SENSING THE PULSE OF THE EARTH WITH QUANTUM TECHNOLOGY

Prof. Dr. Matthias Weigelt

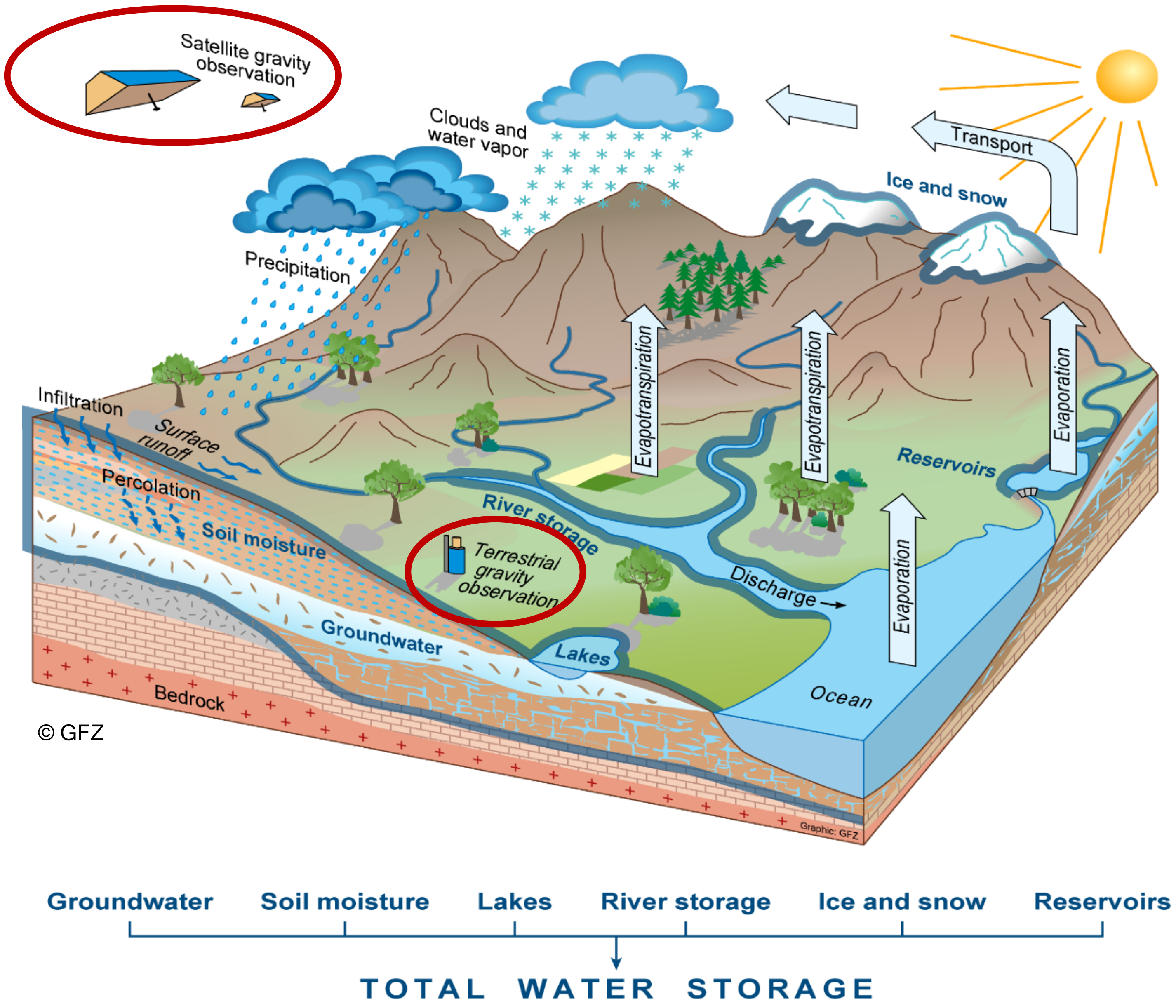
DLR

What is the pulse of the Earth?

- Water cycle
- Ocean circulation
- Carbon cycle
- Nutrient cycle
- Rock cycle

Gravimetry is a universal tool to sense the pulse of the Earth

Water cycle



Continental water balance

$$\Delta S = P - ET - Q$$

P: Precipitation
ET: Evapo(trans)piration
Q: Runoff
ΔS: Storage change

The carbon cycle in sight …

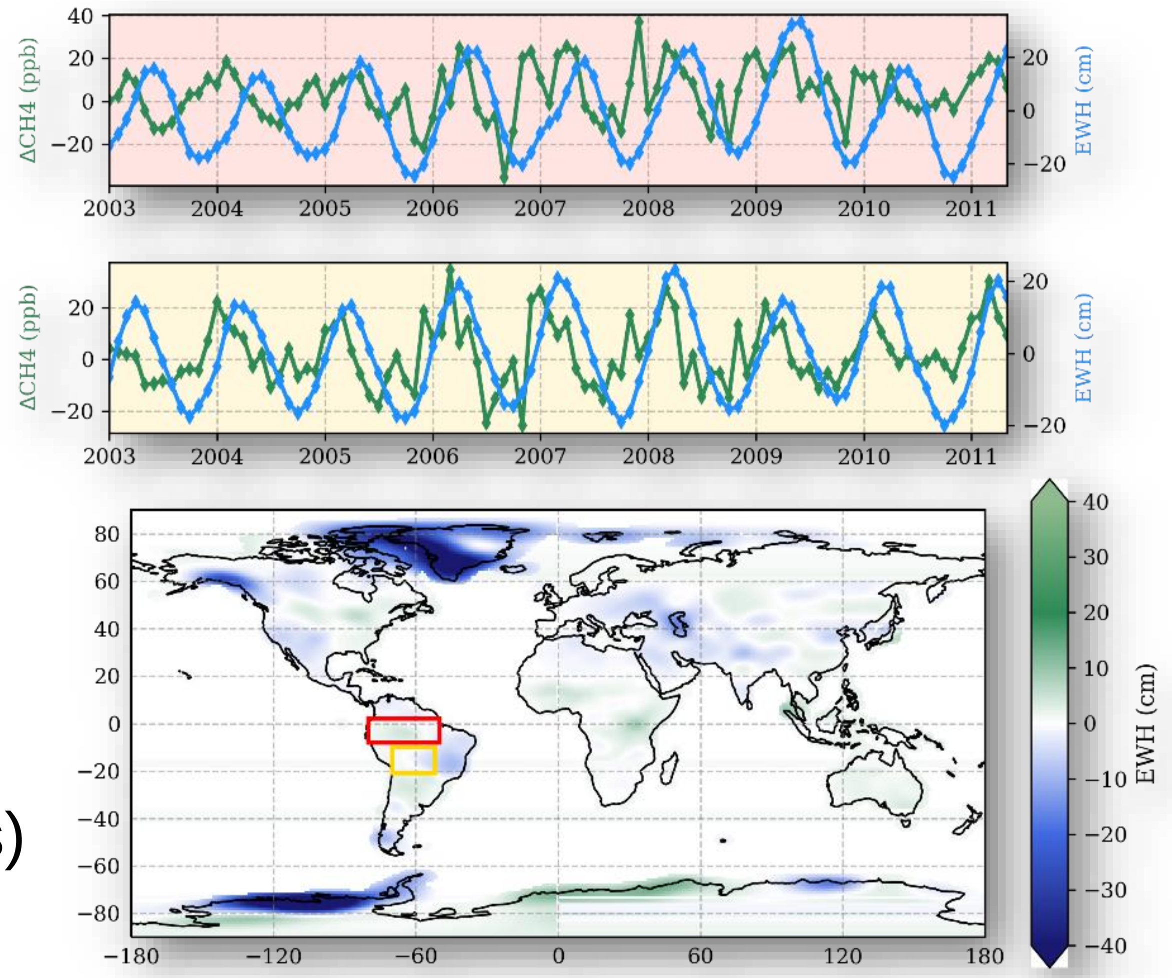
Wetlands are the largest natural Methan (CH4) source

Project:

Wechselwirkung zwischen Kohlenstoff- und Wasserkreislauf

CH4 is produced during

anaerobic decomposition (Methanogenesis)



Klemme et al. 2022

Observing gravity is observing climate change

INSTITUTE FOR SATELLITE GEODESY AND INERTIAL SENSING

Deutsches Zentrum für Luft und Raumfahrt (DLR e.V.)
Institut für Satellitengeodäsie und Inertialsensorik (DLR-SI)
Callinstrasse 30b, 30167 Hannover

Our mission

DLR-SO

DLR-GK

DLR-SC

DLR-FL

DLR-QT

DLR-KN

DLR-RY

...

Satellite geodesy
- highly precise data for climate change
- better gravity field data
- global reference systems for space and time using ultra-cold atoms

Inertial sensors
- navigation for intelligent mobility
- new sensors for satellite missions and exploration
- Quantum gas und optical interferometry

Research
- mission and concept studies
- data analysis
- simulations
- hybrid sensor technology

Development
- space qualification
- prototypes
- systems engineering tools

Technology transfer
- cooperationen (inter-)national
- industry
- start-up
- patents

DLR

NASA

cnes

AIRBUS

OHB

Leibniz Universität Hannover

Universität Bremen

...

DLR-SI in numbers

- Locations
  - Hannover
  - Bremen

- Human Resources
  - Scientific Personal 40
  - HiWi 4
  - Master/Bachelor 3
  - Administrative MA 6

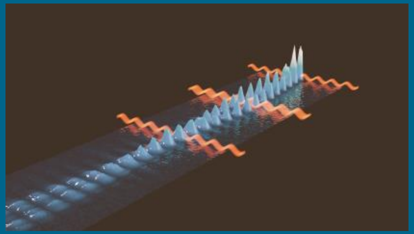
- Close co-location to the Universities

Utilizing the fundamental properties of atoms and molecules
to improve measurement accuracy and resolution

Laser interferometry

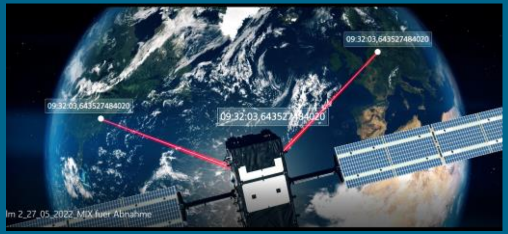
- Long-term stability, high-precision distance measurements
- High-precision measurement of the smallest angles

Atom interferometry



- Absolute, drift-free, highly accuarte
- Accelerometer
- Rotation sensor

Optical clocks



- absolute, drift-free, highly accurate
- navigation
- reference system for height profiles

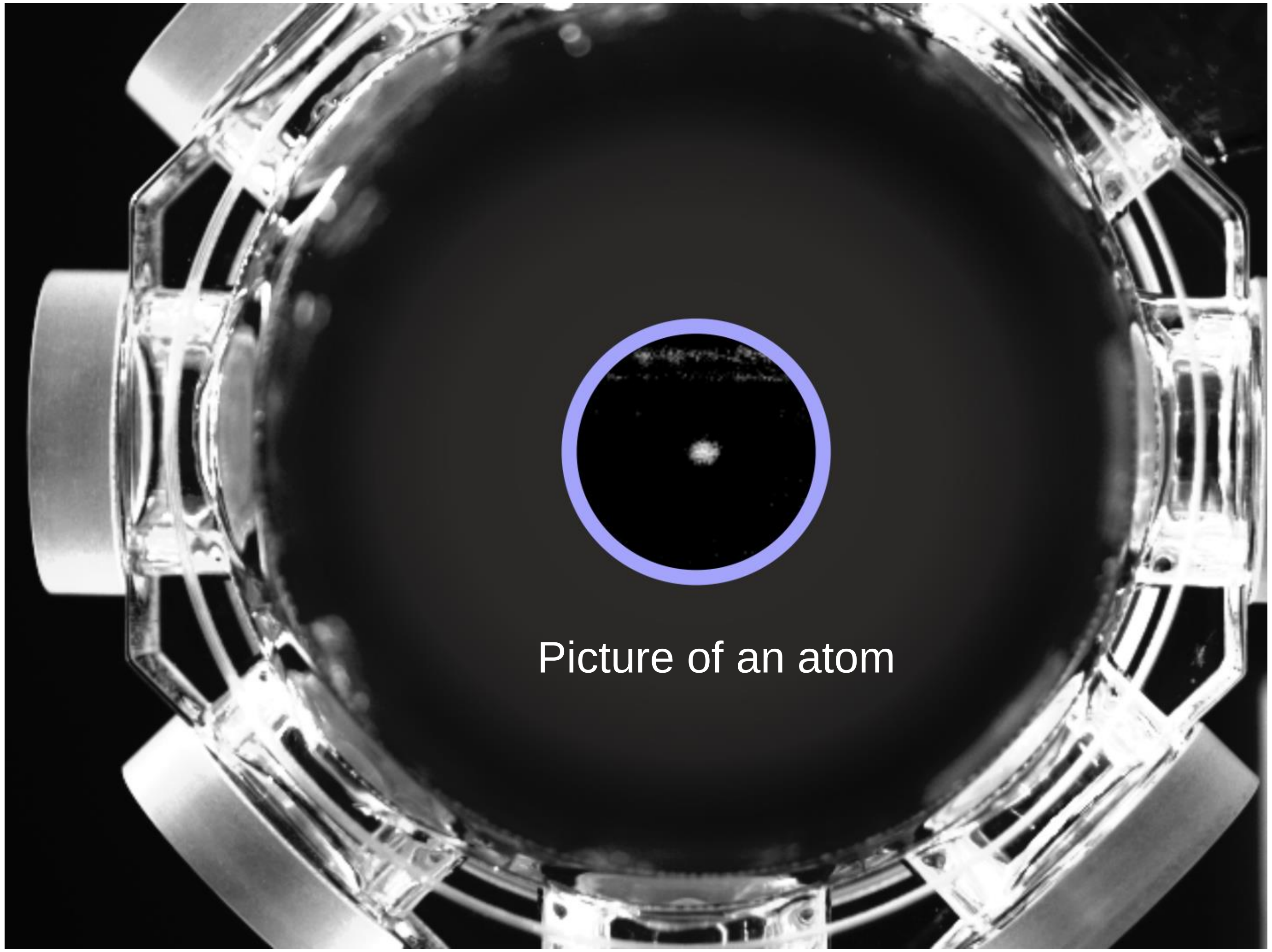
Digital Twin: orbit propagation considering all disturbing forces (environment, space weather, satellite), simulation of sensors, systems engineering tools

