Ideas for Future Gravity Missions

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Summer School Alpbach 2019
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Outline of the presentation

- Introduction to gravity and measurements
- What can we learn from GOCE ?
- What are important parameters for a gravity mission?
- Existing ideas for future gravity missions
- New ideas for future gravity missions

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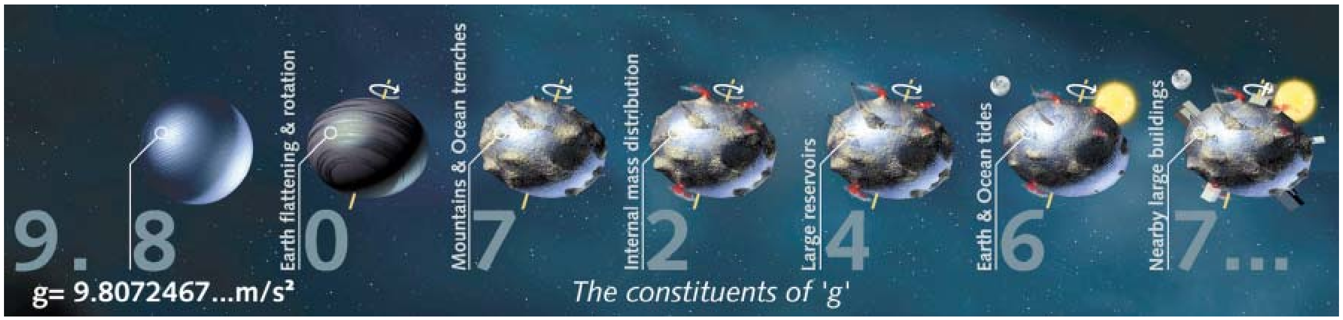
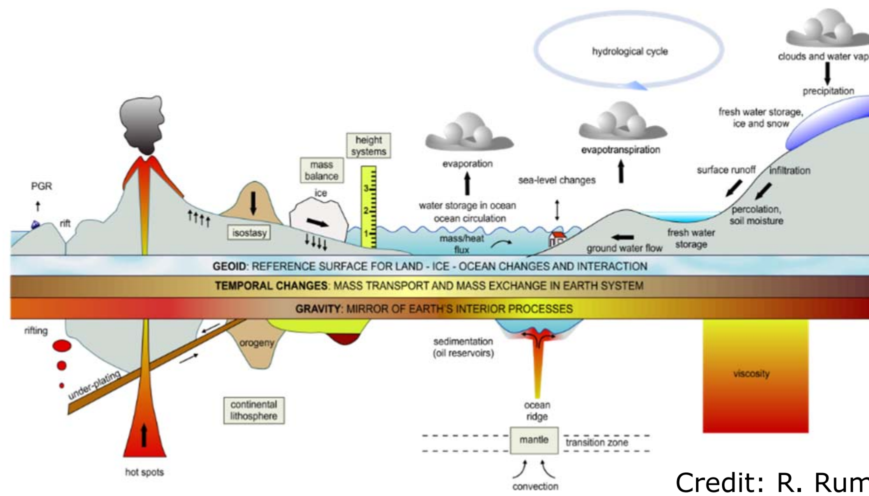
Gravity related to mass distribution & mass transport

Gravity relates to the **mass distribution** of the Earth



Mass RE-distribution (=transport) causes variations in the gravity field.

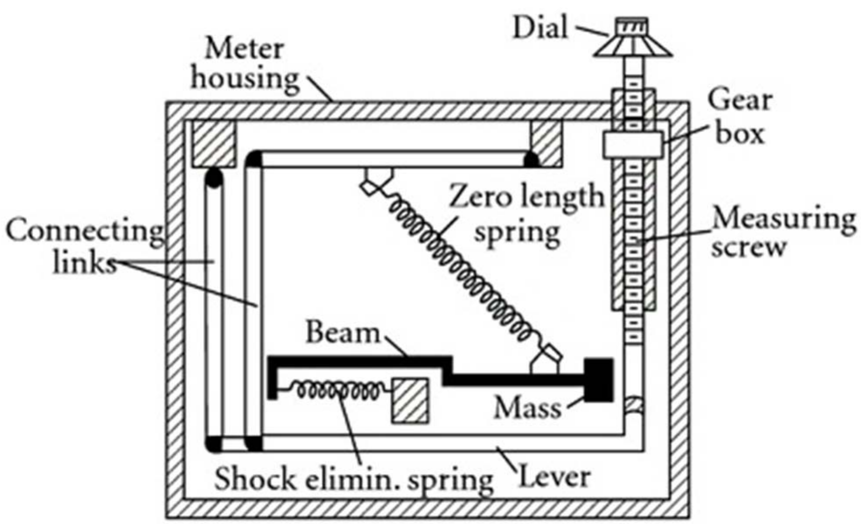
On short time scales, mass transport is almost exclusively caused by water transport.



Credit: R. Rummel

How can we measure gravity on ground ?

Relative gravity: precision 0.1 μGal (or 10^{-9} m/s^2)

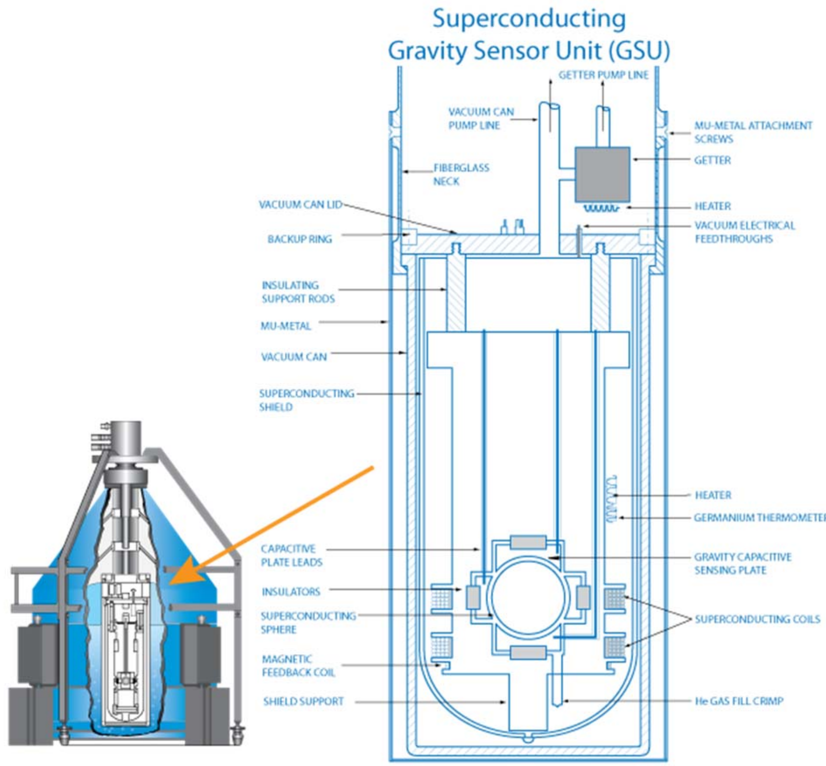


Credits: Micro G LaCoste

How can we measure gravity on ground ?

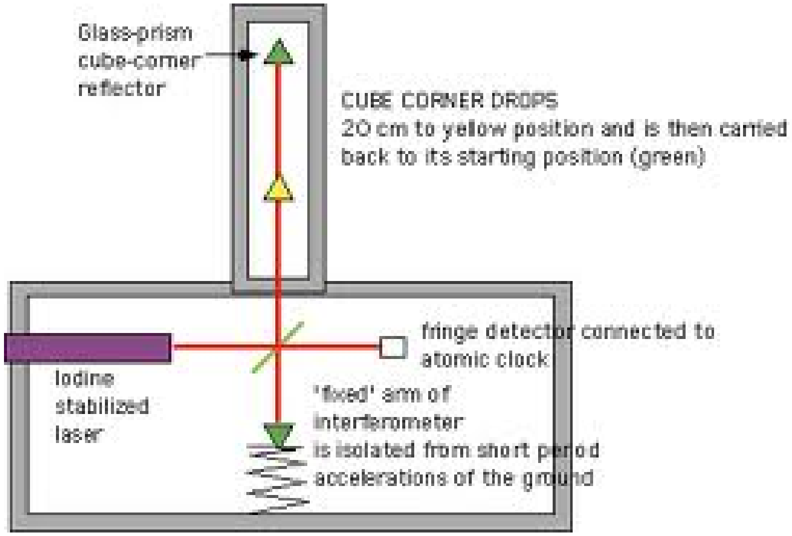
Relative gravity: precision 1 nGal (or 10^{-11} m/s^2)

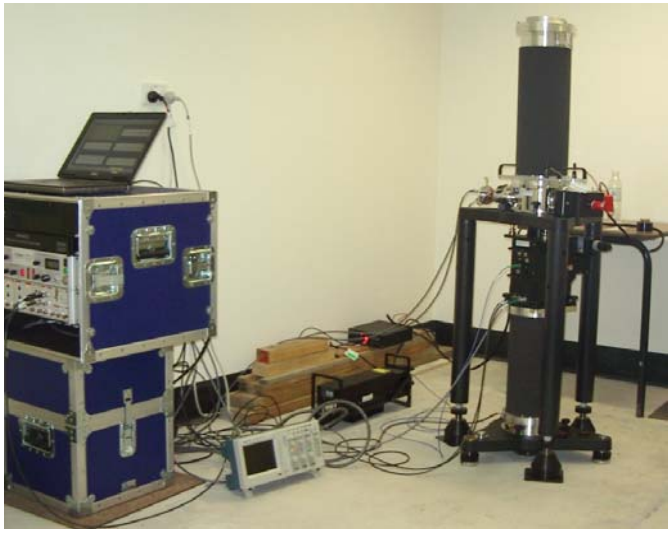
Credits: GWR Instruments Inc.



How can we measure gravity on ground ?

