POLITECNICO
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Quantum Atomic Sensors in Space for Earth Observation

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Workshop on Cold Atoms and Climate Change

King’s College London, 22-23 March 2022

Outline of the presentation

- Observation of the Earth gravity field from space, and its contribution to the study of global change phenomena
  - Gravimetry, gradiometry and missions for the Earth gravity field
  - Current limitations of gravimetry missions and geophysical requirements

- Towards Quantum Space Gravimetry (QSG): Quantum Sensors for Earth Observation

- The MOCAST+ proposal for a Quantum Space Gravimetry mission

Earth sciences and gravimetry

Gravity field observations allow to observe and monitor **mass and mass transport** in the Earth system.

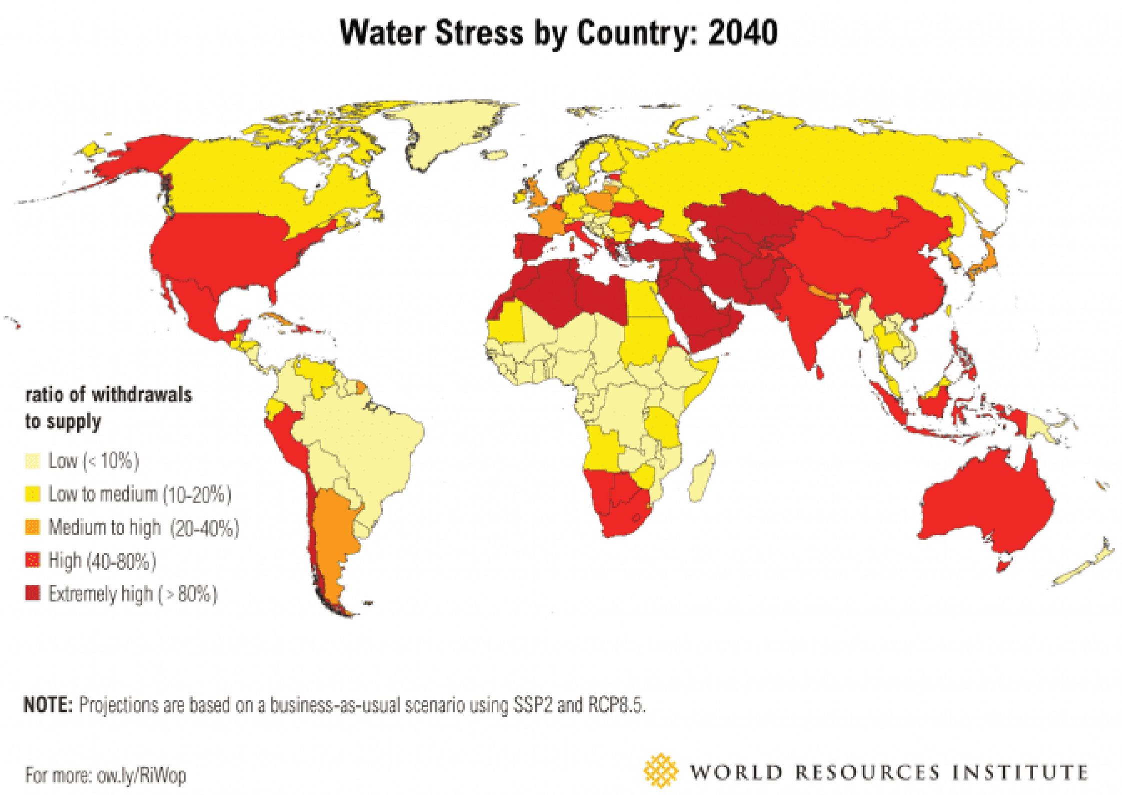
Gravity field observations from space significantly contribute to a number of Essential Climate Variables (ECVs) as defined by GCOS (Global Climate Observing System).

These ECVs effect phenomena that are changing the world we live in:

- **climate change,**
- **water resources,**
- **flooding,**
- **melting of ice masses,**
- **global sea level rise.**

⇩

Significant societal benefit for e.g. **operational prediction of floods and droughts**, and applications in **water management**.



(World Resources Institute, 2015)
https://reliefweb.int/map/world/water-stress-country-2040

Initiatives by IUGG and IAG

DGK Deutsche Geodätische Kommission
der Bayerischen Akademie der Wissenschaften

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Observing Mass Transport to Understand Global Change and to Benefit Society: Science and User Needs

– An international multi-disciplinary initiative for IUGG –

edited by

Roland Pail

with contributions of

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Global User Community Science Team (IUGG, IAG, GGOS) Report - R. Pail ed. (2015)

(IUGG XXVI General Assembly Prague, 2015)

Resolution 2:

Future Satellite Gravity and Magnetic Mission Constellations

*The **International Union of Geodesy and Geophysics***

Considering

- The interest and need of the IUGG scientific community to understand processes of global mass transport in the Earth system, and the interaction among its subsystems including continental hydrology, cryosphere, atmosphere, ocean and solid Earth, in order to close the global water budget and to quantify the climate evolution of the Earth,
- The long lead time required to bring an earth observation system into operation,

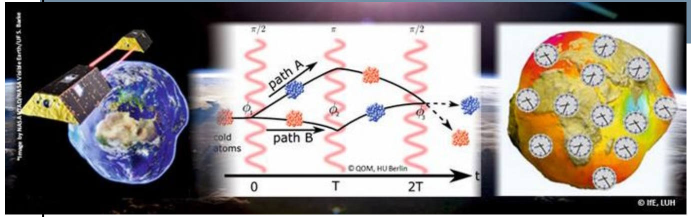
Acknowledging

- The experience acquired in the last decade within the IUGG in analyzing data from dedicated satellite missions such as CHAMP, GRACE, GOCE and Swarm for the purpose of estimating the gravity and magnetic fields and their time variations,
- The clear expression of need from the user communities so far, and the definition of joint science and user requirements for a future satellite gravity field mission constellation by an international working team under the umbrella of IUGG,

Noting

- The need for a long-term sustained observation of the gravity and magnetic fields and related mass transport processes of the Earth beyond the lifetime of GRACE and the GRACE Follow-On planned for the 2017 - 2022 period, and beyond the lifetime of Swarm, currently 2013 to 2018,
- The demonstrated need for satellite constellations to improve temporal and spatial resolution and to reduce aliasing effects,

Urges
International and national institutions, agencies and governmental bodies in charge of supporting Earth science research to make all efforts to implement long-term satellite gravity and magnetic observation constellations with high accuracy that respond to the aforementioned need for sustained observation.