Geodetic Modelling
Preparation of gravity field data for the public and data analysis tools

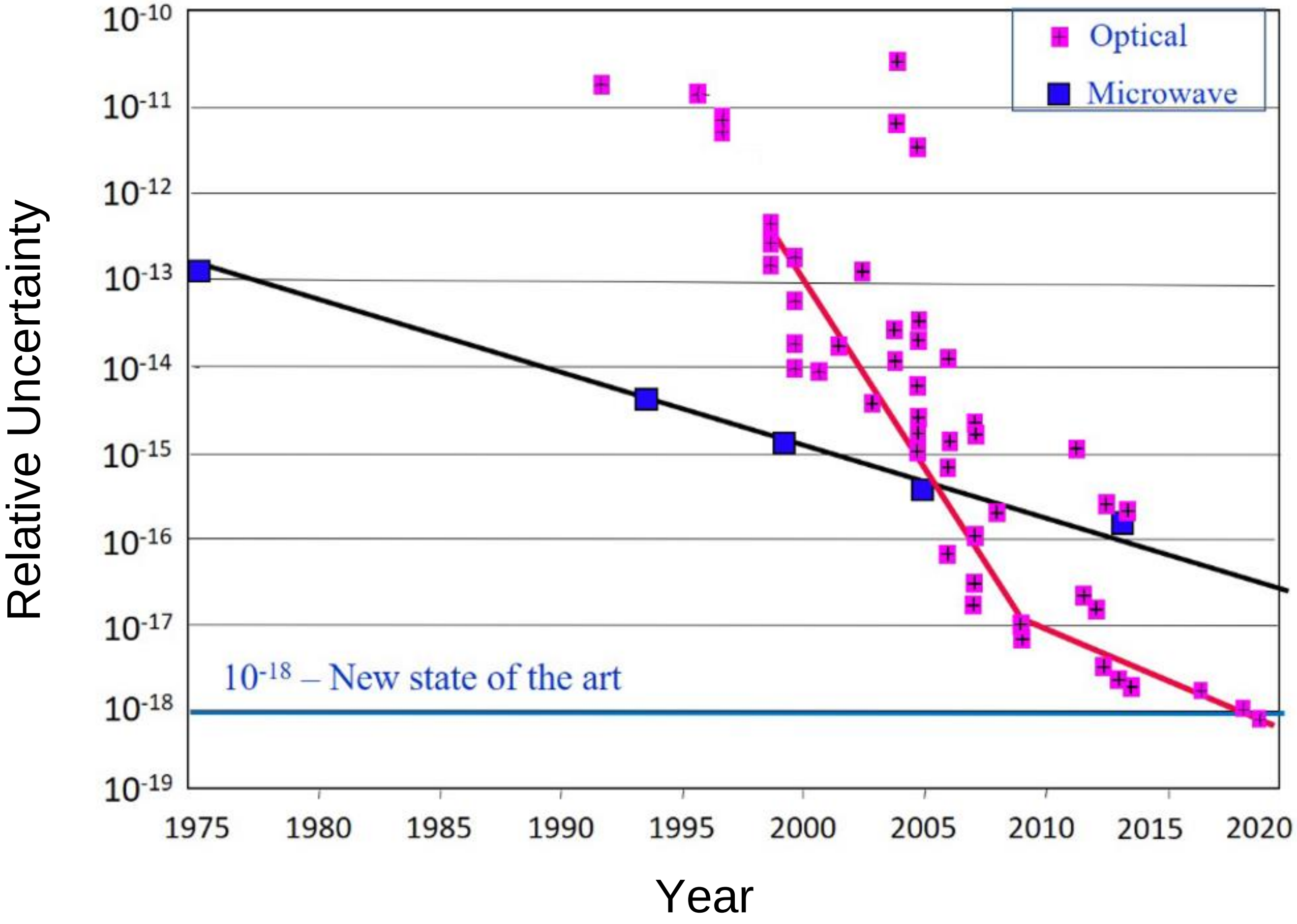
OPTICAL FREQUENCY METROLOGY

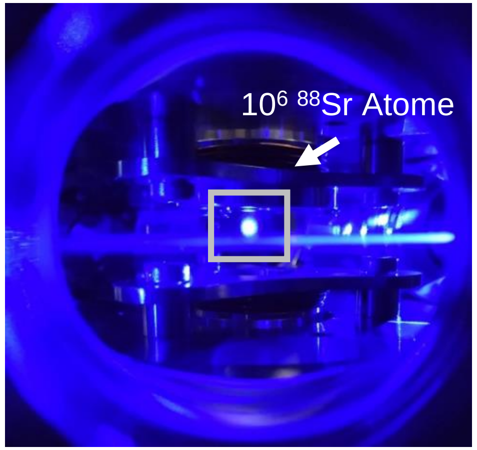
Quantum Sensors

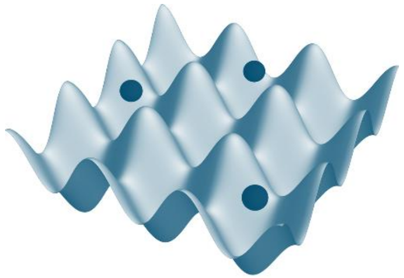
- Isolating atoms from a noisy environment
- Controlling atoms on the quantum level (→ wave properties)
- Using atoms for ultra-precise interferometer
  - Accelerometry
  - Rotational Sensors
  - Gravimetry/Gradiometry
  - Time- and Frequency



Improving the precision of clocks







Optical lattice clock

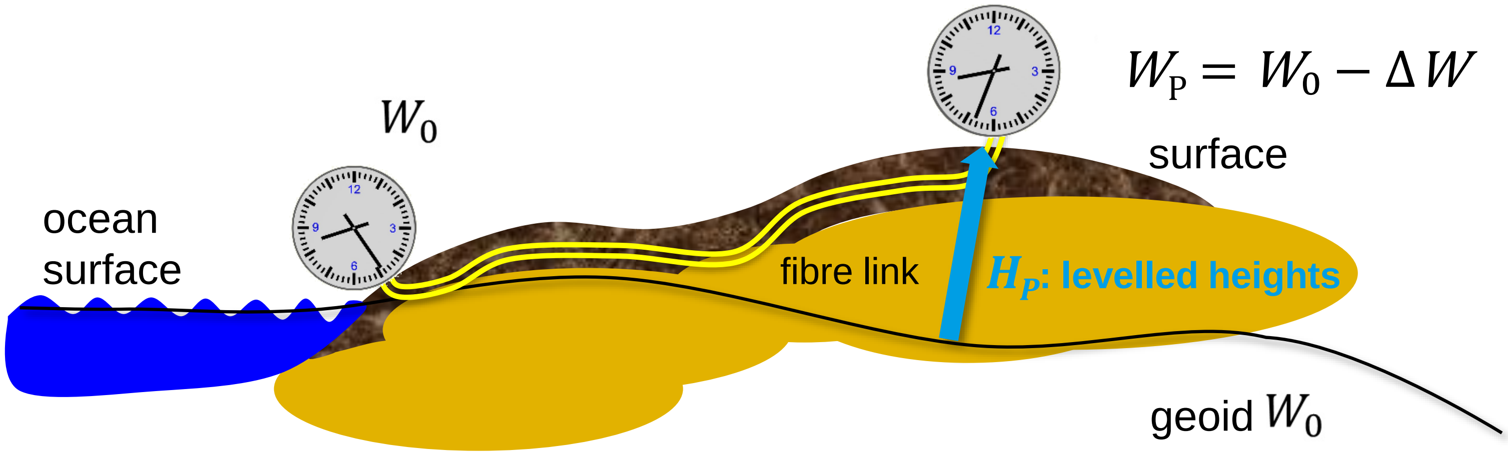
Derevianko et al., arXiv:2112.10817 (2021)

Networks of Clocks: Objectives

- relativistic frequency change: $\frac{\Delta f}{f} = \frac{W_0 - W_P}{c^2}$
- gravity potential W: Newtonian + centrifugal terms
- height: $H_P = \frac{W_0 - W_P}{\bar{g}} = \frac{c^2}{\bar{g}} \frac{\Delta f}{f}$

➔ Chronometric levelling over long distances

➔ Clock-based height system

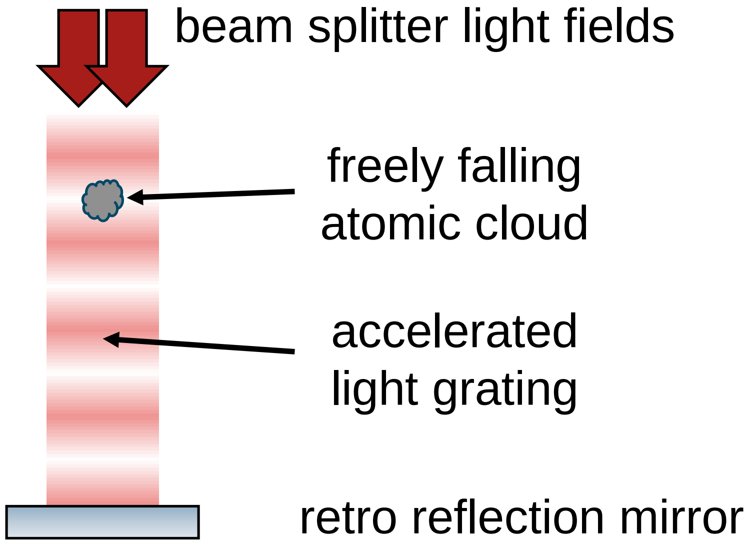


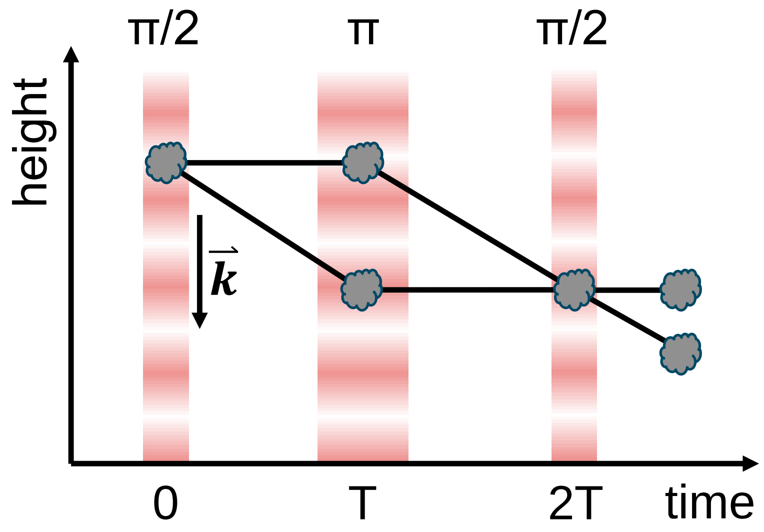
Vermeer, Reports of the Finnish Geodetic Institute **83(2)**, 1(1983); Bjerhammar, Bull. Geodesique **59**, 207 (1985).

ATOM INTERFEROMETRY

Atom interferometry

Atoms in free fall, Mach-Zehnder like π/2 – π – π/2 pulse geometry:





Interferometer phase, ϕ_i imprinted at pulse i: $\phi_{tot} = \phi_1 - 2\phi_2 + \phi_3$

Acceleration $\vec{a}$, effective wave vector $\vec{k}$: $\phi_{acc} = \vec{\boldsymbol{k}} \cdot \vec{a}\, \boldsymbol{T}^2$

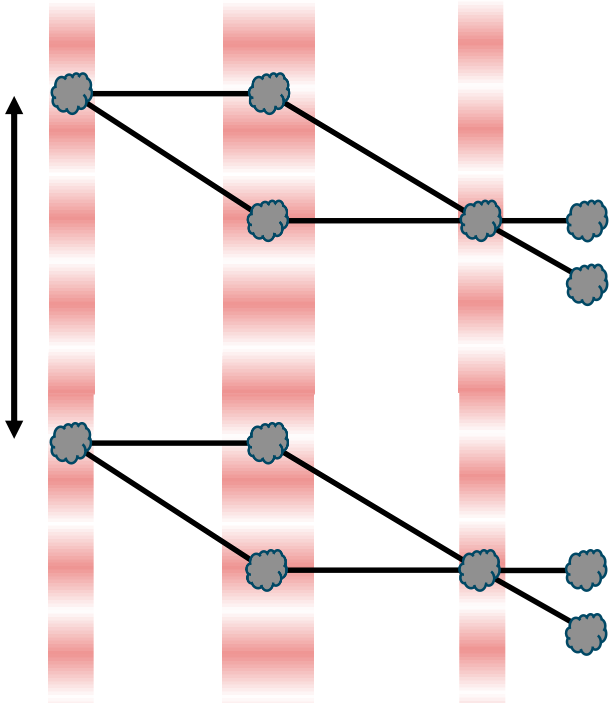
Forward drift velocity $\vec{v}$, rotation $\vec{\Omega}$, enclosed area $\vec{A}$: $\phi_{rot} = 2(\vec{\boldsymbol{k}} \times \vec{v}) \cdot \vec{\Omega}\, \boldsymbol{T}^2 \sim \vec{\boldsymbol{A}} \cdot \vec{\Omega}$

Gravity gradiometer

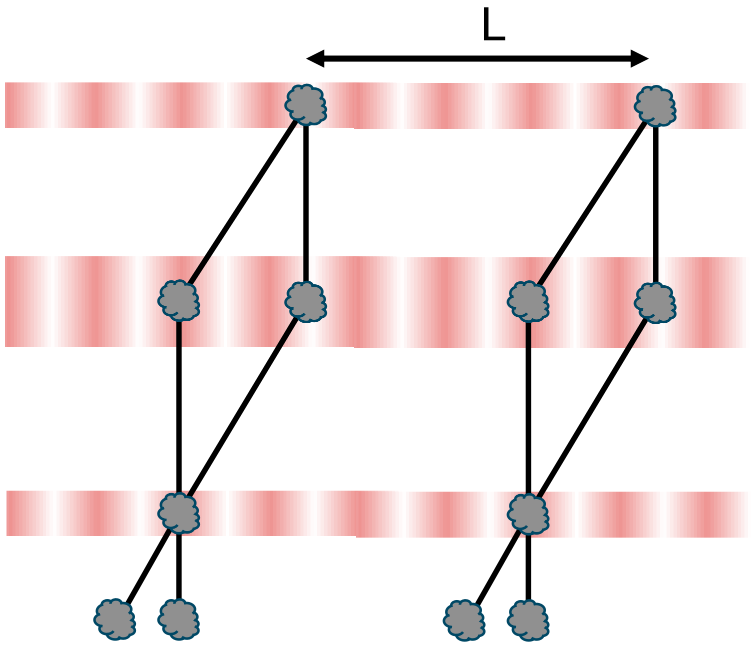
Combination of two Mach-Zehnder like atom interferometers, simultaneous interrogation with the same light field → extraction of mean gravity gradient between the two interferometers from the differential signal

