NEROGRAV

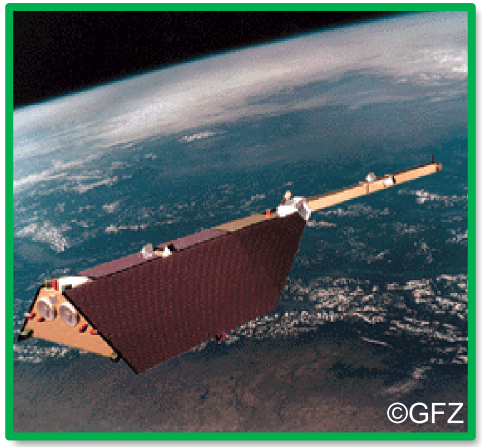
New Refined Observations of Climate Change from Spaceborne Gravity Missions

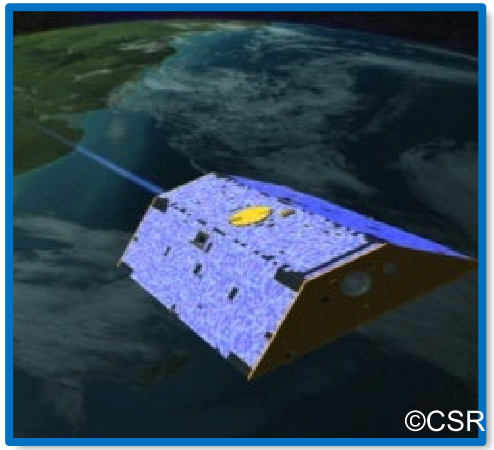
International Spring School
Neustadt an der Weinstraße, Germany, March 10-14, 2025

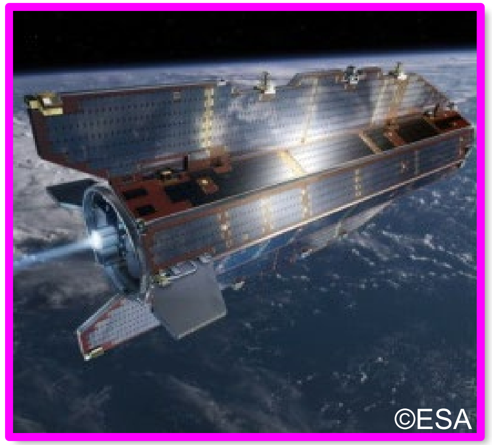
The Future: Satellite Missions with Quantum Sensors

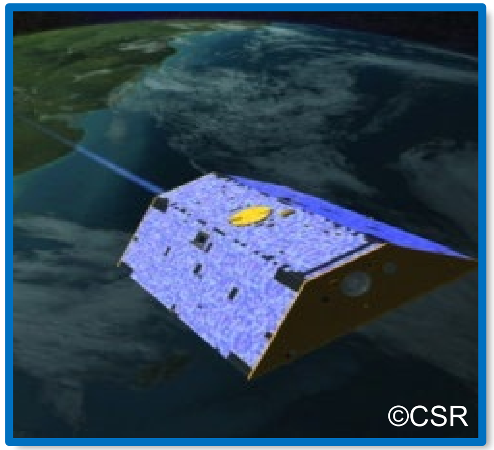
Matthias Weigelt (DLR)

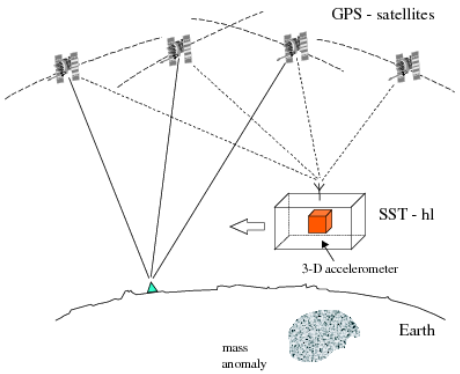
Satellites as test masses

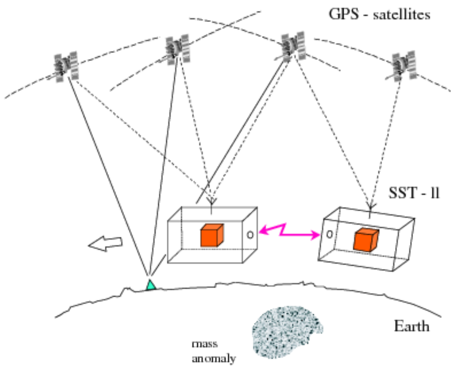


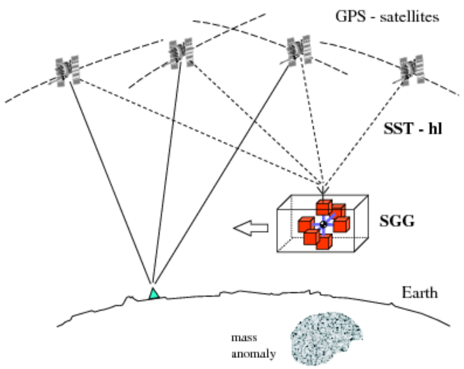


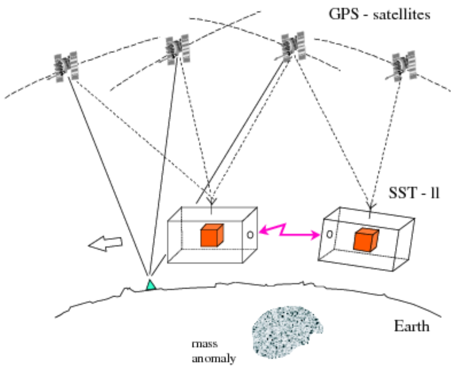


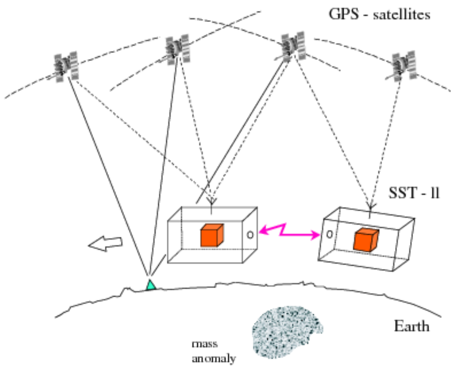












CHAMP (GFZ, 2000-2010)

GRACE (NASA/DLR, 2002-2017)

GOCE (ESA, 2009-2013)

GRACE-FO (NASA/GFZ, 2018-203X)

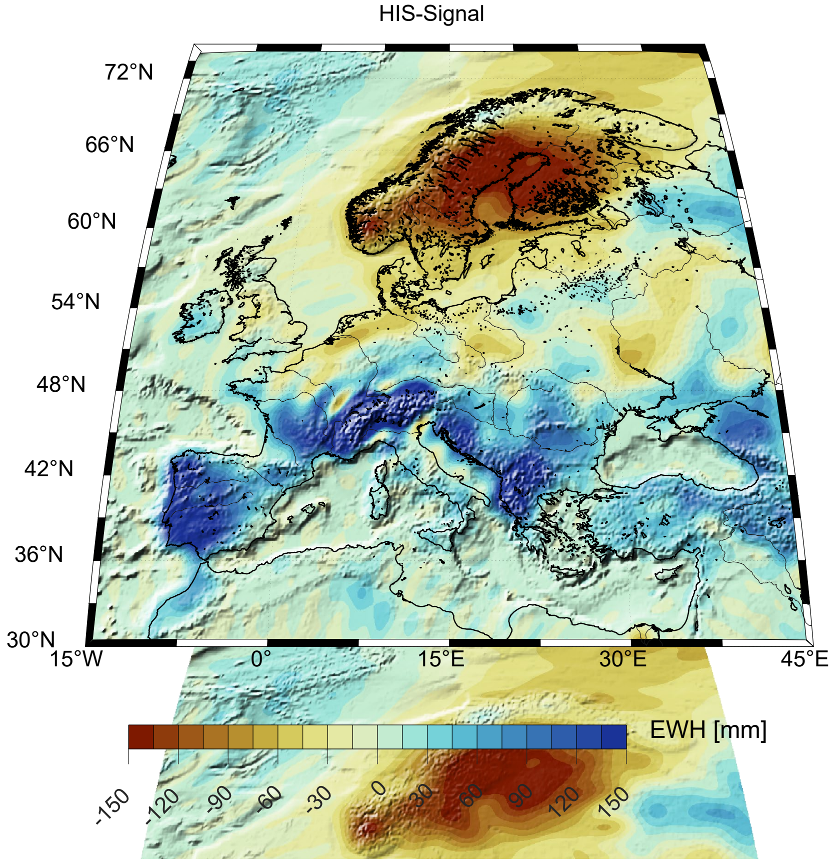
GRACE-C (2028-203X)

NGGM (2031-203X)