IAG Project "**Novel Sensors and Quantum Technology for Geodesy**" (Qu-Ge)
coordinated by Jurgen Mueller (IFE, Hanover, Germany)

Working Groups
WG Q.1 "**Quantum gravimetry in space and on ground**", Chair: Franck Pereira dos Santos
WG Q.2 "**Laser interferometry for gravity field missions**", Chair: Michael Murböck
WG Q.3 "**Relativistic geodesy with clocks**", Chair: Gerard Petit

Workshops and Conference Sessions on Cold Atoms and Gravimetry

EGU 2021 (April 2021)
Session G4.1 Modern Concepts for Gravimetric Earth Observation (Convener: Jürgen Müller)

Workshop on Quantum Gravimetry in Space and on Ground (26-27 May 2021)
Organized by QuGe WG Q.1 (Chair: Franck Pereira dos Santos)

IAG Scientific Assembly 2021 (June-July 2021)
Session 6.4: QuGe - Novel Sensors and Quantum Technology for Geodesy (Convener: Jürgen Müller)

EPS 2021 (July 2021)
The second EPS (European Physical Society) Conference on Gravitation

Community Workshop on Cold Atoms in Space and the corresponding Community Roadmap Process (September 2021)
Organizers: Oliver Buchmüller, John Ellis et al. -> arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022 https://arxiv.org/abs/2201.07789

ESA 5th Quantum Technology Conference (23-25 November 2021)
Session on Quantum Sensing (Chairs: Olivier Carraz, Eamonn Murhy)

Workshop STE-QUEST (17-18 May 2022)

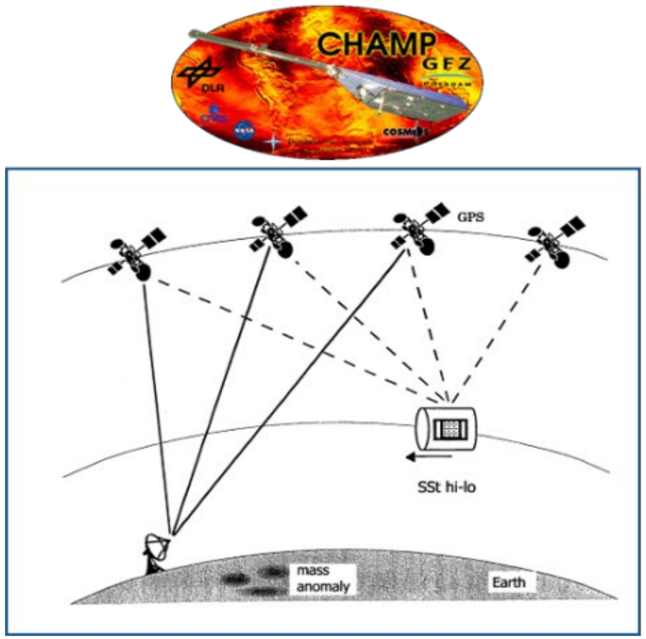
EGU 2022 (23-27 May 2022)
Session G4.1 Modern Concepts for Gravimetric Earth Observation (Convener: Jürgen Müller)

COSPAR 2022 Scientific Assembly (16-24 July 2022)
Session H0.5 "Advanced Methods for Geodesy, Metrology, Navigation and Fundamental Physics" (Convenors: Roberto Peron, Jürgen Müller)

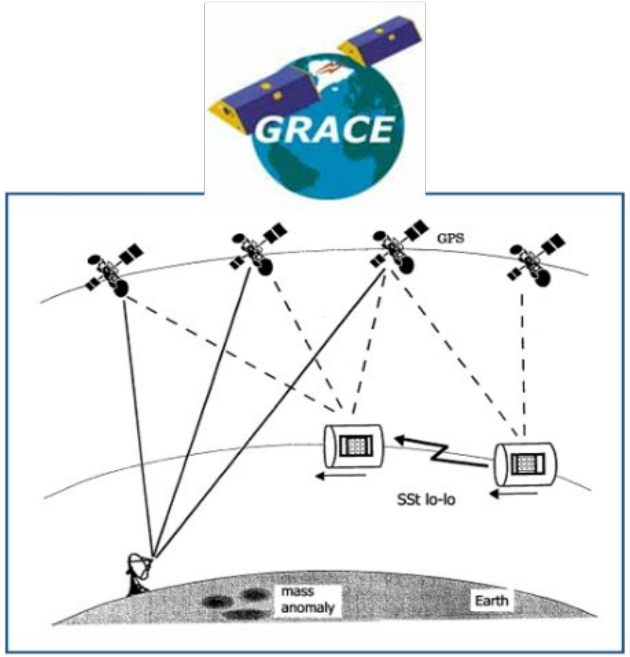
Also:
ESA Living Planet Symposium (23-27 May 2022)
Hotine-Marussi Symposium on Mathematical Geodesy (13-17 June 2022) Topic: advancing geodetic theory through new observation sensors.

Gravity field missions: different concepts

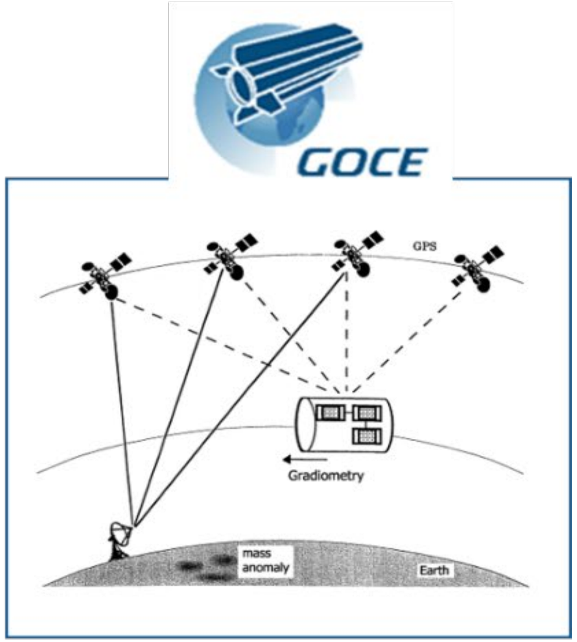
SST in the high-low mode
(CHAMP 2000-2010)



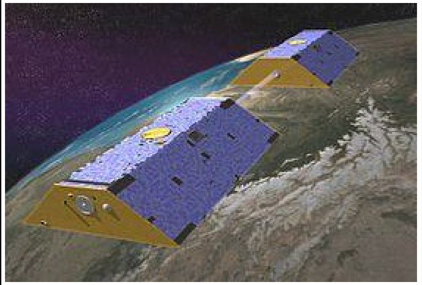
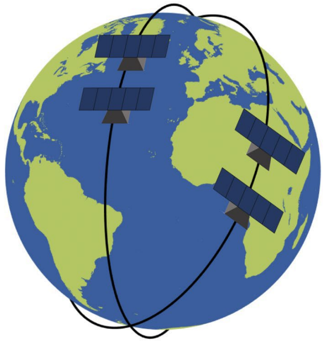
SST in the low-low mode
(GRACE 2002-2015)



SGG plus high-low SST
(GOCE 2009-2013)



Missions for the Earth gravity field

	Space missions like GRACE have formed a well-organized user community tracking the Earth mass movement to study environmental changes on a global scale using data from satellite measurements			***Static gravity field***
	CHAMP (2000-2010)	***GRACE (2002-2017)***	***NGGM ($\sim$2028)***	***GOCE (2009-2013)***
	A "pathfinder mission" for the SST concept (EA)	*GRACE / GRACE-FO (2018 - …) / NGGM long-term monitoring of the gravity field, time variations*		*Gradiometry + low orbit for high accuracy static gravity field*
				
Accuracy of EA (electrostatic accelerometer)	*$\sim 10^{-10}$ m/s^2*	*$\sim 10^{-11}$ m/s^2*	*$\sim 10^{-11}$ m/s^2*	*$\sim 10^{-12}$ m/s^2*
Geoid undulations	*$\sim$10 cm @ 350 km*	*$\sim$10 cm @ 175 km*	*$\sim$1 mm @ 500 km (every 3 days) $\sim$1 mm @ 150 km (every 10 days)*	*$\sim$1 cm @ 100 km*
Gravity anomalies	*$\sim$0.02 mGal @ 1000 km*	*$\sim$1 mGal @ 175 km*		*$\sim$1 mGal @ 100 km*

Current limitations of space gravimetry missions and users' priorities

- ***Higher spatial resolution*** *(>> lower orbits, 300-350 km) for detection of gravity changes (movement of mass in Earth system)*