Absolute gravity: accuracy 1-2 µGal (or 10^{-8} m/s^2)





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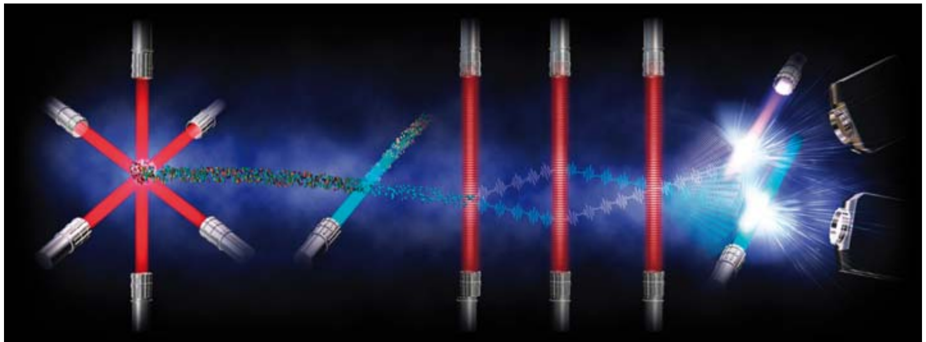
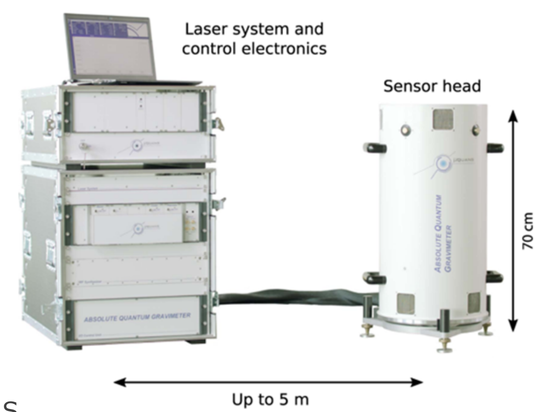
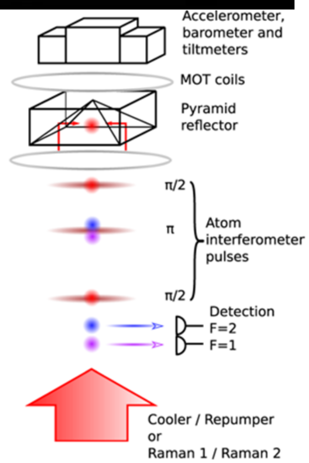
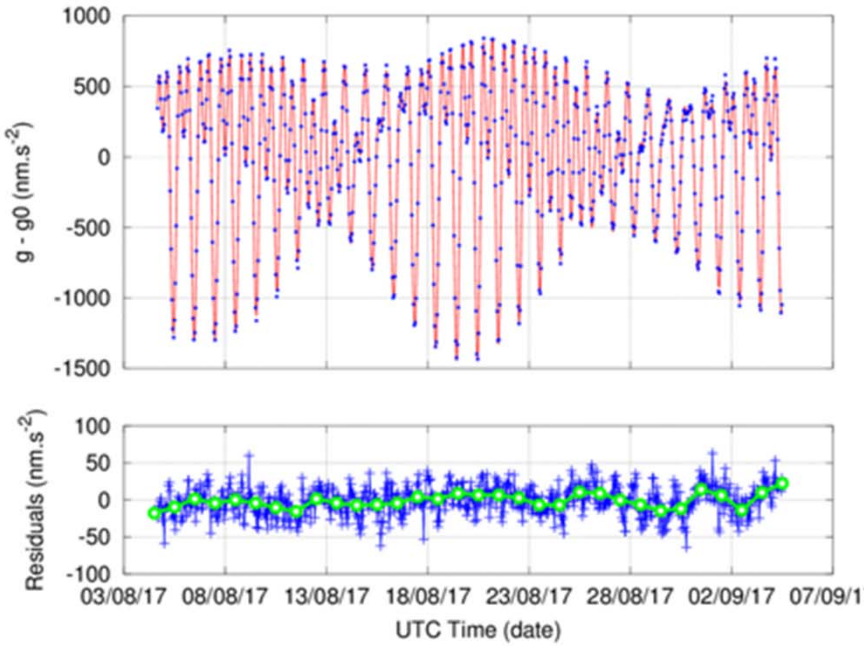


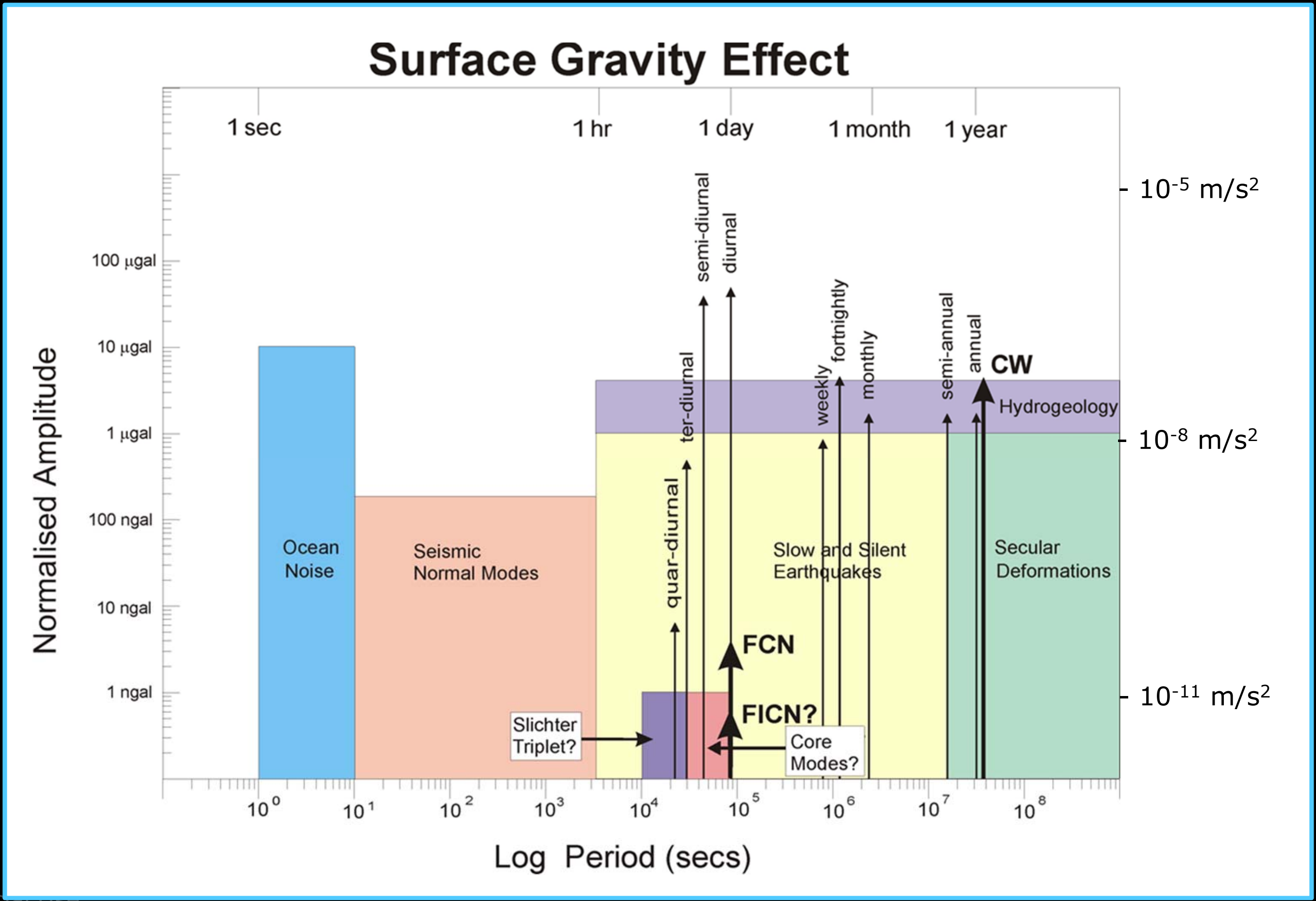






Credits: MuQuans, LP2N

What is observable on ground?



