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Earth sciences user requirements as a basis for a future quantum space gravimetry mission

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with a contribution by Braitenberg, Pastorutti and Pivetta (UNITS, Italy)

Community Workshop on Cold Atoms in Space 23-24 September 2021

Earth sciences need gravimetry

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

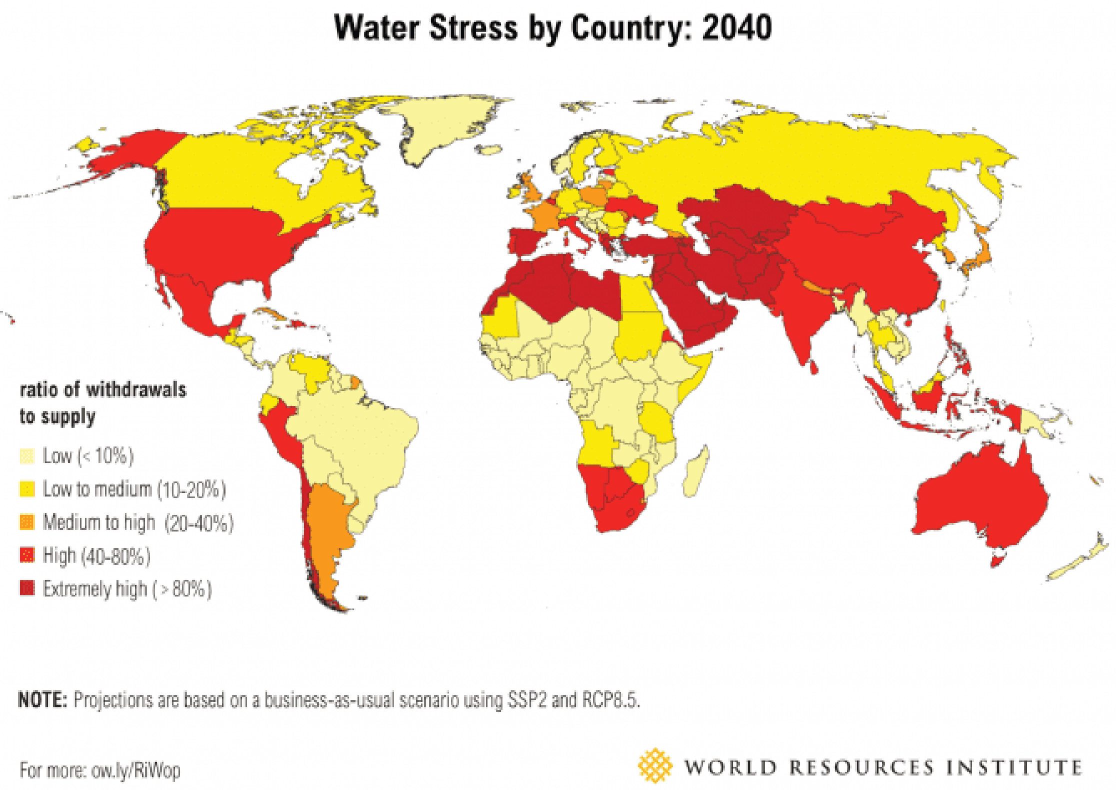
Gravity field observations from space significantly contribute to a number of Essential Climate Variables (ECVs) as defined by GCOS (Global Climate Observing System).

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 (2015) and IAG (KO Dec. 2020)

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

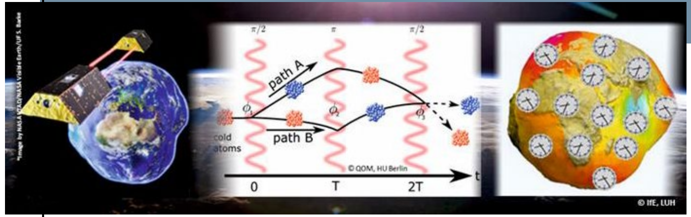
- The experience acquired in the last decade within the IUGG in analyzing data from dedicated satellite missions such as CHAMP, GRACE, GOCE and Swarm for the purpose of estimating the gravity and magnetic fields and their time variations,
- The clear expression of need from the user communities so far, 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

What is gravimetry …

***GRAVIMETRY**: measurement of the spatial variations of the Earth gravity field from one point to another on or over the Earth surface.*

On board a satellite: use of accelerometers in orbit to measure non-gravitational forces, gravity field can be determined by precise orbit tracking.

Applications: static gravity field (geodesy, geophysics) and <u>time-variations of the gravity field</u> (climate change, hydrology, geodynamics, earthquakes).
Accuracy requirements ~ 10^{-11} m/s^2.

