

Monitoring Earth's gravitational field variations using quantum technologies

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- Global mass distribution phenomena \Rightarrow gravimetry
- 2 application: glacier melting & earth mantle movement monitoring
- Classical gravitometer (GRACE and GOCE)
- Quantum gravimeters (CARIOQA)
- Quantum advantage
- Political landscape and cooperation challenges

Mass transport and mass distribution

- Elements affecting transport and redistribution of mass in the Earth system:
 - Circulation in ocean and atmosphere
 - Ice melting, sea level changes
 - Flow in Earth's mantle ...

→ How much mass is transported and what is its distribution ?
- Goal : Understand global water cycle and enable better future climate scenario predictions



Satellite gravimetry

Basics

Applications

Classic

Quantum

Politics

- Global picture of earth mass and gravitational phenomena
 - ground monitoring too limited

- Output signal types:
 - Static gravity field \Rightarrow earth density structure

 - Temporal gravity variation
 - \Rightarrow Tidal signals, Post glacial rebound, Seismic effects, Geodetic effects...

Ice mass balance and sea level changes

Basics

Applications


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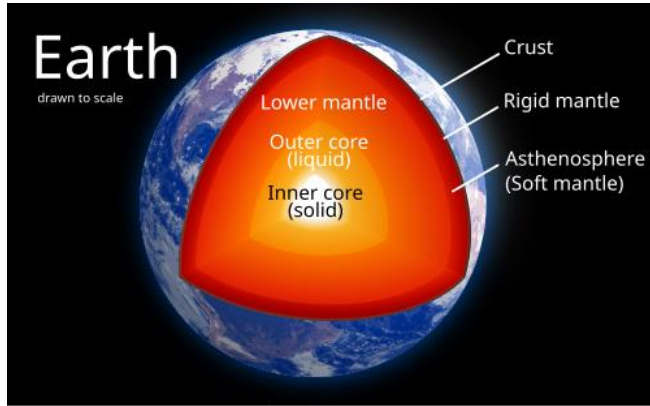
- Continuous exchange of water between ice sheets and oceans
- Change in mass redistribution → change in gravity potential

! Not uniform !

 Gravity field measurement enables precise estimations of ice mass balance and better predictions in sea level changes

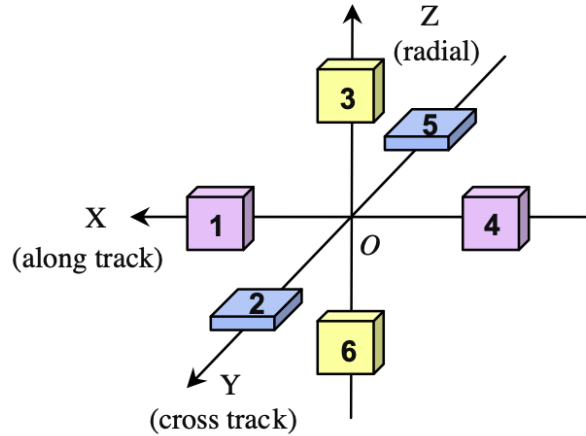
- Sea level changes impact both society and environment !

Earth mantle movements

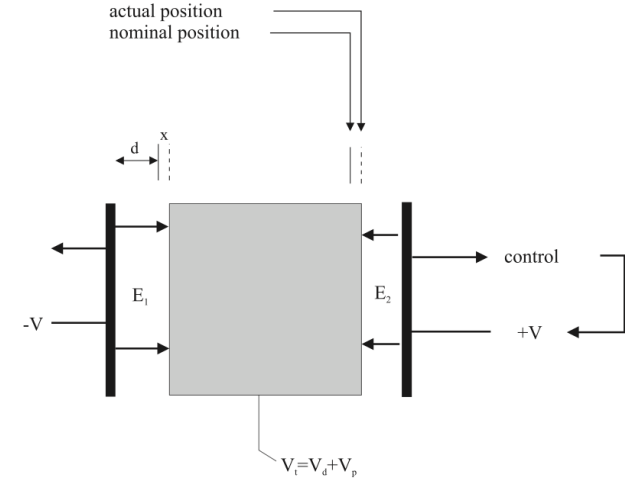


- Temporal gravity variation
- First measurement with classical sensors
- Earth modelling
- Effects on climate:
 - Sea levels
 - Ice sheet stability after mass redistribution
 - Ocean circulation and ridge
 - Indirect: atmosphere as influence volcano activity

Classical gravimeter - basics



Schematics of a the most modern classical gravimeter
Z. Zhu, Advances in Space Research, 2013



Schematics of capacitive accelerometer
B. Frommknecht, Advances in Geosciences, 2003

- Withdraw: bias, long-term drift, and scale-factor errors
- Gyroscope needed for isolation from motion → misalignment possible

Classical gravimeter - GRACE mission



Source: Helmutz center of science

- 2 satellite – measure distance difference between them
 - not carrying instruments: it is the instrument!