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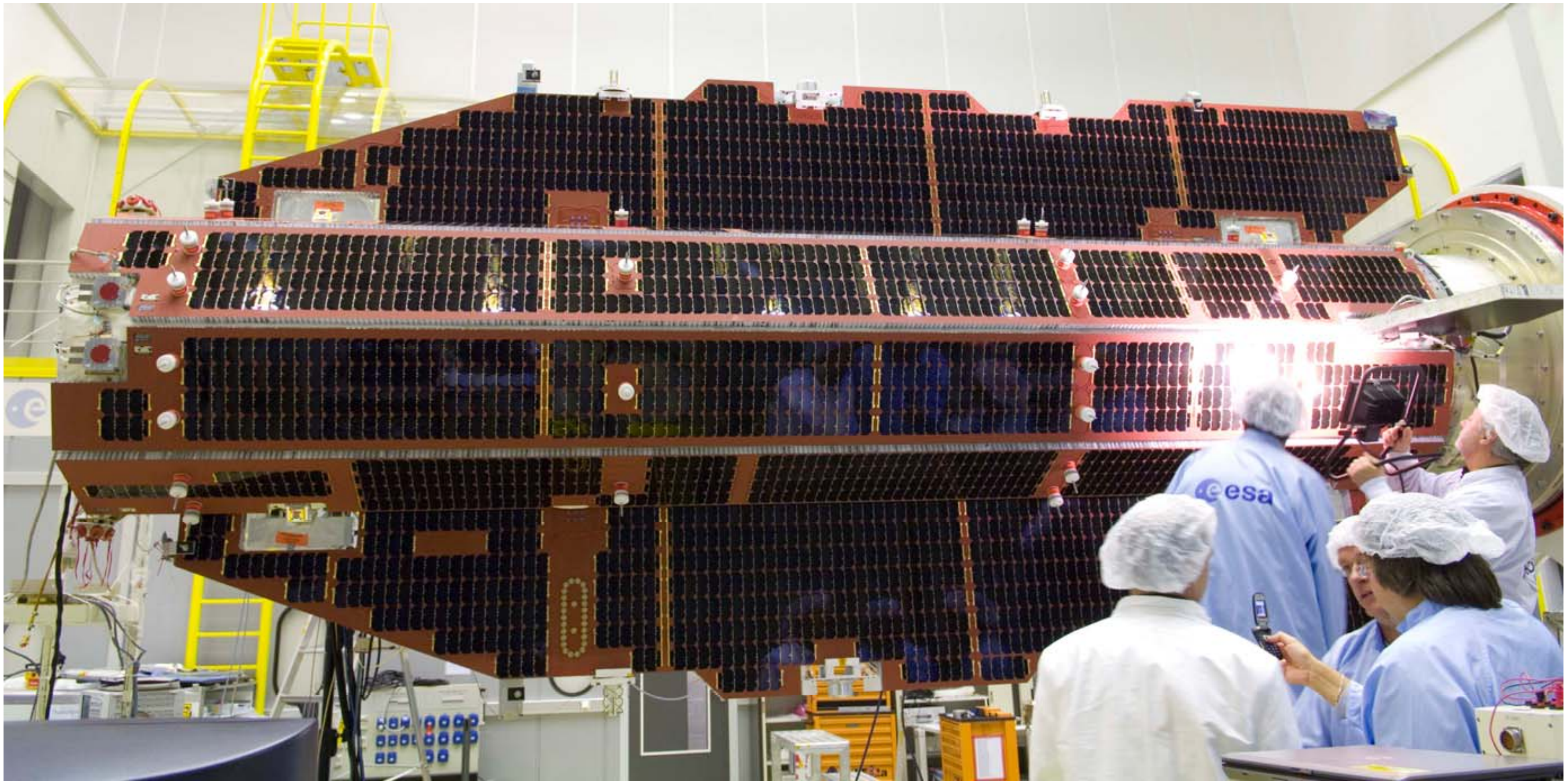
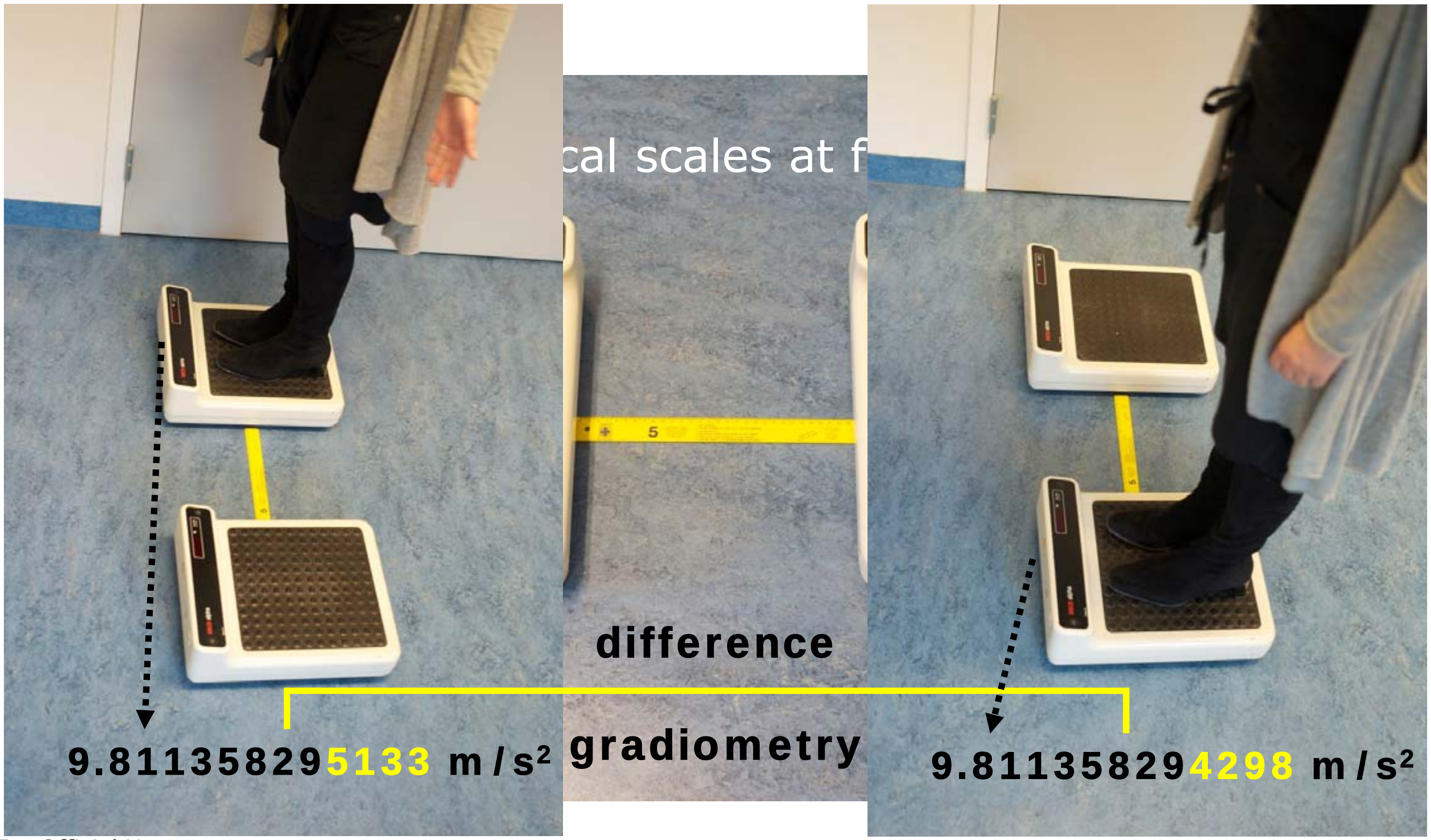
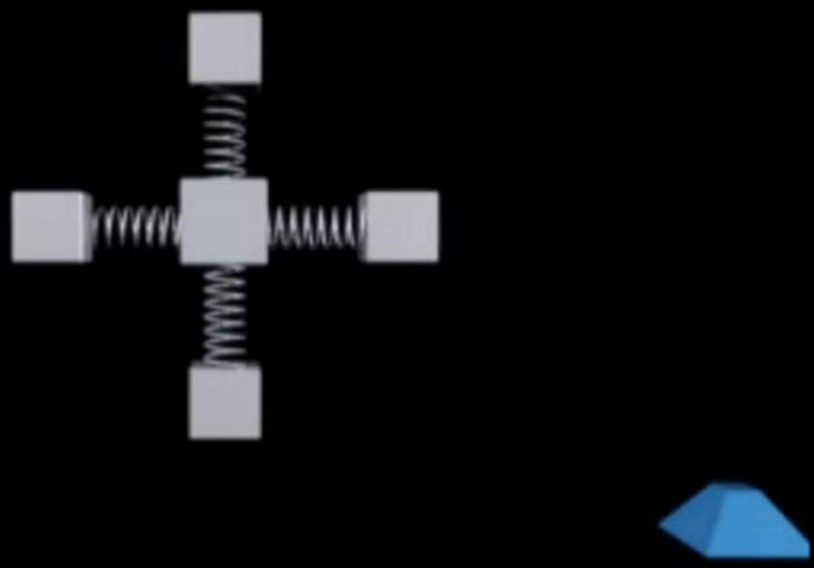
GOCE: Formula 1 under Satellites