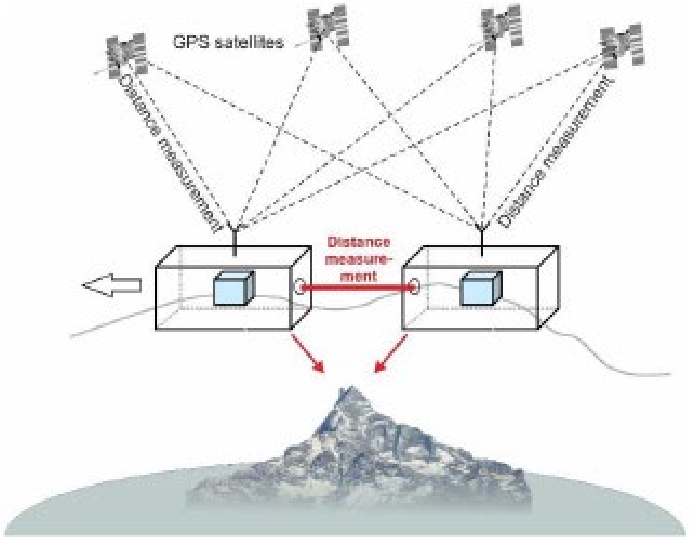


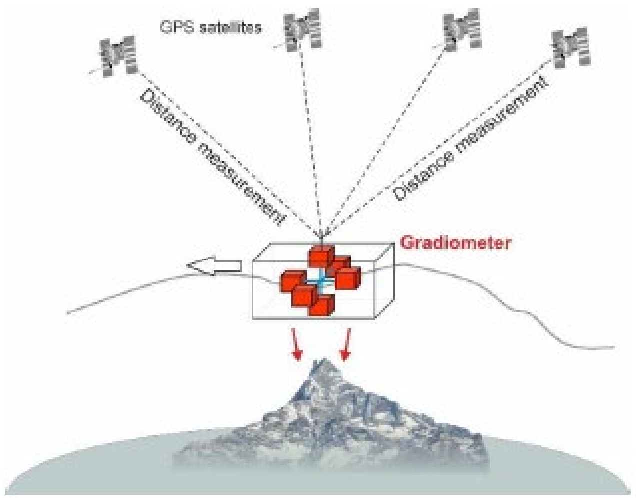
Figure: (Pail, 2021)

GRACE (2002-2017) / **GRACE-FO** (2018 - …) / **NGGM** (~ 2028)
>> long-term monitoring of the gravity field and its time variations

… and gradiometry

***GRADIOMETRY**: measurement of gravity differences between points inside a satellite, by using pairs of accelerometers.*
Accuracy requirements ~ 10^{-12} m/s^2.

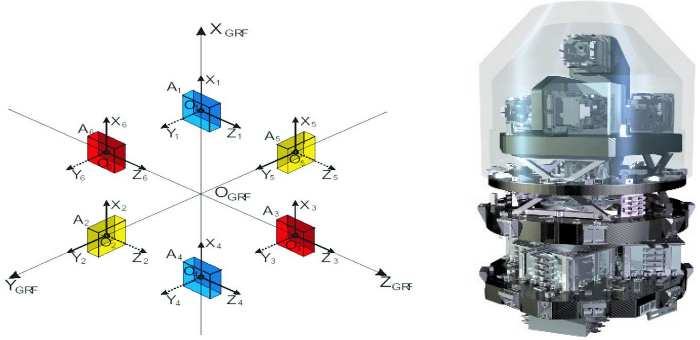
Note: complementary ground/airborne measurements are needed to improve the accuracy at higher harmonic resolution (short wavelengths)
>> High-resolution gravity field models



This figure: (Pail, 2021)

ESA **GOCE** (2009-13) mission exploited gradiometry for a unique mapping of static gravity field:

- *Basis for geoid (sea level reference), global height system.*
- *Background data for geophysics and understanding Earth interior.*