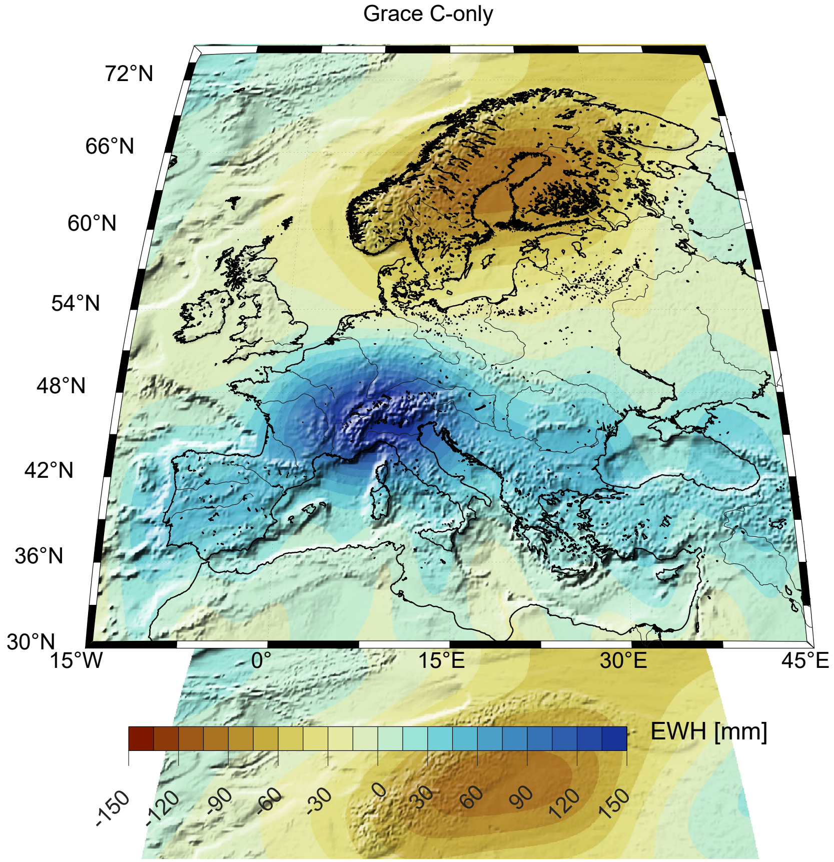
MAGIC

Challenges of existing systems

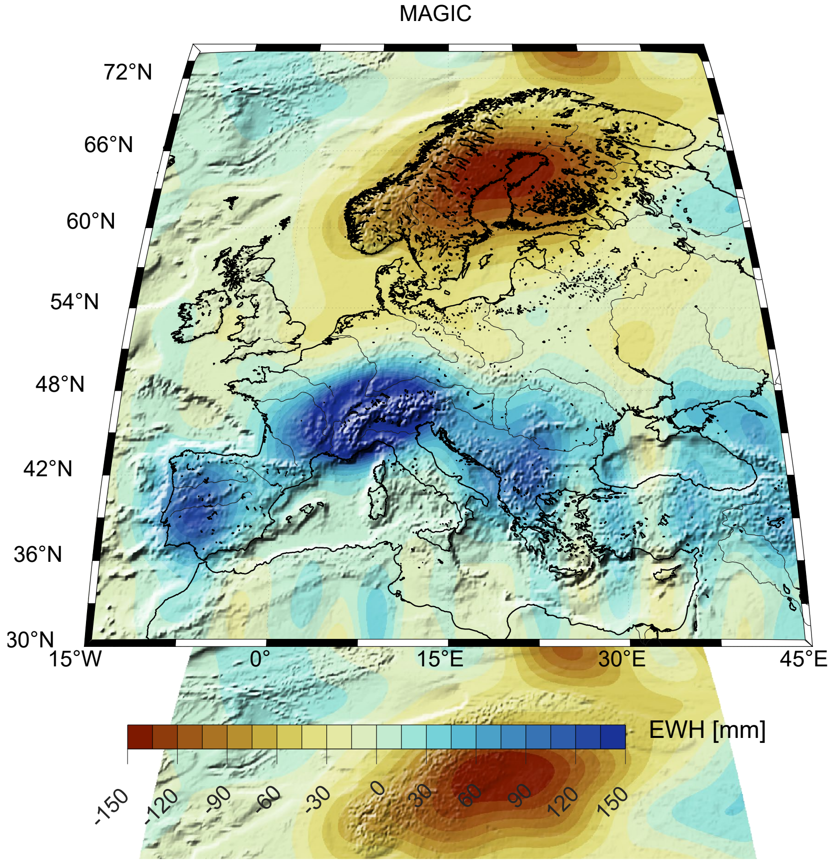
LIMITED SPATIAL AND TEMPORAL RESOLUTION



Simulated signal with a spatial resolution of 50km

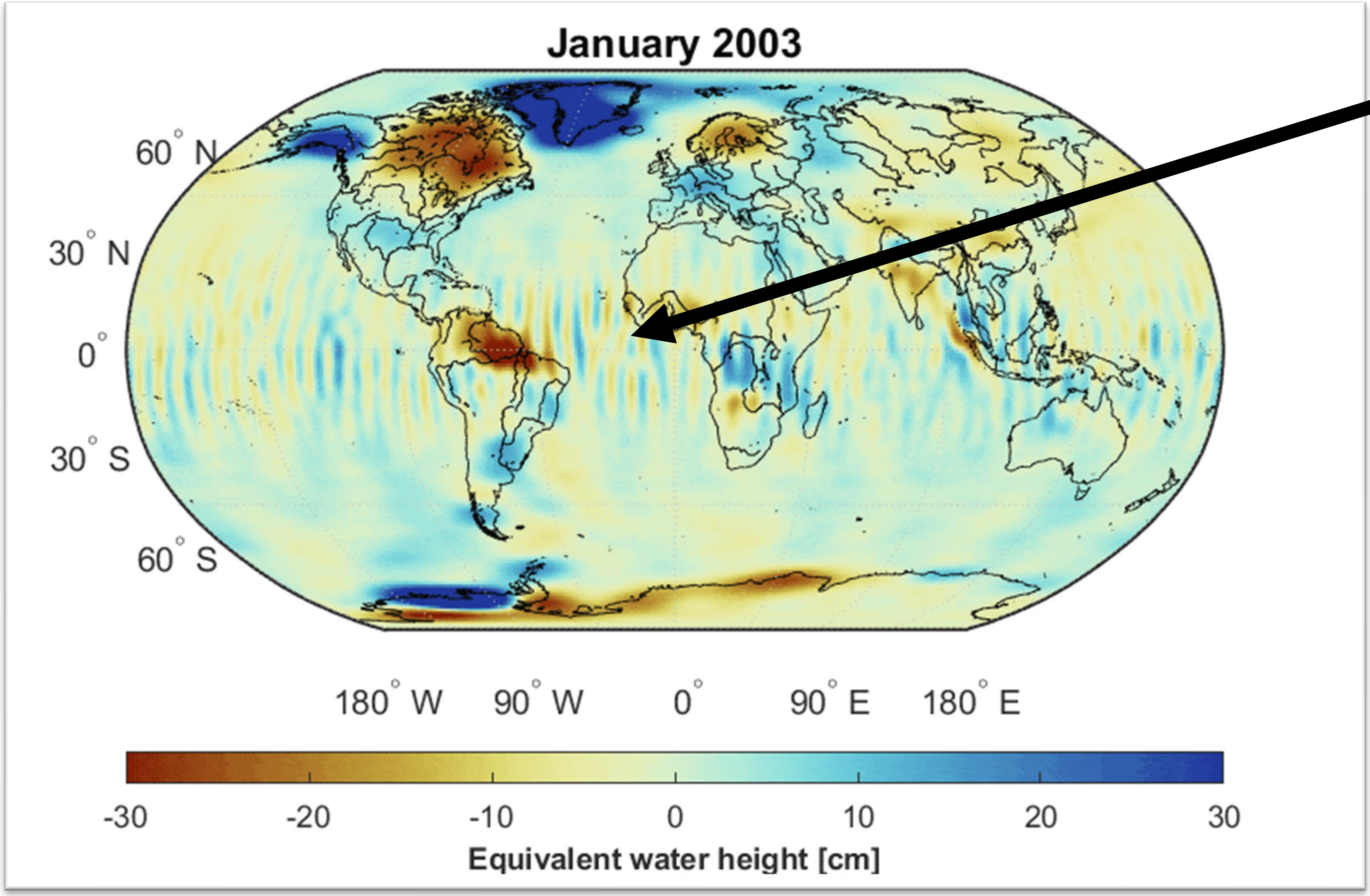


Recovery with a single pair and a resolution of 400km

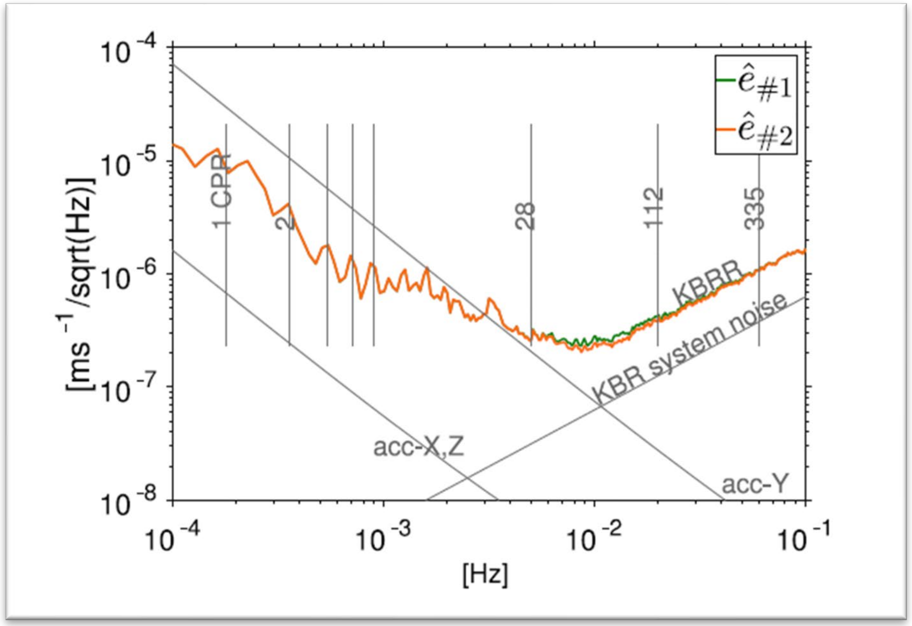


Recovery with a double pair and a resolution of 250km

Challenges of existing systems

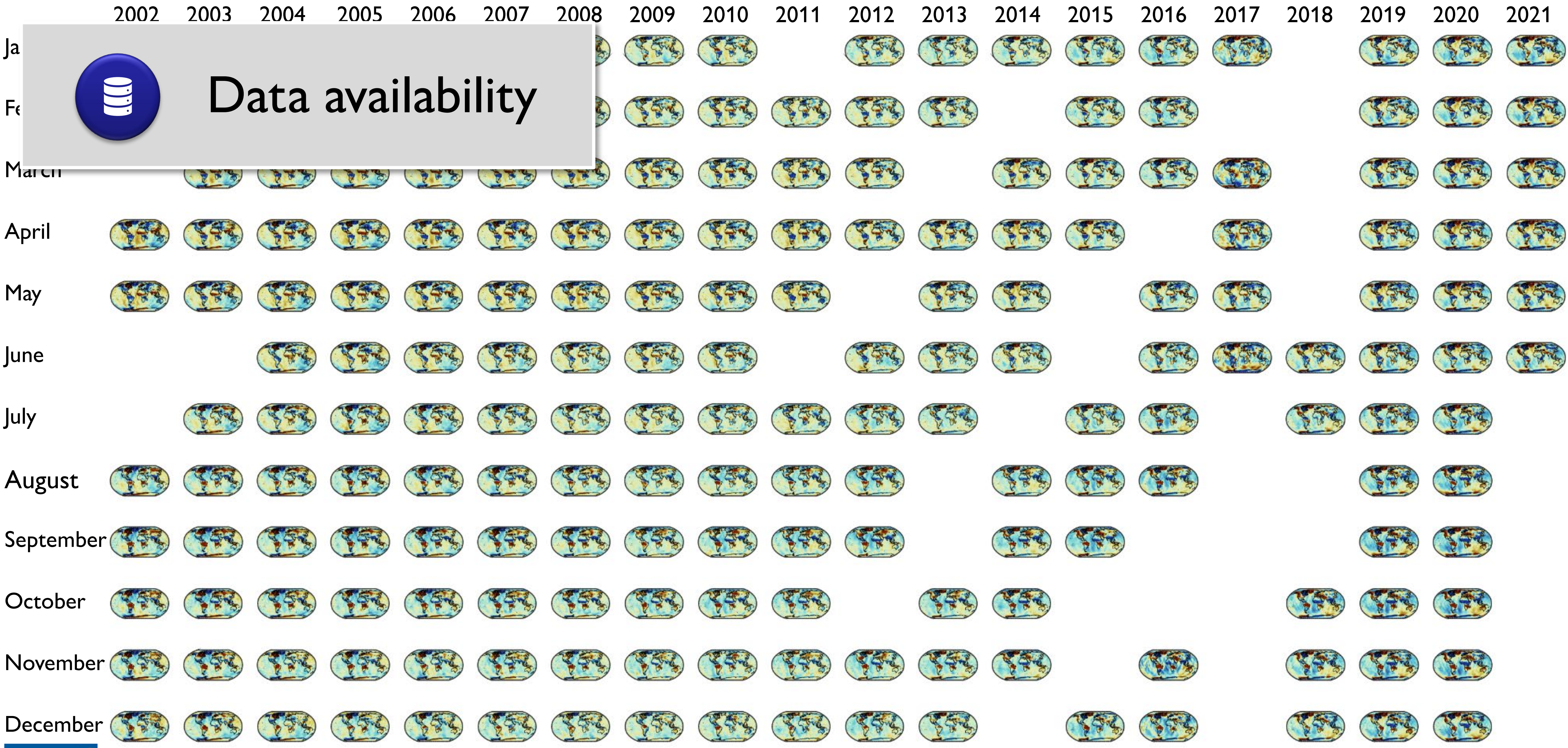


- BACKGROUND MODELS
- SENSOR NOISE



Goswami et al. 2018, *Analysis of Attitude Errors in GRACE Range-Rate residuals*

Challenges of existing systems



based on ITSG 2018

Challenges of existing systems

SPATIAL AND TEMPORAL RESOLUTION

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

SENSOR NOISE

Preventing the full exploitation of the observation systems

BACKGROUND MODELS

Aliasing of unwanted geo-physical signal

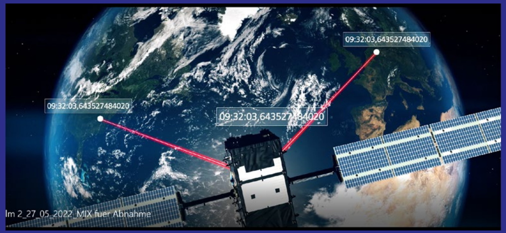
DATA AVAILABILITY

Any?
Redundancy?
Latency?
Spatial coverage?
Sensitivity?

Harvesting quantum technology

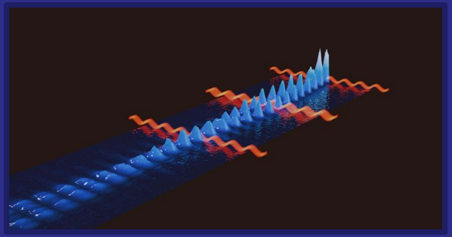
Utilizing the fundamental properties of atoms and molecules
to improve measurement accuracy and resolution

Optical frequency metrology



Absolute, drift-free and highly accurate for navigation and reference system

Atom interferometry



Absolute, drift-free and highly accurate accelerometers and rotation sensor

Laser interferometry

High-precision measurements of distances and smallest angles

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

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New Refined Observations of C

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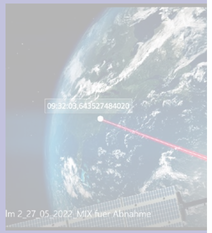
Harvesting quantum technology

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

Optical
me



Absolute, dr
accurate for
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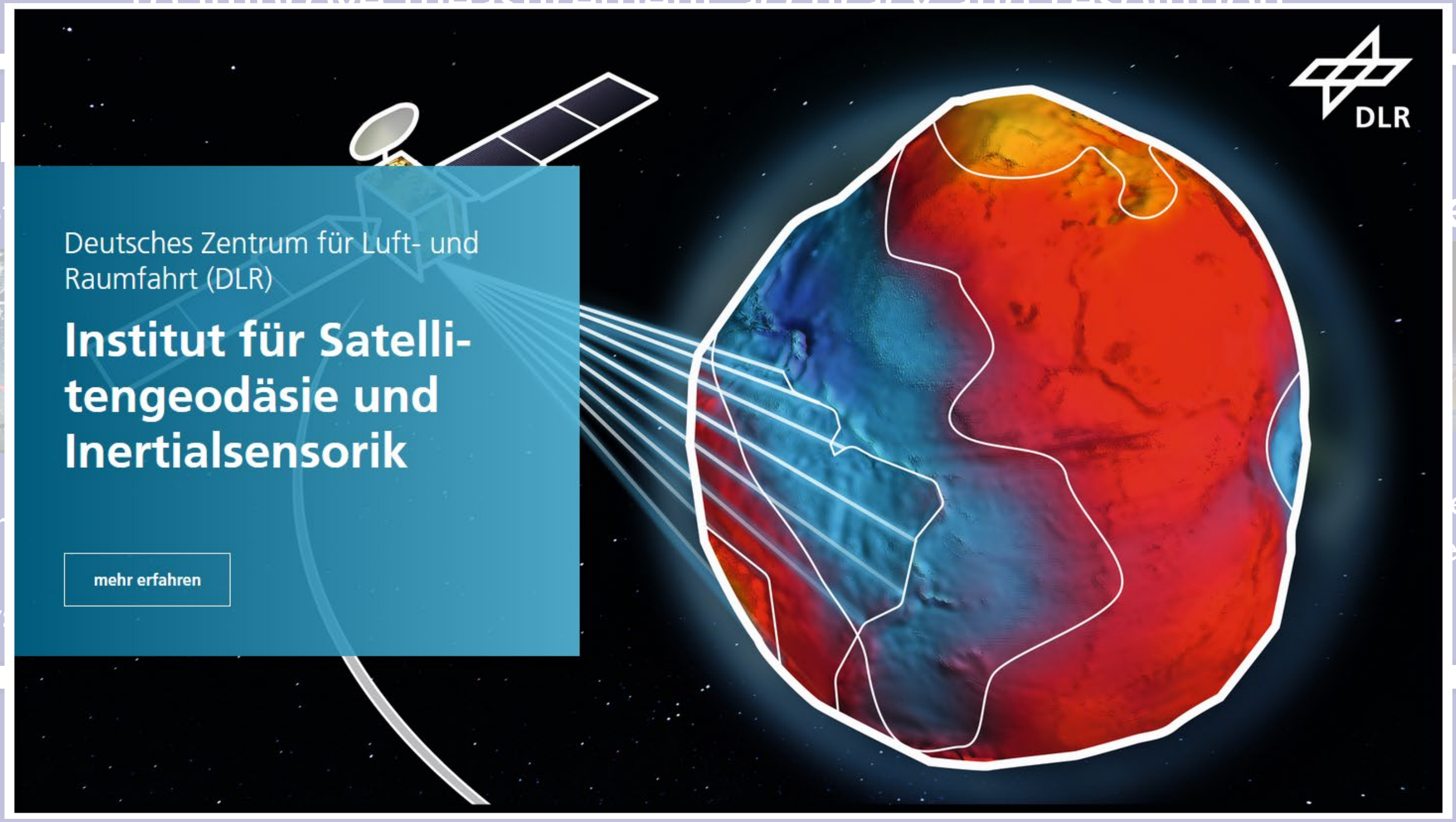

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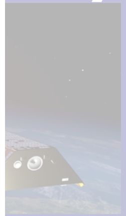