Vertical orientation

Baseline separation L



Horizontal orientation



[McGuirk et al., PRA 65, 033608 (2002); Fixler et al., Science 315, 74 (2007); Biedermann et al., PRA 91, 033629 (2015); Chiow et al., PRA 93, PRA 93, 013602 (2016); Rosi et al., Nature 510, 518 (2014); Asenbaum et al. PRL 118, 183602 (2017)]

State of the art in AI-based quantum sensors

Rotation sensors

Stability:
- 30 nrad/s in 1s
- 0.1 nrad/s after averaging

Uncertainty:
- Few nrad/s to 10 nrad/s

Gravimeters

Stability:
- 42 nm/s^2 in 1s
- 0.5 nm/s^2 after averaging

Systematic uncertainty:
- 40 nm/s^2
- Limited by wave front distortions [1)]

Transportable, sea, flight, commercial versions

Gravity gradiometers

Stability:
- $3 \cdot 10^{-8}$ $1/s^2$ in 1s

Systematic uncertainty
- $8 \cdot 10^{-8}$ $1/s^2$

Determination of gravitational constant

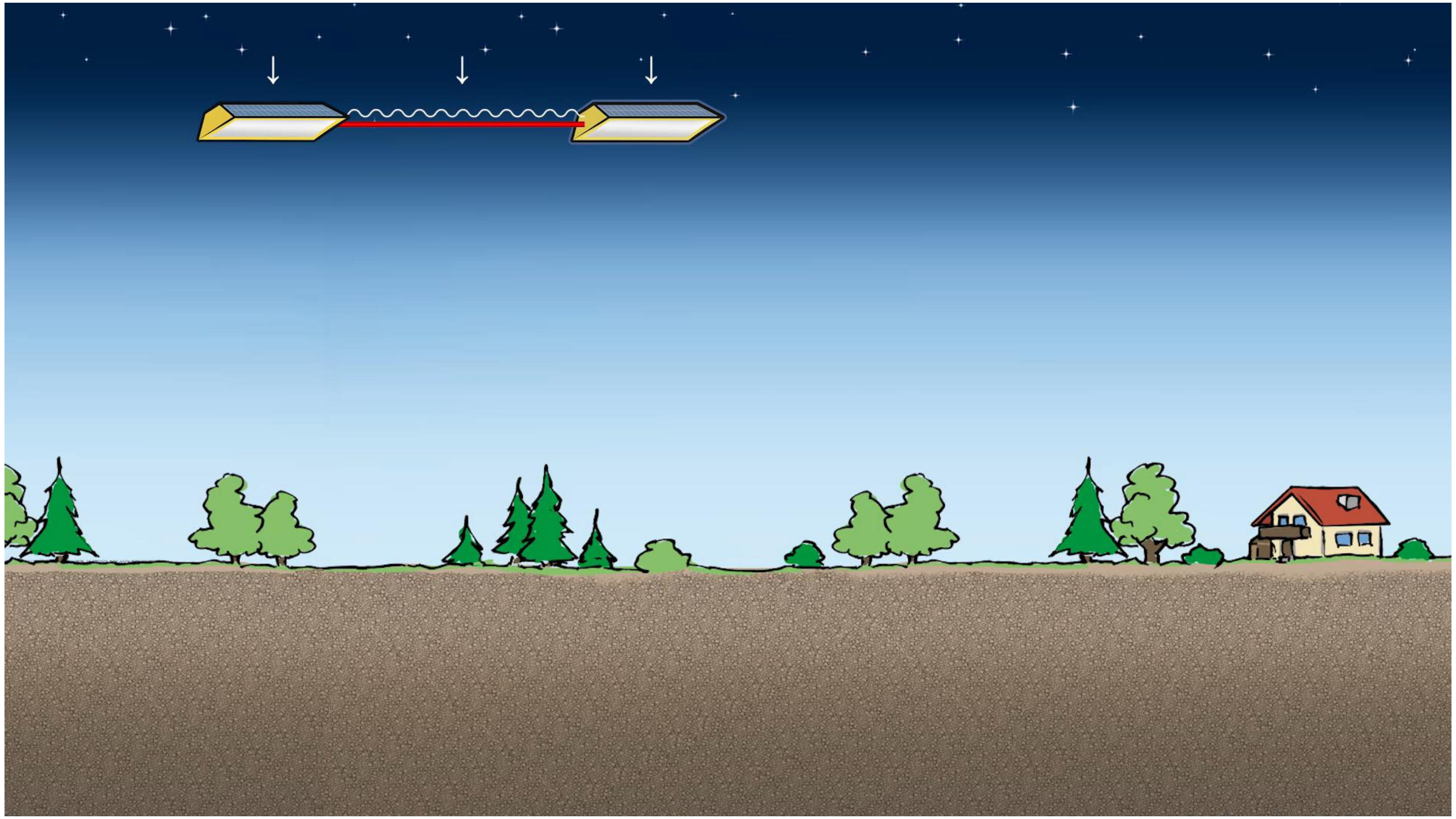
[From: Chen et al., arXiv:2303.00239; Gautier et al., Sci. Adv. 8, eabn8009 (2022); Berg at al., PRL 114, 063002 (2015); Stockton et al., PRL 107, 133001 (2011); Gauguet et al., PRA 80, 063604 (2009); Gillot et al., Metrologia 51, L15-L17 (2014); 1) reduced in Karcher et al., NJP 20, 113041 (2018); Freier et al., JoP:CS 723, 012050 (2016); Hu et al., PRA88, 043610 (2013); Wu et al., Sci. Adv. 5, eaax0800 (2019); Bidel et al., Nat.Comm. 9, 2041 (2018); Bidel et al., JoG 94, 1432 (2020); muquans.com; McGuirk et al., PRA 65, 033608 (2002); Fixler et al., Science 315, 74 (2007); Biedermann et al., PRA 91, 033629 (2015); Chiow et al., PRA 93, PRA 93, 013602 (2016); Rosi et al., Nature 510, 518 (2014); Asenbaum et al. PRL 118, 183602 (2017)]

LASER INTERFEROMETRY

From observing geometry to understanding the forces …

GRACE-FO observation systems

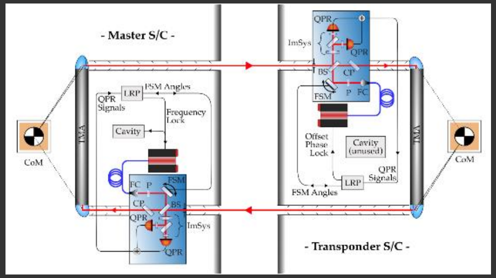
- Initial orbit height: 485 km
- Inclination: ~ 89°
- Key technologies:
  - GPS
  - Accelerometer
  - Ranging system
- Observation quantity:
  - distance (range)
  - change of distance (range rate)

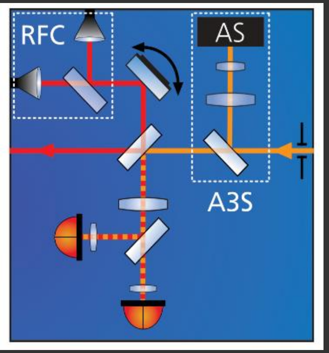


Satellite Gravimetry with laser interferometry

Components for the next generation optical bench designs

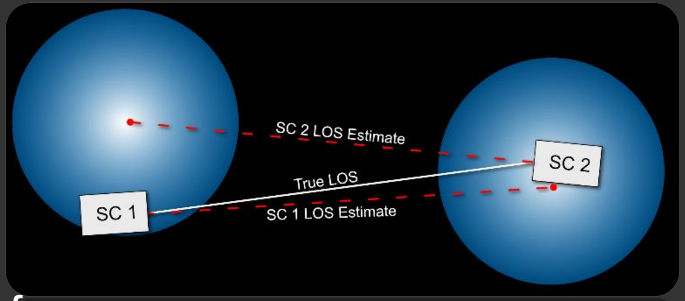
- Laser ranging as main science instrument requires improved redundancy schemes
- Miniaturization of components
- Novel concepts

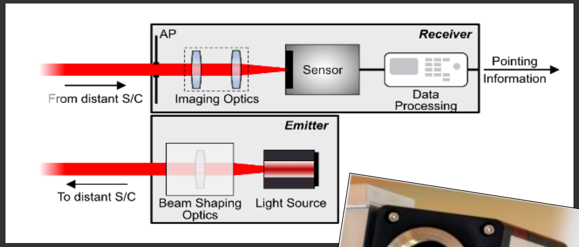


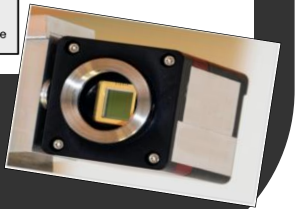


Dedicated Constellation Acquisition Systems

- Laser link acquisition is the most critical step during commissioning of the instrument
- Dedicated hardware mitigates risks and speeds up this process



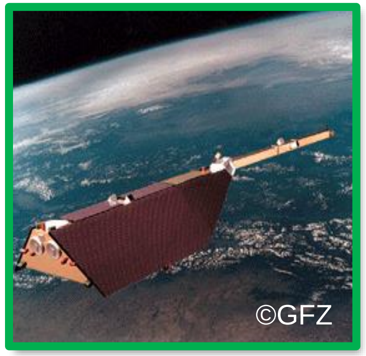


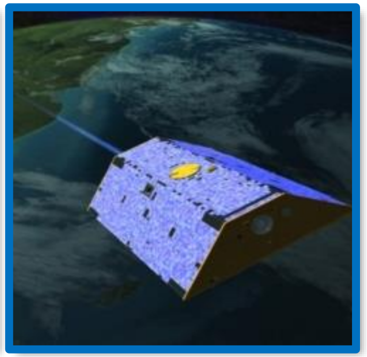


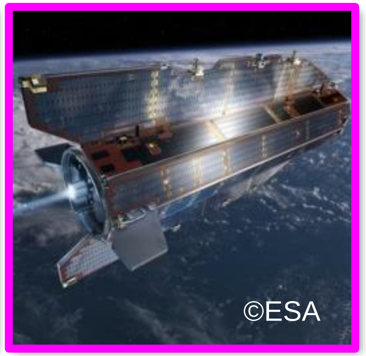
MiniCAS:

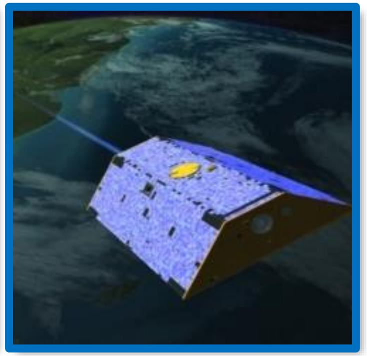
- Compact, modular, low SWaP design

Continuity of mass transport measurements









CHAMP (GFZ, 2000-2010)

GRACE (NASA/DLR, 2002-2017)

GRACE-FO (NASA/GFZ, 2018-2030)

GOCE (ESA, 2009-2013)

MAGIC

GRACE-C (2028-203?)

NGGM (2031-203?)

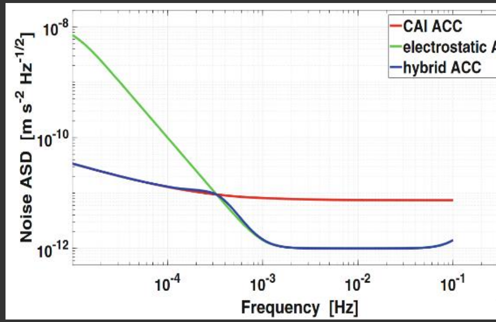
Gravity missions enabled spectacular results:

- insights into the global water cycle
- polar and mountain ice mass loss
- changes in ocean surface currents
- unification of height systems
- sea level rise

Satellite Gravimetry in the post-MAGIC era
- Accelerometry -

A) Cold Atom Interferometers

- Hybridization with optical sensor
- Absolute measurements
- Drift-free
- Superb precision



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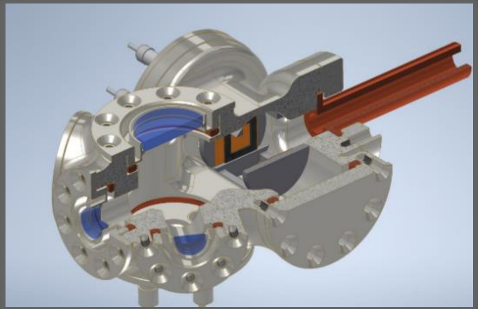
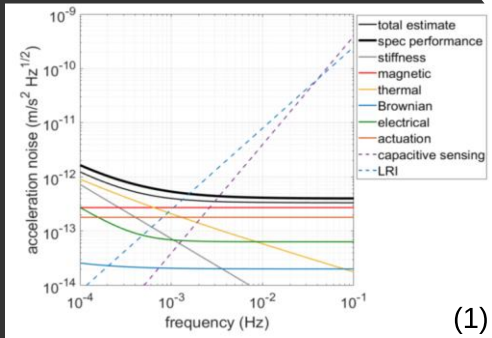
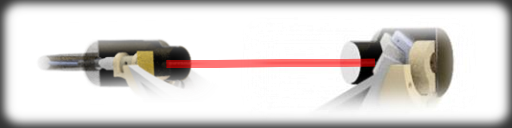


B) Gravitational Reference Sensor

- Based on heritage from LISA Pathfinder
- Superb precision
- Long-term stable
- Capacitive or optical readout
- Multi-axis optical readout requires compact inter-ferometric setups

