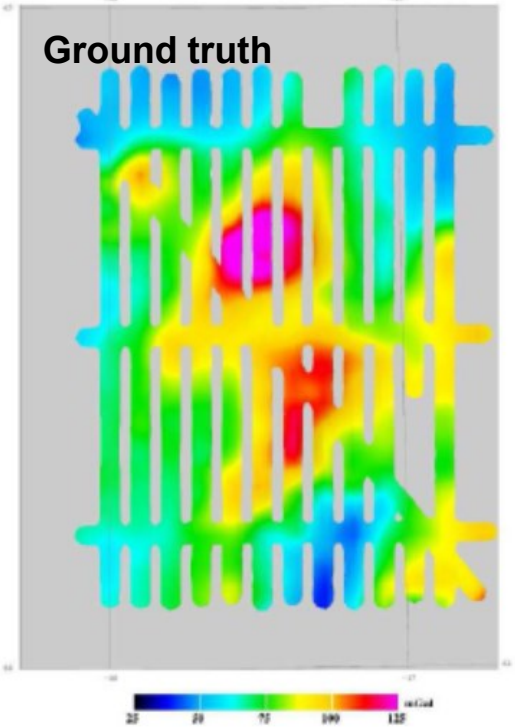
2017: ~ 2 mGal rms accuracy

< 0.1 mGal absolute at Akureyri apt

2019: < 1 mGal rms







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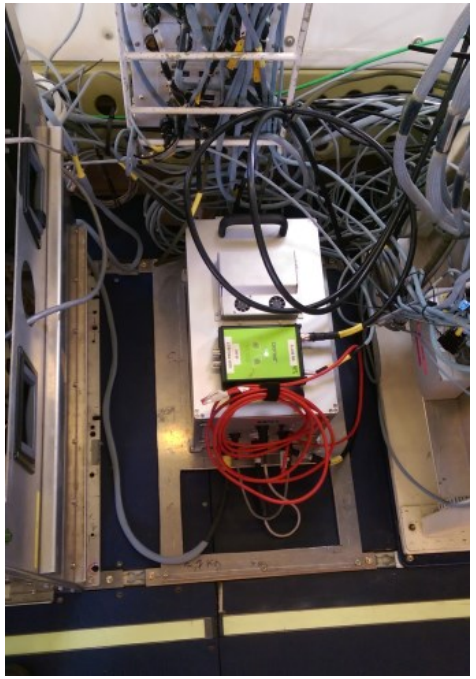
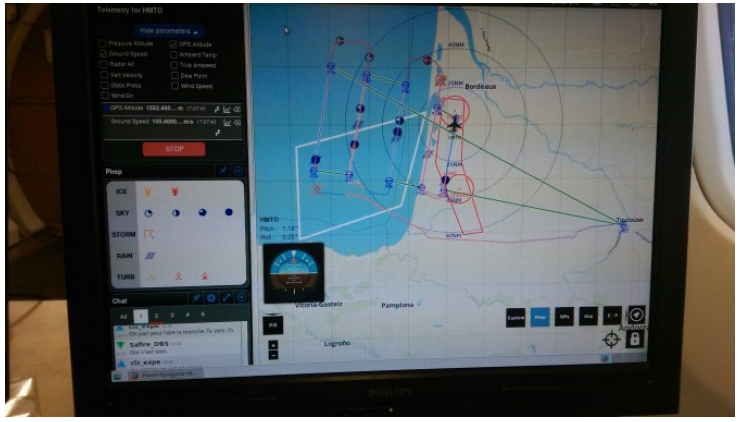
Toulouse 2019

(ONERA/DTU/BGI)

Two classical g-sensors flown





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Summary and conclusions

Outlook good future gravity missions, higher accuracy, resolution … and many other relevant EO missions

NASA decadal plan MCDO .. Mass Change Designated Observable mission .. 2028-2030?

- ESA NGGM/MAGIC (Mass-change and Geosciences International Constellation) .. 2029-30?
- DLR/JPL GRACE-I … 2028?
- EU/ESA CARIOQA – Cold Atoms Pathfinder … 2029?
  CARIOQA = *Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry*
- China ??

Longer term: Cold atom gradiometer mission – “GOCE follow-on” … 2035 ??