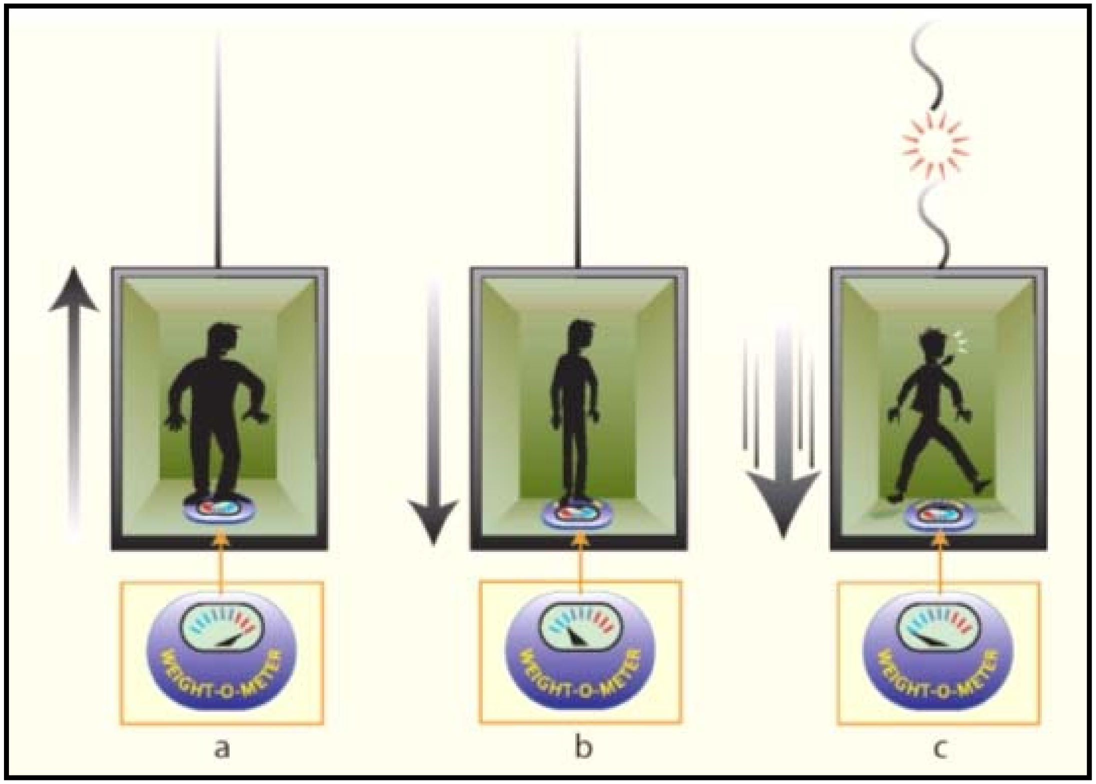
Scale, gravity, gradiometry



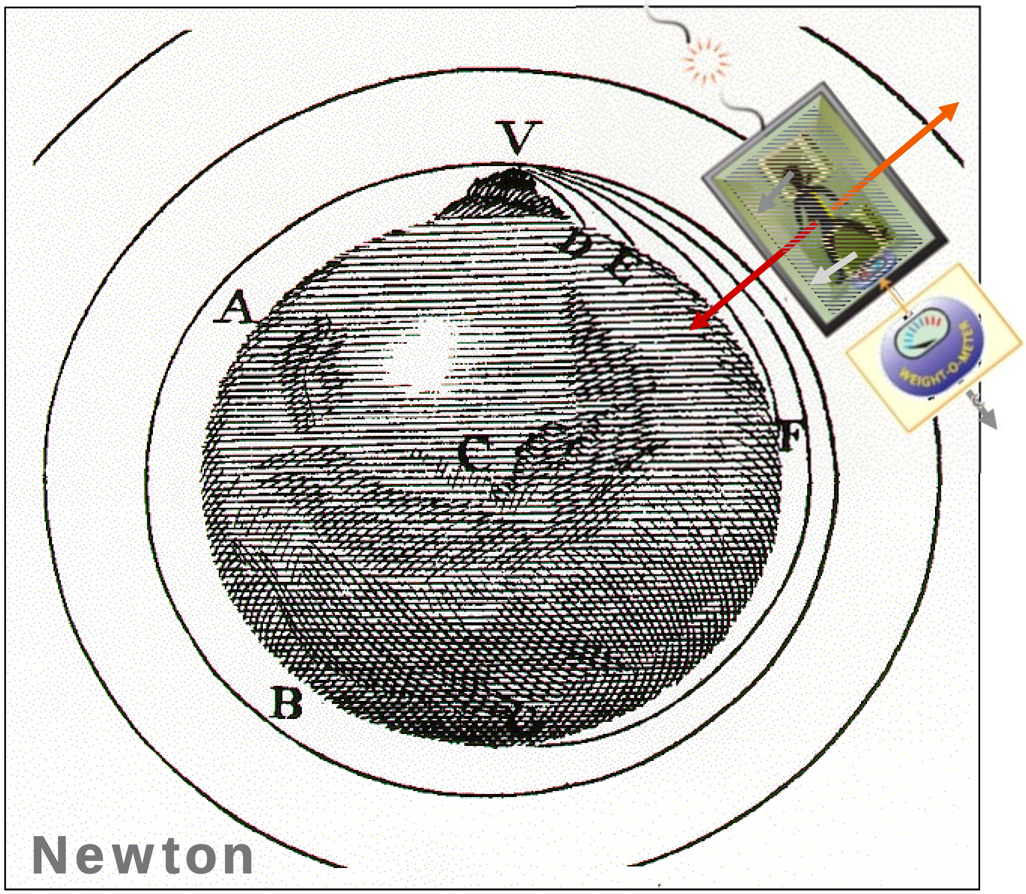
Principle of Gradiometry



Scale and motion



Gravity and Satellite orbit



… Get a Feeling for the Numbers

0.5 gram 

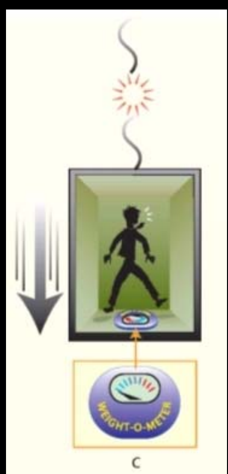
Super-tanker acceleration
due to attracting snowflake:

0.000000000005 m/s^2

smallest acceleration measurable
in space by GOCE

1 000 000 metric tonnes

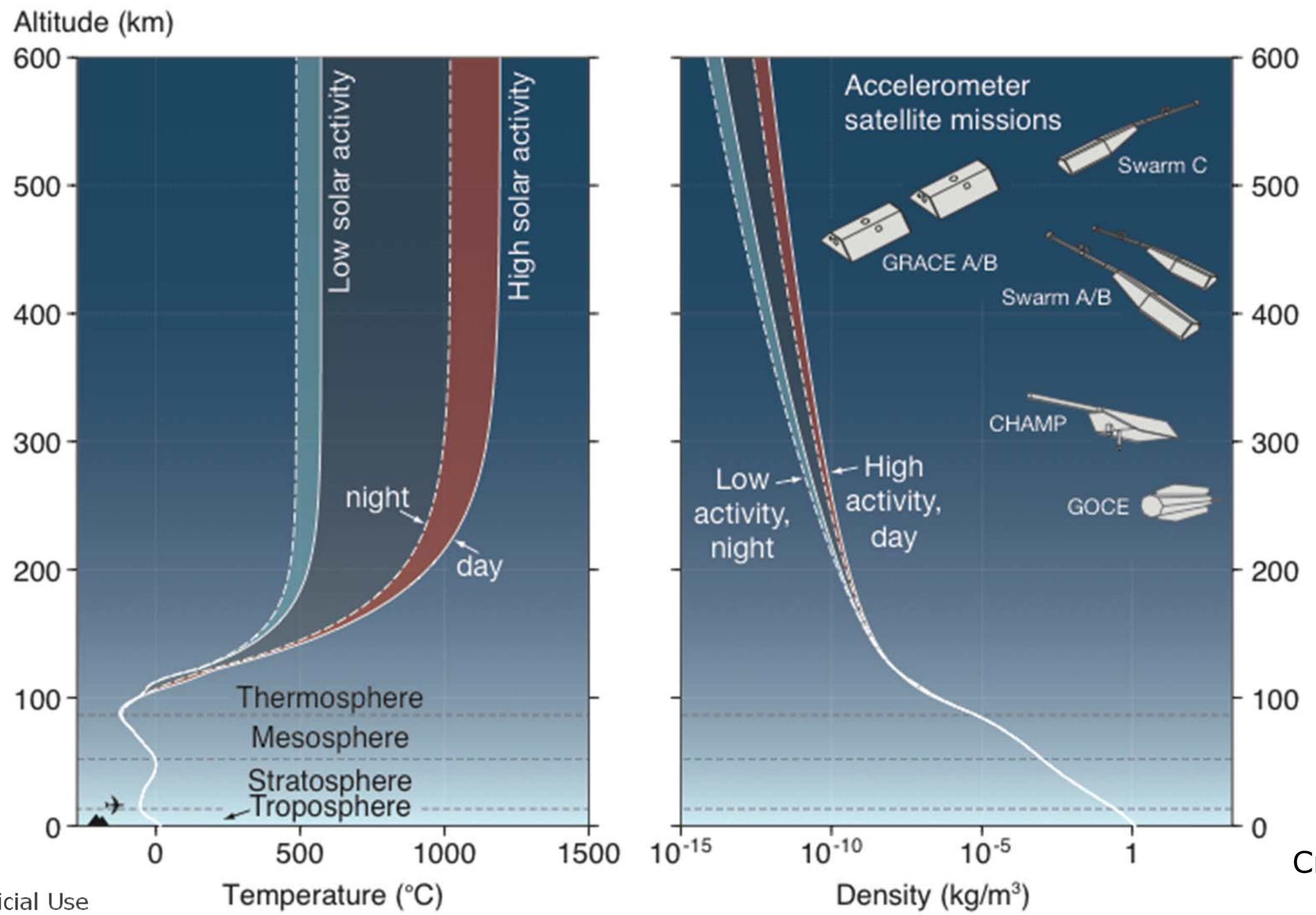
Gravity and Satellite Orbit (255 km and 8 km/s)



“free fall”

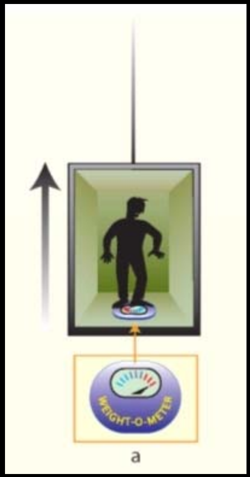
Challenging orbit knowledge 1-2 cm

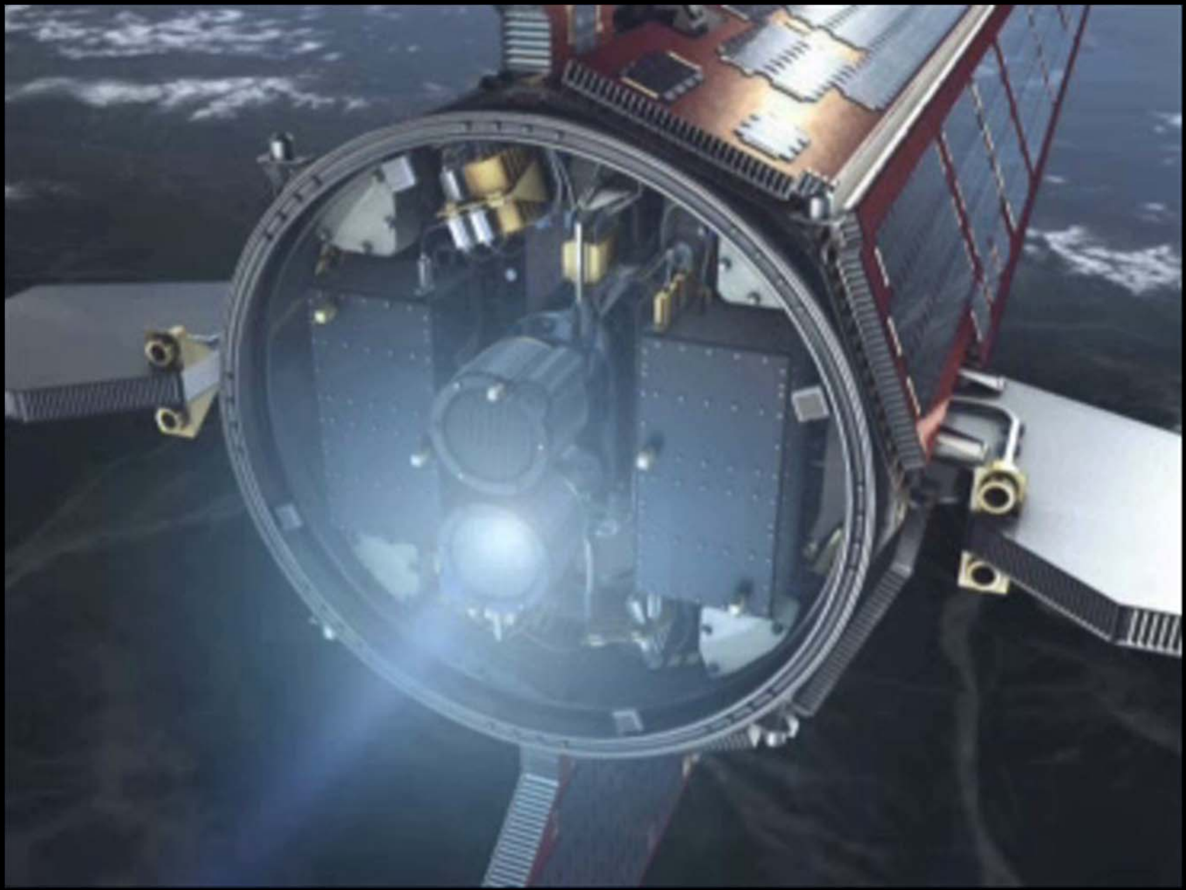
For sensitivity fly as low as possible but ….