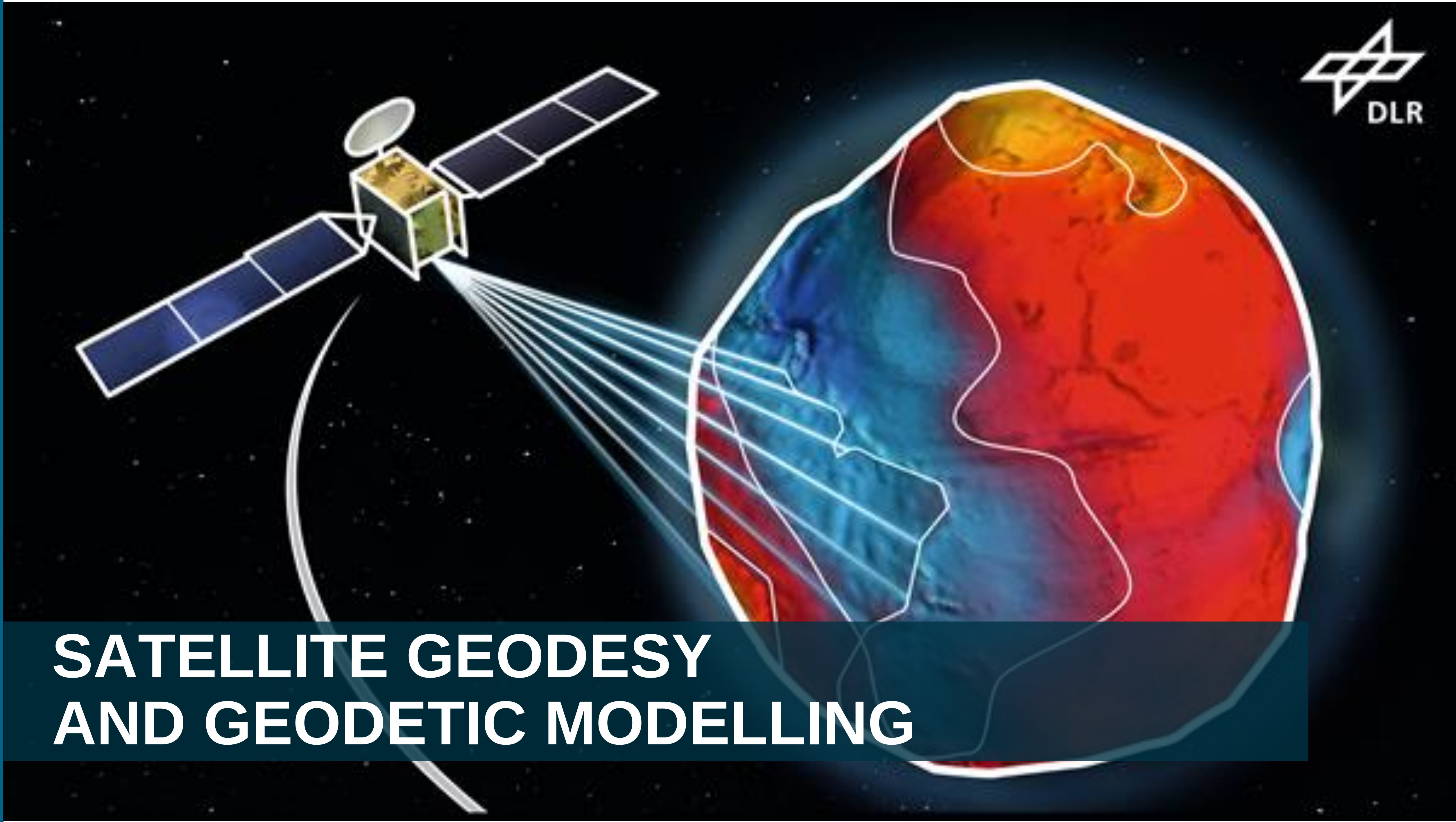


(1)




(1)

(1) https://doi.org/10.1007/s00190-022-01659-0
(2) https://doi.org/10.1007/1345_2022_151



SATELLITE GEODESY AND GEODETIC MODELLING

ATOM INTERFEROMETRY IN SPACE

CARIOQA-PMP

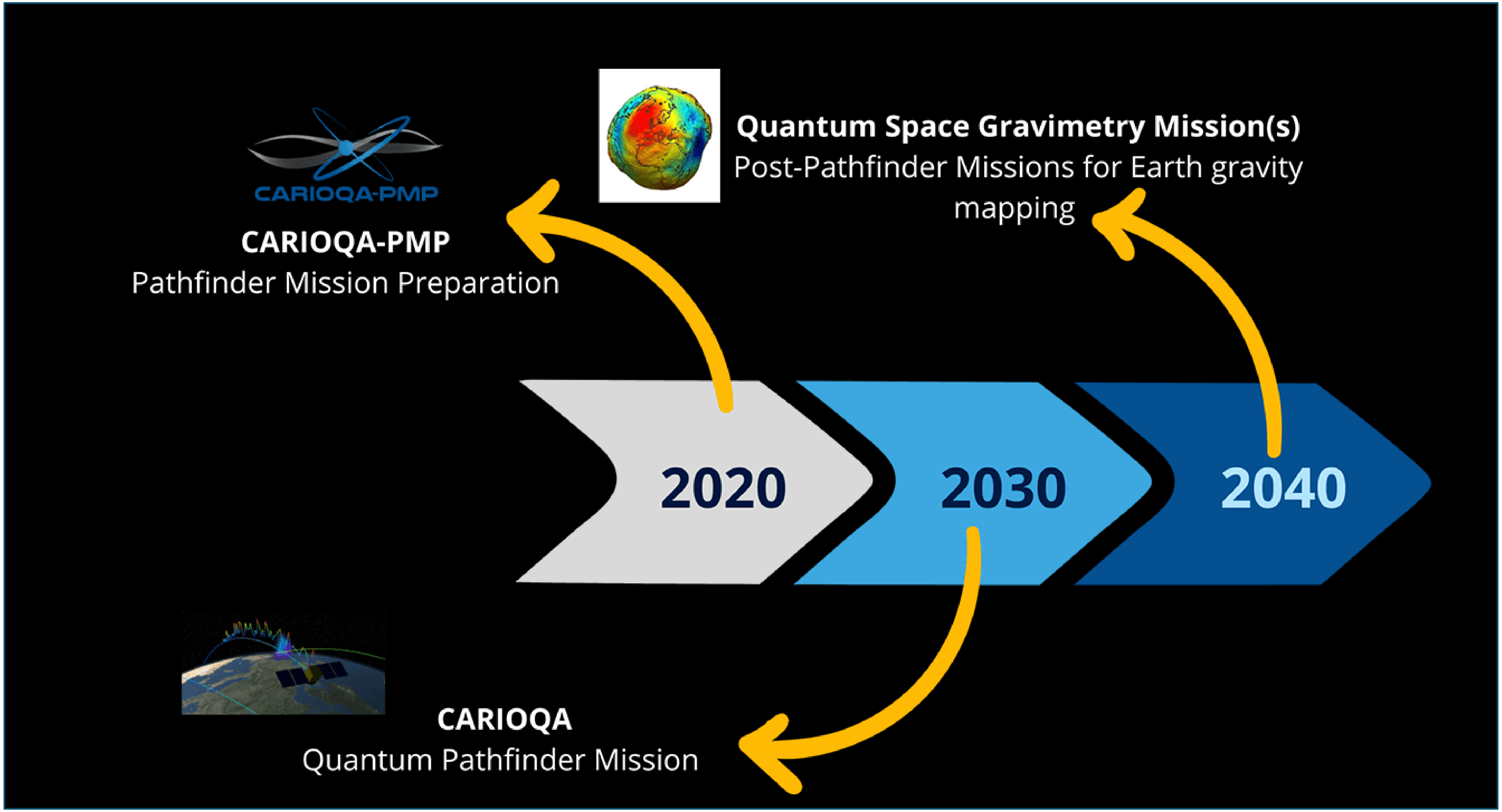
stands for

Cold **A**tomium **R**ubidium **I**nterferometer in **O**rbit for **Q**uantum **A**ccelerometry

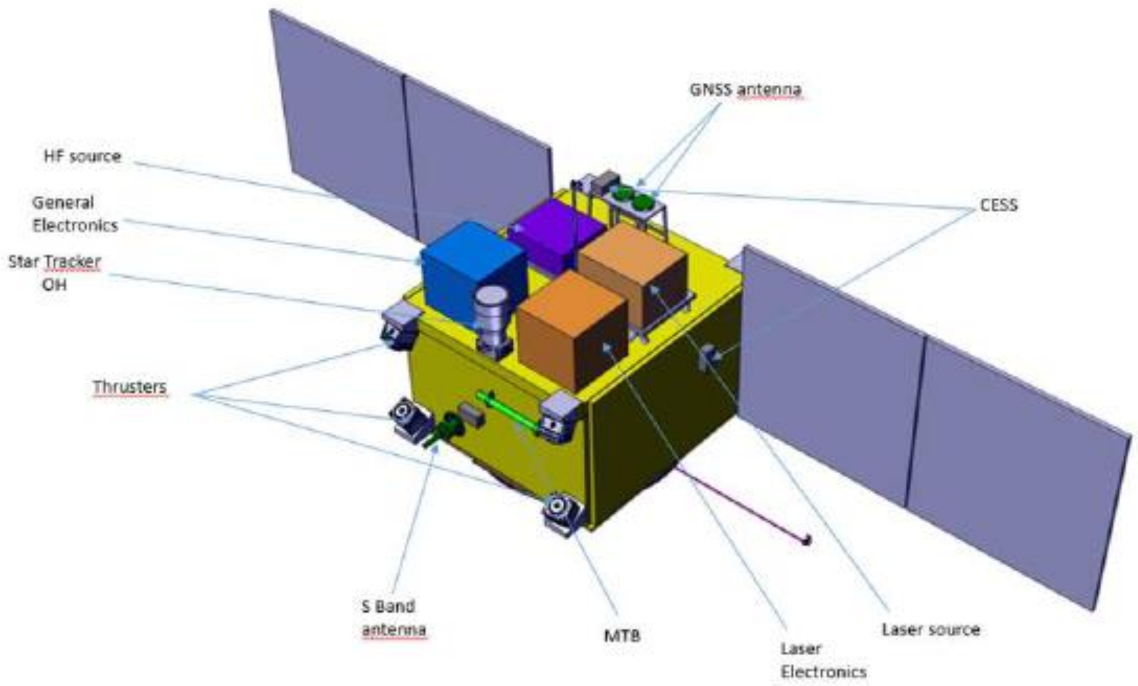
- **P**athfinder **M**ission **P**reparation -

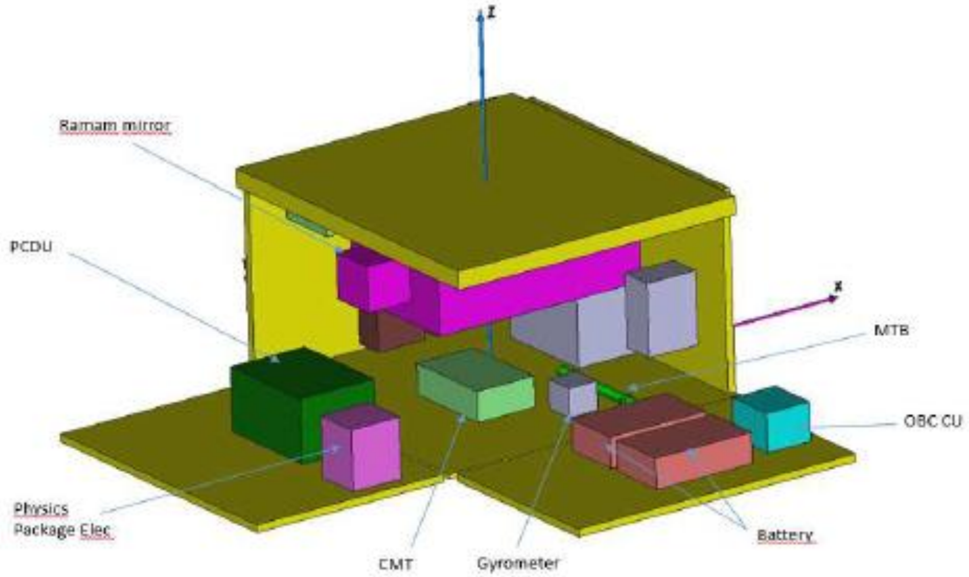
Through a Quantum Space Gravimetry Pathfinder Mission
CARIOQA-PMP aims at developing a new technology to be used in space within the next decade: a quantum gravimeter/ accelerometer

Timeline


CARIOQA-PMP
CARIOQA-PMP
Pathfinder Mission Preparation
Quantum Space Gravimetry Mission(s)
Post-Pathfinder Missions for Earth gravity mapping
2020
2030
2040
CARIOQA
Quantum Pathfinder Mission