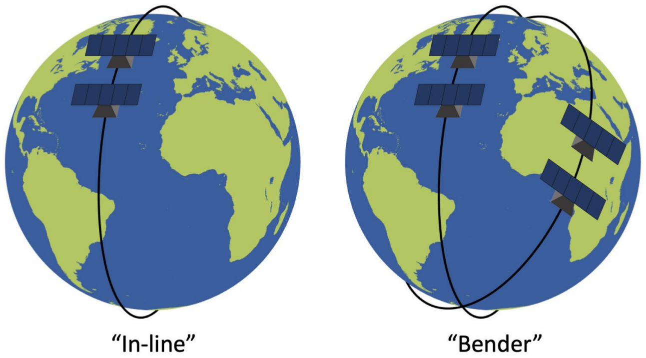
  A space mission will not be able to map the higher frequency details of the gravity field, due to the atmospheric limitations of the orbit height: full detailed mapping of the spatial gravity field variations down to a few km resolution must be supplemented by ***airborne and surface*** *gravity measurements.*

- ***Higher revisit time*** *(>> satellite constellations) for improved temporal resolution → operational service applications*

- ***Higher accuracy*** *in the measurements (>> new technologies: laser interferometry, cold atom accelerometers)*
  accelerometer better than $\sim 10^{-10}$ - 10^{-11} m/s^2 *(measurement range of* $\pm 10^{-4}$ m/s^2*);*
  gradiometer $\sim 10^{-12}$ $m/s^2/\sqrt{Hz}$ *for GOCE-like mission (over a larger spectral measurement band).*

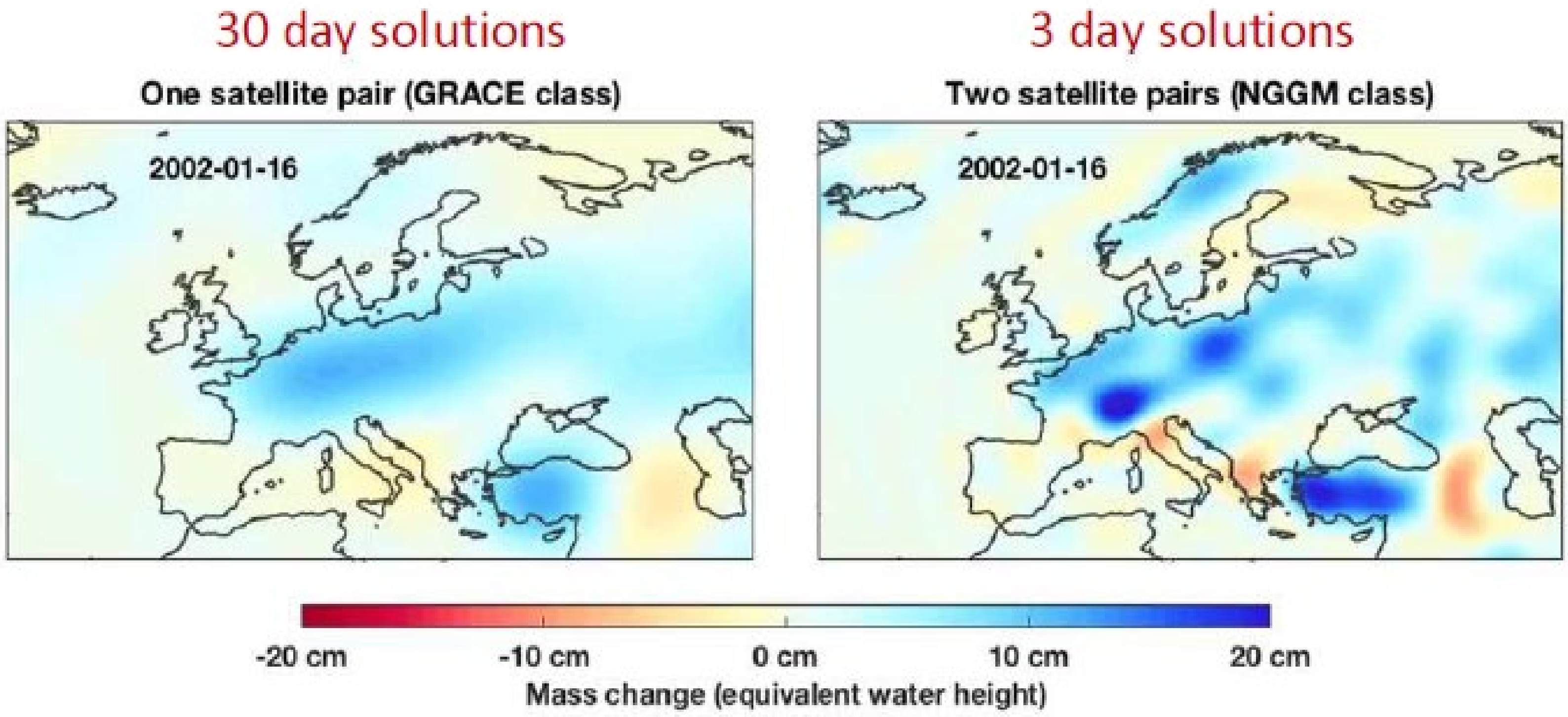
- ***Extension of observation time series*** *→ separation of natural and anthropogenic forcing*

Higher spatial and temporal resolution from double-pair mission



"In-line" (GRACE class) formation (left)
and "Bender" (NGGM class) formation (right)
(Haagmans et al., 2020)

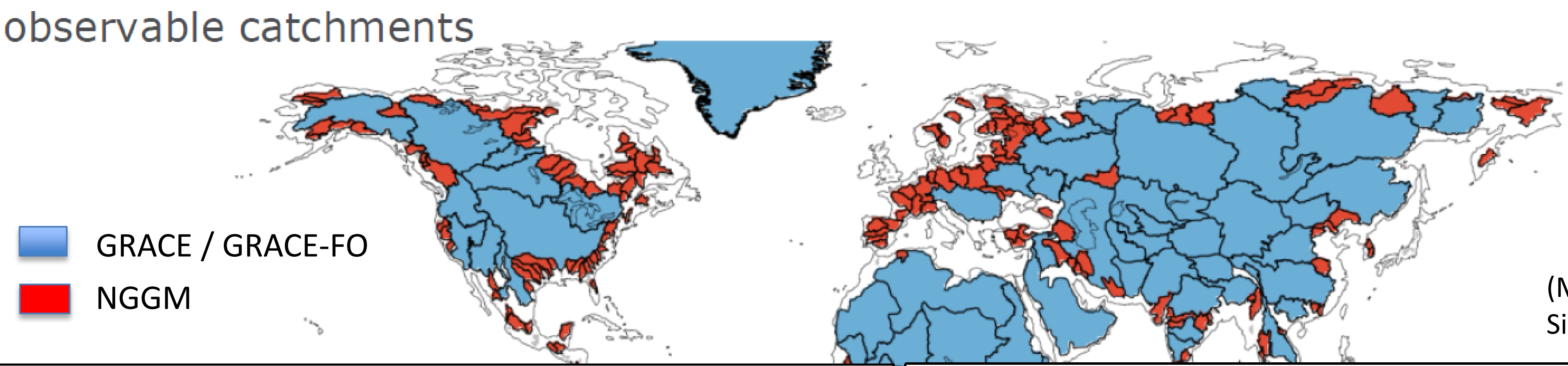
- Higher spatial and temporal resolutions



(Massotti, Haagmans and Silvestrin, 2021)