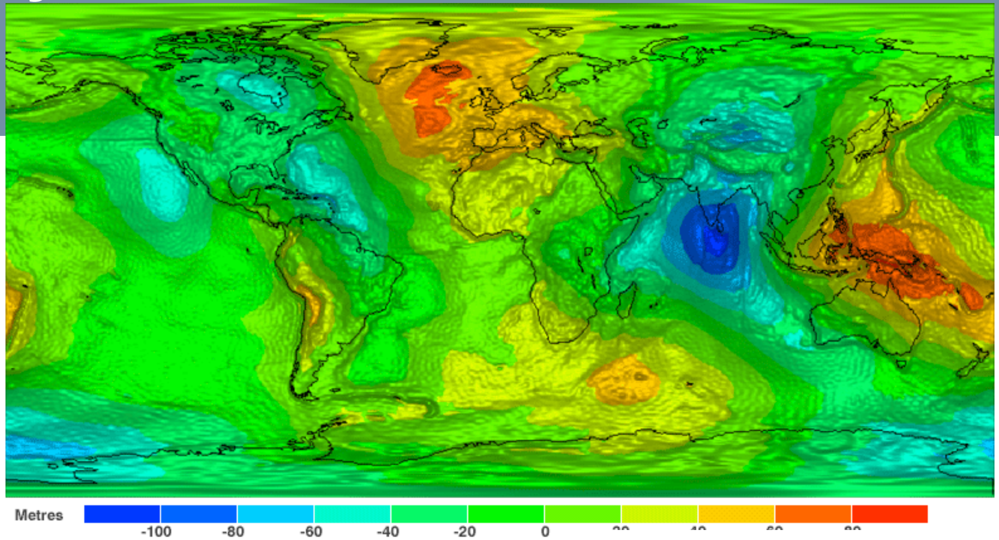
The GOCE EGG gradiometer

Past, current and planned missions for the Earth gravity field

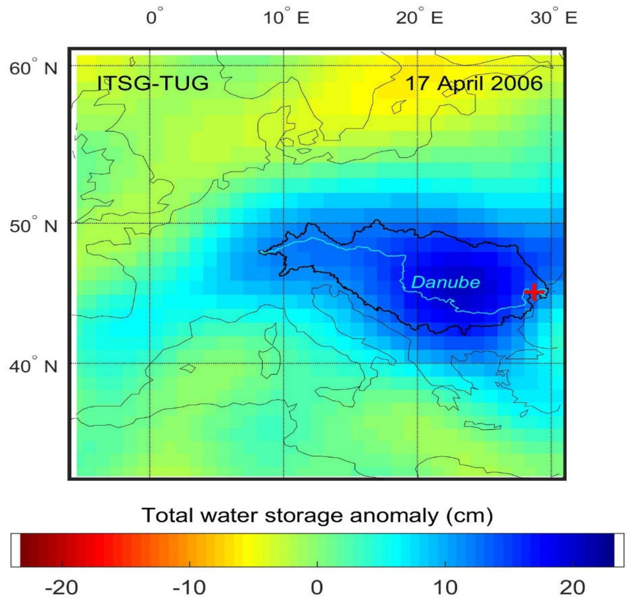
	Space missions like GRACE have formed a well-organized user community tracking the Earth mass movement to study environmental changes on a global scale using data from satellite measurements			*Static gravity field*
	CHAMP (2000-2010)	***GRACE (2002-2017)***	***NGGM (~2028)***	***GOCE (2009-2013)***
	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)	*~10^{-10} m/s^2*	*~10^{-11} m/s^2*	*~10^{-11} m/s^2*	*~10^{-12} m/s^2*
Geoid undulations	*~10 cm @ 350 km*	*~10 cm @ 175 km*	*~1 mm @ 500 km (every 3 days)* *~1 mm @ 150 km (every 10 days)*	*~1 cm @ 100 km*
Gravity anomalies	*~0.02 mGal @ 1000 km*	*~1 mGal @ 175 km*		*~1 mGal @ 100 km*

Main scientific applications of space gravimetry

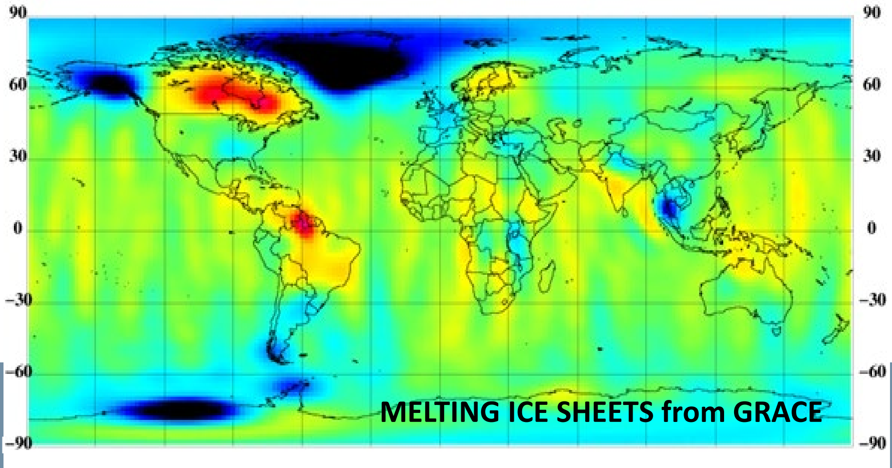
- ***Geodesy****: geodetic reference systems (geoid), height datum, inertial navigation, GNSS levelling.*
- ***Solid Earth Geophysics****: understanding deep Earth structure (one of few EO methods to “look” inside the Earth), monitoring of tectonic processes in the marine environment, mega-fault movements in subduction areas.*
- ***Hydrology, Oceanography, Climatology****: time variations in the mass of glaciers and lakes; ocean current mapping, sea level changes; mass exchange between atmosphere, oceans, cryosphere and solid earth.*



GEOID MODEL FROM GOCE DATA



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



MELTING ICE SHEETS from GRACE

Defining geophysical requirements
(Braitenberg et al., 2021)