Credits: E. Doornbos

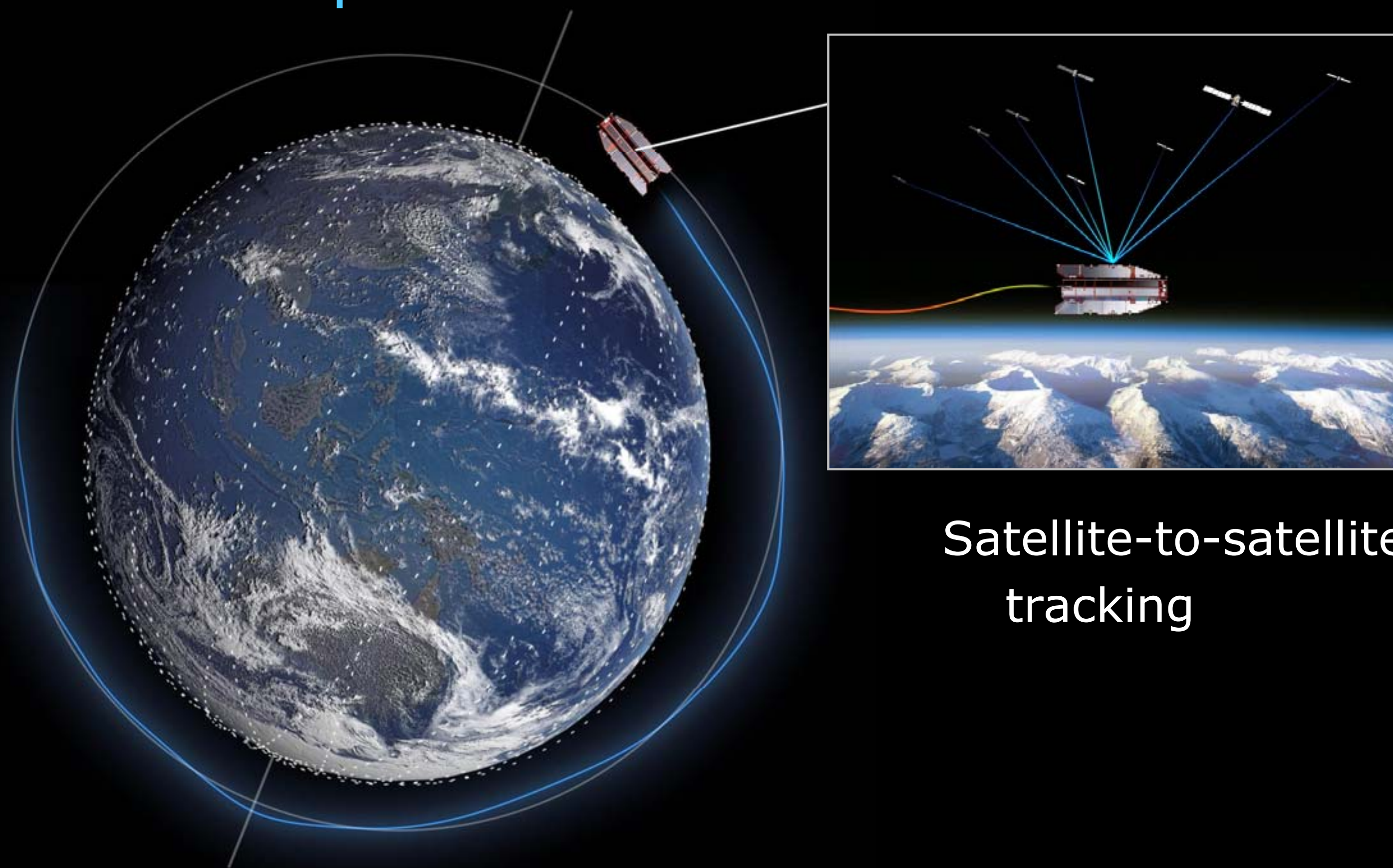
Atmosphere disturbs "free fall"





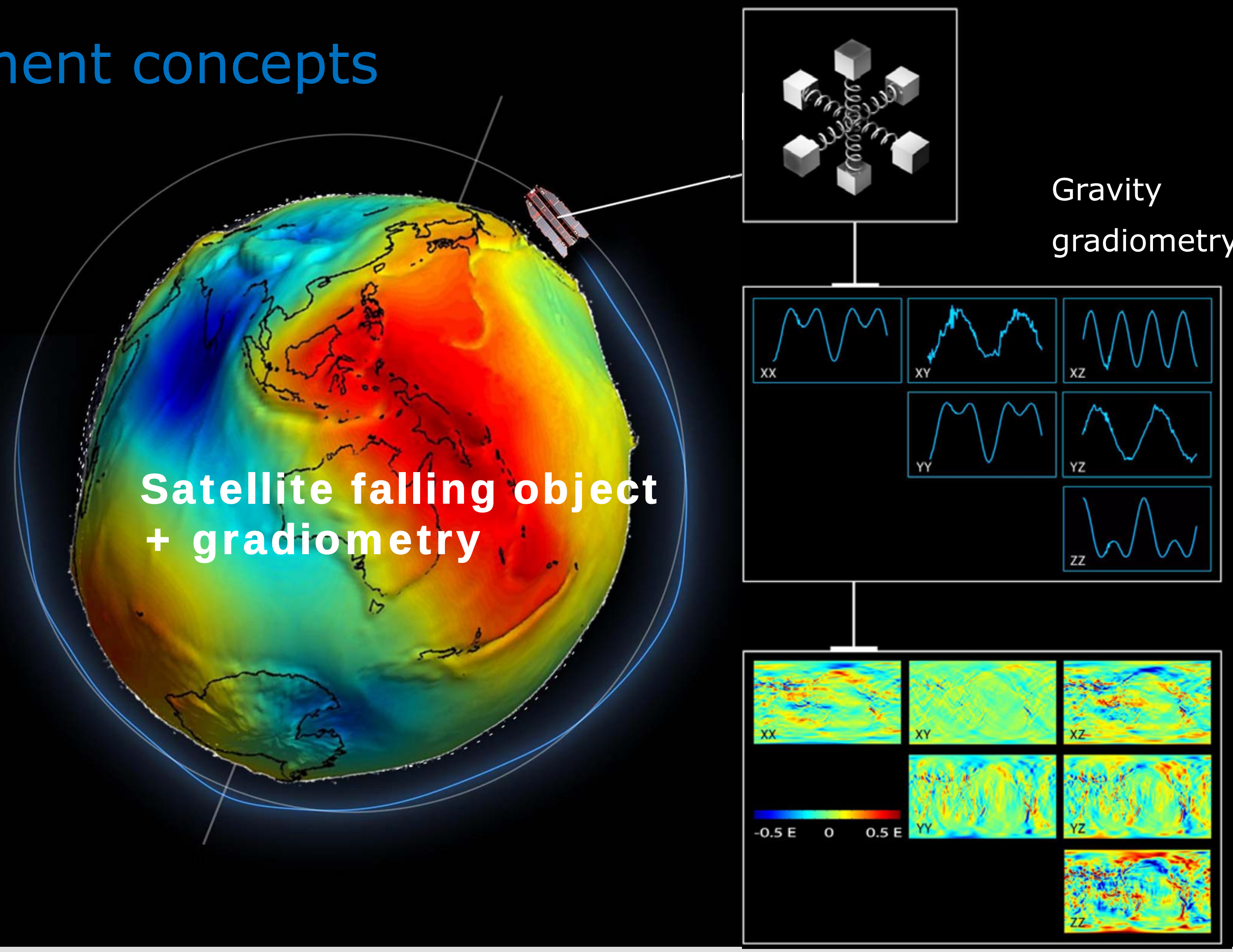
Disturbance compensated "cruise control"

Measurement concepts



Satellite-to-satellite tracking

Measurement concepts

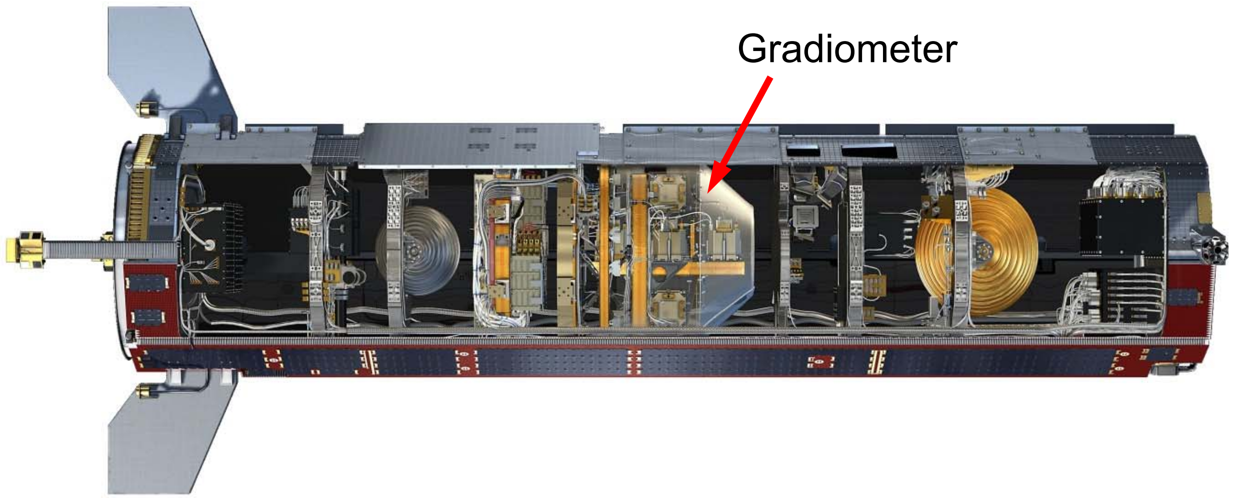


The GOCE satellite

Sun-synchronous, 61 day repeat orbit at 256 km altitude

- Orbit as low as possible to maximize signal strength
- Significant aerodynamic forces and torques act on satellite

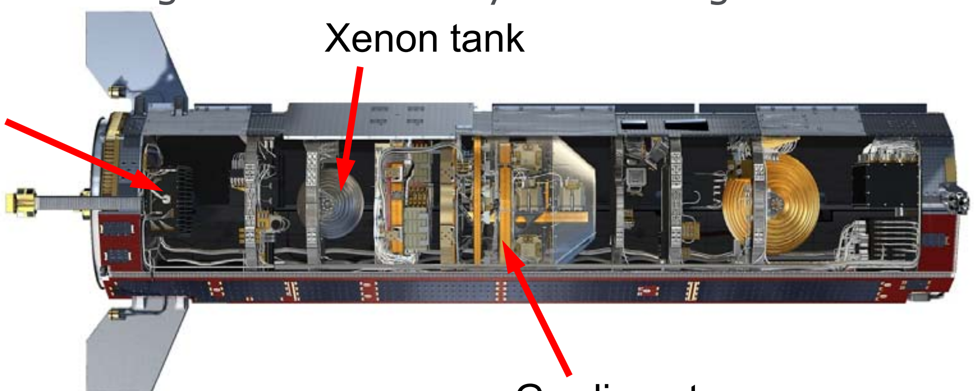
Gradiometer needs 'quiet environment'



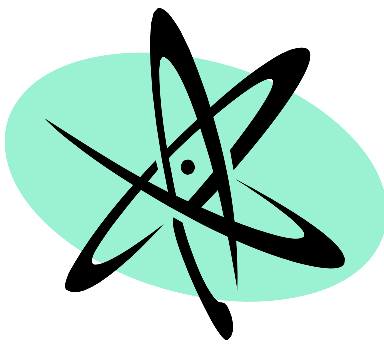
The GOCE satellite

Achieving a ‘quiet environment’

- Continuous drag-free control along the flight direction (→ altitude & micro-g conditions)
- Gradiometer
  - Extreme mechanical stability (carbon-carbon honeycomb structure)
  - Thermally decoupled from satellite, thermal control (10 mK over 200 s)
- Satellite
  - No moving parts (→ vibrations), stable under varying thermal loads (→ eclipses)
  - Slim shape for minimizing effect of aerodynamic drag



… and the pico-metre stability



1 Ångström

Atomic diameter is ➡ 1 Ångström = 1E-10 m

A picometre = 1E-12 m ➡ 1% of an atom !!!