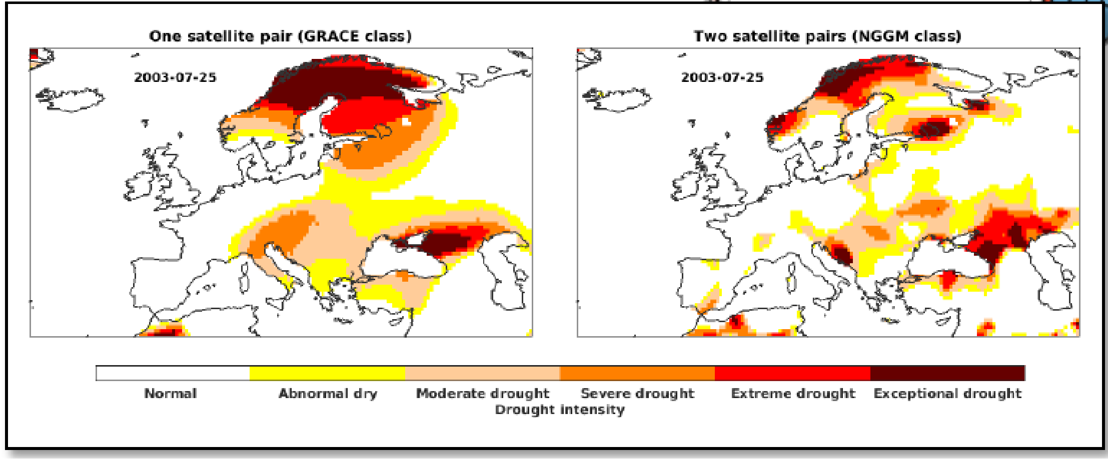
Higher spatial and temporal resolution from double-pair mission

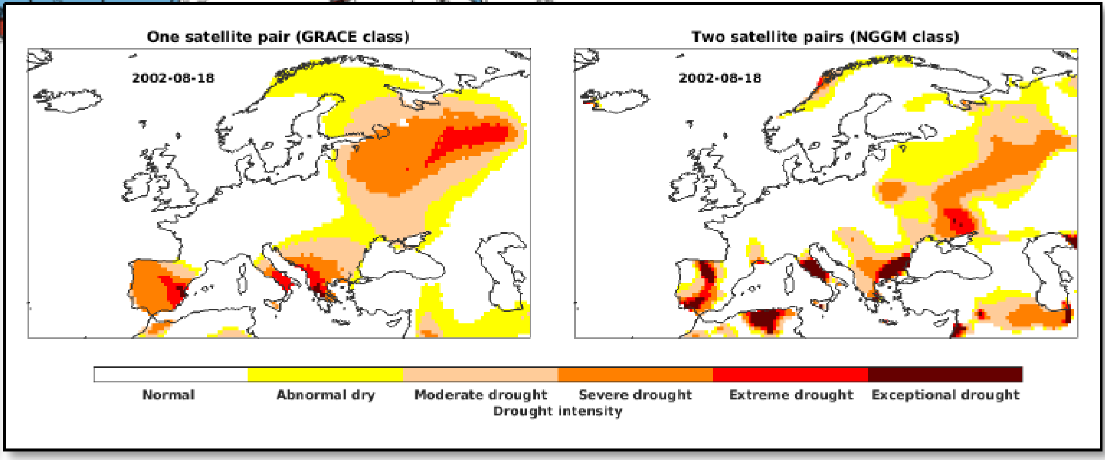
Possible better results for hydrology: better closure of the water cycle, drought and wetness indexes



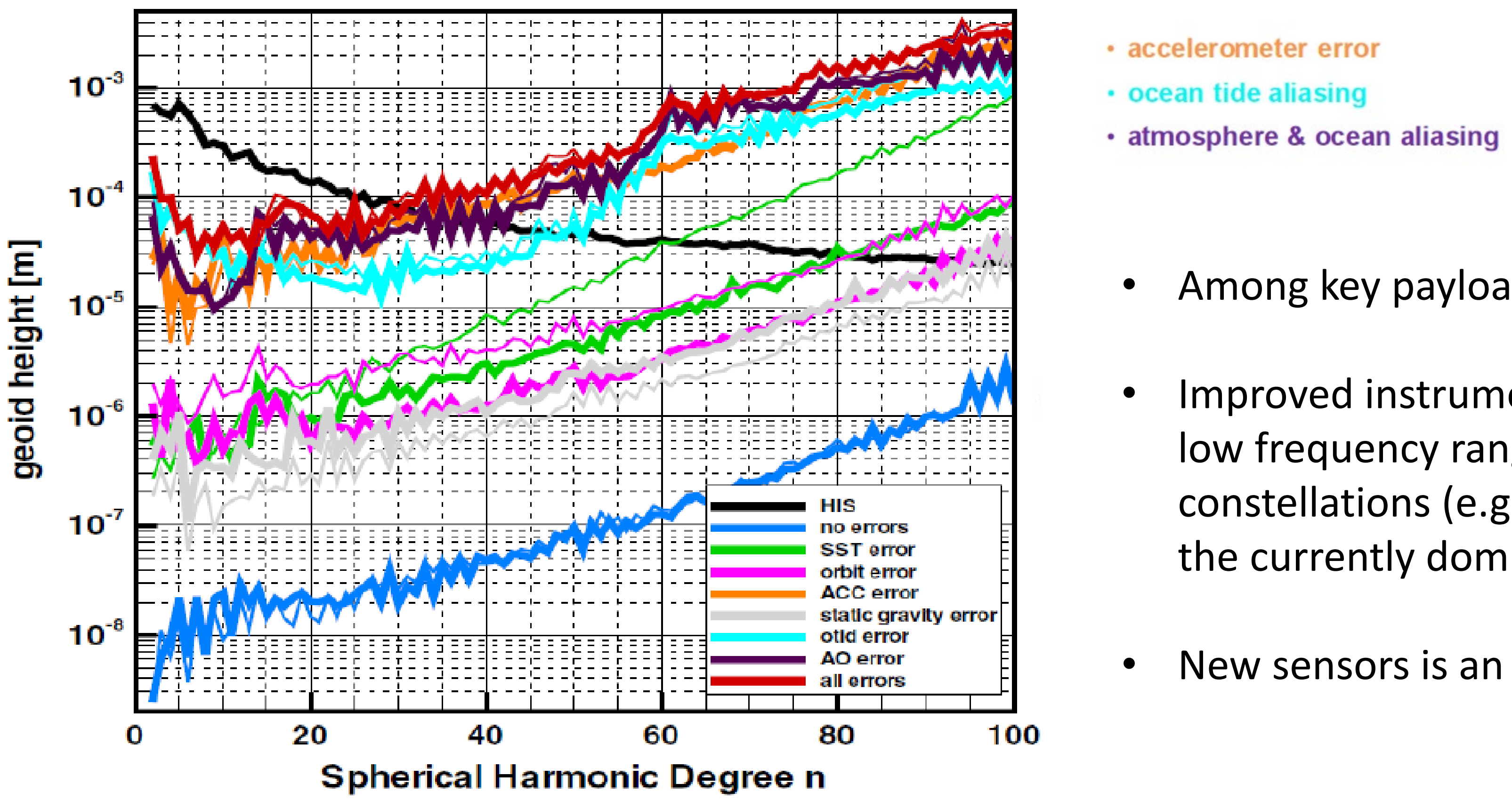
(Massotti, Haagmans and Silvestrin, 2021).

Drought intensity





Gravimetry missions - Error budget
Need of higher accuracy in the measurements



(Flechtner et al., 2016)

- Among key payload, ACC is a very large error contributor.
- Improved instrument performance (especially ACC in the low frequency range) becomes important for satellite constellations (e.g., double pairs), due to the reduction of the currently dominant error sources of tidal aliasing.
- New sensors is an interesting future option.