Preliminary satellite concept





from Lévèque et al. 2022

Consortium

CARIOQA-PMP brings together **leading 17 players from 5 EU countries:**

Coordination
CNES and DLR under CNES lead

Satellite instrument development

Airbus Defence and Space, Exail, TELETEL, LEONARDO

Quantum sensing

LUH, SYRTE, LP2N, LCAR, ONERA, IESL/FORTH

Space geodesy, Earth sciences

LUH, TUM, POLIMI, DTU

Impact maximization and impact assessment

FORTH/ PRAXI Network, G.A.C. Group

Anticipated sensitivity

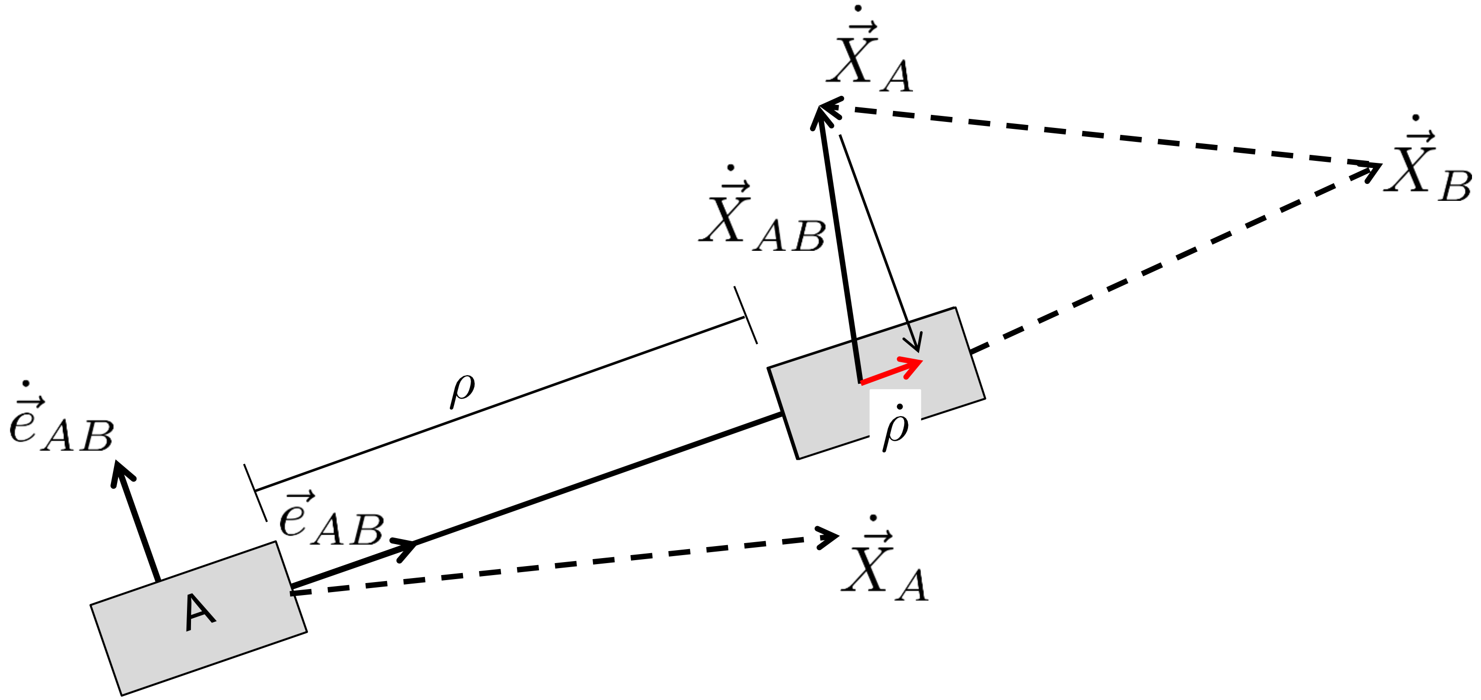
Instrument	Applications	Sensitivity
Absolute quantum gravimeter (SYRTE)	Ground/Laboratory	5×10^{-8} m.s^{-2}.Hz$^{-1/2}$
Commercial absolute quantum gravimeter (IXBLUE/Muquans)	Ground/Field applications	5×10^{-7} m.s^{-2}.Hz$^{-1/2}$
Absolute atom accelerometer/gravimeter in microgravity (ICE/LP2N)	Microgravity	6×10^{-7} m.s^{-2}.Hz$^{-1/2}$
Quantum Pathfinder Mission (CARIOQA)	**Satellite**	**1×10^{-10} m.s^{-2}.Hz$^{-1/2*}$**
Quantum Space Gravimetry Missions	Satellite	1×10^{-12} m.s^{-2}.Hz$^{-1/2}$

**Targeted Quantum projection noise floor*

from Lévèque et al. 2022

LASER INTERFEROMETRY IN SPACE

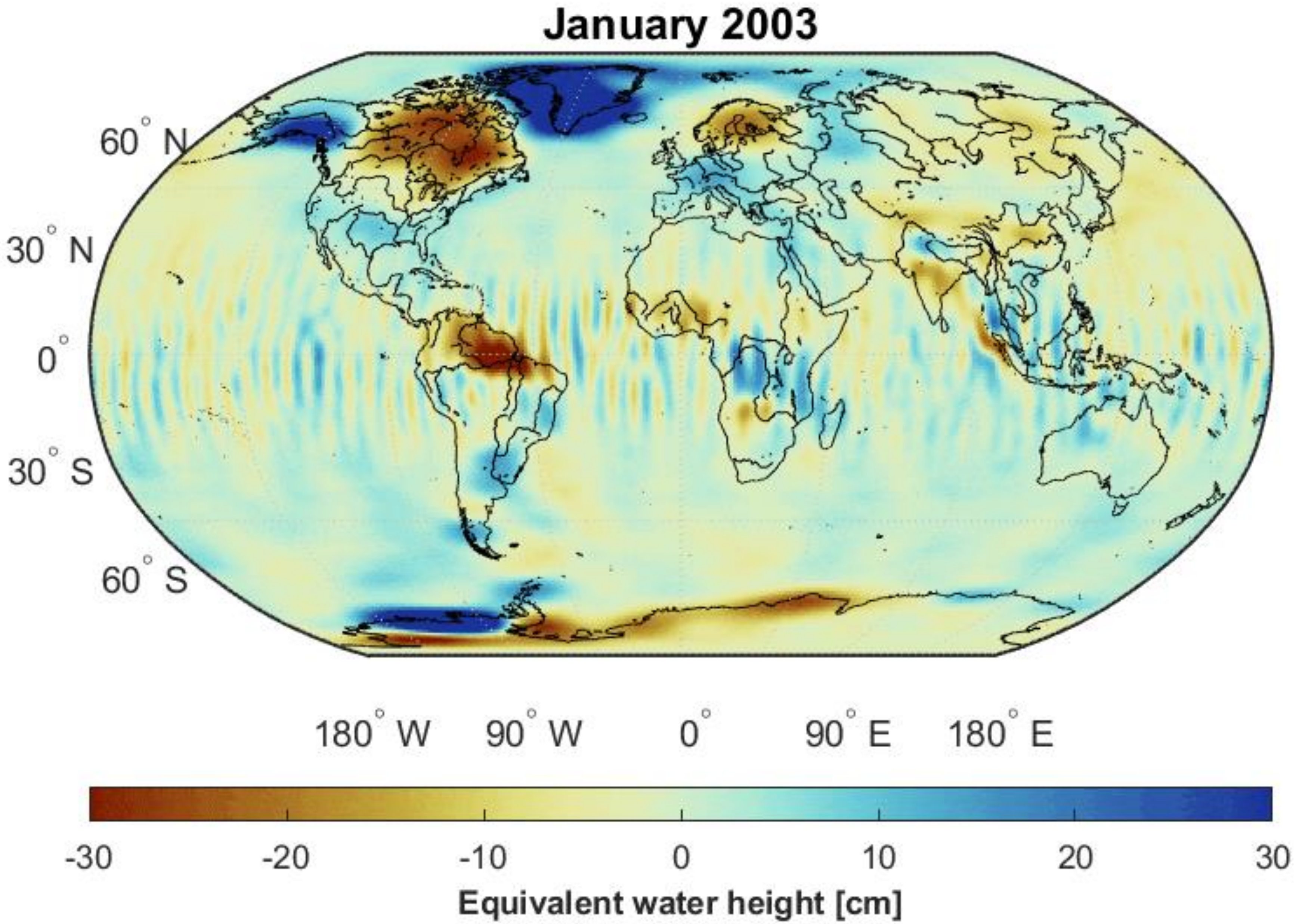
The standard approach



$$\dot{\rho} = \dot{\vec{X}}_{AB} \cdot \vec{e}_a$$

Rummel et al. 1978

Sensing the pulse, but …



Challenges of existing systems

DLR

SPATIAL AND TEMPORAL RESOLUTION

Limited to approx. 300km - 400km and 1 month

SENSOR NOISE

Preventing the full exploitation of the ranging systems

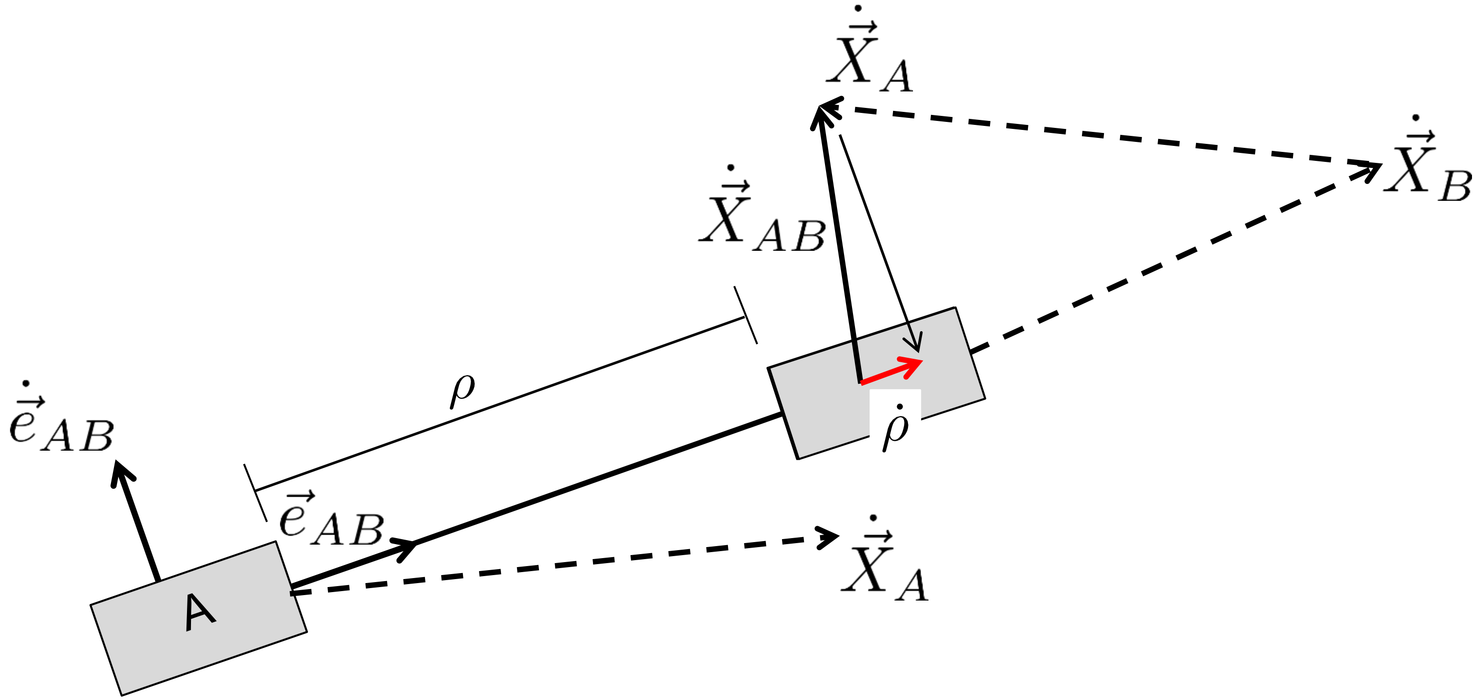
BACKGROUND MODELS

Aliasing of unwanted geo-physical signal

DATA AVAILABILITY

Any?
Latency?
Spatial coverage?
Sensitivity?

The second dimension …



Rummel et al. 1978

$$\dot{\vec{X}}_{AB} \cdot \vec{e}_a = \dot{\rho}$$
$$\dot{\vec{X}}_{AB} \cdot \vec{e}_r = \rho|\dot{\vec{e}}_a|$$

- Standard Approach

$$\dot{\rho} = \dot{\vec{X}}_{AB} \cdot \vec{e}_a$$

- Two-dimensional approach

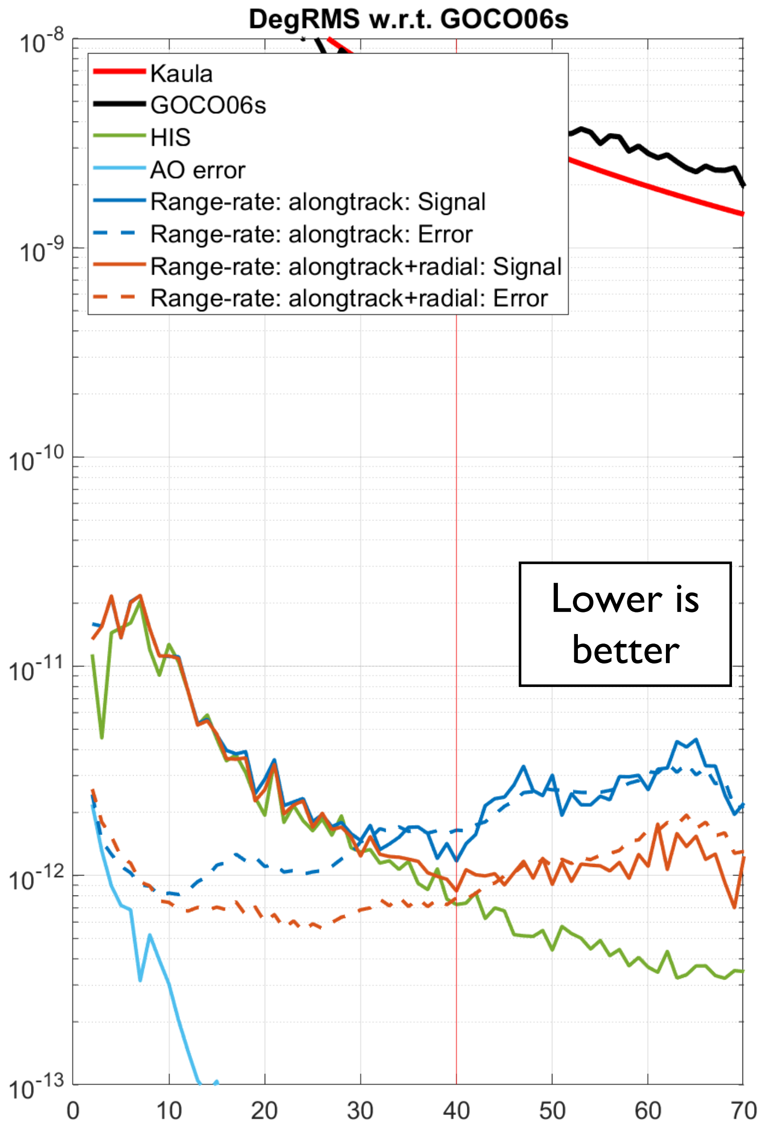
$$\dot{\vec{X}}_{AB} = \dot{\rho}\vec{e}_a + \rho\dot{\vec{e}}_a$$