- 2002 – 2017
- 1 measure every 30 days, time varying field
- 220 km of distance between, 1 μm of error
- Spatial resolution ~ 200 km
- Gravity resolution $\sim 1 \text{ mGal} = 10^{-5} \text{ m/s}^2$
 - 30 days integration time needed
- Sensitivity band: low- f , large-scale Δm
 - basins, ice sheets, aquifers

Classical gravimeter – GOCE mission



- Electrostatic Gravity Gradiometer (EGG)
 - 6 accelerometers together coupled with GPS

- 2009 – 2013
- 1 measure per second, static earth field
- Extremely low orbit: 255 km
- Spatial resolution ~ 90 km
- Gravity resolution ~ 1 mGal = 10^{-5} m/s²
- Sensitivity band: high- f small- scale crustal var
 - tectonics, lithosphere structure, ocean circulation, ...

Quantum gravimeter: generalities

Basics

Applications

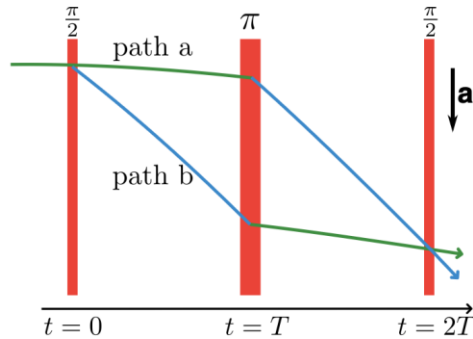
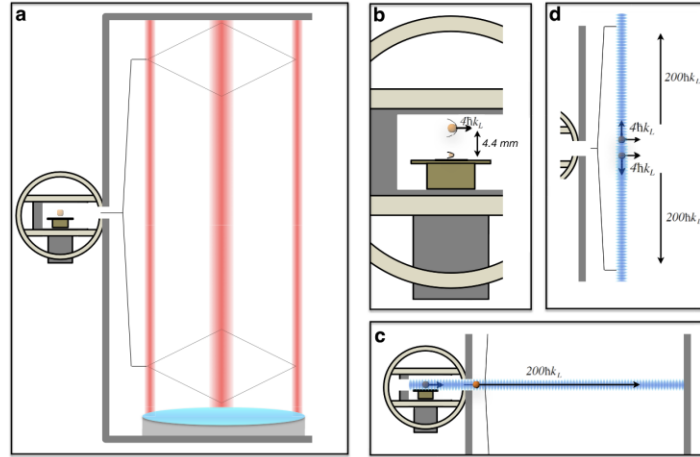
Classic

Quantum

Politics

- Technology developed in ~1990s
- Uses Atomic interferometry :
 - Based on quantum superposition and Raman effect
- Already tested on Earth, never tested in space
- Measure of gravity gradient : Cold atom interferometer
- Measures the gravitational redshift effect : Optical clock

CAI (Cold atom interferometer)



Cloud of cooled down atoms moved into interferometry region



Atoms beam split into two halves (up and down) to feed two interferometers



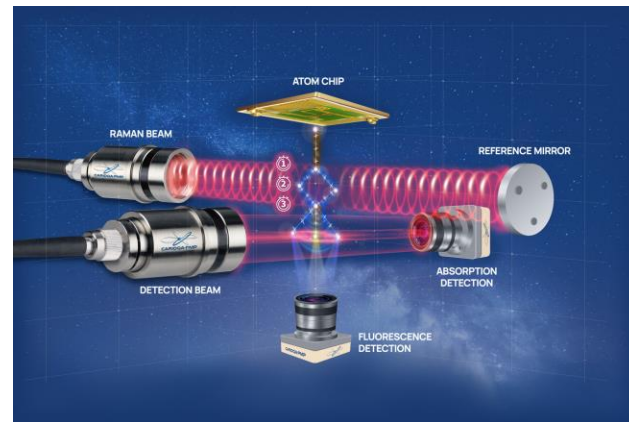
Each cloud is split, reflected and recombined



Gravity gradient retrieved from phase shift of atomic matter wave:

$$\Delta\Phi = k(a_2 - a_1)T^2 = k\gamma DT^2$$

- Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry
 - European mission, set to be launched in 2030
 - Quantum space gravity missions by 2040
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- Goals:
 - Accurate mapping of Earth's gravity field and atmosphere modelling
 - Better understanding of water cycle and Earth's interior structure
 - Sustainable resources management and climate change modelling



Quantum advantage

- Long-term stability
- Less affected by drifts
- Increased sensitivity and accuracy (low nano-g range on Earth, even better in space)

Classical : 10^{-5} m/s² VS Quantum: 10^{-9} m/s²

- Simplify data processing (less noise)
- Direct measuring, no calibration needed

Political associated landscape

- Military interests: can locate nuclear silo or submarines
- Natural resources interests: can locate new sources of rare materials/gas
- Quantum race between China, AUKUS, NATO → huge investement
- Threat to open science (ex CARIOQA mission) for security reasons

- Accurate Earth's gravity field measurements can lead to improvements in climate change predictions and global water cycle understanding
- Promising quantum technology
- Greater accuracy, better stability
- First quantum mission launch : 2030, results expected in ~2040

Thank you for your attention