Quantum sensors for Space Gravimetry vs «classical» sensors

Most relevant features of quantum accelerometers and the classical electrostatic accelerometers used so far for space accelerometry

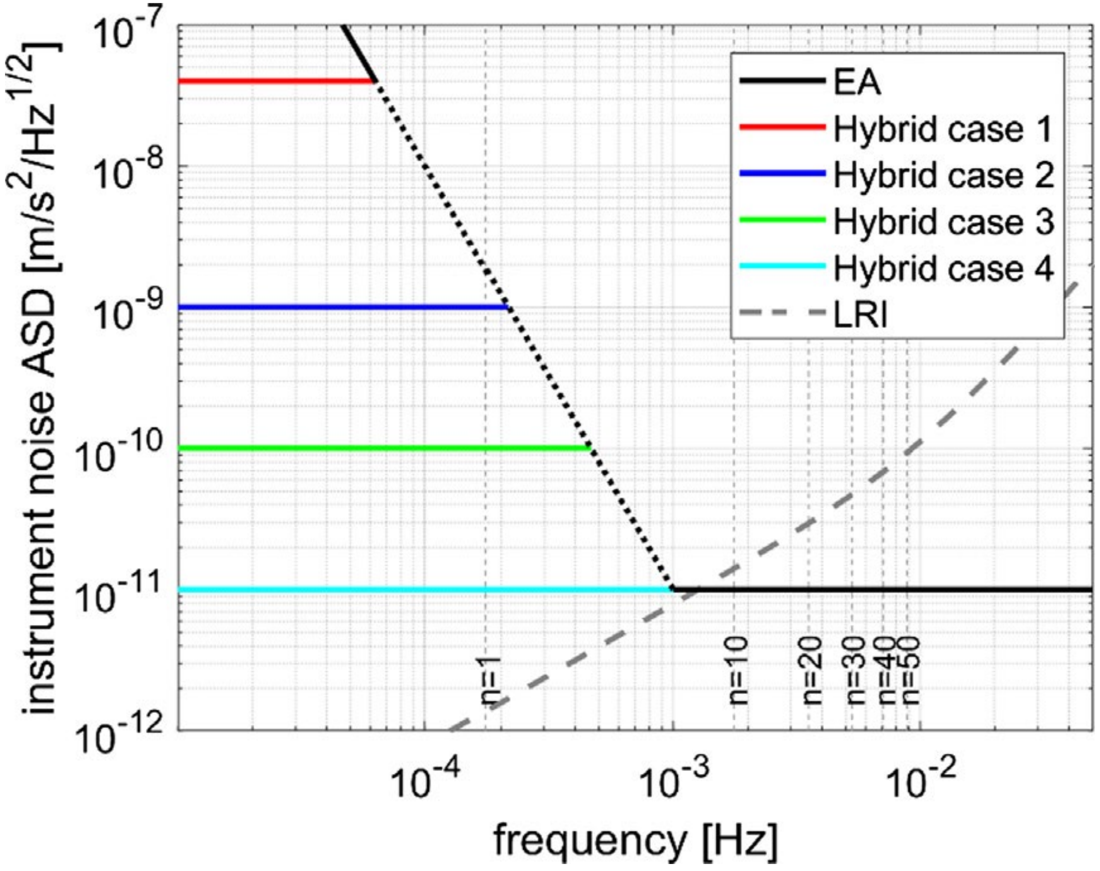
	Atomic accelerometer	Electrostatic accelerometer
Sensitivity	4×10^{-8} m/s^2/Hz$^{1/2}$ on ground (projection for space at 10^{-12} m/s^2/Hz$^{1/2}$ for interrogations of more than 20 s)	3×10^{-12} m/s^2/Hz$^{1/2}$ (demonstrated)
Measurement bandwidth	≤ 0.1 Hz	[0.005-0.1] Hz
Scale factor	Absolute	Calibration required
Stability	No drift	Drift
Measurement capability	Single axis	Three axes
Proof mass motion	Residual velocities $\rightarrow$ Coriolis acceleration	
SWaP	High	Low
TRL	Intermediate	High

Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map.
arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022
https://arxiv.org/abs/2201.07789

Quantum sensors for Space Gravimetry: hybrid accelerometers

Hybrid accelerometer noise specifications provided by ONERA (EA/CAI-hybridization currently realized in one axis).

- Case 1: achieved on-ground performance with state-of-the-art cold atom gravimeters (rather pessimistic for a space-based application).
- Case 2: more realistic considering the current level of CAI technology.
- Case 3: rather optimistic.
- Case 4: ideal hybridization scenario, where the noise level of the CAI is able to extend the white noise behaviour of the EA in the measurement bandwidth down to very low frequencies.
- LRI: Laser Ranging Interferometer noise in terms of range accelerations.



(Abrikosov et al., Advances in Space Research, 2019)

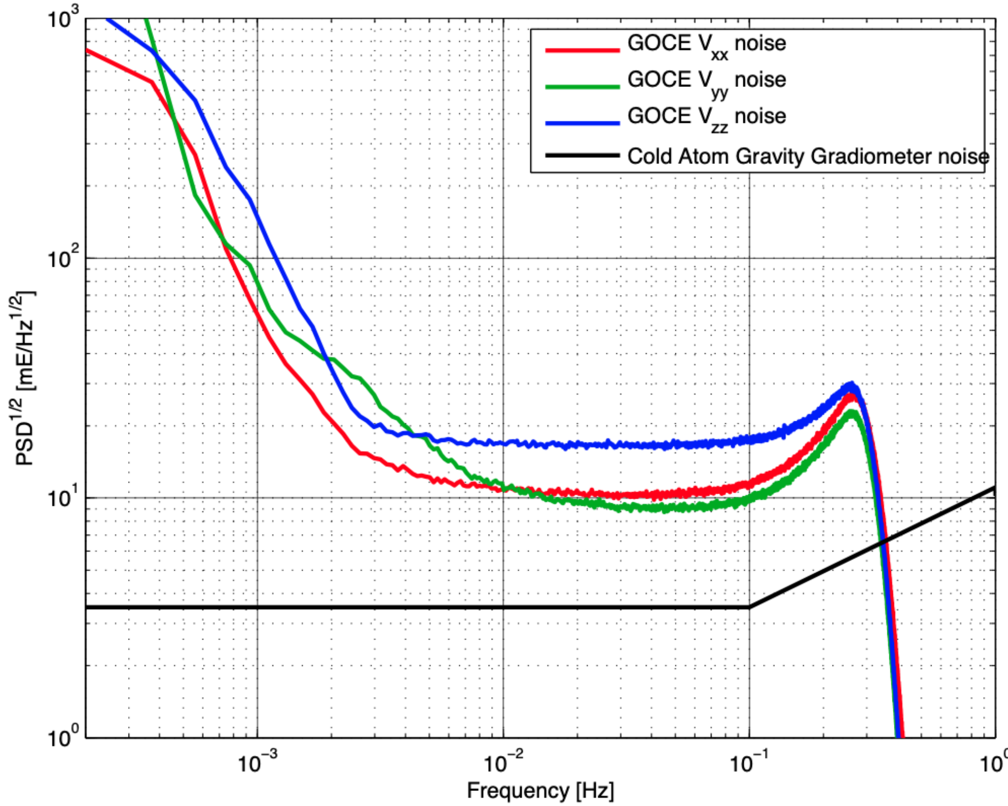
Quantum sensors for Space Gravimetry: cold atom gradiometer

A space quantum accelerometer is expected to reach sensitivities in the low 10^{-12} m/s^2/Hz$^{-1/2}$ when stretching the interrogation times to 20 s, similar to the very best electrostatic accelerometers, such as used for GOCE, but in a wider measurement band extending down to lower frequencies.