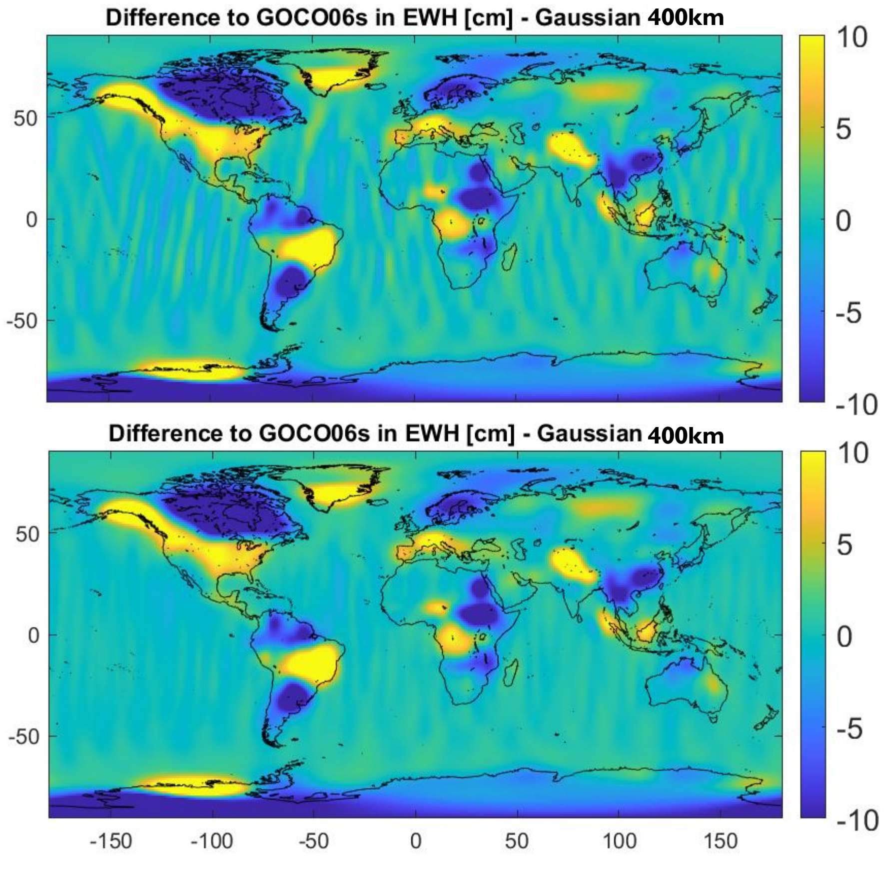
introducing:

$$\vec{e}_r = \frac{\dot{\vec{e}}_a}{|\dot{\vec{e}}_a|} \rightarrow \dot{\vec{e}}_a = |\dot{\vec{e}}_a|\vec{e}_r$$

$$\dot{\vec{X}}_{AB} = \dot{\rho}\vec{e}_a + \rho|\dot{\vec{e}}_a|\vec{e}_r$$

Simulation results: 2D





Range-rate alongtrack only

Smoother is better

Range-rate alongtrack+radial

The third dimension

Range observables:

$$\vec{X}_{AB} = \rho \cdot \vec{e}^{\,a}_{AB}$$

$$\dot{\vec{X}}_{AB} = \dot{\rho} \cdot \vec{e}^{\,a}_{AB} + \rho \cdot \dot{\vec{e}}^{\,a}_{AB}$$

$$\nabla V_{AB} = \ddot{\vec{X}}_{AB} = \ddot{\rho} \cdot \vec{e}^{\,a}_{AB} + 2 \cdot \dot{\rho} \cdot \dot{\vec{e}}^{\,a}_{AB} + \rho \cdot \ddot{\vec{e}}^{\,a}_{AB}$$

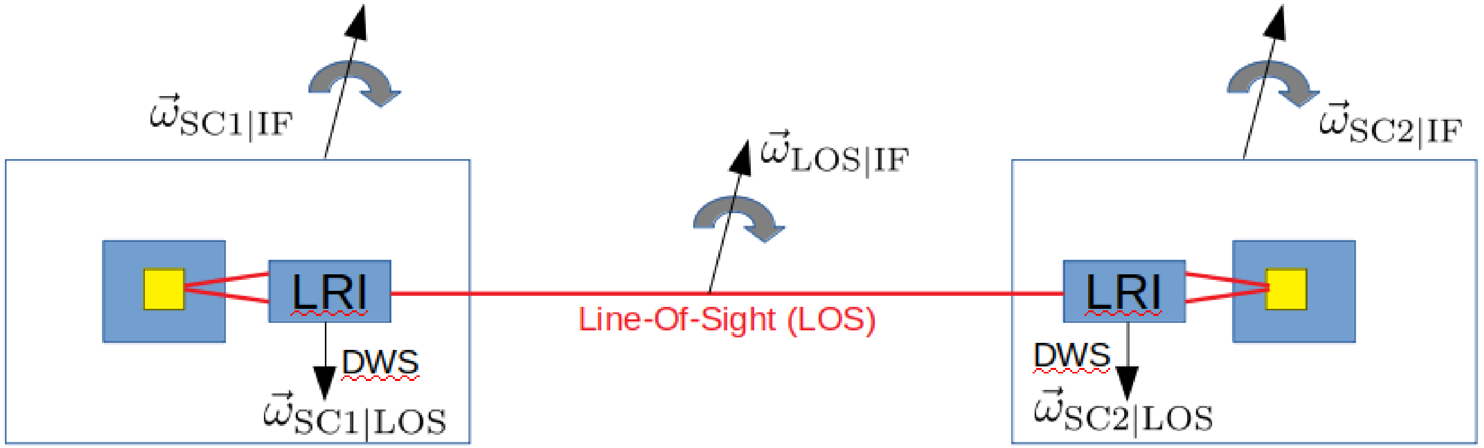
3D Approach:

$$\begin{aligned}
\nabla V_{AB} \cdot \vec{e}^{\,a}_{AB} &= \ddot{\rho} \quad + \quad 0 \quad - \quad \rho\,(\omega_c)^2 \\
\nabla V_{AB} \cdot \vec{e}^{\,r}_{AB} &= 0 \quad - \quad 2\,\dot{\rho}\,\omega_c \quad - \quad \rho\,\dot{\omega}_c \\
\nabla V_{AB} \cdot \vec{e}^{\,c}_{AB} &= 0 \quad + \quad 0 \quad - \quad \rho\,\omega_a\omega_c
\end{aligned}$$

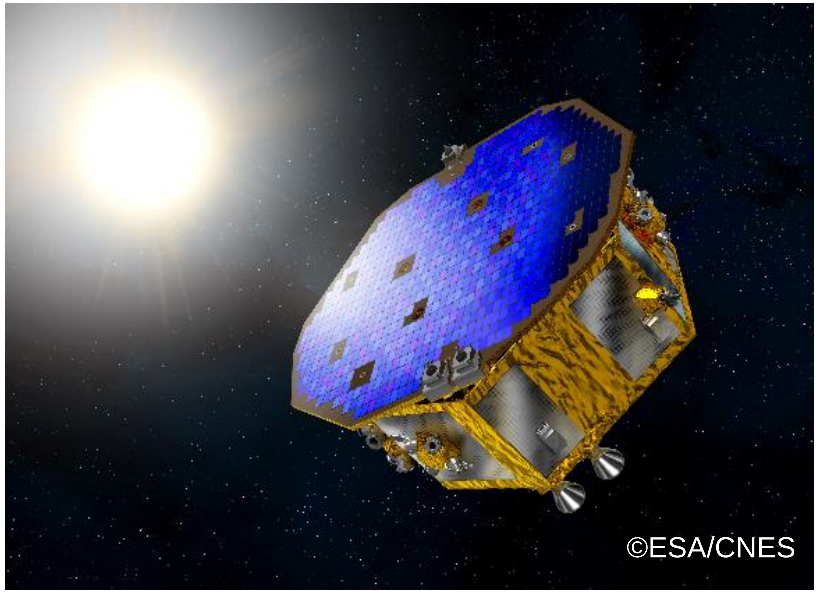
Weigelt 2017
The Acceleration Approach

GRACE-3D Payload Concept

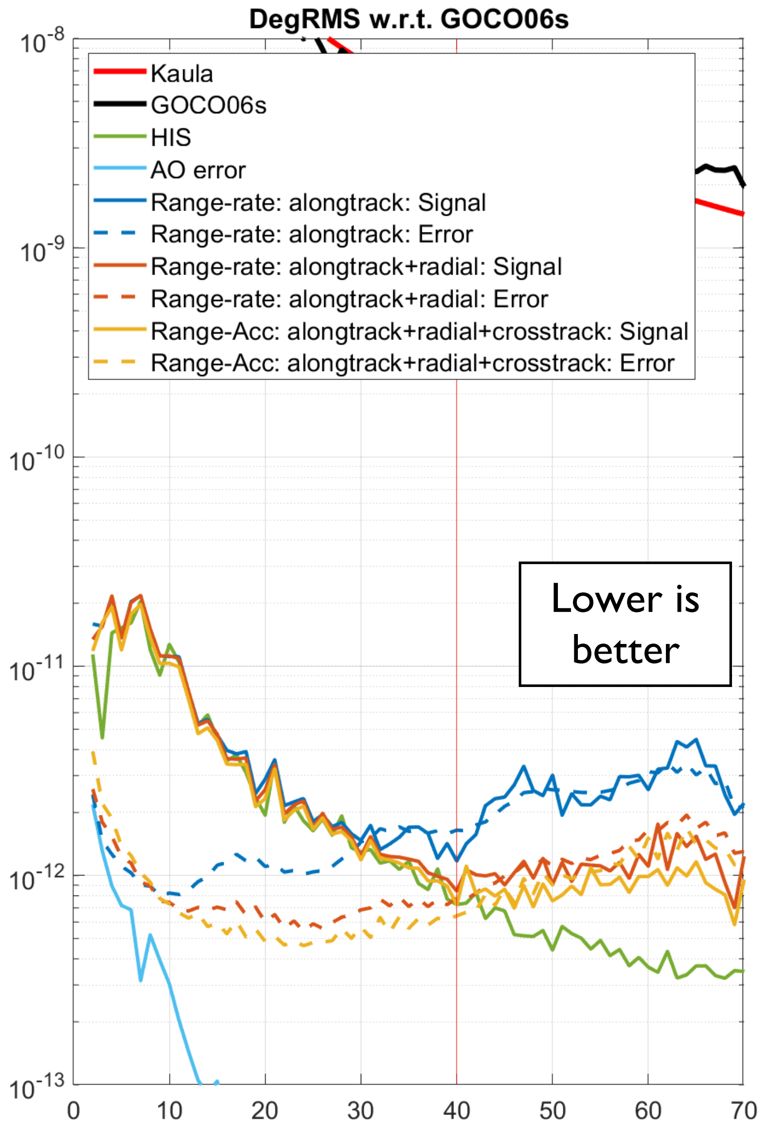
Gravitational Reference Sensors will exploit LISA technology and enable a multi-dimensional observation