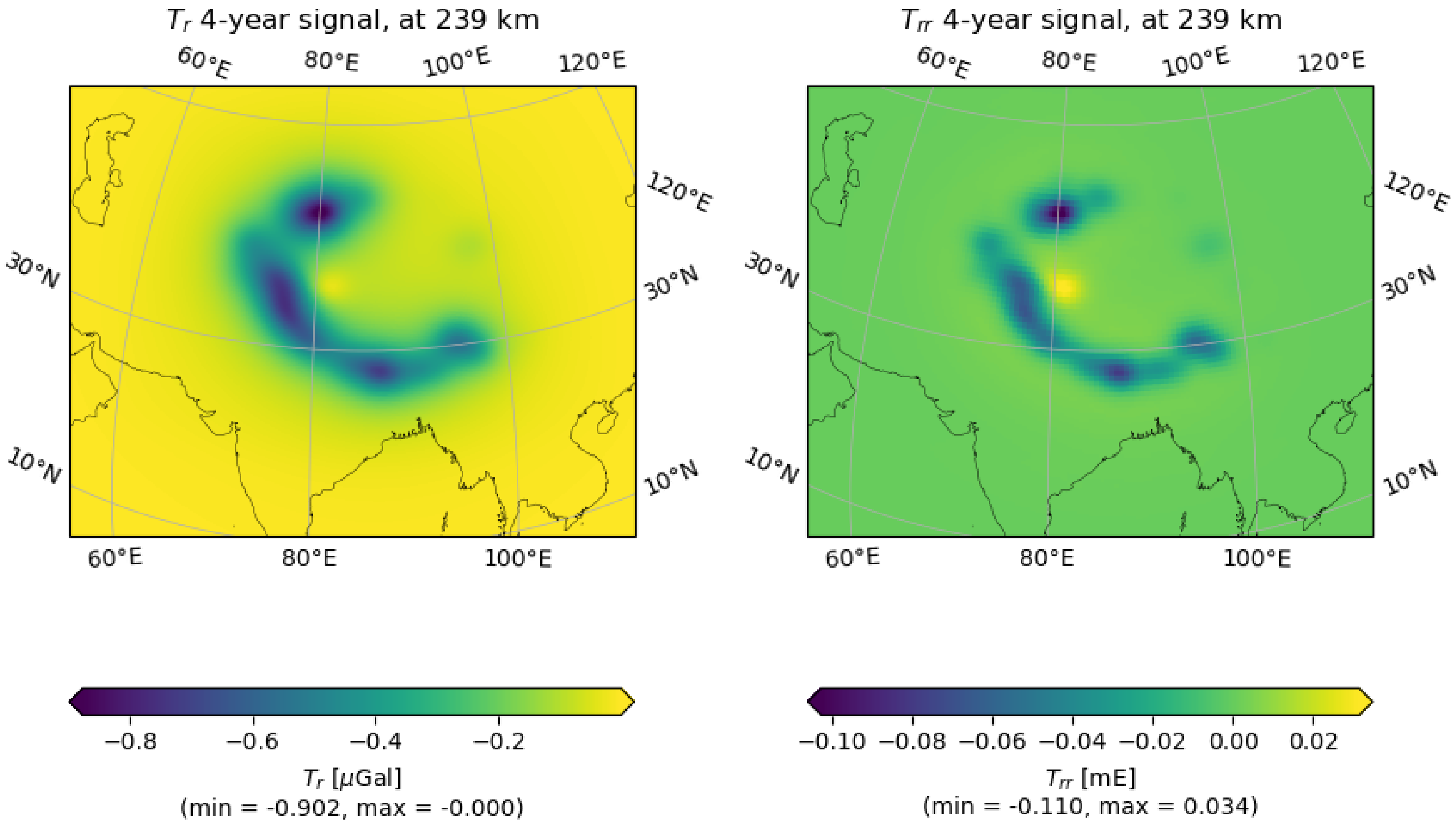
- To define user requirements, simulations of gravity signal generated by different geophysical phenomena are compared to the accuracies simulated for satellite and payload.

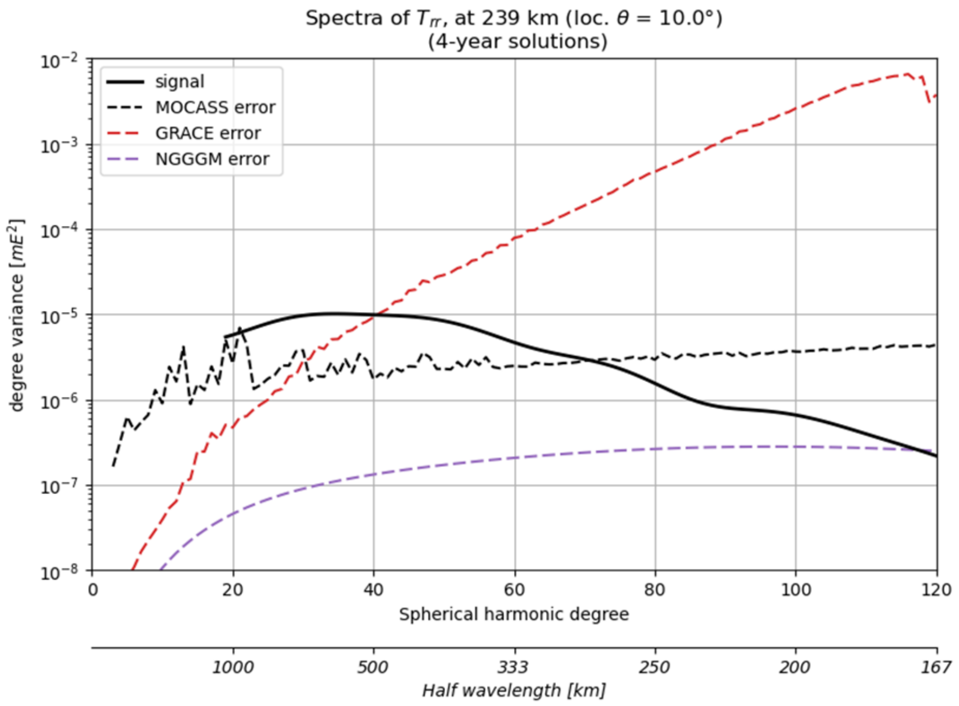
- (Braitenberg et al., 2021) describe simulations of:

    - **Glaciers** in South America and in High Mountains of Asia.
      Outlines, area, volume, deglaciation rates -> conversion to mass loss
    - **Uplift** in Tibet (GNSS measured) and conversion to mass change
    - **Seamounts** and mass change due to their growth
    - **Earthquakes**- coseismic and post-seismic movement and gravity change (Wang et al., 2007)
    - **Geologic structures**: useful in mineral exploration, geothermal potential estimate (Pastorutti & Braitenberg, 2019)

Defining geophysical requirements - Glaciers in HMA: localized spectrum of modelled gradient, compared to satellite noise curves
(Braitenberg et al., 2021)

4-year signal, **glaciers mass change for Tibet-Himalaya**





"**MOCASS**" (a study funded by ASI proposing a satellite gradiometry mission based on cold atom interferometry)
Migliaccio et al., 2019 (Surveys of Geophysics)
Reguzzoni et al. 2021 (PAGEOPH).

"**NGGM**"
Purkhauser et al., 2020, (Geophys.J.Int.)

"**GRACE**"
ITSG-Grace2014 , Mayer Gürr et al., 2014, GRACE Sci. team meeting

Users' requirements (geophysics)

Phenomenon	Requirement	Signal	Services
Glaciers (static)	60% of existing mountain glacier area	1 μGal @ d/o120. ground level	Glaciers volume estimation in support to ground measurements of depth
Seamount growth	10 m thickness eruption ➔ Volume change 1.6 10^9 m^3	0.2 μGal @ d/o 40 @ 250 km height	Global monitoring of underwater mass changes
Glaciers mass variations	Detect localized deglaciations 0.1 m over 2000 km^2	0.1 μGal @ d/o 50 @ 250 km height	Glaciers mass variations monitoring, mass tracking between cryosphere/hydrosphere

(Braitenberg, Pastorutti and Pivetta, 2021)

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)*

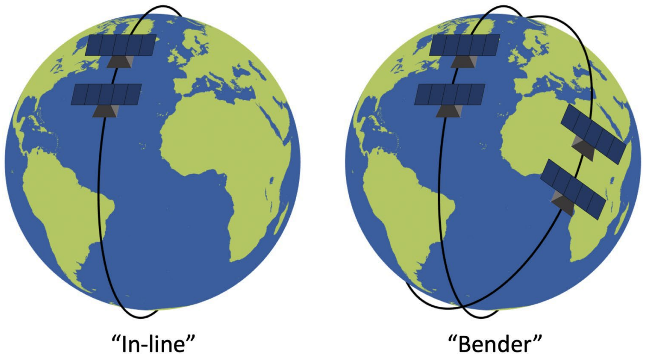
  A space mission will not be able to map the higher frequency details of the gravity field, due to the atmospheric limitations of the orbit height: full detailed mapping of the spatial gravity field variations down to a few km resolution must be supplemented by ***airborne and surface*** *gravity measurements.*