- Absence of drifts is a consequence of the absolute character of quantum sensors, with stable scale factors determined by the wavelength of the laser beam-splitters and the duration of the measurement, and the possibility of evaluating accurately systematic effects.

- On the other hand, they are so far limited to single axis measurements, and have a much higher Size, Weight and Power (SWaP) budget.

- However, whilst the technology is currently less mature, it is being demonstrated in a number of national and international projects.

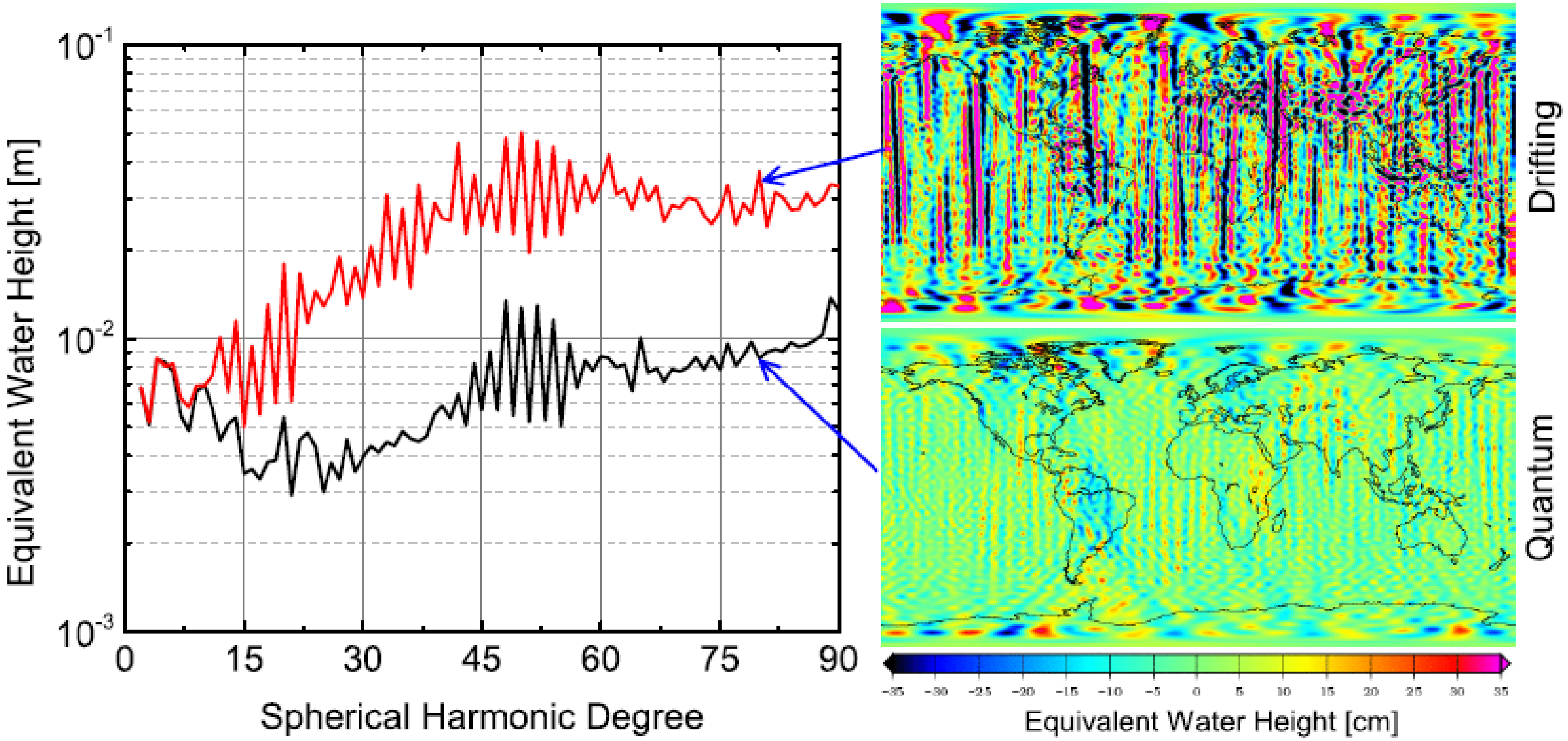


Comparison between the noise spectra in GOCE gradiometers and in a prospective cold atom gradiometer, illustrating the latter's reduced level at low frequencies (Carraz et al., 2014)

Quantum sensors: potential gain in Earth Observation by quantum accelerometers

Uncertainties in the gravity field recovery as a function of spherical harmonic degree, evaluated in equivalent water height (computations carried out without any empirical periodic parameter adjustment in the gravity field reconstruction).

Quantum accelerometers (black)
Drifting accelerometers (red)



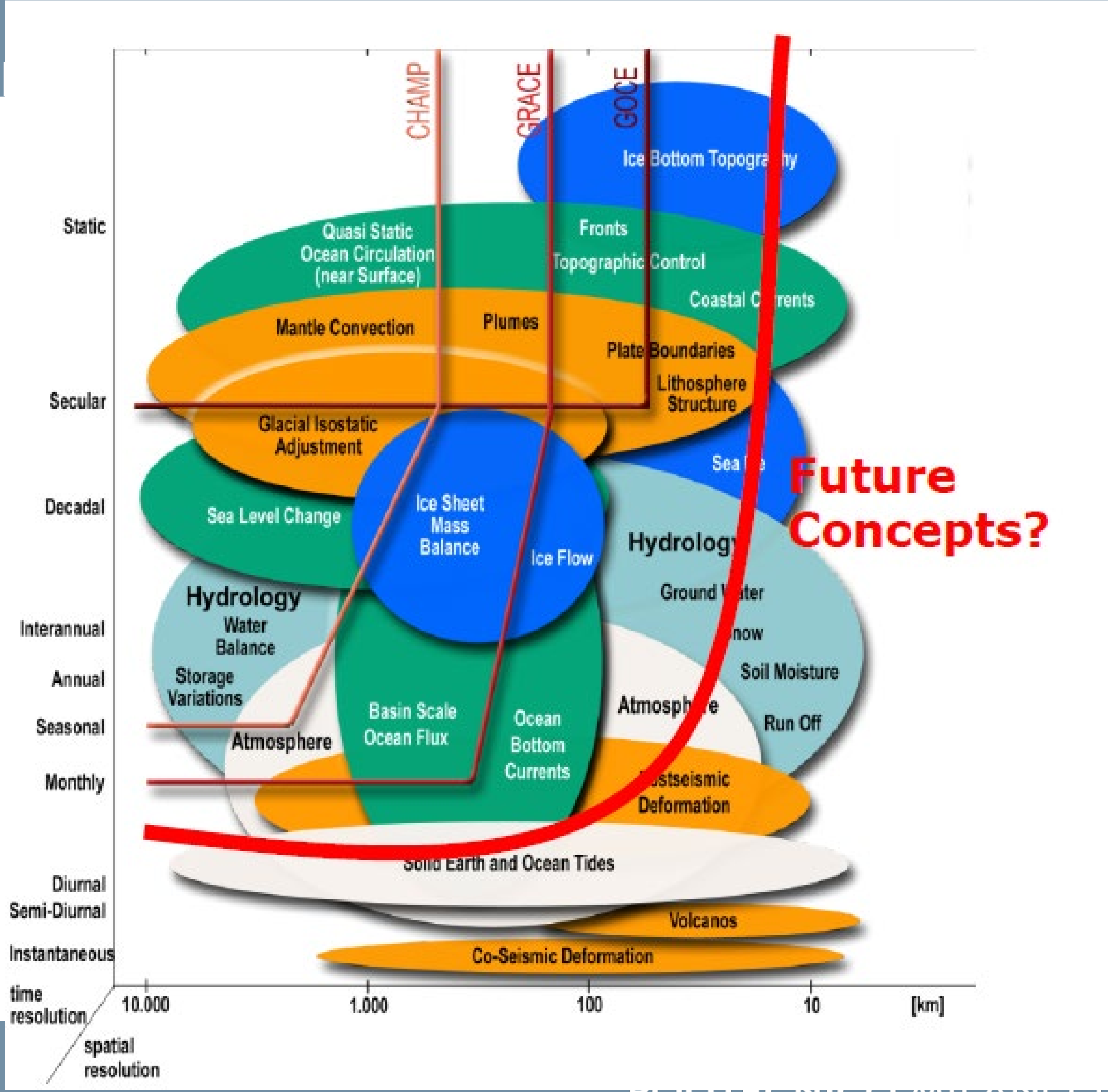
(Lévèque et al., 2021)