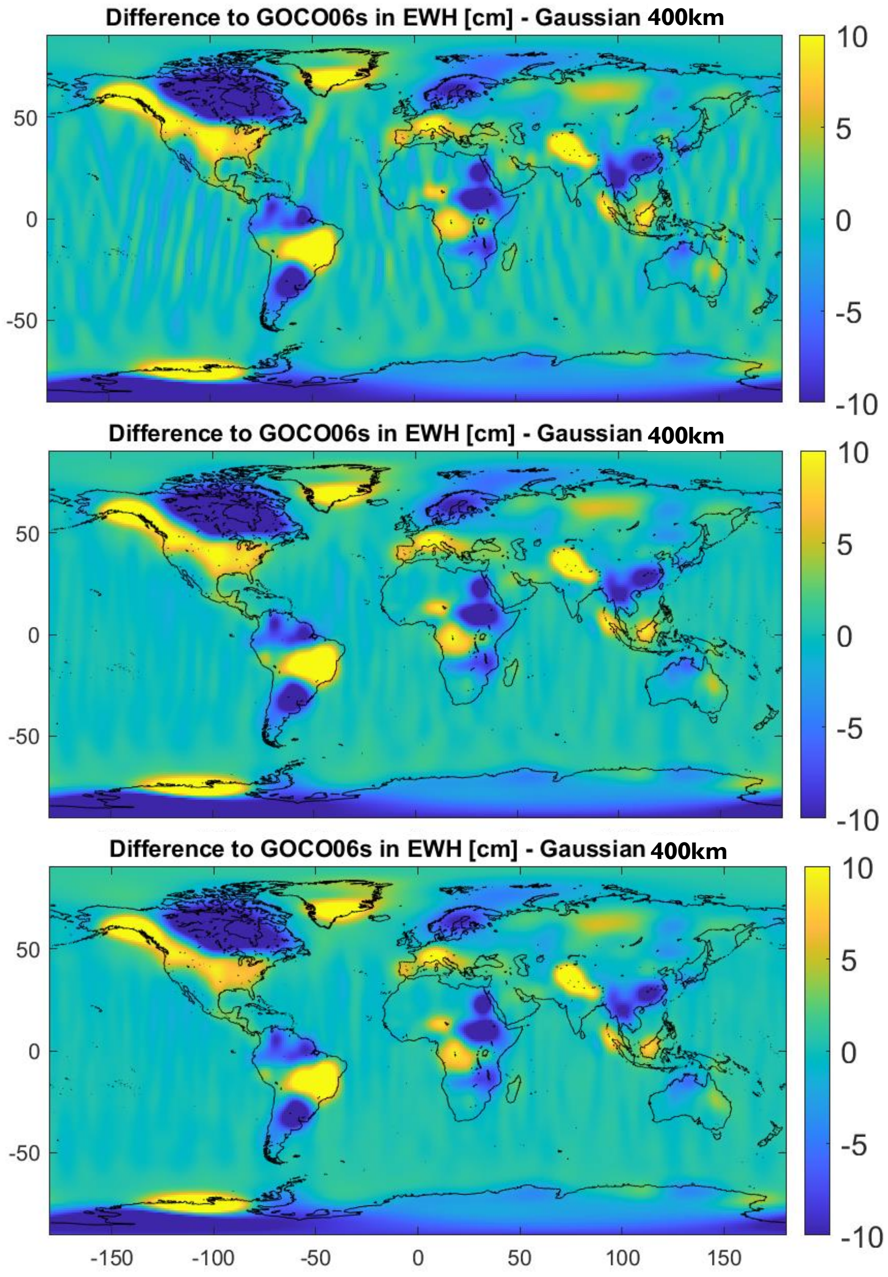


courtesy V. Müller, AEI



Simulation results: 3D





Range-rate alongtrack only

Smoother is better

Range-rate alongtrack+radial

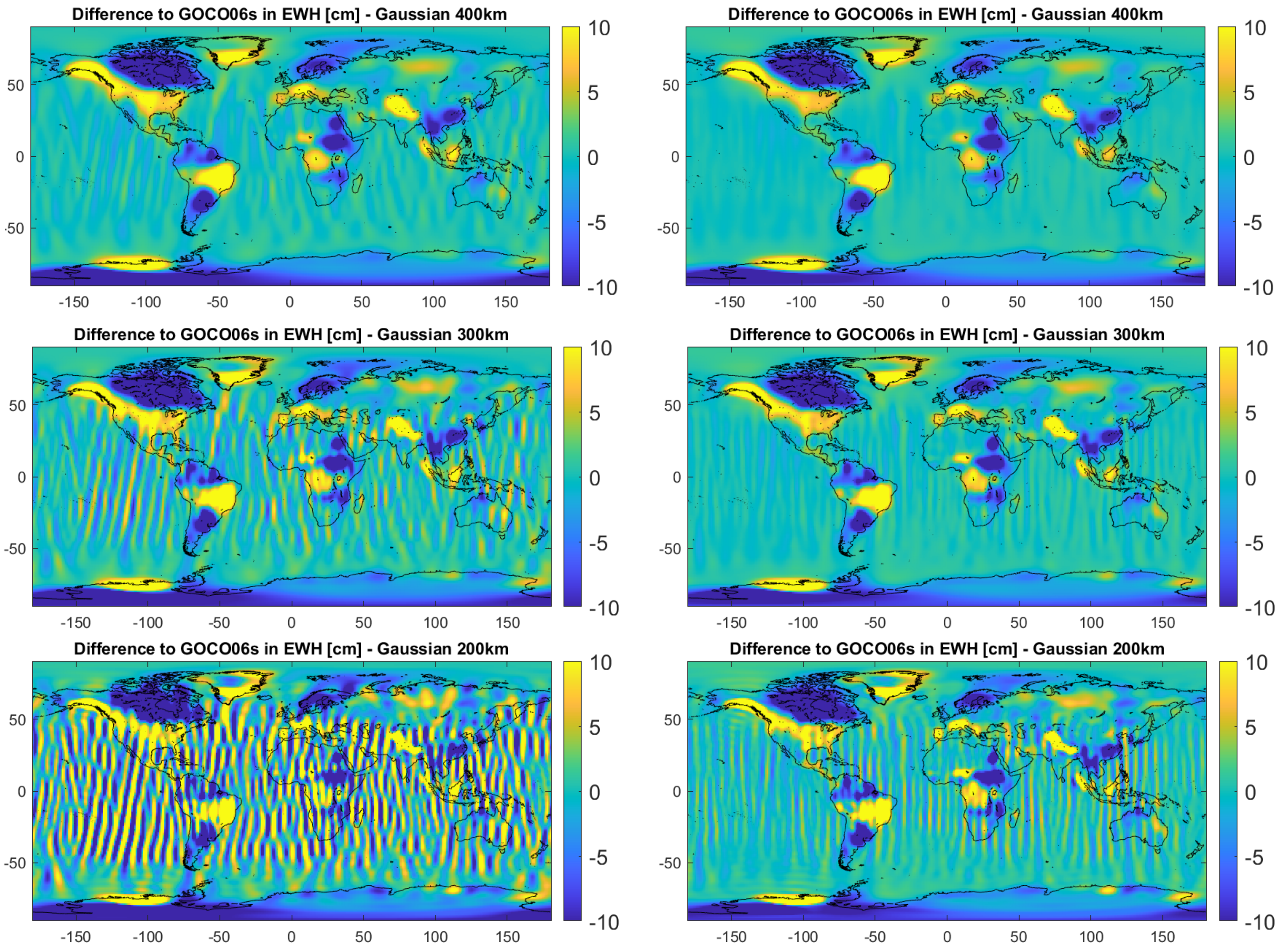
Range-acceleration alongtrack+radial+crosstrack

Improving the spatial resolution by factor 1.5 – 2

Gaussian Filtering with 400km radius

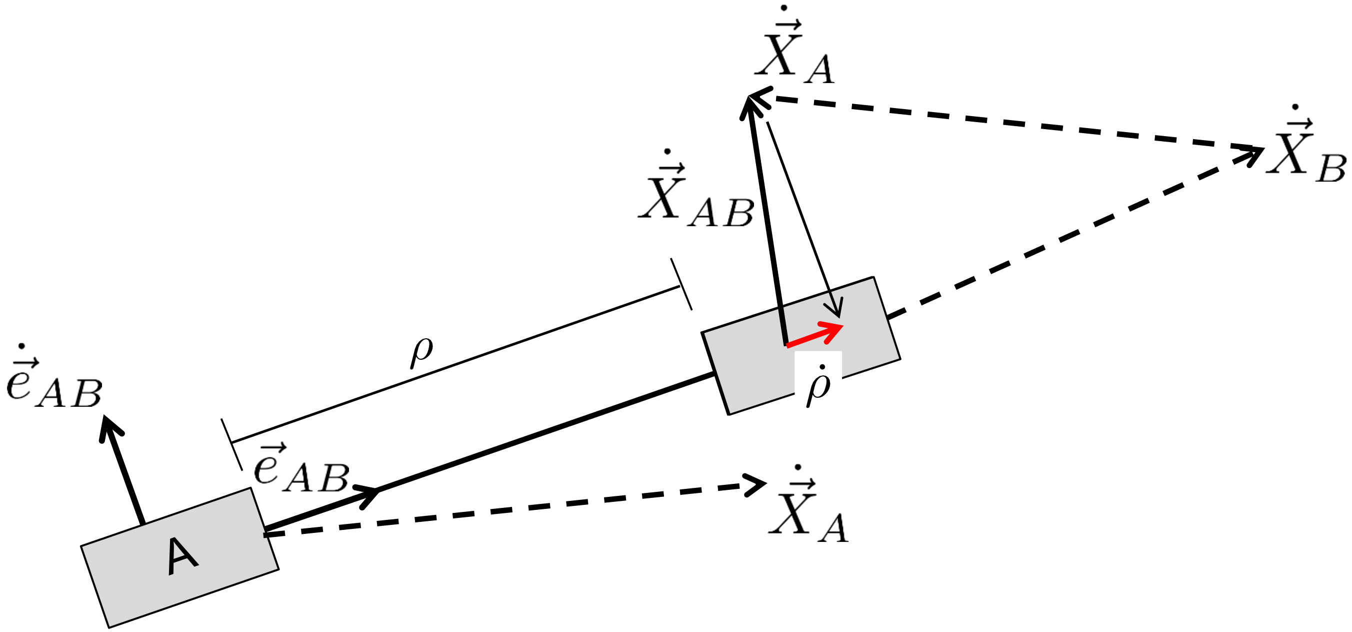
Gaussian Filtering with 300km radius

Gaussian Filtering with 200km radius



EXPLOITING LASER INTERFEROMETRY TODAY

Line-of-sight gravity difference



Rummel et al. 1978

- Range to range-acceleration

$$\vec{X}_{AB} = \rho \cdot \vec{e}^{\,a}_{AB}$$

$$\dot{\vec{X}}_{AB} = \dot{\rho} \cdot \vec{e}^{\,a}_{AB} + \rho \cdot \dot{\vec{e}}^{\,a}_{AB}$$

$$\ddot{\vec{X}}_{AB} = \ddot{\rho} \cdot \vec{e}^{\,a}_{AB} + 2 \cdot \dot{\rho} \cdot \dot{\vec{e}}^{\,a}_{AB} + \rho \cdot \ddot{\vec{e}}^{\,a}_{AB}$$

- Multiplication with $\vec{e}^{\,a}_{AB}$

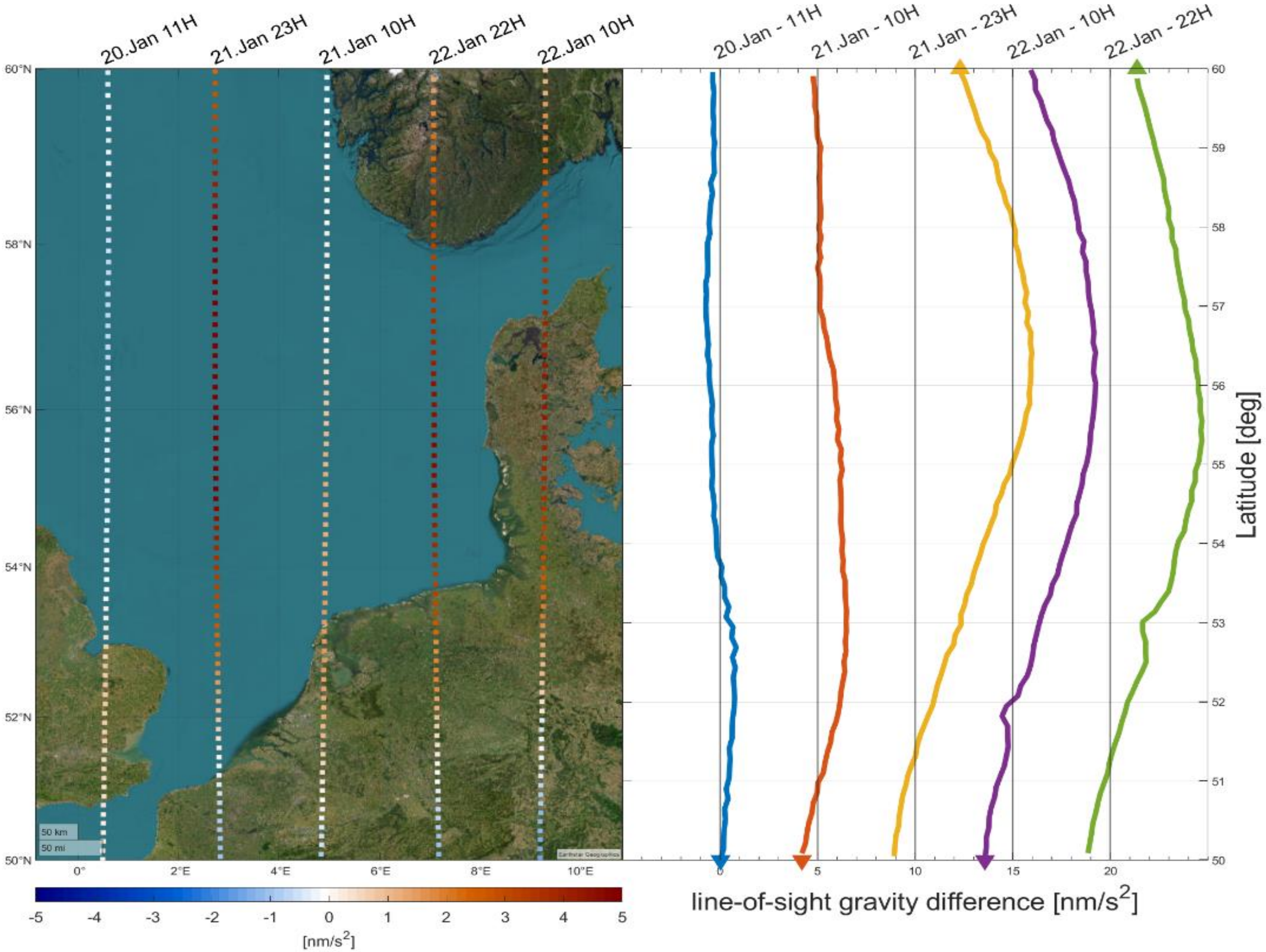
$$\ddot{\vec{X}}_{AB} \cdot \vec{e}^{\,a}_{AB} = \ddot{\rho} + \rho \cdot \ddot{\vec{e}}^{\,a}_{AB} \cdot \vec{e}^{\,a}_{AB}$$

- Approximation by an empirical transfer function

$$\ddot{\vec{X}}_{AB} \cdot \vec{e}^{\,a}_{AB} = \Phi\left(\ddot{\rho}\right)$$

Single-track analysis capabilities

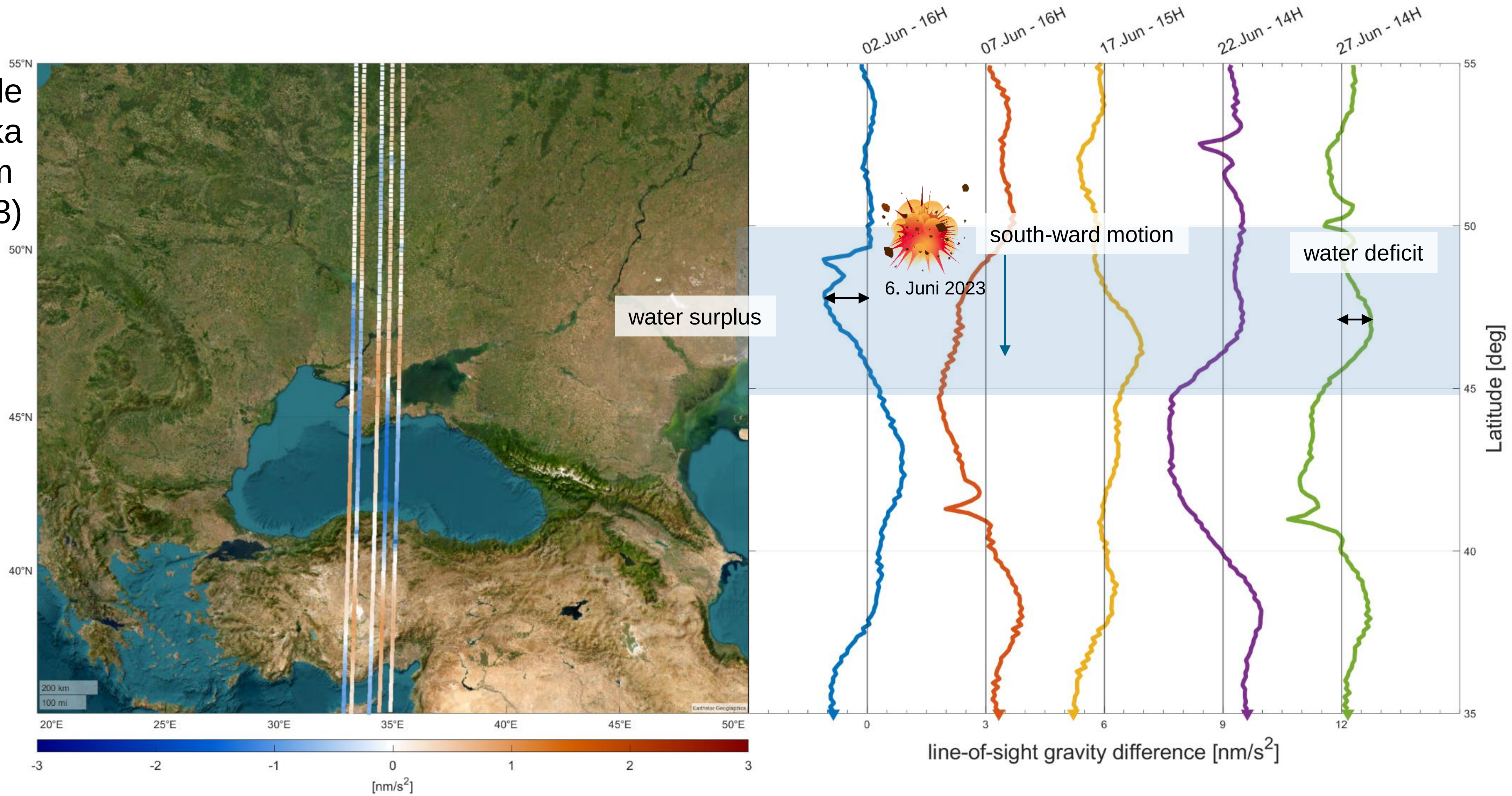
Line-of-sight gravity differences allows observation of sub-monthly mass variations