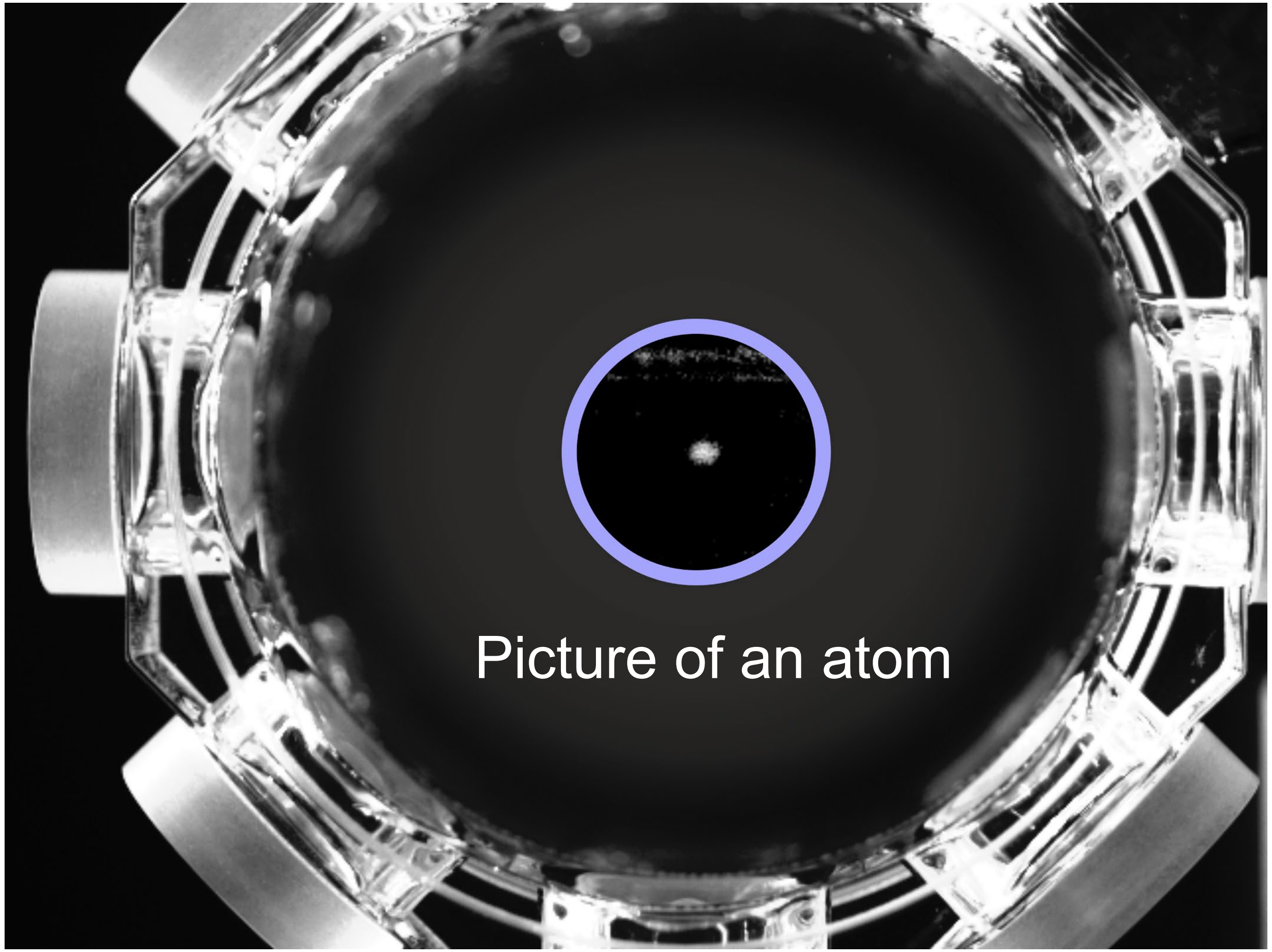
ements
est angles

Geodetic Modelling

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

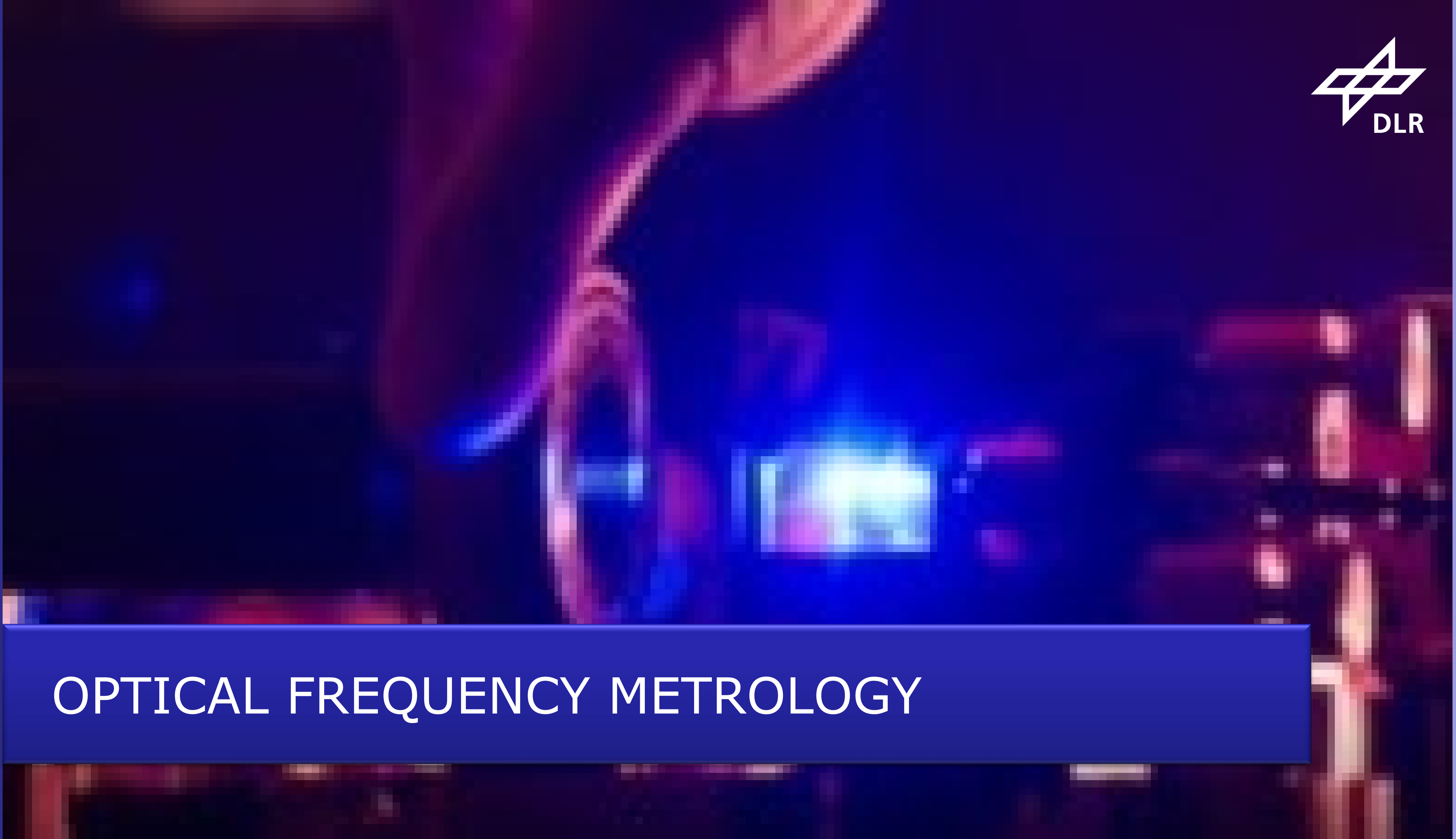
Quantum Sensors

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

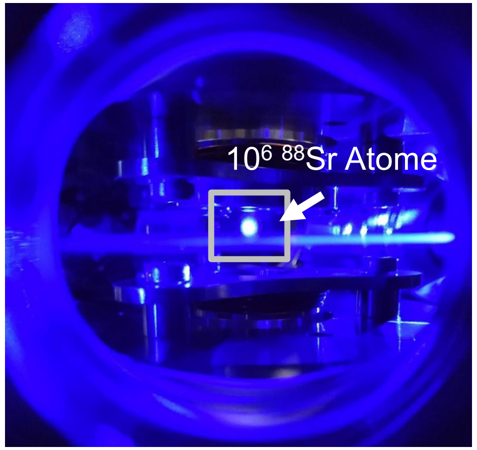


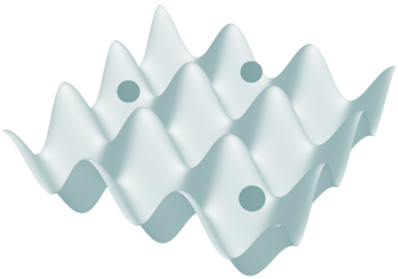
courtesy of Carsten Klempt

OPTICAL FREQUENCY METROLOGY



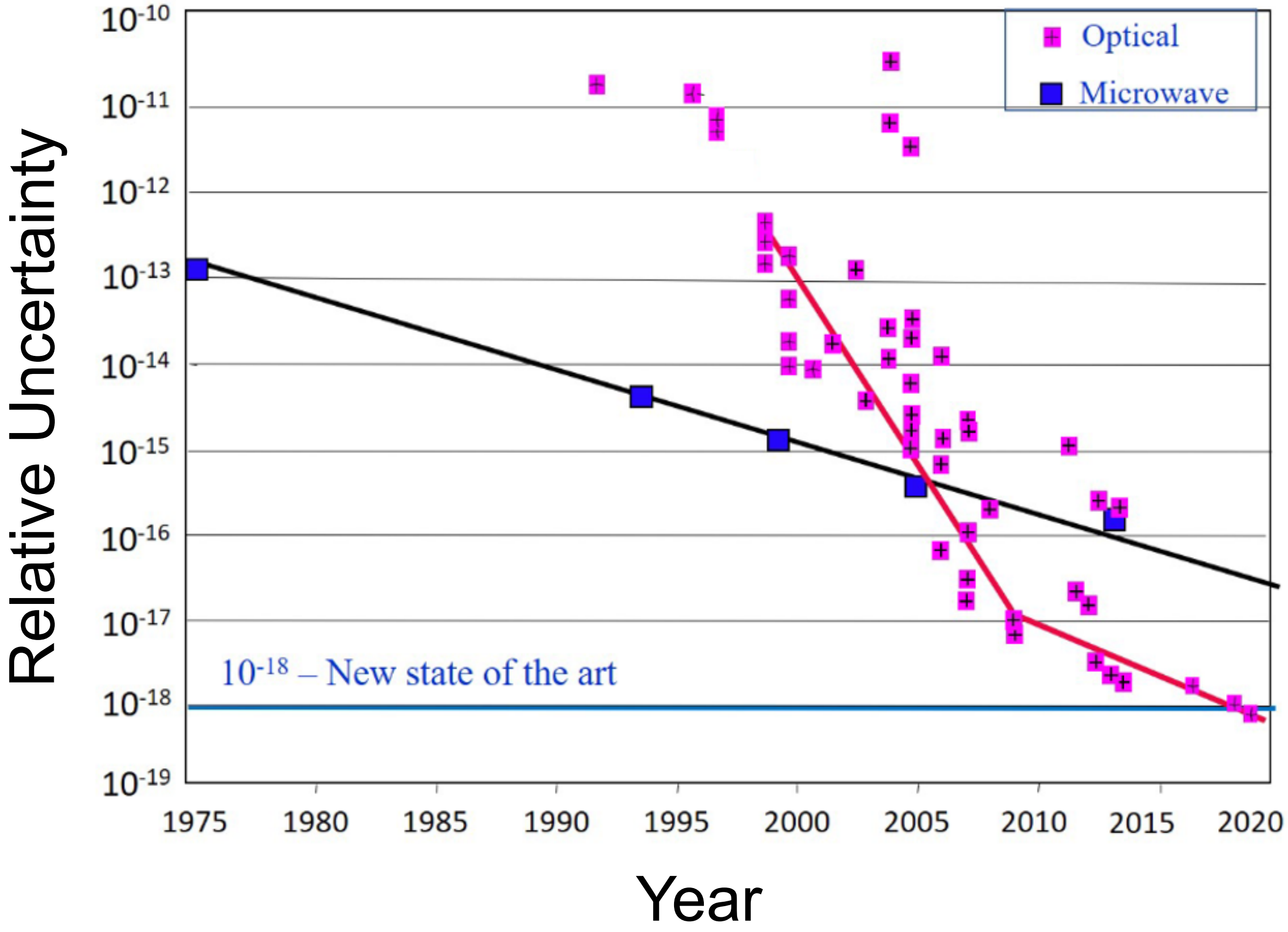
Improving the precision of clocks



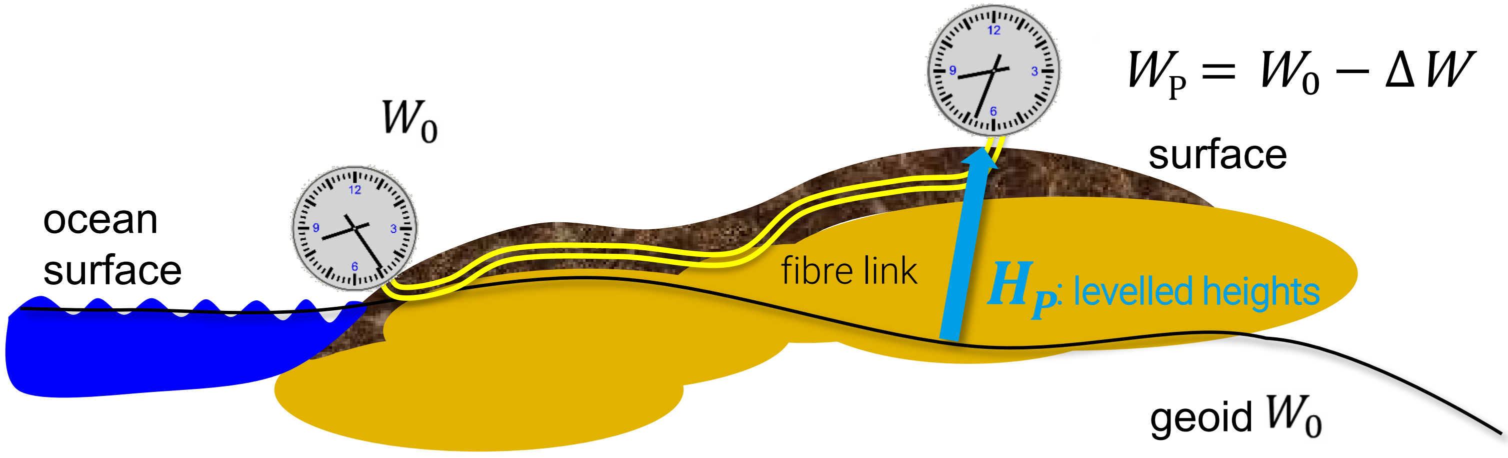


Optical lattice clock

Derevianko et al., arXiv:2112.10817 (2021)