Quantum sensors: potential gain in Earth Observation by quantum accelerometers

The ellipses represent the required measurement resolutions for the indicated scientific objectives, with the spatial resolution on the horizontal axis and the temporal resolution on the vertical axis.

Also shown:
sensitivity curves of the “classical" CHAMP, GRACE and GOCE missions;
prospective sensitivity of a possible quantum gravimetry mission employing atom interferometry.

(Visser et al., 2017), adapted



Quantum sensors: progress in the relative accuracy of atomic clocks

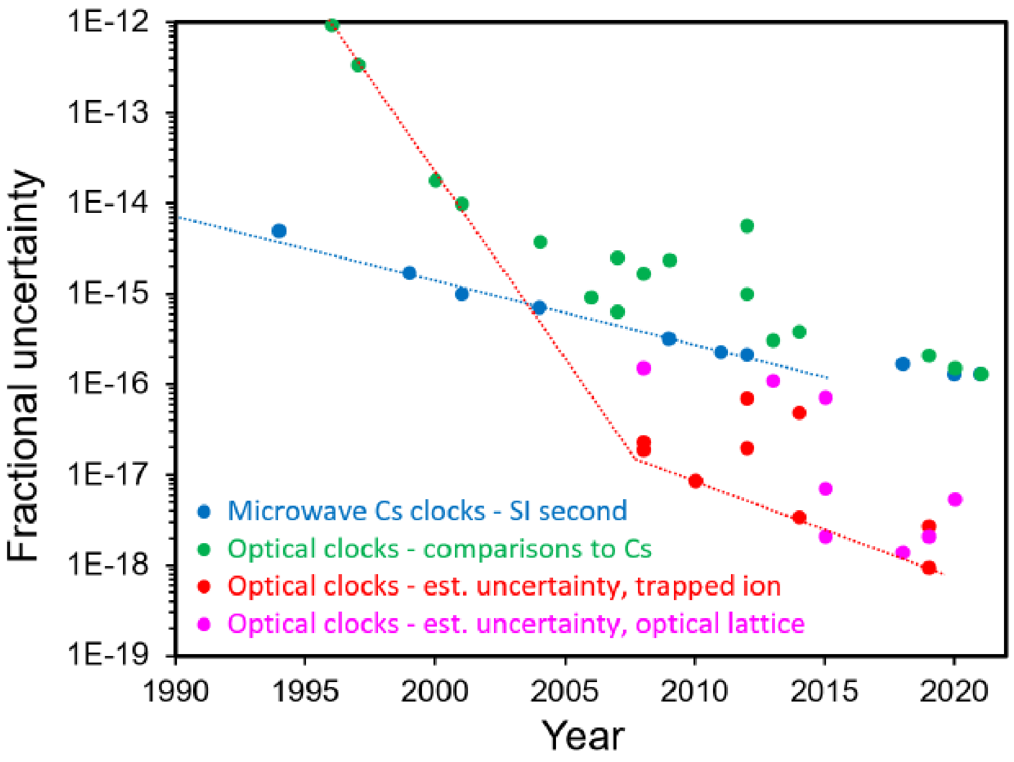
Potential gain in Earth Observation by chronometric levelling

A combination of ground and space clocks together with high performance time and frequency dissemination capabilities in particular via satellites can benefit the stabilization and long-term validation of **physical height networks** --> improved height reference system as required by the United Nations.

Atomic clocks offer access to the observation of **gravity potential differences,** in addition to the observation of its derivatives.

(See results of MOCAST+ study)

Progress in the relative accuracy of atomic clocks



Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map.
arXiv:2201.07789v1 [astro-ph.IM] 19 Jan 2022
https://arxiv.org/abs/2201.07789

Quantum Space Gravimetry pathfinder mission

- Main goal of the pathfinder mission: to demonstrate the maturity of the cold atom technology to operate in space (technical maturity of key components in space, such as long operation times or rotation compensation).
- The payload should go beyond the present-day performance of ground atom accelerometers (few 10^{-8} $m/s^2/\sqrt{Hz}$) by one to two orders of magnitude, thanks to the long interrogation times (several seconds) in microgravity.

- For the quantum sensor to perform optimally, the platform needs to be designed to meet clear constraints (centre of gravity, rotation compensation, etc.).
- Also orbit, altitude, flight modes and accommodation of payload within the platform should be chosen accordingly.
- It will allow preparing for missions with larger interrogation times (more than 10 s) with performance of $\sim 10^{-11} - 10^{-12}$ m/s^2/sqrt(Hz), suitable for the users community.

- For geodesy and geophysics: the pathfinder will in any case provide interesting observations and useful results for the recovery of the gravity field, even though a clear improvement will be available to end-users in geodesy and geophysics only from a subsequent fully-fledged quantum gravimetry mission.

Quantum Space Gravimetry pathfinder mission

Possible scenarios

- Embarking the quantum sensor as a passenger on the ESA/NASA NGGM/MAGIC mission (Next Generation Gravity Mission / Mass-change and Geosciences International Constellation):
  - an SST geodesy mission poses tremendous technical challenges and carries significant technological and programmatic risks for both aspects of the mission (both classical and quantum sensors).

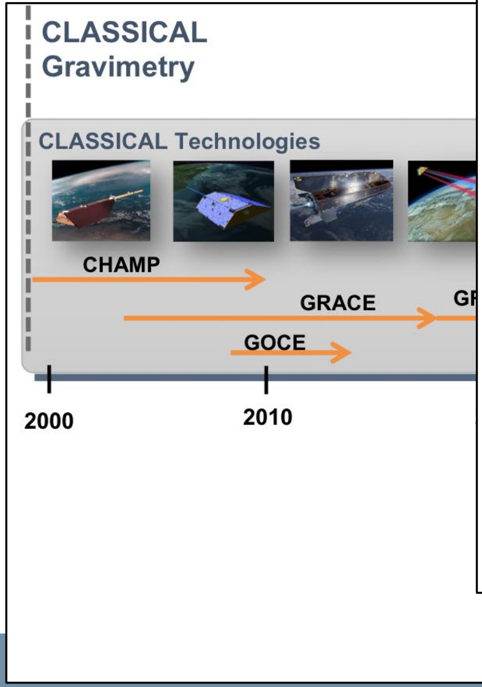
- Dedicated PM within this decade with a performance of up to 10^{-10} $m/s^2/\text{sqrt(Hz)}$.
  - balance of need to have a test of the quantum technology in space and level of expectation from the quantum gravimetry PM;
  - milestone for other communities, such as the fundamental physics one.