Example: Goran (2021)

Single-track analysis capabilities

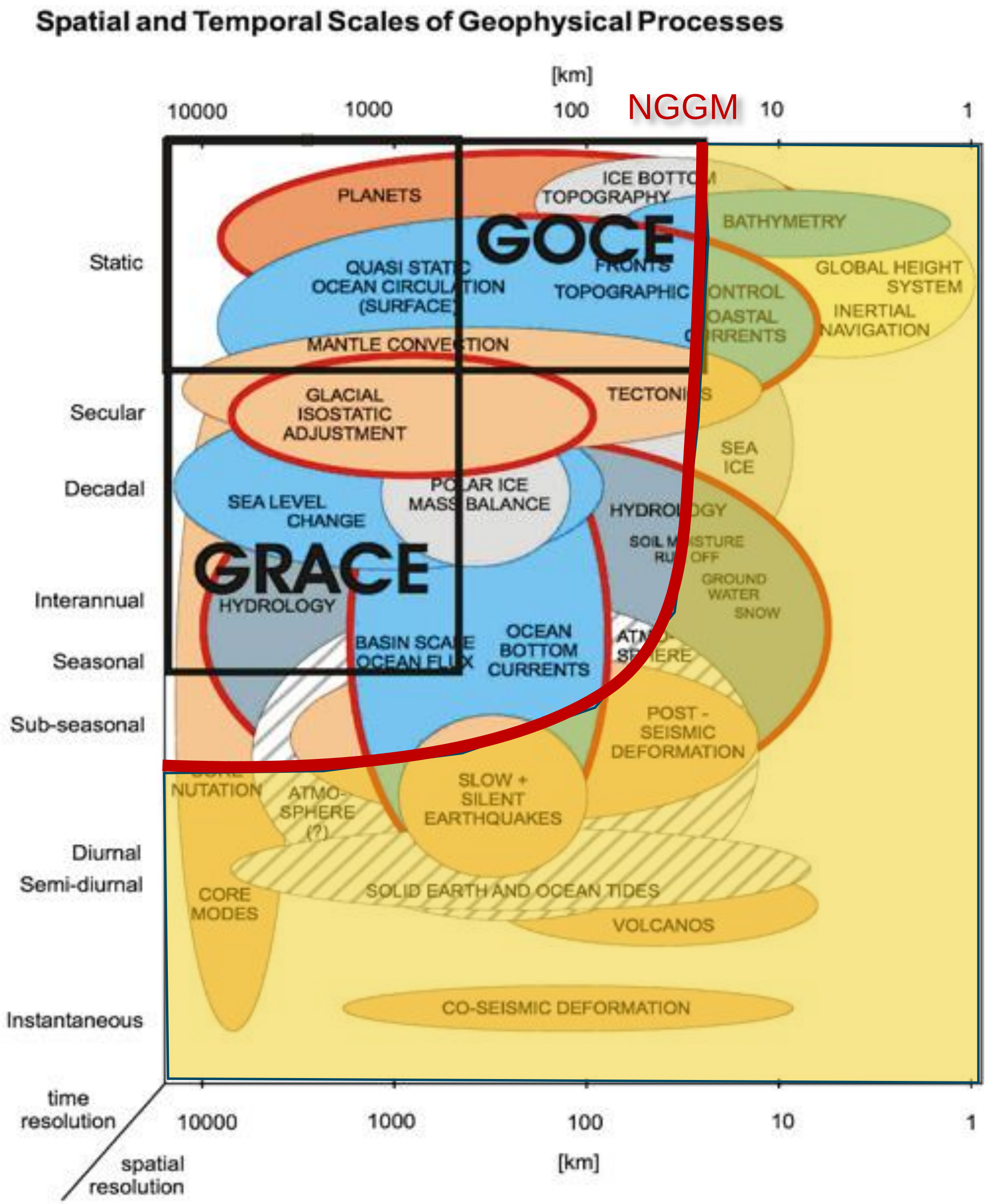
Example Kachowka dam (2023)



Increasing the spatial and temporal resolution

Beyond satellites

Towards sensor combination



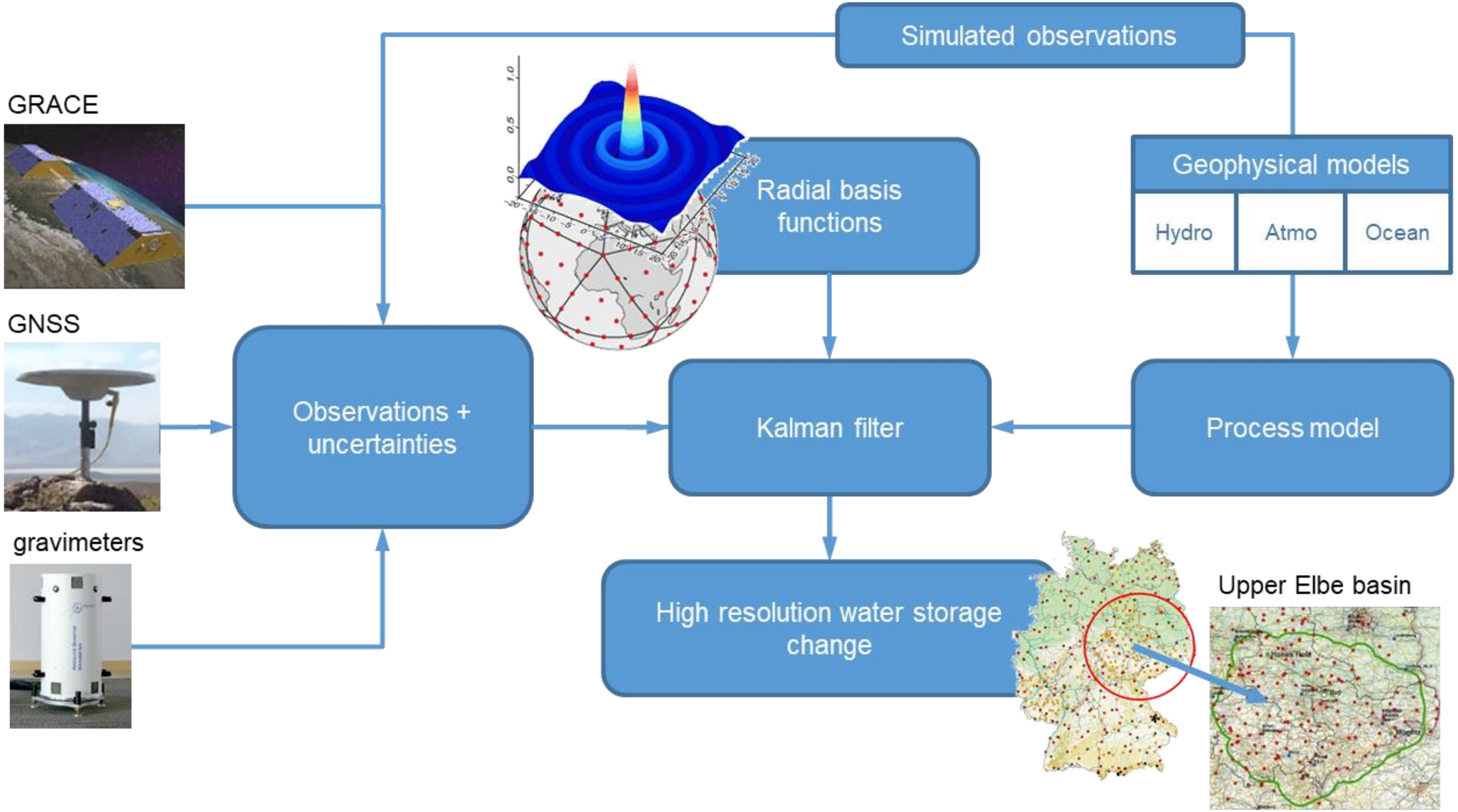
Augmentation with additional observations systems is needed.

Observation techniques:

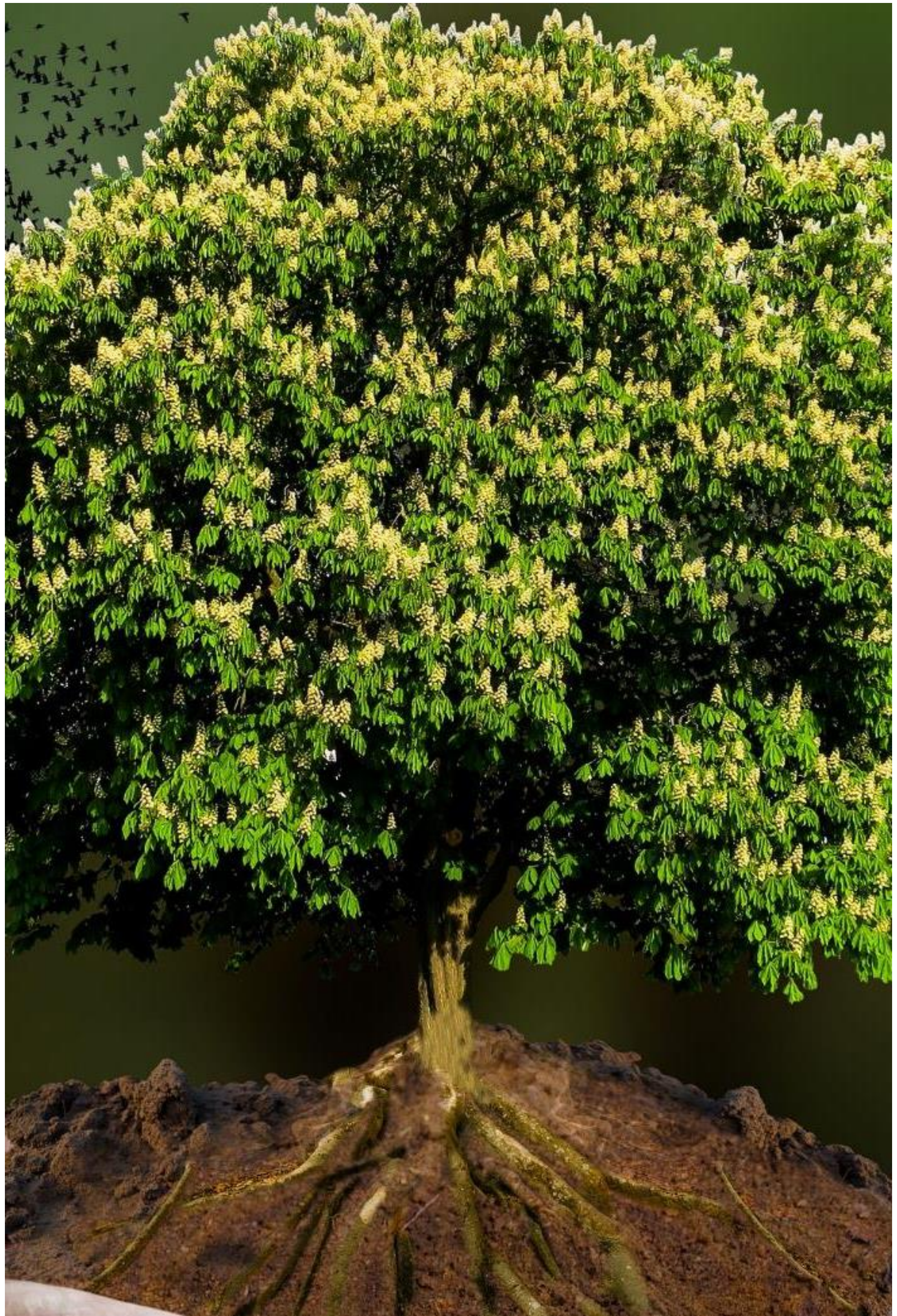
- GNSS
- InSAR
- Clocks
- Terrestrial Gravimetry

Sensor combination

Combination requires a reliable, flexible and robust estimation technique.



Modelling of Mass Variations Down to Small Scales by Quantum Sensor Fusion



Possible applications

Resource management

Natural hazard monitoring and prediction

Sea-level rise monitoring and coastal protection

Clock-based height reference systems

Observation of short-term geophysical signals

Future satellite concepts

Fundamental objectives

Exploit

Exploit quantum technology and relativistic modelling for geodetic applications

Integrate

Integrate space and terrestrial sensors

Establish

Establish gravity field observations on all temporal and spatial scales

THANK YOU

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Quantum sensors for interplanetary missions

DLR

- Objective: Evaluating the potential of using quantum sensors for interplanetary missions
- Adapting VENQS for Mars simulations
- Planned extensions:
  - Precise gravity field model
  - Tides and 3rd body forces
  - Atmospheric drag
  - Solar radiation pressure + Albedo