Challenging requirement

GOCE Elements

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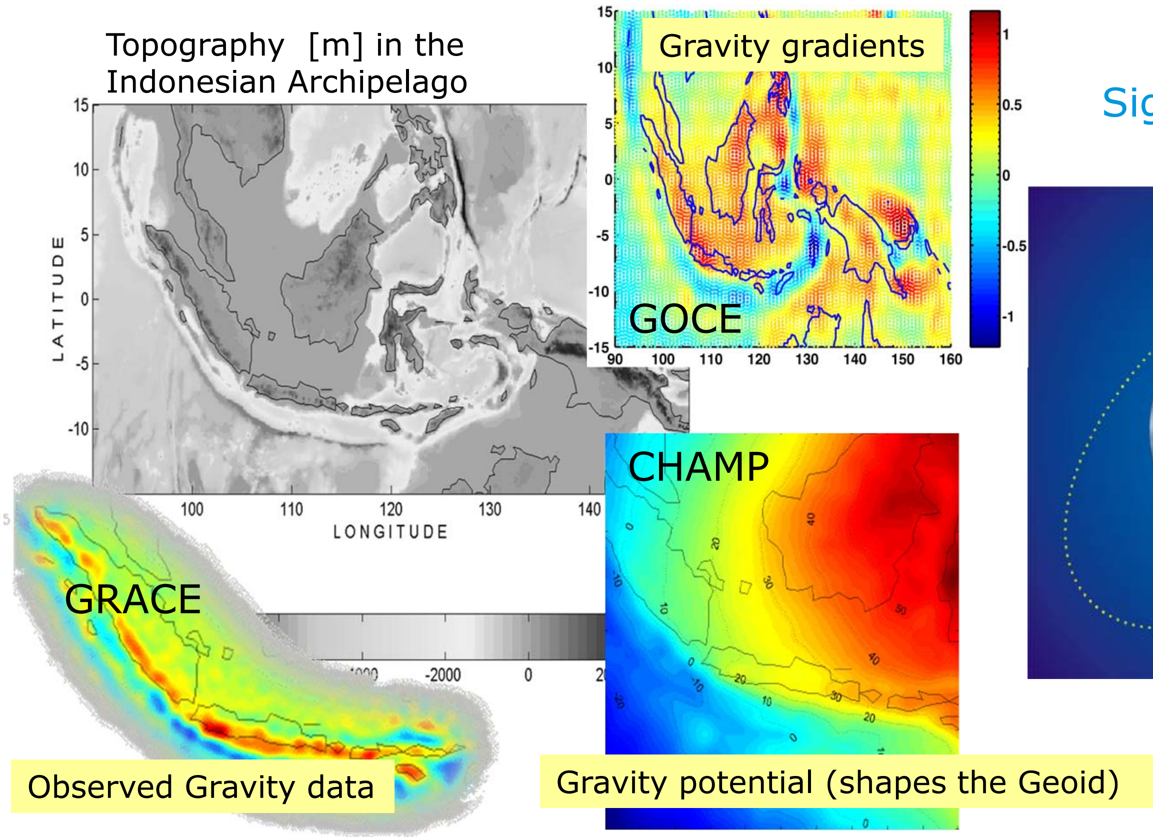
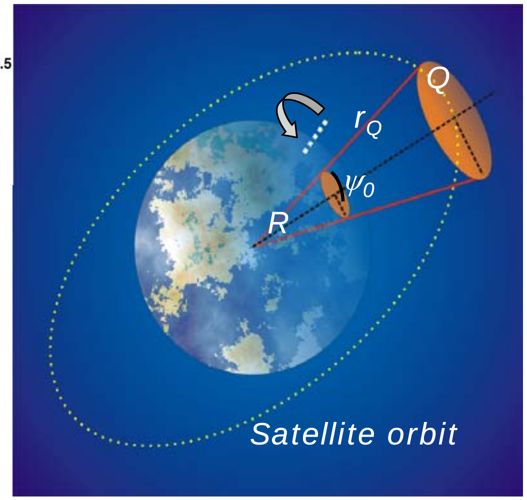
Gravity potential, gravity or gravity gradient

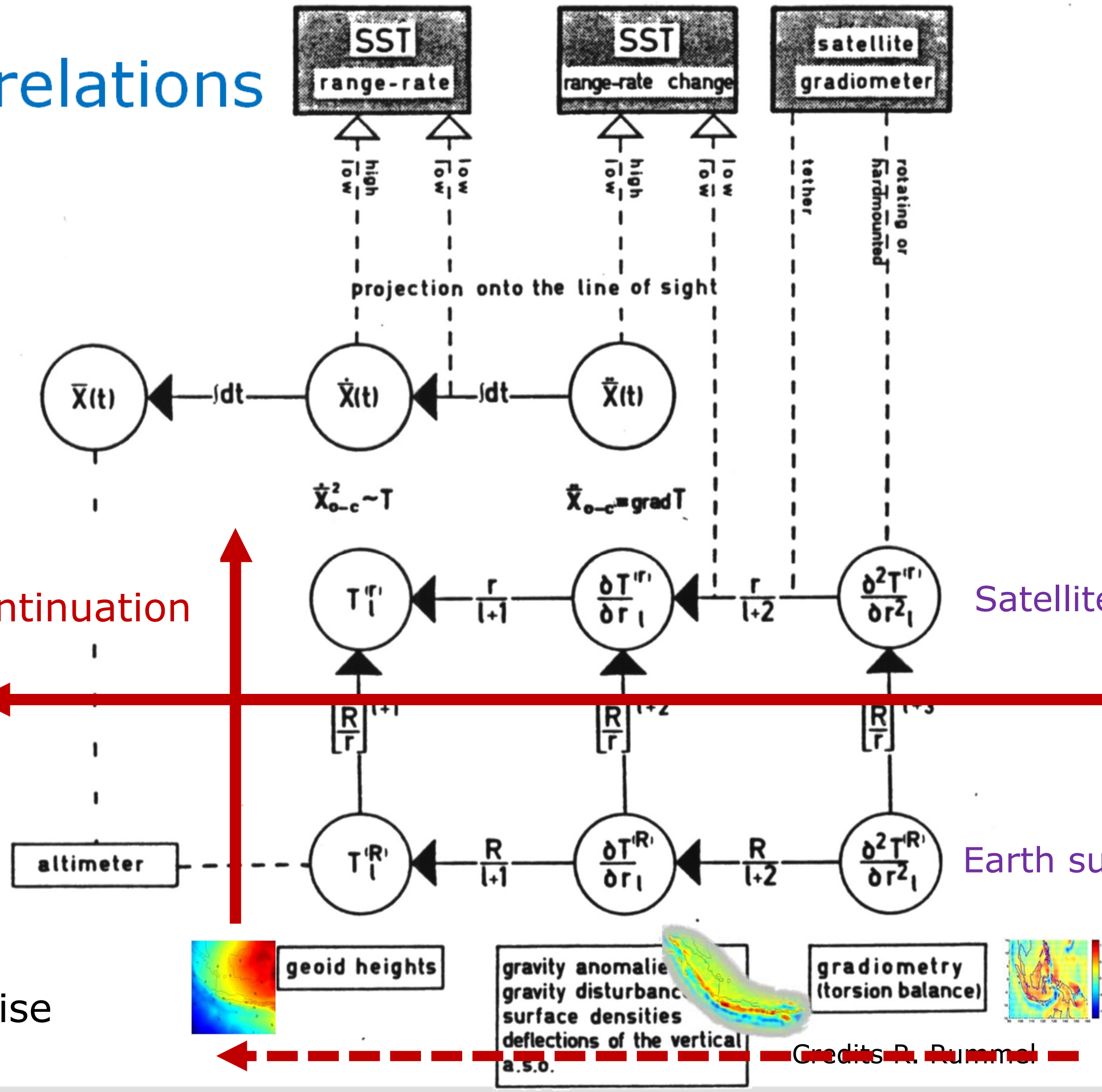


Signal attenuates at satellite height



(Haagmans, Prijatna, Omang, 2003)