Networks of Clocks: Objectives



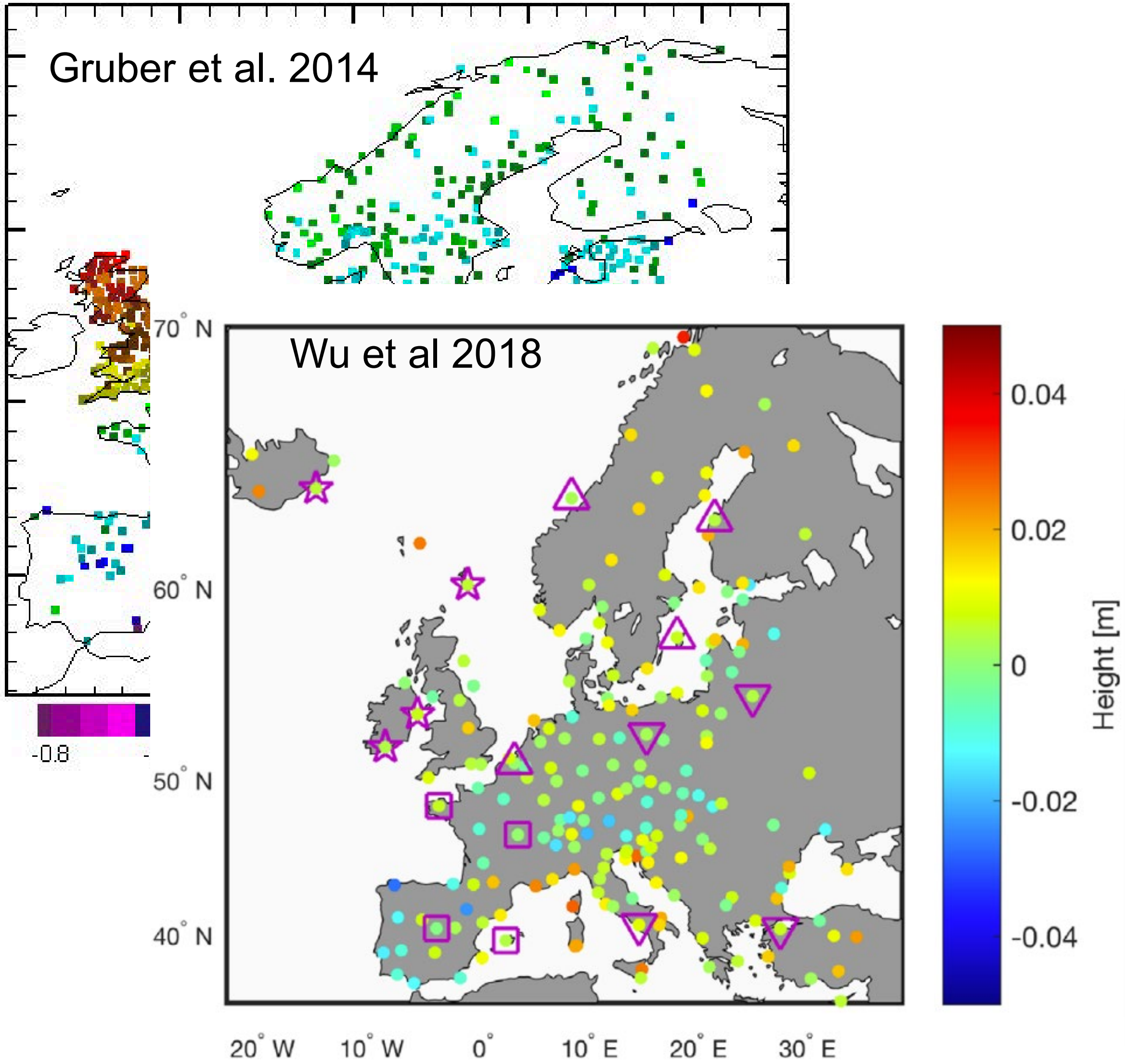
Vermeer, Reports of the Finnish Geodetic Institute **83(2)**, 1(1983); Bjerhammar, Bull. Geodesique **59**, 207 (1985).

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

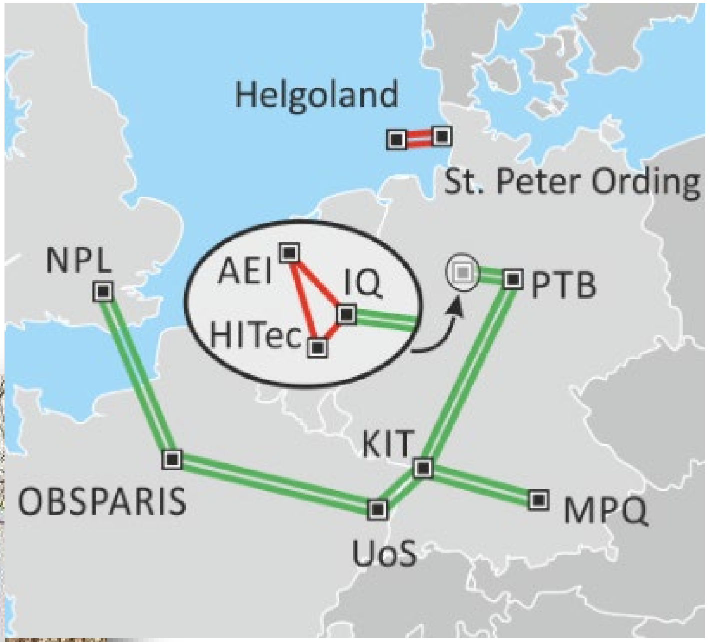
➔ Chronometric levelling over long distances

➔ Clock-based height system

Timely opportunities



Terra



courtesy of TerraQ

Challenges of existing systems

SPATIAL AND TEMPORAL RESOLUTION

Clocks +

SENSOR NOISE

Clocks ✓

BACKGROUND MODELS

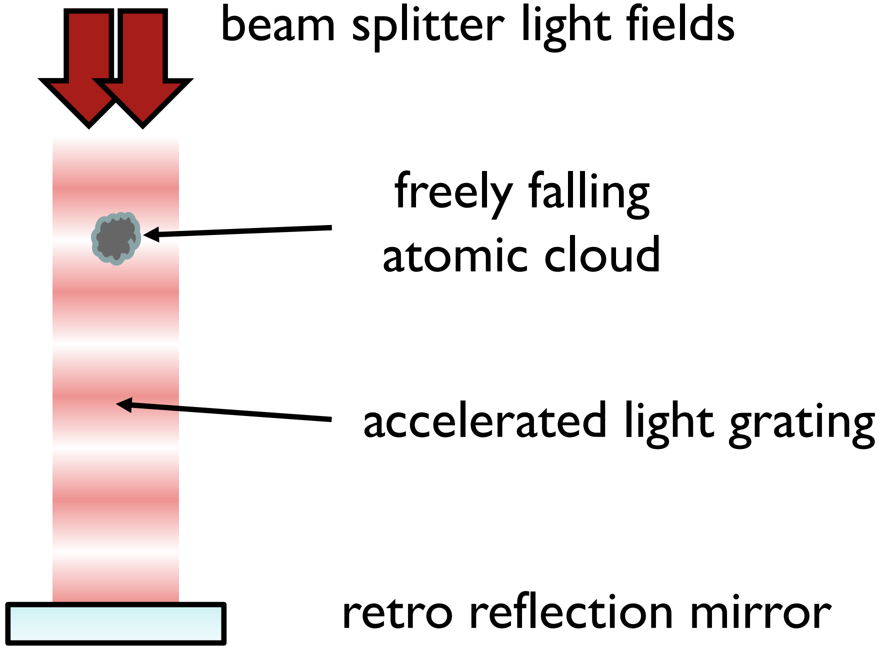
DATA AVAILABILITY

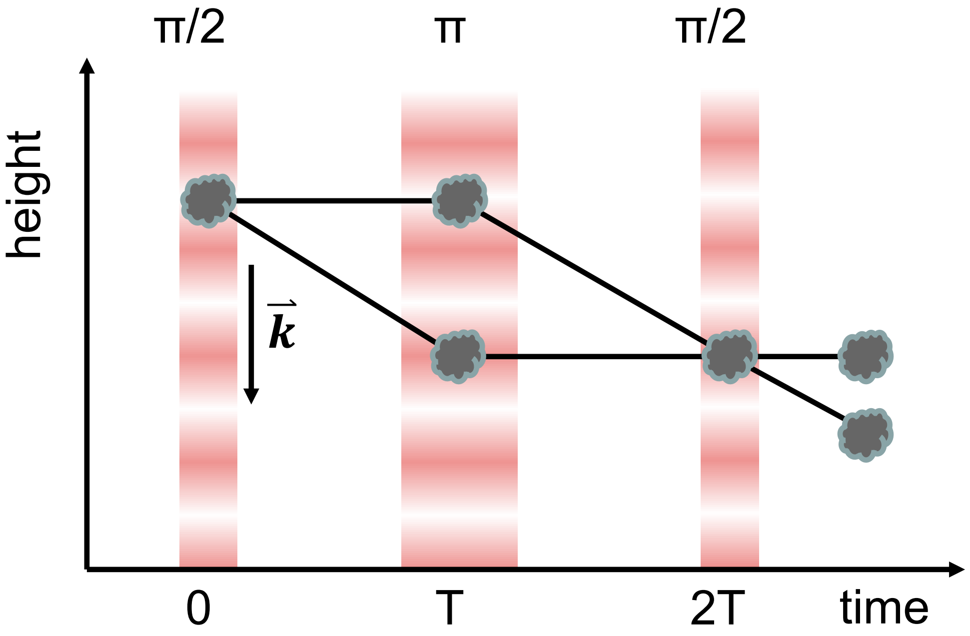
Clocks +

ATOM INTERFEROMETRY

Atom interferometry

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





courtesy of Christian Schubert

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

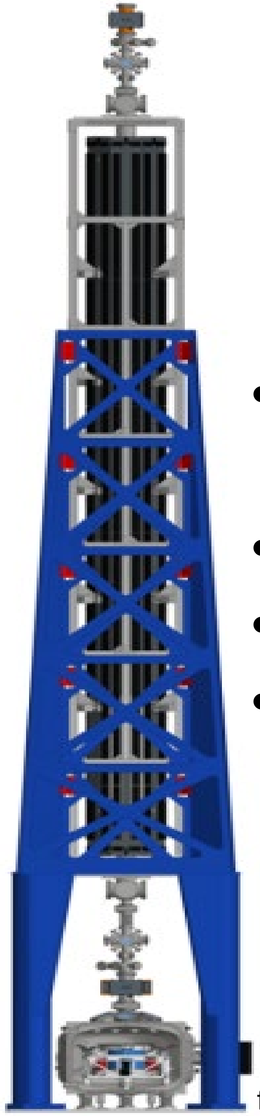
Atom interferometry for Geodesy

Quantum gravimeter

from Heine et al. 2020

- Absolute Gravimeter
- Transportable
- Drift-free
- Miniaturization

VLBAI

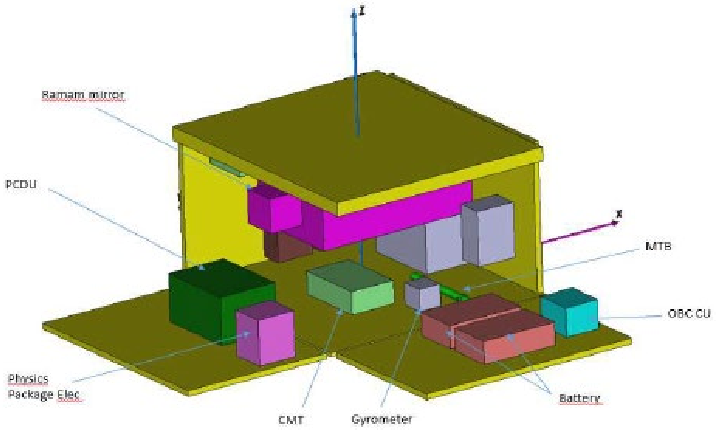


from Schilling et al. 2020

- Absolute Gravimeter
- Stationary
- Drift-free
- Long-term gravity reference

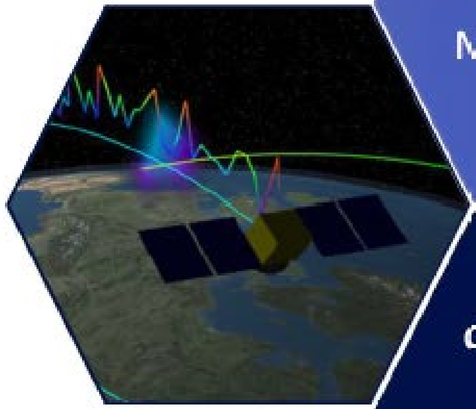
CARIOQA

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



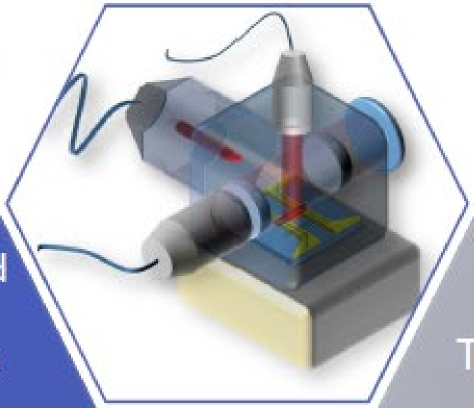
from Lévèque et al. 2022

Six objectives



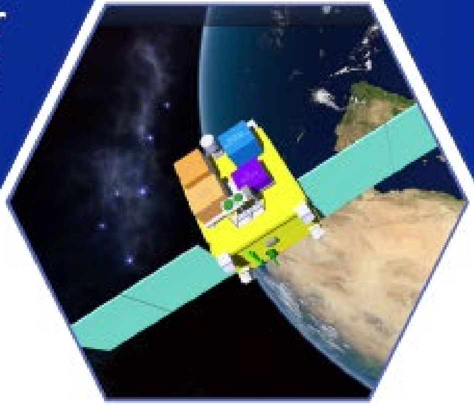
Define advanced scenarios of Quantum Space Gravimetry Missions meeting scientific user needs

Prepare the deployment of a Quantum Pathfinder Mission through simulations



Design a quantum gravimeter/ accelerometer operable on a satellite

Increase the TRL of quantum gravimeters/ accelerometers for use in space



Provide an Engineering Model of the Quantum Pathfinder Mission instrument

Establish a technical and programmatic roadmap validated by European stakeholders