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

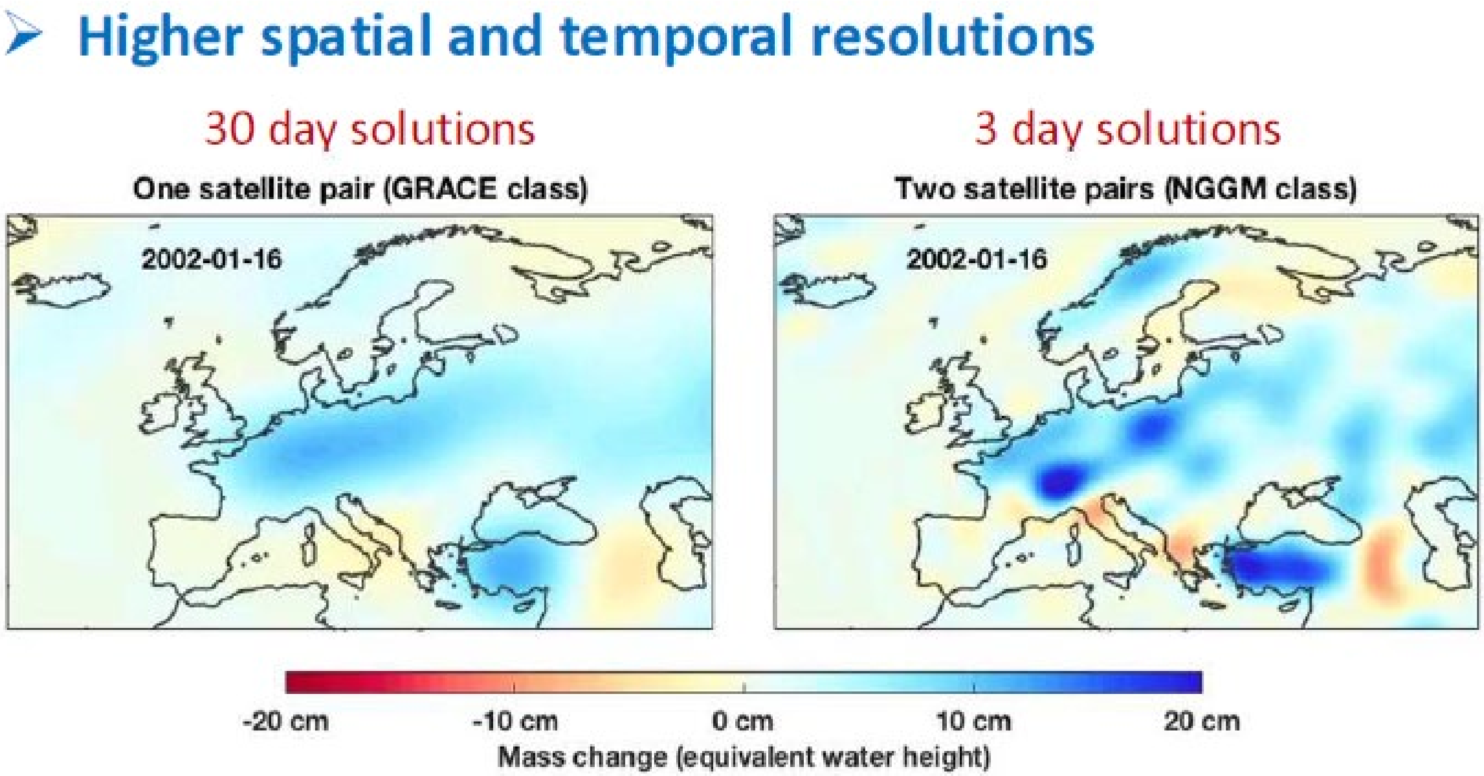
- ***Higher accuracy*** *in the measurements (>> new technologies: laser interferometry, cold atom accelerometers)*
  accelerometer better than $\sim 10^{-10}$ - 10^{-11} m/s^2 *(measurement range of* $\pm 10^{-4}$ m/s^2*);*
  gradiometer $\sim 10^{-12}$ $m/s^2/\sqrt{Hz}$ *for GOCE-like mission (over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



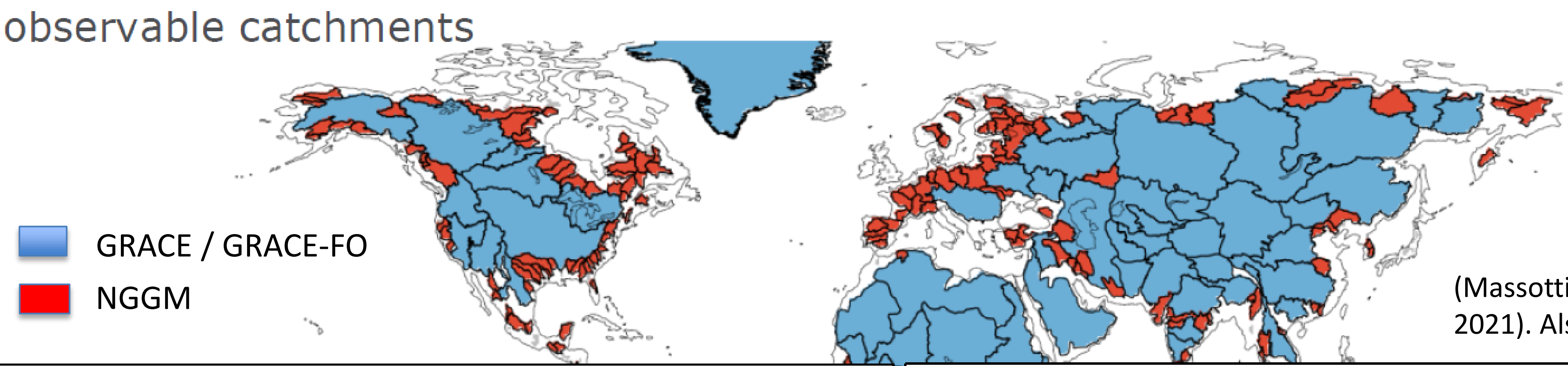
"In-line" (GRACE class) formation (left)
and "Bender" (NGGM class) formation (right)
(Haagmans et al., 2020)



(Massotti, Haagmans and Silvestrin, 2021)
Also in (Pail, 2021)