Gravity field relations

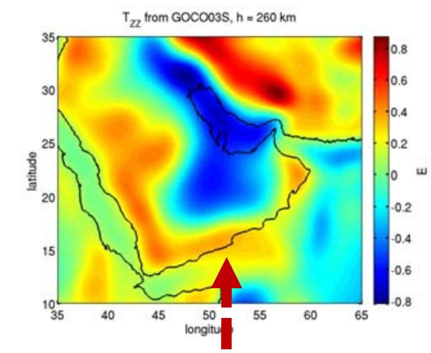


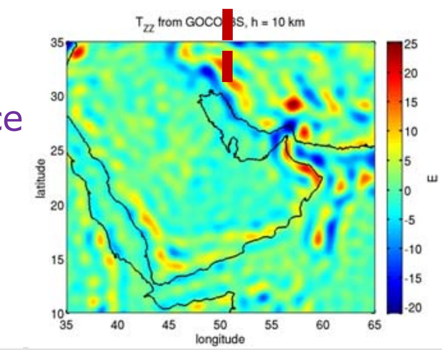
Loose details
by upward continuation

Loose details
by integration

Satellite height

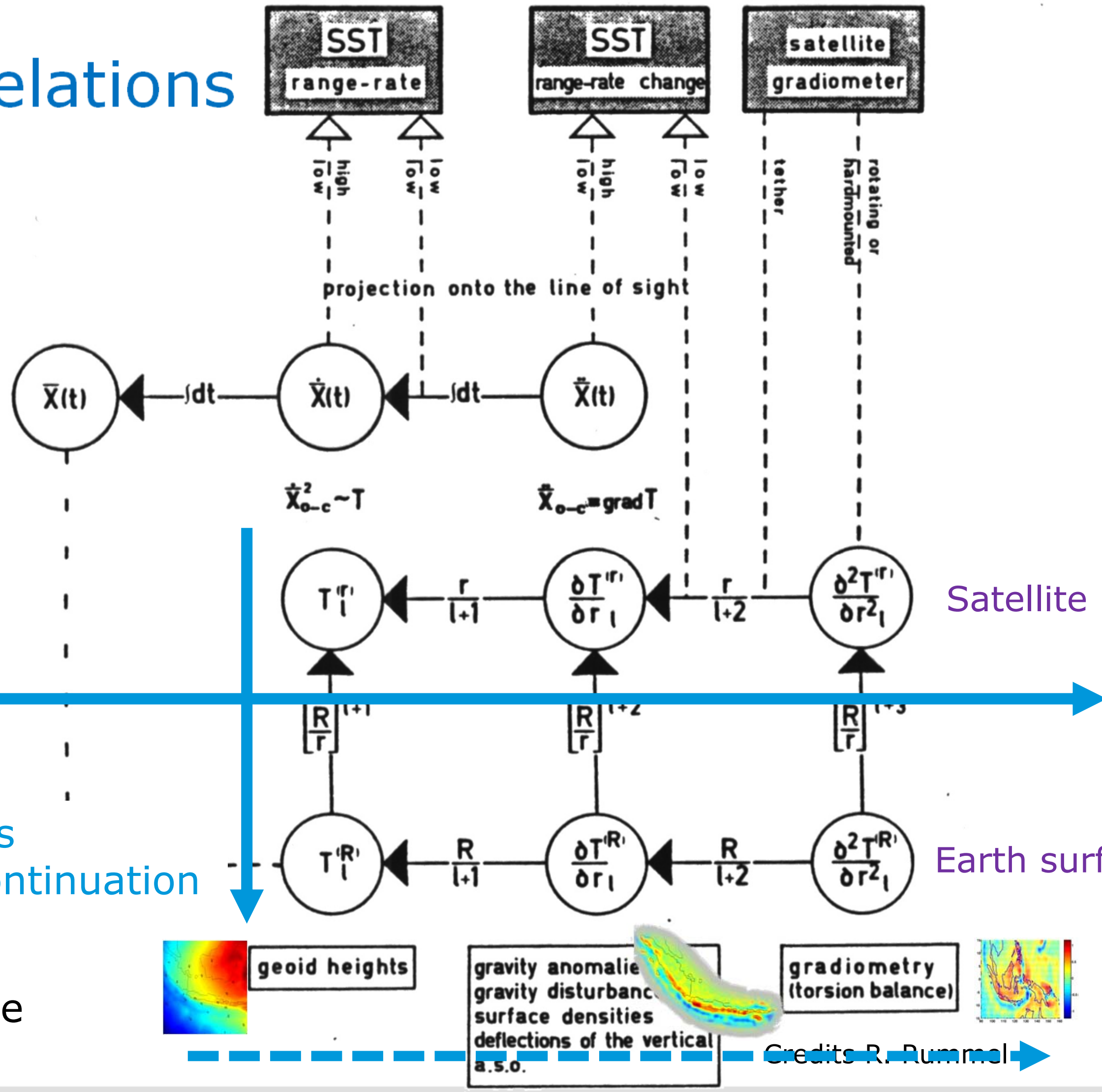
Earth surface





Details: signal and noise

Gravity field relations

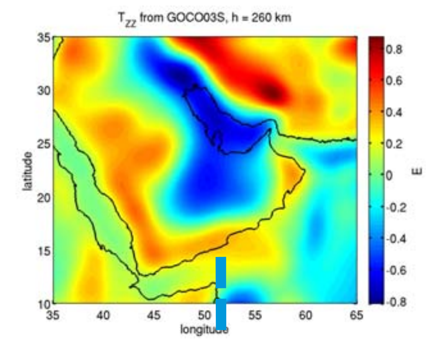


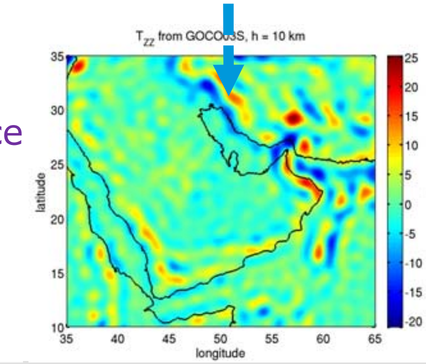
Satellite height

Earth surface

Enhanced details
by differentiation

Enhanced details
by downward continuation

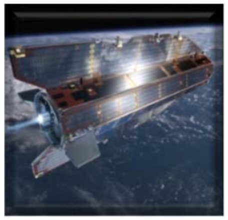


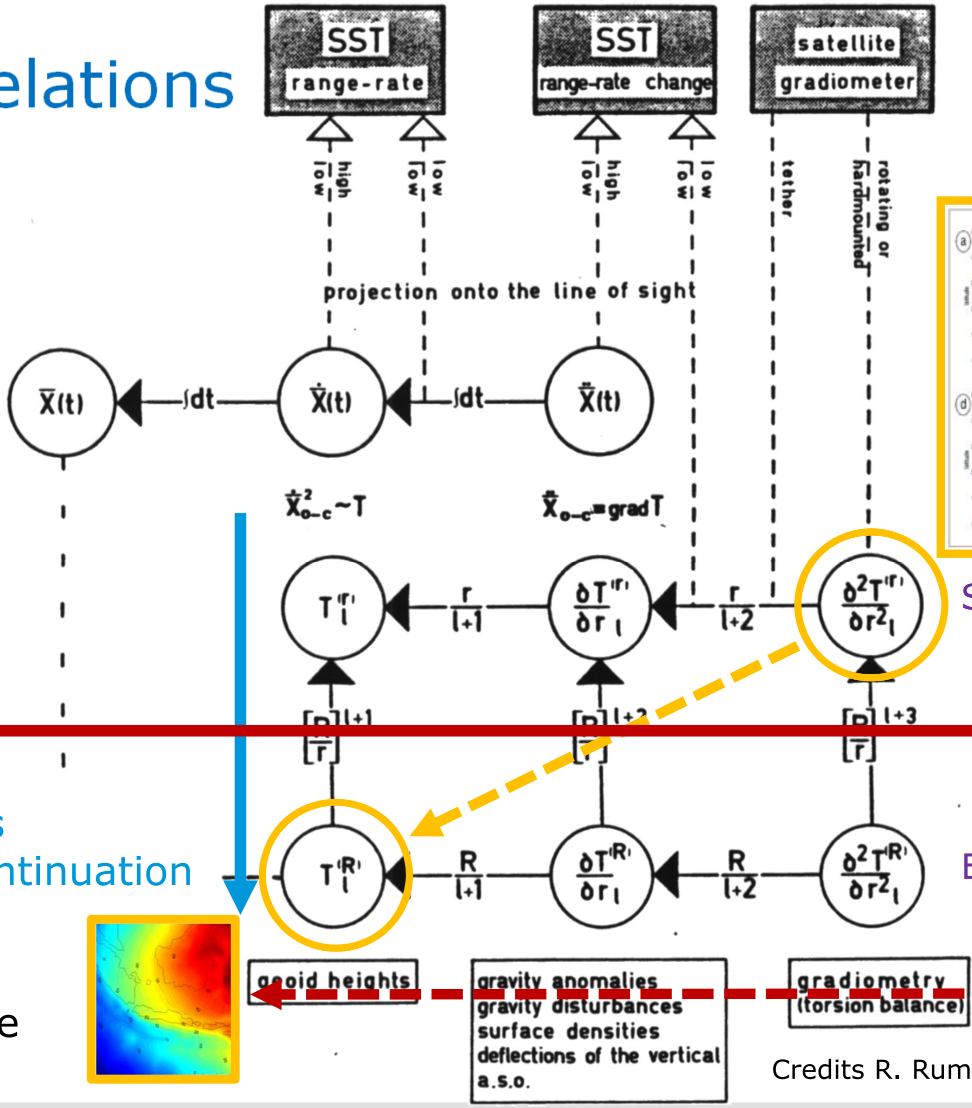


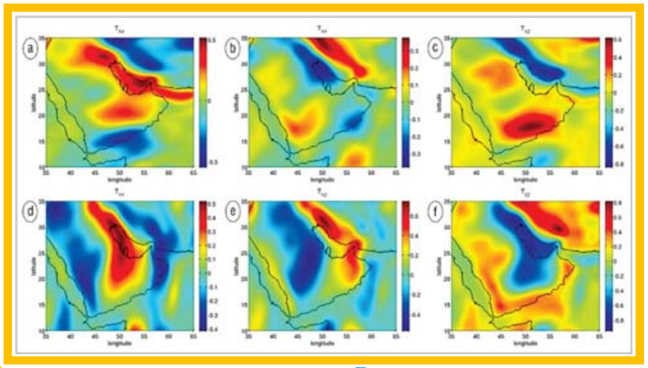
Details: signal and noise

Gravity field relations