Consortium

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

Coordination

CNES and DLR under CNES lead

cnes

DLR Deutsches Zentrum für Luft- und Raumfahrt

Satellite instrument development

Airbus Defence and Space, Exail, TELETEL, LEONARDO

AIRBUS exail teletel LEONARDO

Quantum sensing

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

LCAR Laboratoire Collisions Agrégats Réactivité

Leibniz Universität Hannover

ONERA THE FRENCH AEROSPACE LAB

SYRTE l'Observatoire de Paris | PSL

SYstèmes de Référence Temps-Espace

FORTH FOUNDATION FOR RESEARCH AND TECHNOLOGY - HELLAS

LP2N Laboratoire Photonique Numérique & Nanosciences

Space geodesy, Earth sciences

LUH, TUM, POLIMI, DTU

DTU Technical University of Denmark

TUM Technische Universität München

POLITECNICO MILANO 1863

Leibniz Universität Hannover

Impact maximization and impact assessment

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

FORTH FOUNDATION FOR RESEARCH AND TECHNOLOGY - HELLAS

G.A.C. GROUP Innovation & Performance For Impact

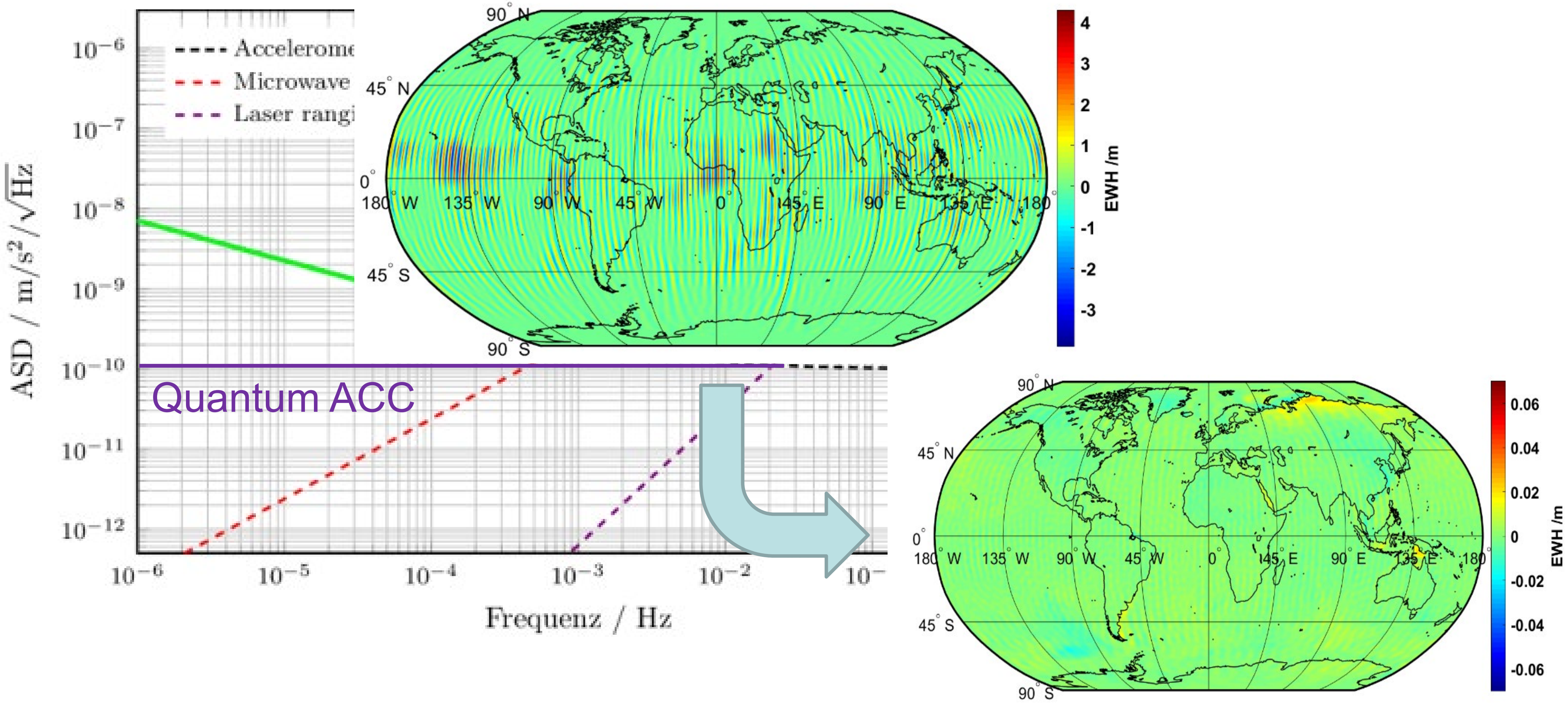
Anticipated sensitivity

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*

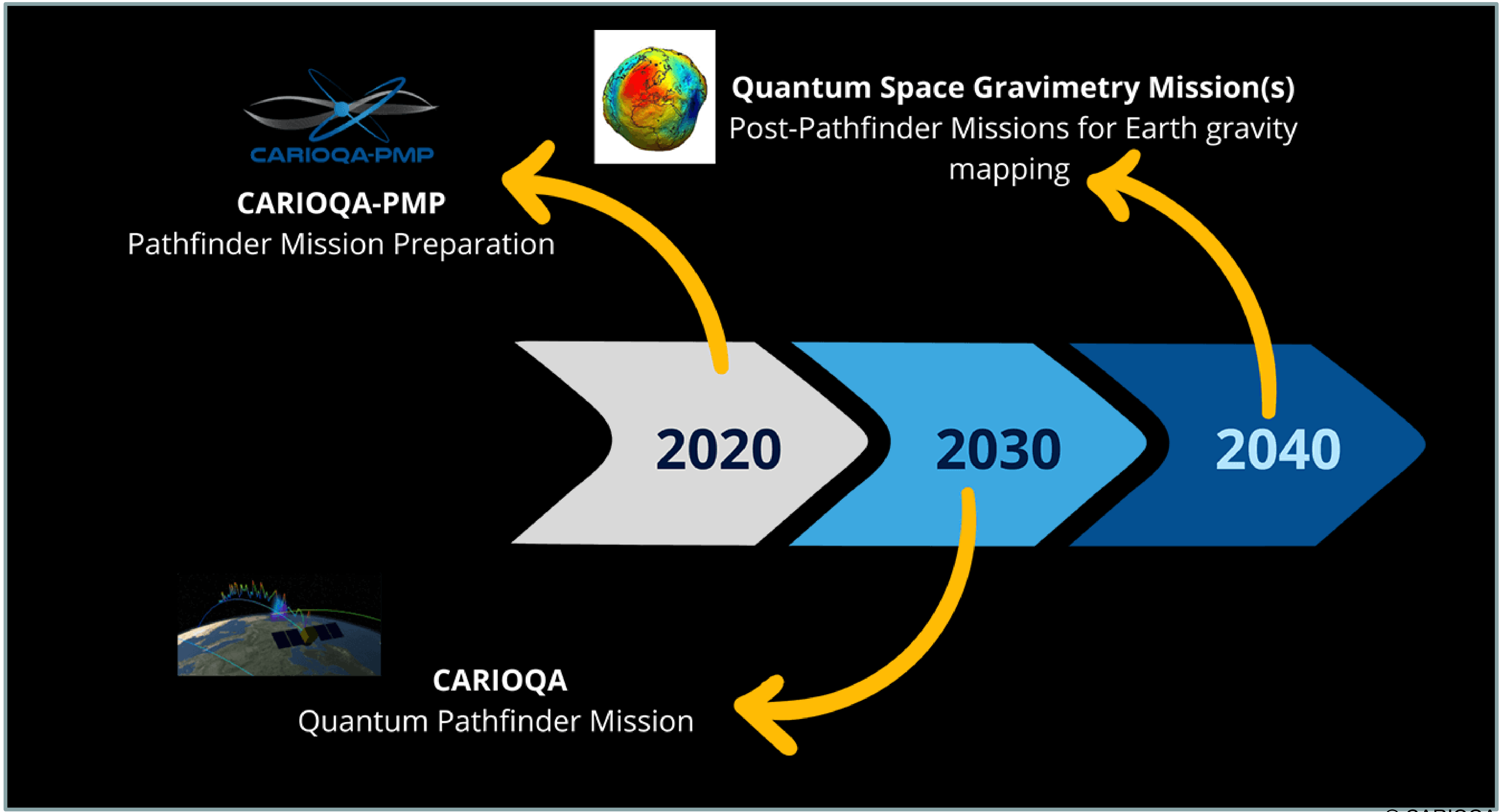
from Lévèque et al. 2022

CARIOQA



Accelerome
Microwave
Laser rangi
Quantum ACC
ASD / m/s²/√Hz
Frequenz / Hz
EWH /m
90° N
45° N
0°
45° S
90° S
180 W
135 W
90 W
45 W
0
45 E
90 E
135 E
180

CARIOQA


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

Challenges of existing systems

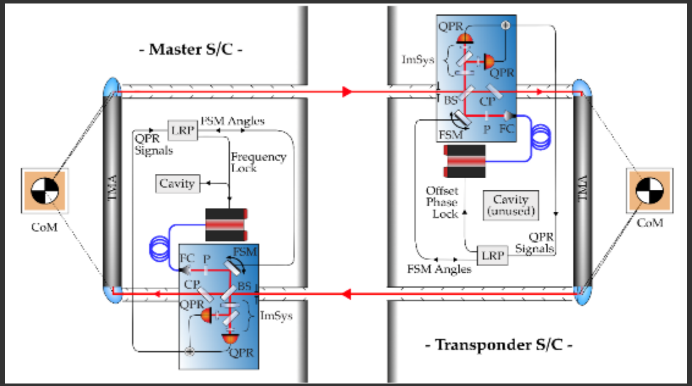
SPATIAL AND TEMPORAL RESOLUTION	SENSOR NOISE	BACKGROUND MODELS	DATA AVAILABILITY
Clocks +	Clocks ✓		Clocks +
CAI ✓	CAI ✓		CAI +

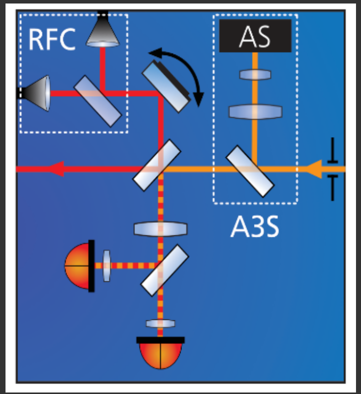
LASER INTERFEROMETRY

Satellite Gravimetry with laser interferometry

Components for the next generation optical bench designs

Miniaturization of components requires novel concepts

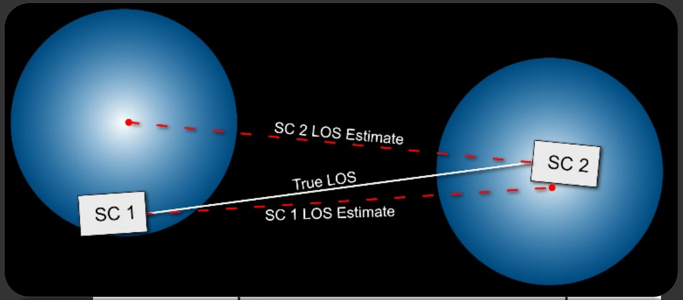


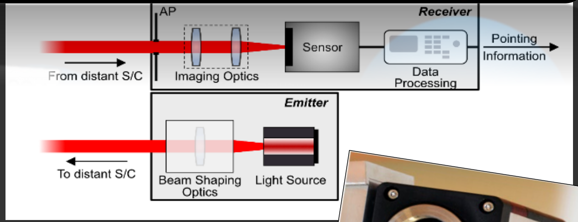


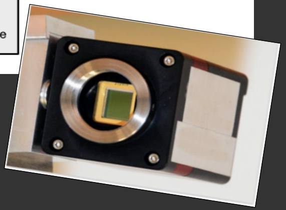
courtesy of Alexander Koch

Dedicated Constellation Acquisition Systems

Laser link acquisition is the most critical step during commissioning of the instrument





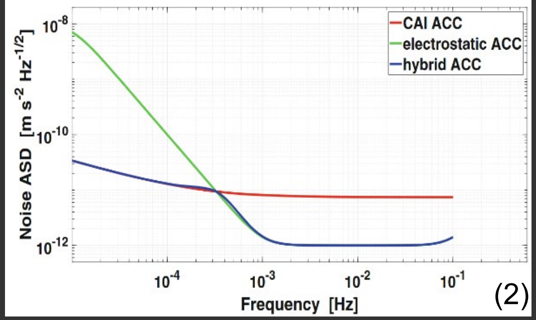


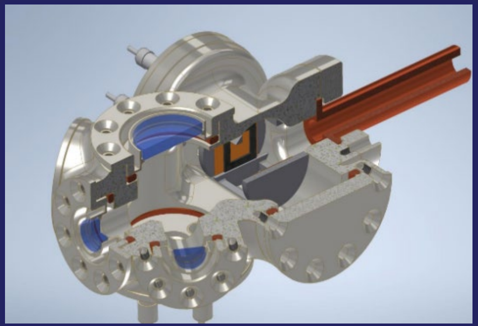
MiniCAS:

- Compact, modular, low SWaP design

Accelerometry in the post-MAGIC era

Cold Atom Interferometers and Hybridization with optical sensor

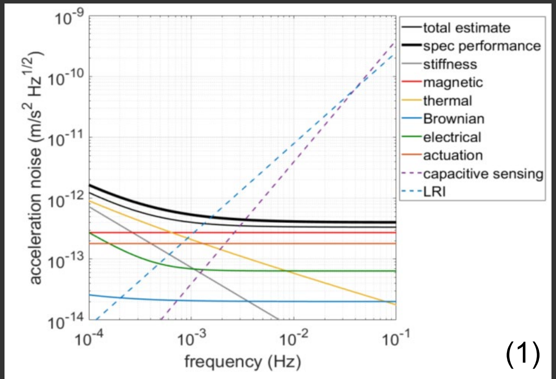


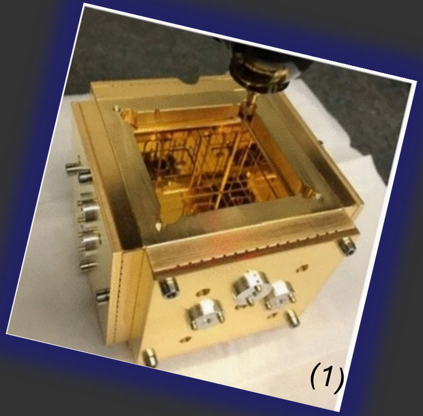


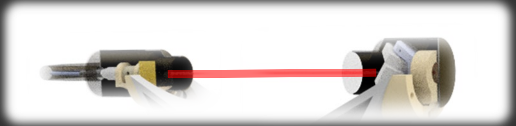
courtesy of Alexander Koch

Gravitational Reference Sensor

Based on heritage from LISA Pathfinder





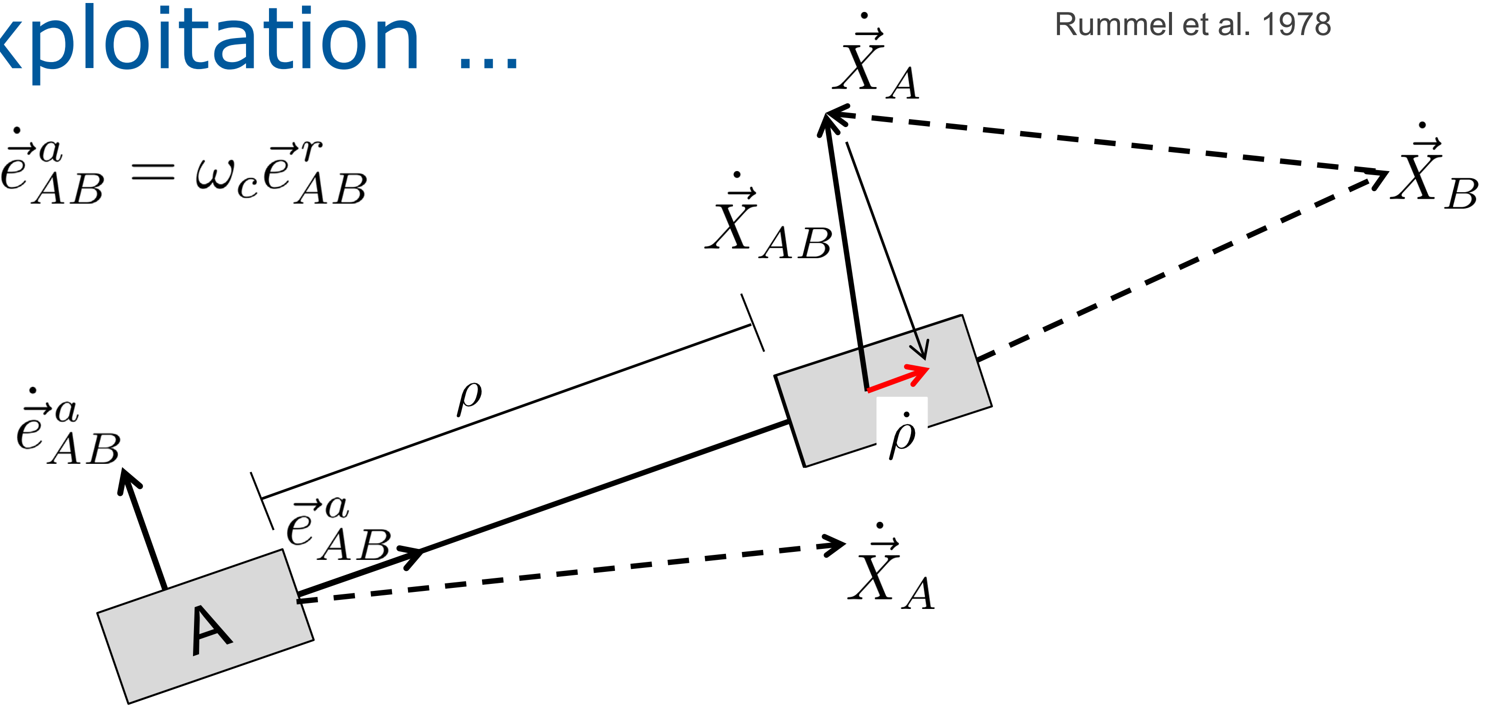


(1) https://doi.org/10.1007/s00190-022-01659-0
(2) https://doi.org/10.1007/1345_2022_151

Geodetic Exploitation …

Rummel et al. 1978

$$\vec{e}^{\,r}_{AB} = \frac{\dot{\vec{e}}^{\,a}_{AB}}{|\dot{\vec{e}}^{\,a}_{AB}|} \rightarrow \dot{\vec{e}}^{\,a}_{AB} = \omega_c \vec{e}^{\,r}_{AB}$$



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

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

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

Standard approach

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

GRACE-like systems are considered one-dimensional.

Multi-dimensional systems

2D Approach:

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

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

$$\dot{\vec{X}}_{AB} \cdot \vec{e}^{\,r}_{AB} = \rho\,\omega_c$$

3D Approach:

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

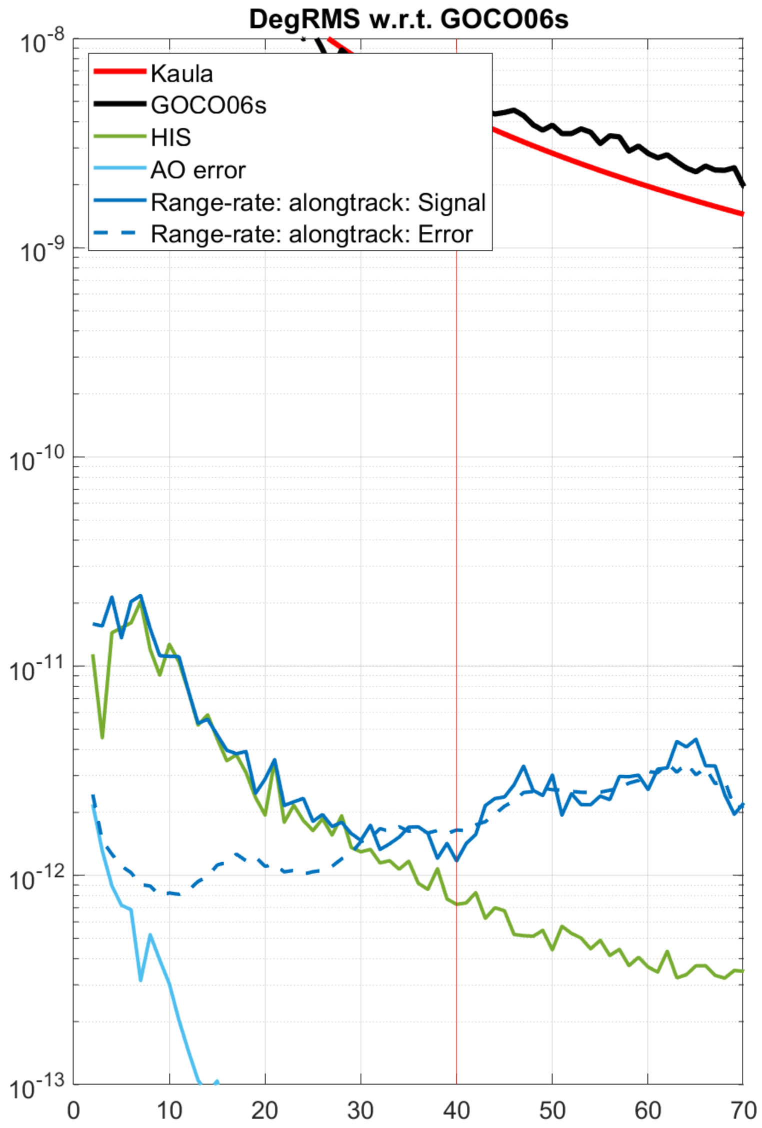
$$\ddot{\vec{X}}_{AB} \cdot \vec{e}^{\,a}_{AB} = \ddot{\rho} \quad + \quad 0 \quad - \quad \rho\,(\omega_c)^2$$

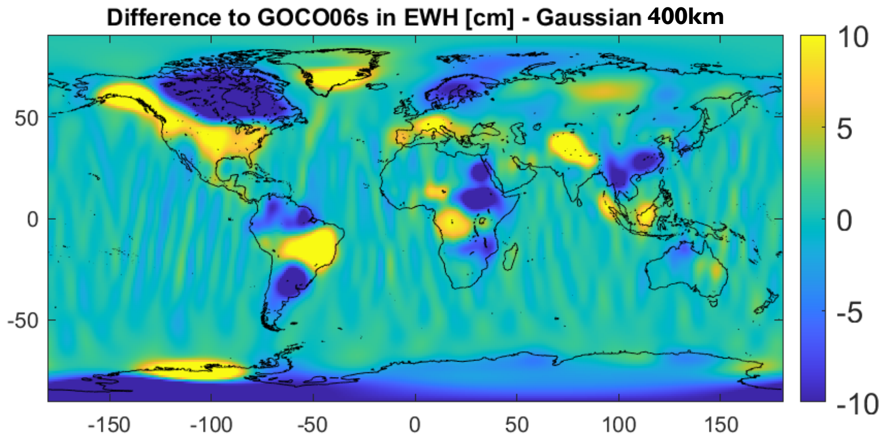
$$\ddot{\vec{X}}_{AB} \cdot \vec{e}^{\,r}_{AB} = 0 \quad - \quad 2\,\dot{\rho}\,\omega_c \quad - \quad \rho\,\dot{\omega}_c$$

$$\ddot{\vec{X}}_{AB} \cdot \vec{e}^{\,c}_{AB} = 0 \quad + \quad 0 \quad - \quad \rho\,\omega_a \omega_c$$