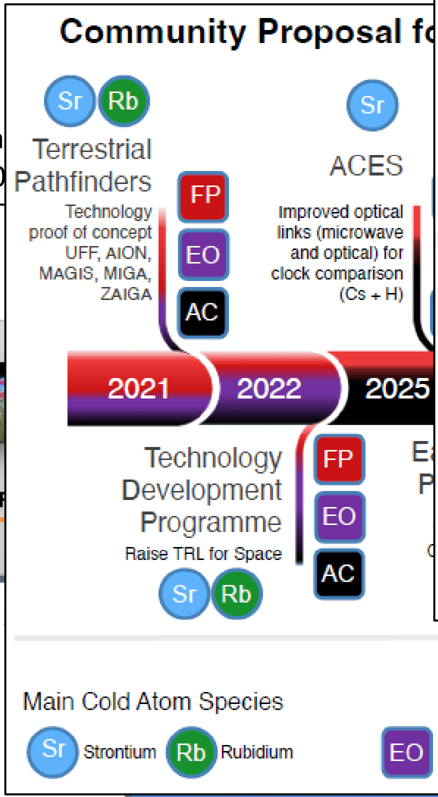
- Implementation of a full-fledged quantum space gravimetry mission to be launched to follow MAGIC.
  Mission scenario and payload baseline will be based on lessons learned from MAGIC and the PM.

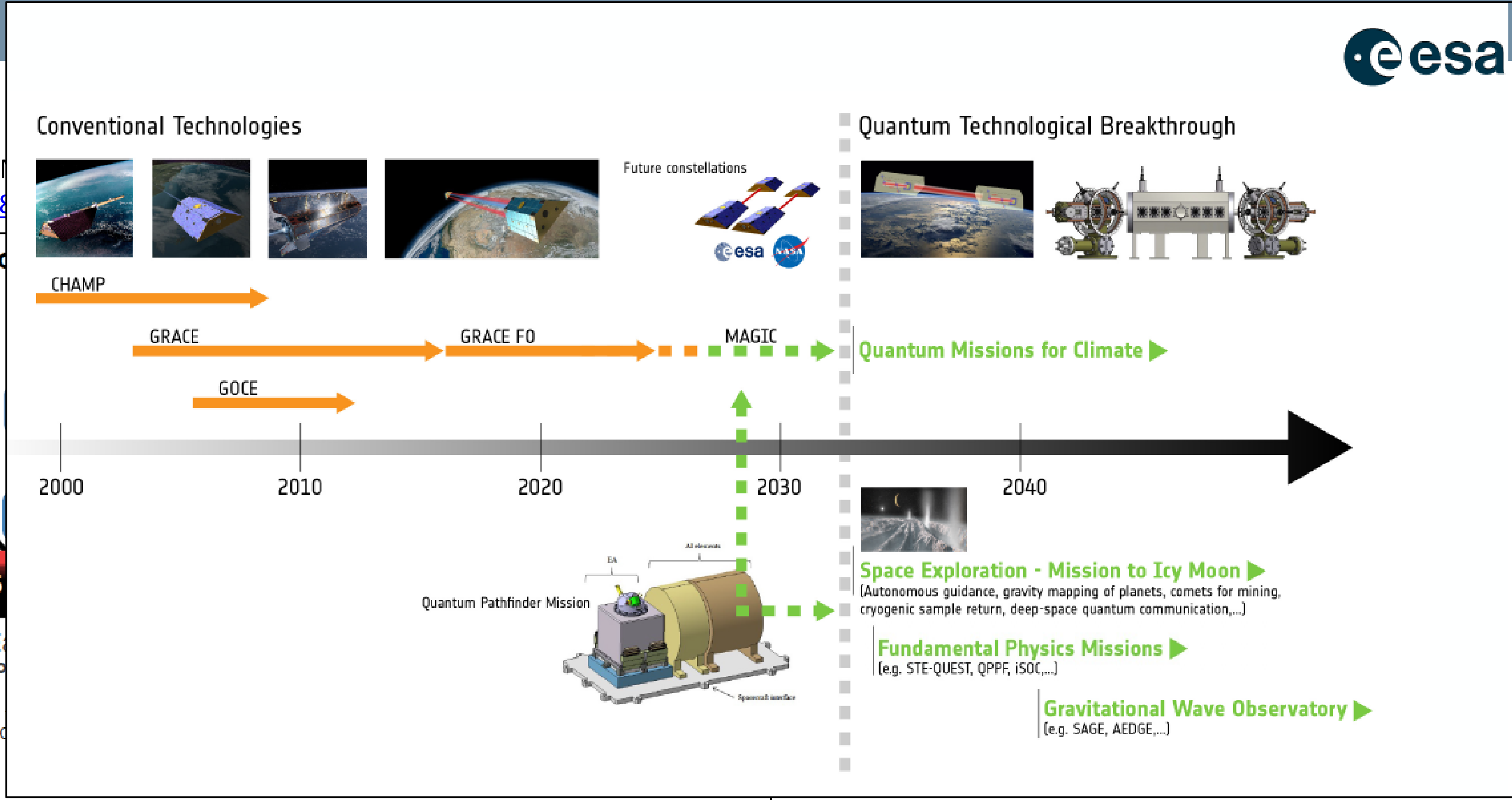
Roadmap to a Quantum Mission for Earth Observation

arXiv:2201.07789v1 [astro-ph.I
https://arxiv.org/abs/2201.0778

EC – DEFIS Quantum Space Gravim
Expert Group (Final Report, Jan. 20







Beyond the pathfinder mission: the MOCAST+ study (2020 – 2022)

MOCAST+

"MOnitoring mass variations by Cold Atom Sensors and Time measures"

- **ASI**
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- **UNITS**
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  Tommaso Pivetta
  Alberto Pastorutti
  Francesco Brandolin
- **UNITN**
  Battista Benciolini
  Alfonso Vitti

The MOCAST+ QSG mission proposal

Looking at a time beyond this decade, after a pathfinder mission, in the MOCAST+ project we have studied a mission based on a single-pair or double-pair (Bender) satellite configuration and an **“enhanced” quantum payload** consisting of:

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

(it is possible to share laser sources but the physics packages are independent).

Goal of the study: to assess the level of accuracy which can be expected from the “enhanced” payload and the level of accuracy which is needed to detect and monitor phenomena identified in the Scientific Challenges of the ESA Living Planet Program (e.g., in Cryosphere, Ocean and Solid Earth).

The study has been funded by the Italian Space Agency (ASI).
Results are not reported here since a paper is currently in preparation.

MOCAST+: summary of results of the study

- The proposed MOCAST+ mission can contribute to improve the current knowledge of the gravity field and of its time variation, provided that the mission configuration is made more “complicated” by considering 1 Hz clock observations, longer inter-satellite distances (about 1000 km) and three satellites for each orbit. Without these “complications”, the mission profile would not be competitive with GRACE / GRACE-FO in the low-medium degrees.
- Using gradiometers only on the two central satellites of the in-line formation can reduce costs and increase spacecraft constellation symmetry, without degrading the quality of the solution too much.
- The optimization of the instrument configuration can have a significant impact on the platform design and associated costs.
- The intrinsic stability of quantum sensors and their valuable performance at the very low degrees, make this concept interesting also for geodetic applications to other Solar system bodies (e.g., Mars), with significant results for planetary exploration.