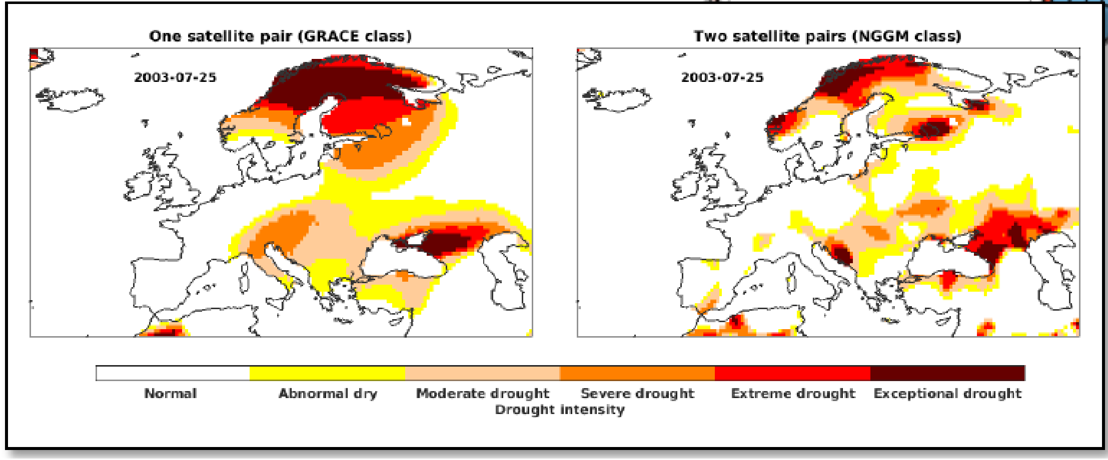
Higher spatial and temporal resolution from double-pair mission

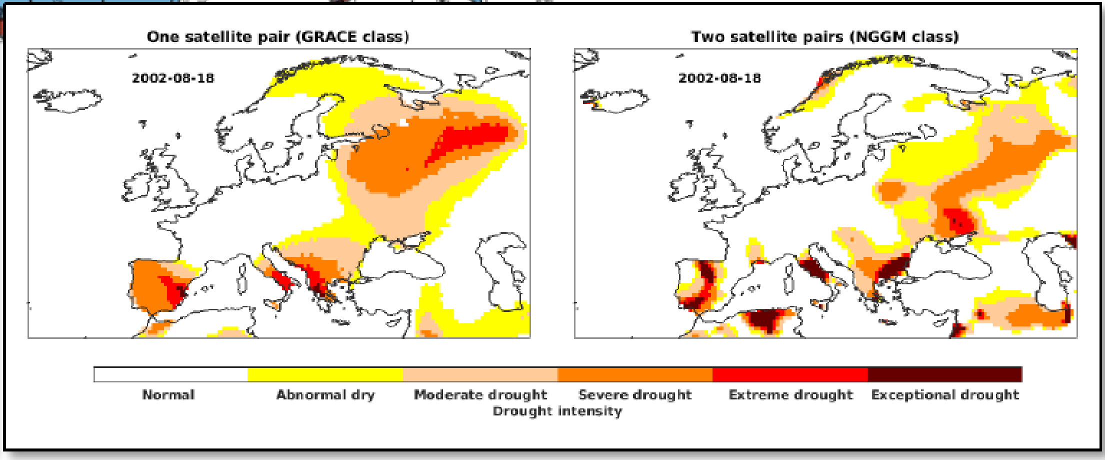
Possible better results for hydrology: better closure of the water cycle, drought and wetness indexes



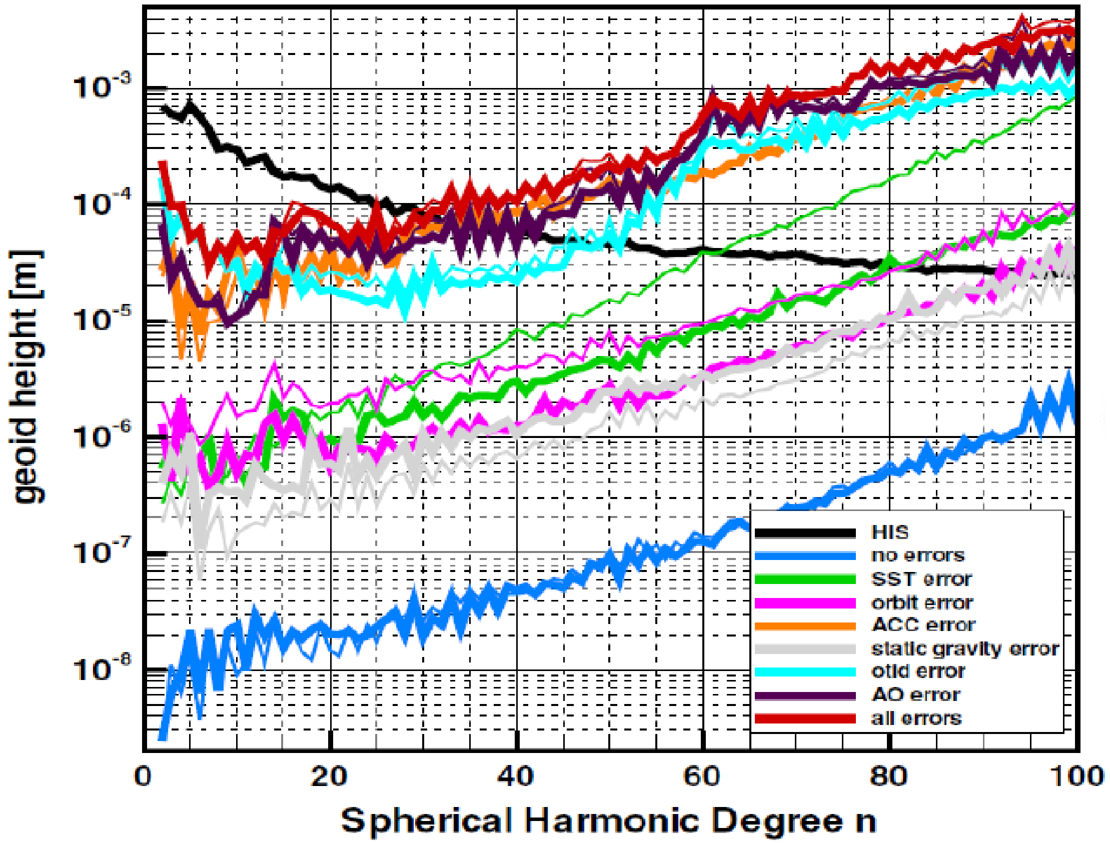
(Massotti, Haagmans and Silvestrin, 2021). Also in (Pail, 2021)