Weigelt 2017
The Acceleration Approach

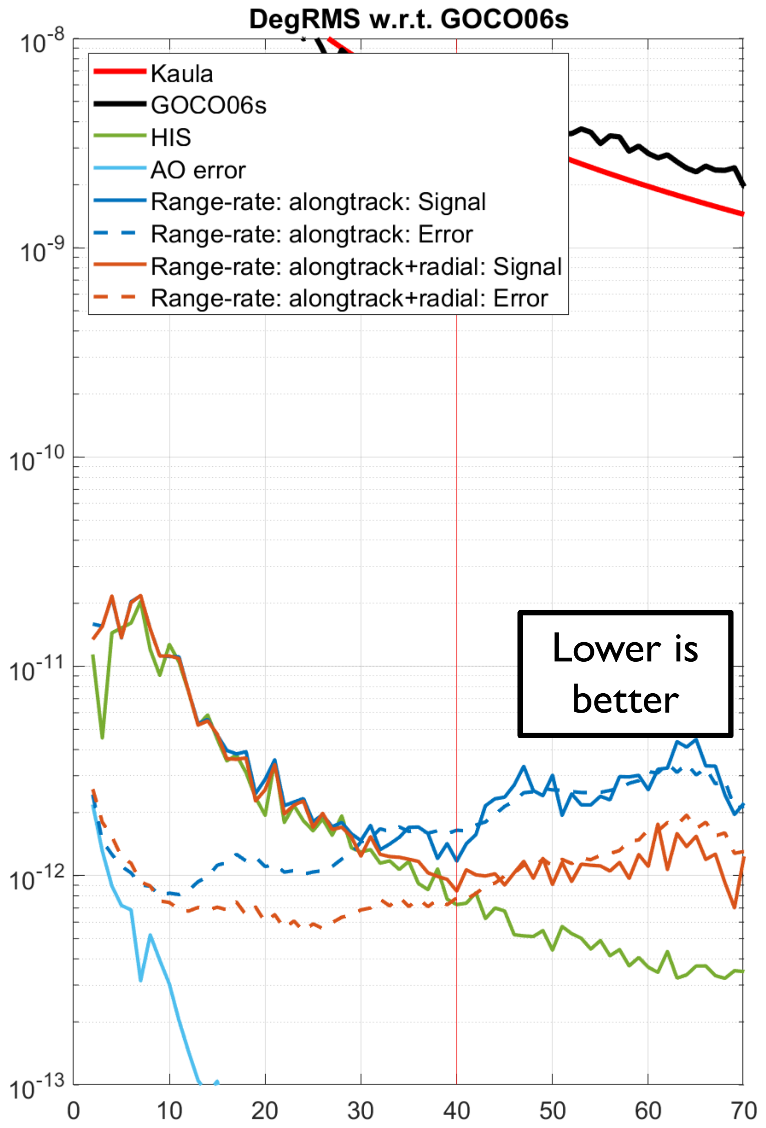
Simulation: the standard case

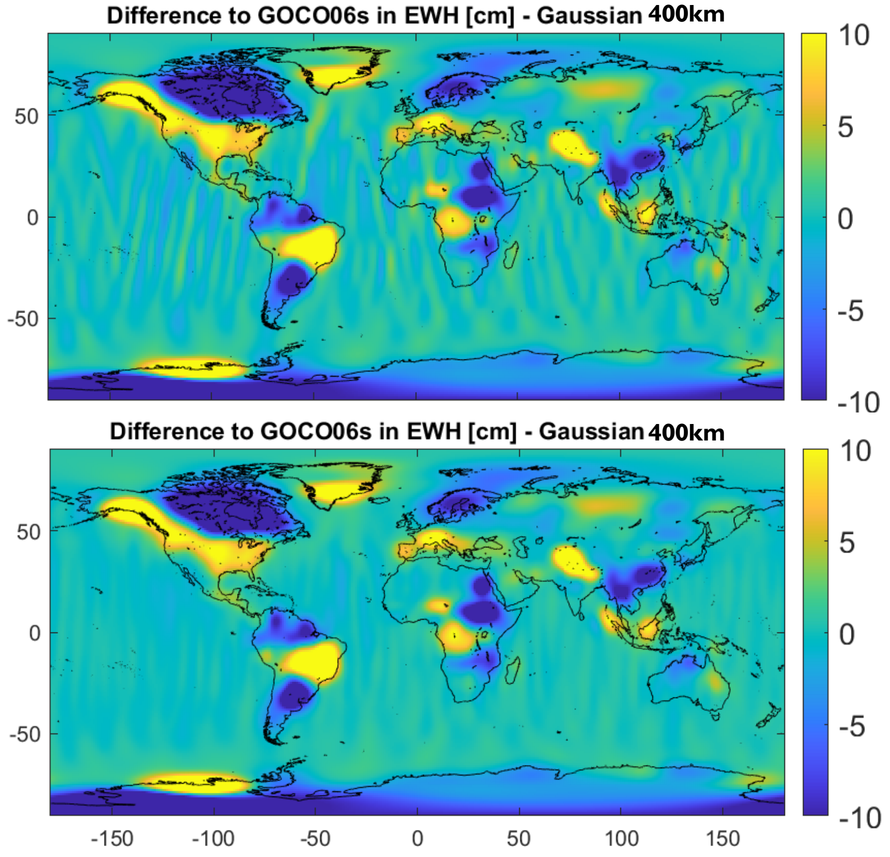




Range-rate alongtrack only

Simulation results: 2D



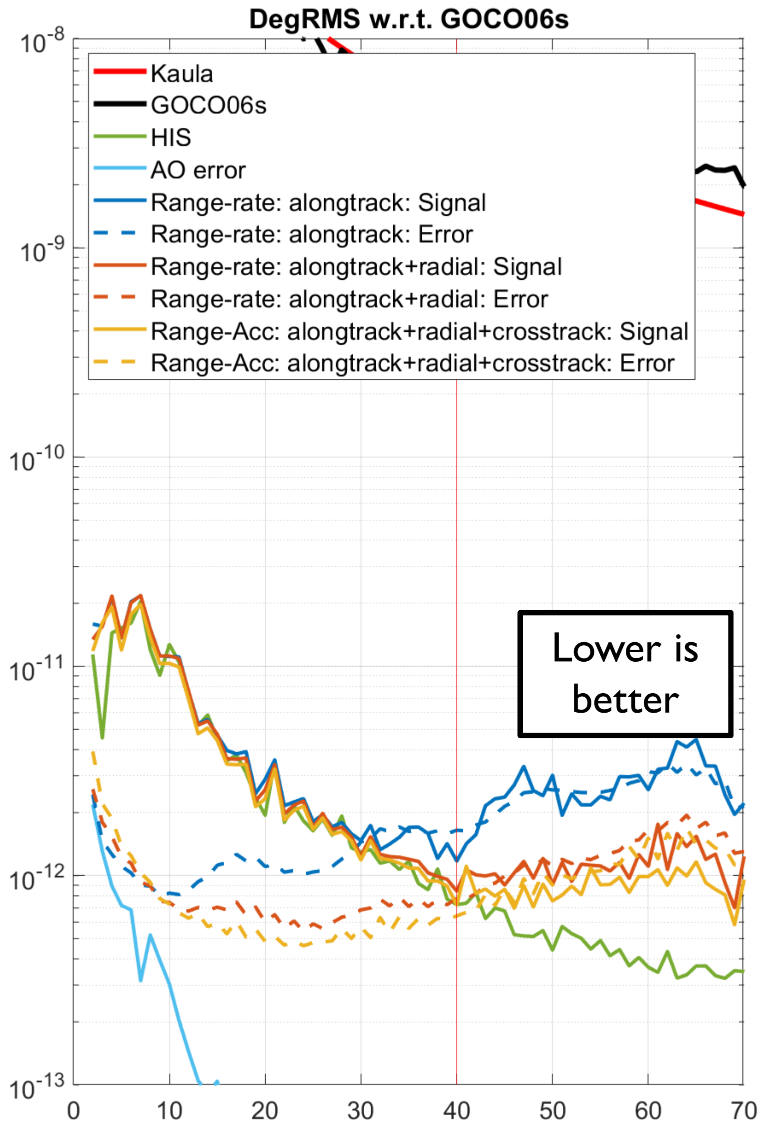


Range-rate along-track only

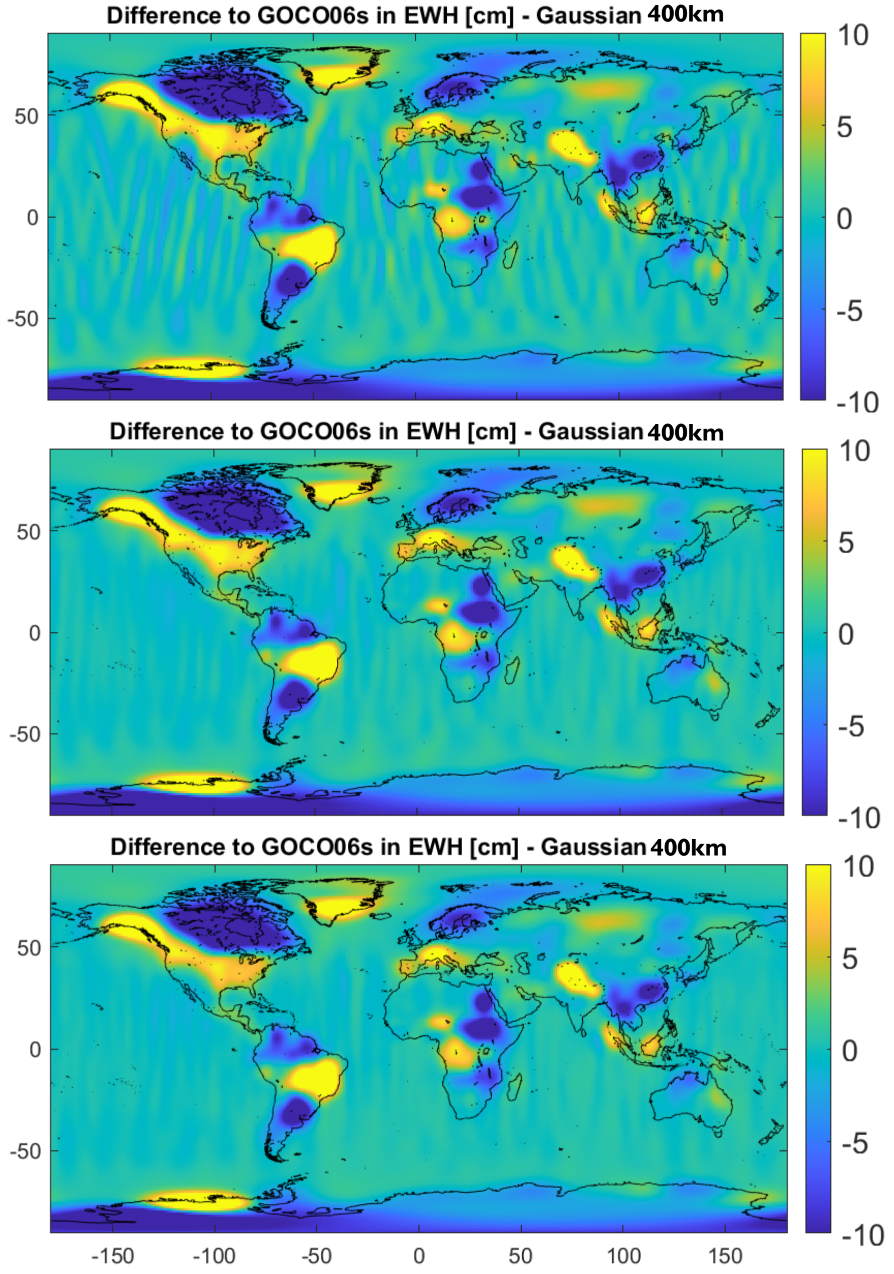
Smoother is better

Range-rate along-track + radial

Simulation results: 3D



Lower is better



Range-rate along track only

Smoother is better

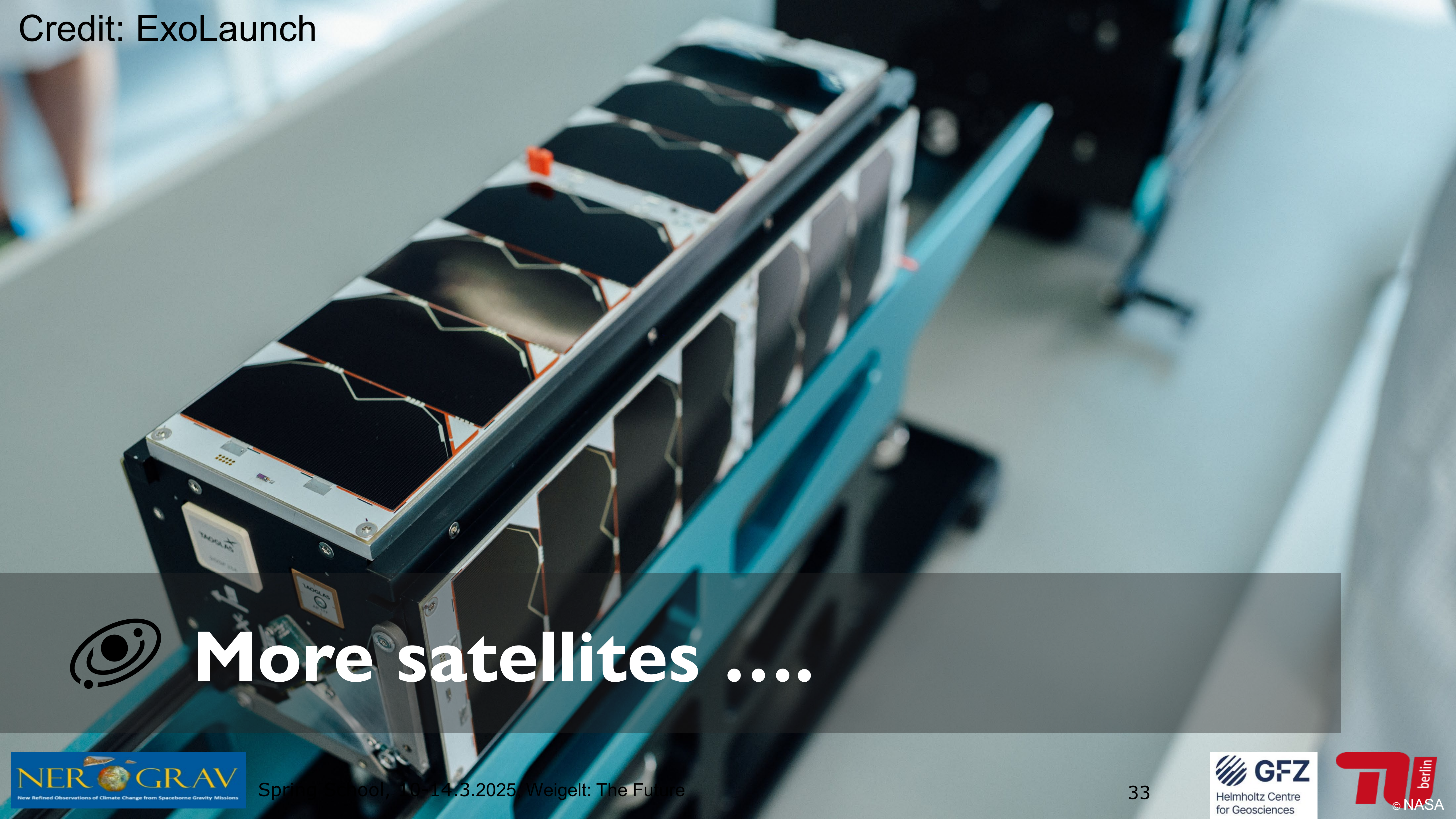
Range-rate along track + radial

Range-acceleration along-track + radial + cross-track

Challenges of existing systems

SPATIAL AND TEMPORAL RESOLUTION		SENSOR NOISE		BACKGROUND MODELS	DATA AVAILABILITY	
Clocks	+	Clocks	✓	?	Clocks	+
CAI	✓	CAI	✓		CAI	+
New Approaches	✓	LRI/LRX	✓		MiniCAS	+
		GRS	✓			

Credit: ExoLaunch



More satellites ....

Ground-track coverage

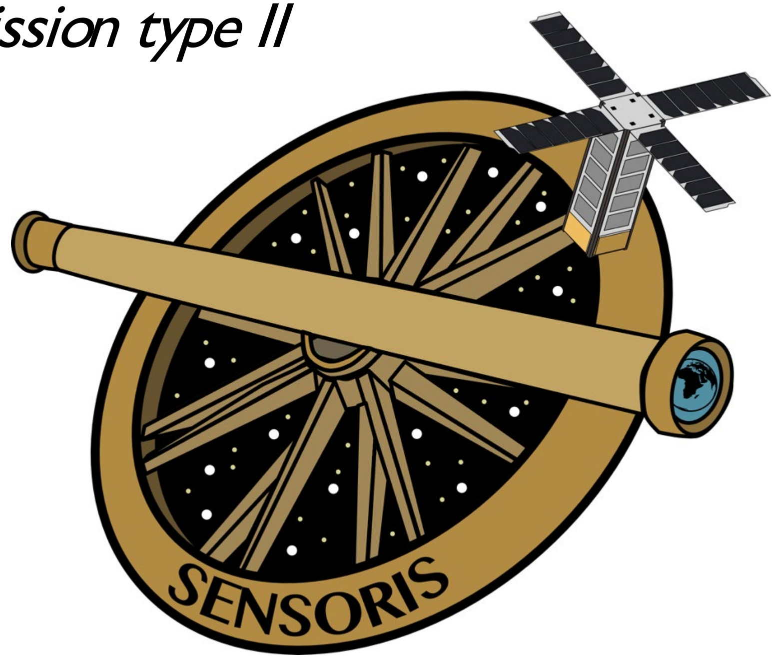
Simulation

SENSORIS

SENSORIS
NewSpace Gravity Field Mission
16 satellites

Budget: 20 million €

submitted to the DLR Scout Call
Mission type II



Why Sensoris?

Limitations of MAGIC:

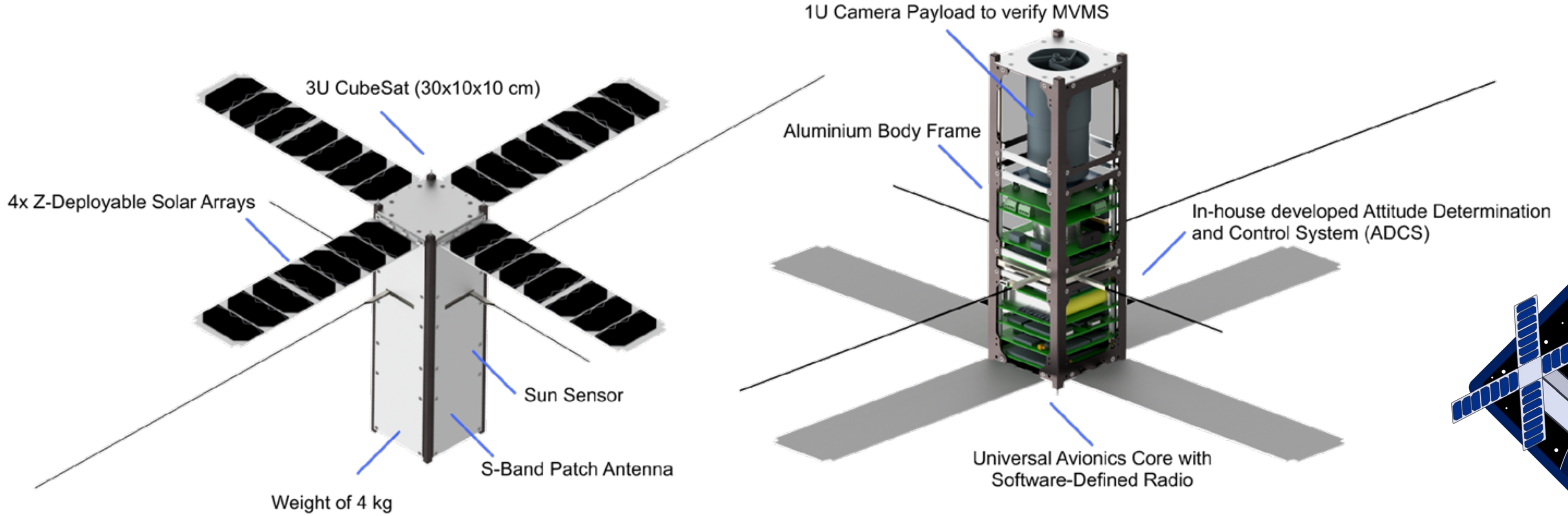
- Costs: two satellite pairs are expected to cost over 1 billion €.
- Temporal resolution is limited to 1 month or 5 days.
- Solutions are limited by background modelling.

Sensoris addresses these challenges by:

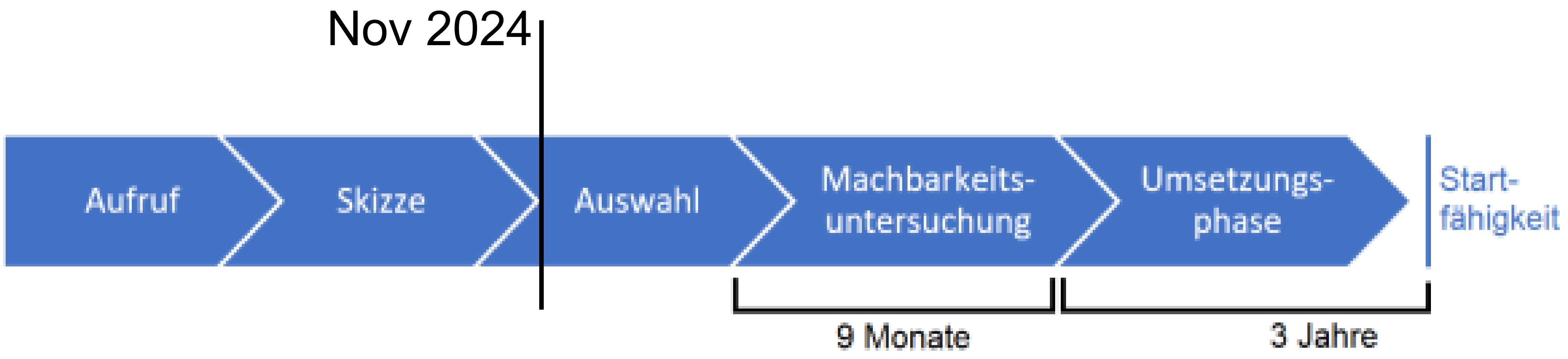
- the utilisation of shelve products and consumer electronics for space applications in order to create smaller, lighter and more cost-effective satellites,
- provide temporally high-resolution (daily) gravity field solutions,
- maximise the added value of the future GRACE-C and NGGM missions by addressing the problem of limiting background modelling and
- generating redundancy in gravity field determination and thus increasing resilience to failures.

Technology

- Based on the VIBES Pioneer
- Bremen‵s 1st Student-Built Satellite to improve the optical performance of spacecrafts using consumer electronics
- One of eight European projects for a free launch opportunity by DLR
- Launch scheduled for 2025 to a 500km sun synchronous orbit



Timetable and long-term perspective



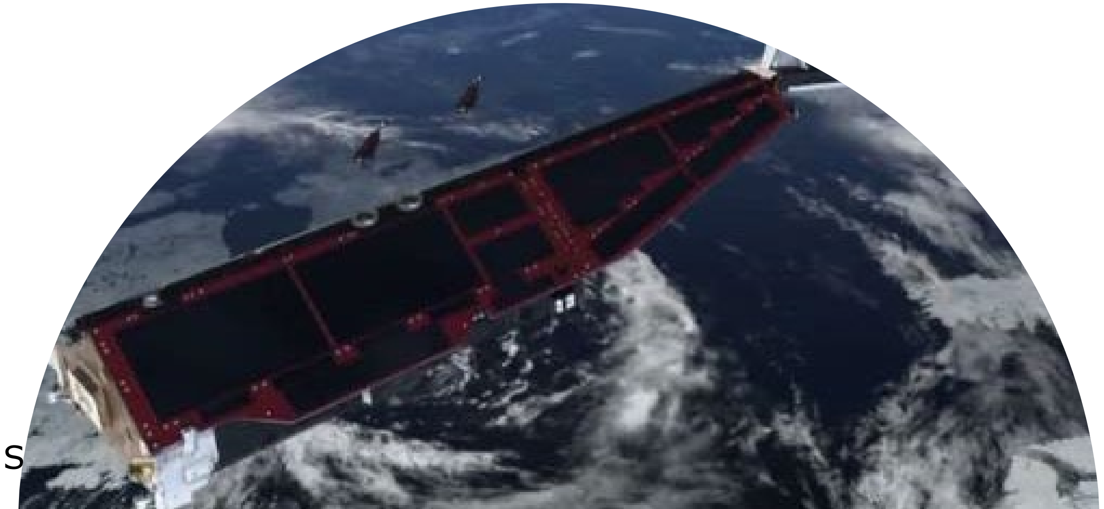
Long-term:

- Scalability: 64+ satellites to increase to half-daily or quarter-daily solutions
- Accelerometry possibly using quantum technology
- Low-low satellite-to-satellite tracking (compact LRI)

Bridging the gap

GNSS and satellite-laser ranging allow to bridge the data gap

ICGEM:
ULux Champ 2013s
geoQ_2018
QuantumFrontiers HLSST_SLR_COMB2019s



Weigelt et al. 2024
Bridging the gap between GRACE and GRACE Follow-On by combining high–low satellite-to-satellite tracking data and satellite laser ranging

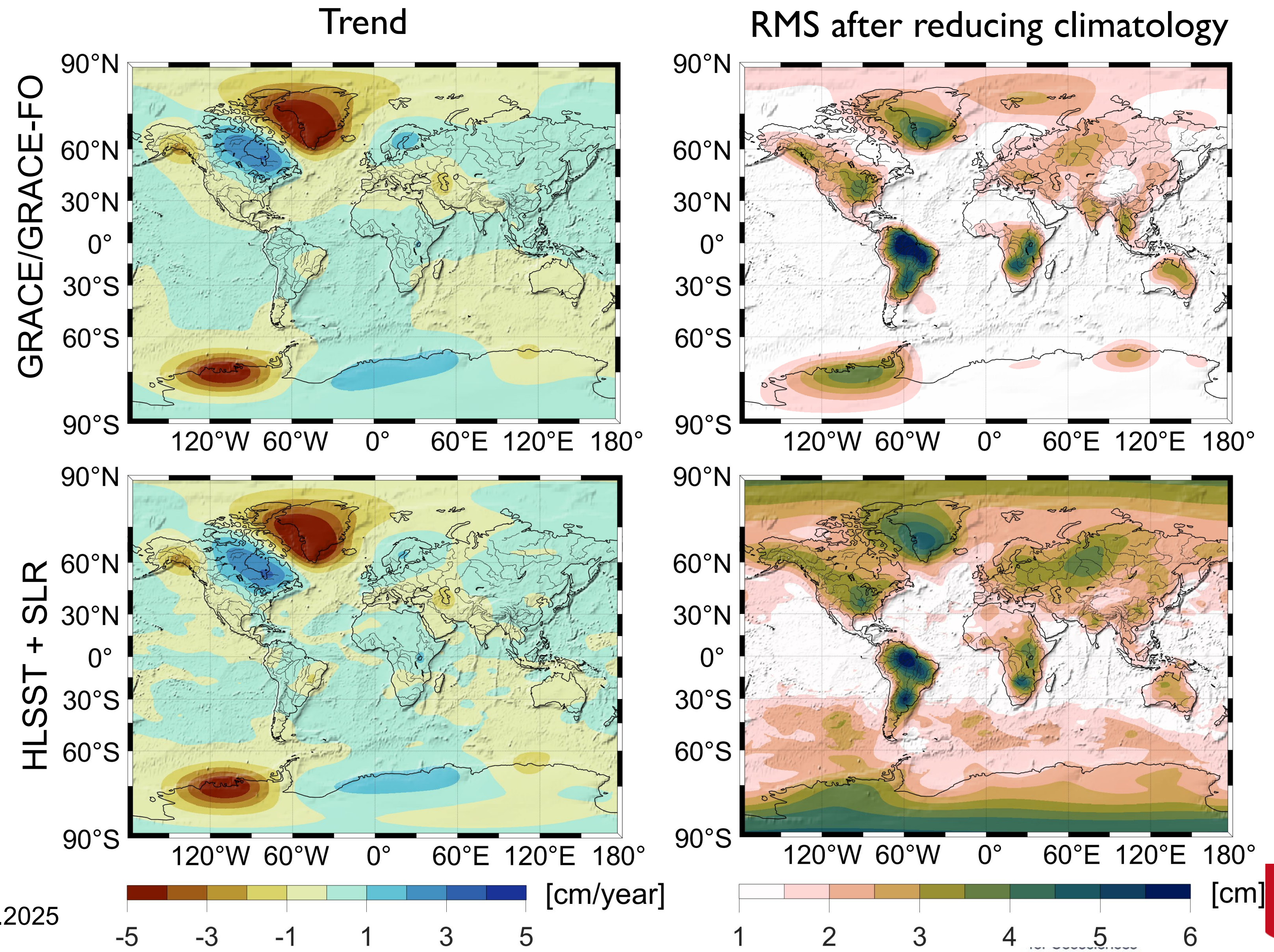
HL-SST+SLR

Gaussian filter 700 km

- Kinematic orbits from
  - Astronomical Institute, University Bern
  - Institute for Geodesy, Graz
  - Institute for Geodesy, Hannover
  - European Space Agency

  totalling 49 kinematic orbit products from 30 satellites.

- Accelerometer data used for CHAMP, GRACE, GRACE-FO and GOCE



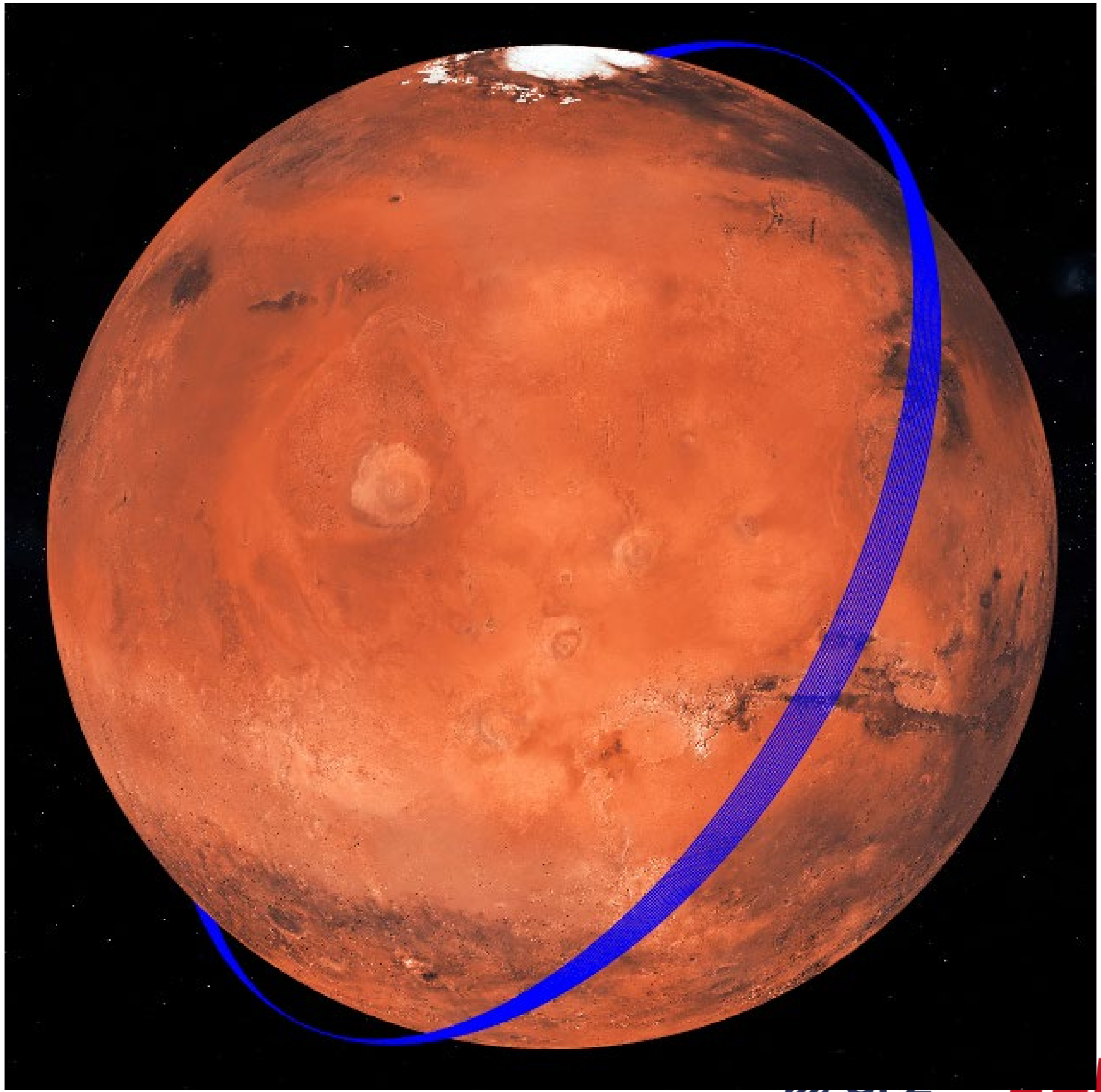
Challenges of existing systems

SPATIAL AND TEMPORAL RESOLUTION	SENSOR NOISE	BACKGROUND MODELS	DATA AVAILABILITY
Clocks +	Clocks ✓	SENSORIS ✓	Clocks +
CAI ✓	CAI ✓		CAI +
New Approaches ✓	LRI/LRX ✓		MiniCAS +
	GRS ✓		SENSORIS ✓


Exploiting quantum technology will bring the innovation needed to overcome the limitations.

From Earth to Planets

- Objective:
  Evaluating the potential of using quantum sensors for interplanetary missions
- Adapting VENQS (Digital Twin Software) for Mars simulations
- Extensions in development:
  - Precise gravity field model
  - Tides and 3rd body forces
  - Atmospheric drag
  - Solar radiation pressure + Albedo



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

People matter for getting the best results

Target-oriented working

Cooperation

Fostering one's own initiative

Trust and appreciation

Embracing tolerance and respect

Living a bold culture of venture

Committed people are the key to sense gravity