Drought intensity





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



(Flechtner et al., 2016)
Also in (Pail, 2021)

- accelerometer error
- ocean tide aliasing
- atmosphere & ocean aliasing

- 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.

Users’ needs in numbers

Consolidated Science and User Needs

… expressed in numbers

Threshold

Spatial resolution	Equivalent Water Height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400 km	5 mm	0.5 mm/yr	50 µm	5 µm/yr
200 km	10 cm	1 cm/yr	0.5 mm	0.05 mm/yr
150 km	50 cm	5 cm/yr	1 mm	0.1 mm/yr
100 km	5 m	0.5 m/yr	10 mm	1 mm/yr

- In combination with GRACE & GRACE-FO more reliable estimates of trends
- Improved spatial resolution
- Improved temporal resolution: reduction of aliasing

Target

Spatial resolution	Equivalent Water Height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400 km	0.5 mm	0.05 mm/yr	5 µm	0.5 µm/yr
200 km	1 cm	0.1 cm/yr	0.05 mm	5 µm/yr
150 km	5 cm	0.5 cm/yr	0.1 mm	0.01 mm/yr
100 km	0.5 m	0.05 m/yr	1 mm	0.1 mm/yr

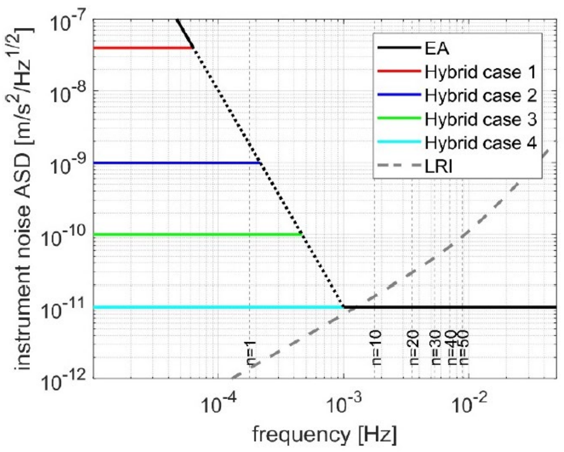
- Significant leap forward
- Significantly increased spatial and temporal resolution
- New applications (science, societal benefit)

→ **Only new mission concepts will meet these science and user needs**

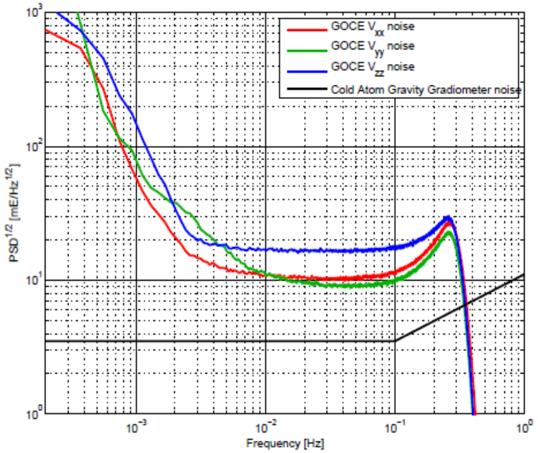
Source: (Pail, 2021)

Conclusions

- In satellite gravimetry, consolidated users' requirements point towards double-pair mission architecture (higher spatial resolution and revisit time, with the highest science return of all realistic observation concepts).
- Among key payload for a gravimetry mission, the accelerometer is one of the largest error contributor (although the instrument noise is not the limiting factor of gravity field performance).
- Improved instrument performance (especially ACC in the low frequency range) becomes important for satellite constellations (e.g. double pairs), provided there is a reduction of the currently dominant error sources of tidal models.
- Earth sciences will greatly benefit from future gravimetry missions with higher sensitivity, drift-free measurements, superior low frequency performance and higher absolute accuracy.
- **Quantum Space Gravimetry** (QSG) is expected to fulfil the needs for future improved gravity field measurements, **offering higher spatial resolution, much increased accuracy, and long-term stability.**



Hybridization classical accelerometers/CAI for SST (Carraz et al., this workshop)



Noise power spectral density for the cold atom gradiometer, as compared to the one of GOCE (Carraz et al. 2014)