Example GOCE







Satellite height

Earth surface

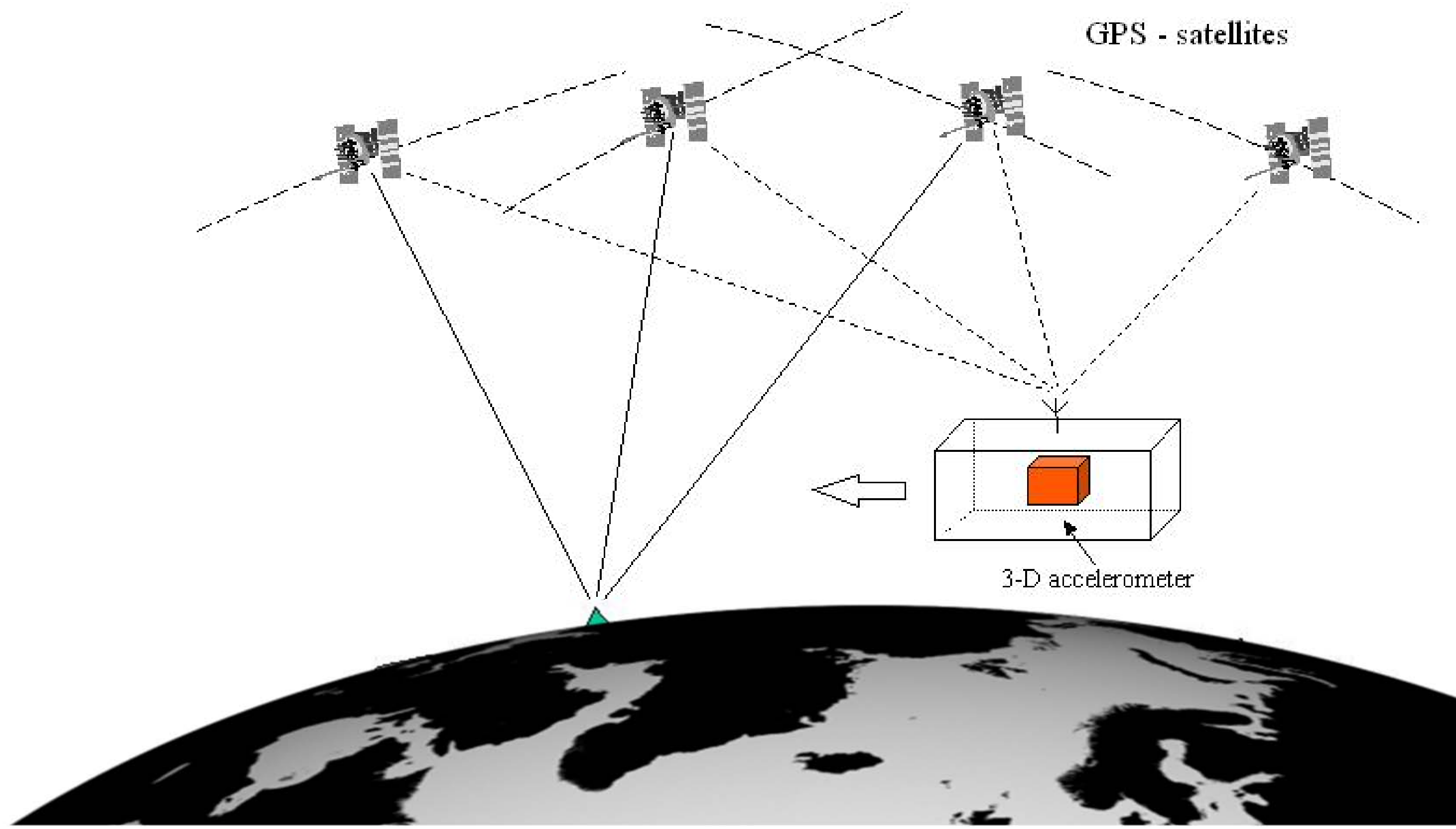
Loose details
by integration

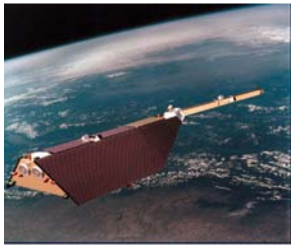
Enhanced details
by downward continuation

Details: signal and noise

Credits R. Rummel

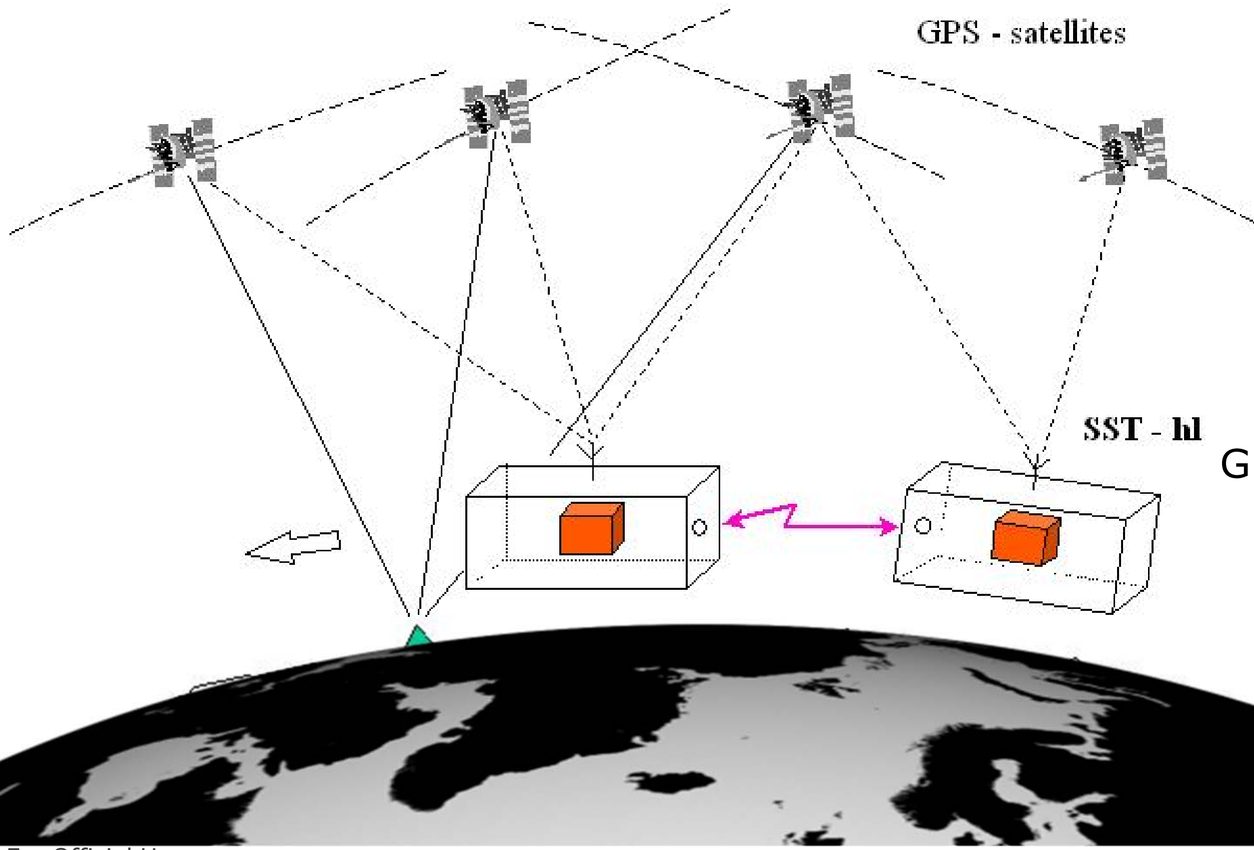
Satellite: falling object
High-low Satellite-to-Satellite Tracking (SST)

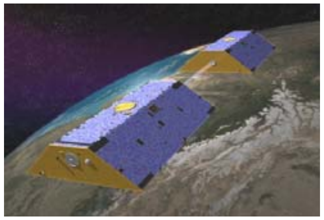




CHAMP (DE)
2000-2010

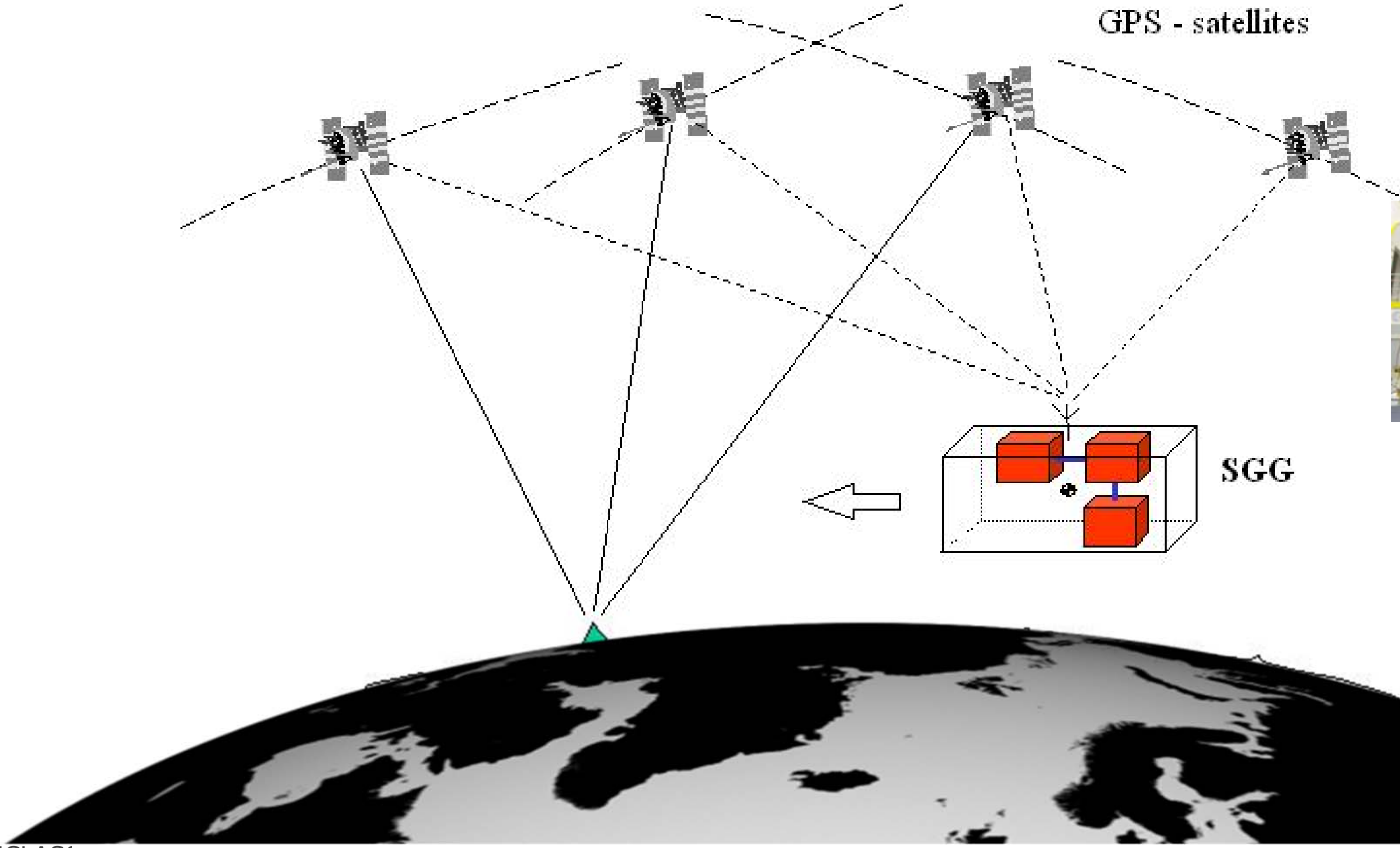
Two-satellites: falling objects including ranging LOW-LOW SST

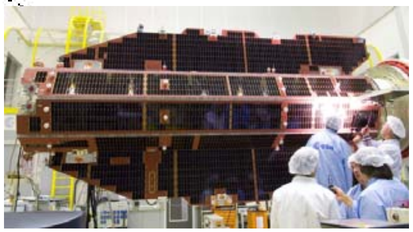




GRACE & GRACE-FO (US,DE)
2002-present

Satellite + 6 proof masses: falling objects
High-Low SST and gradiometry





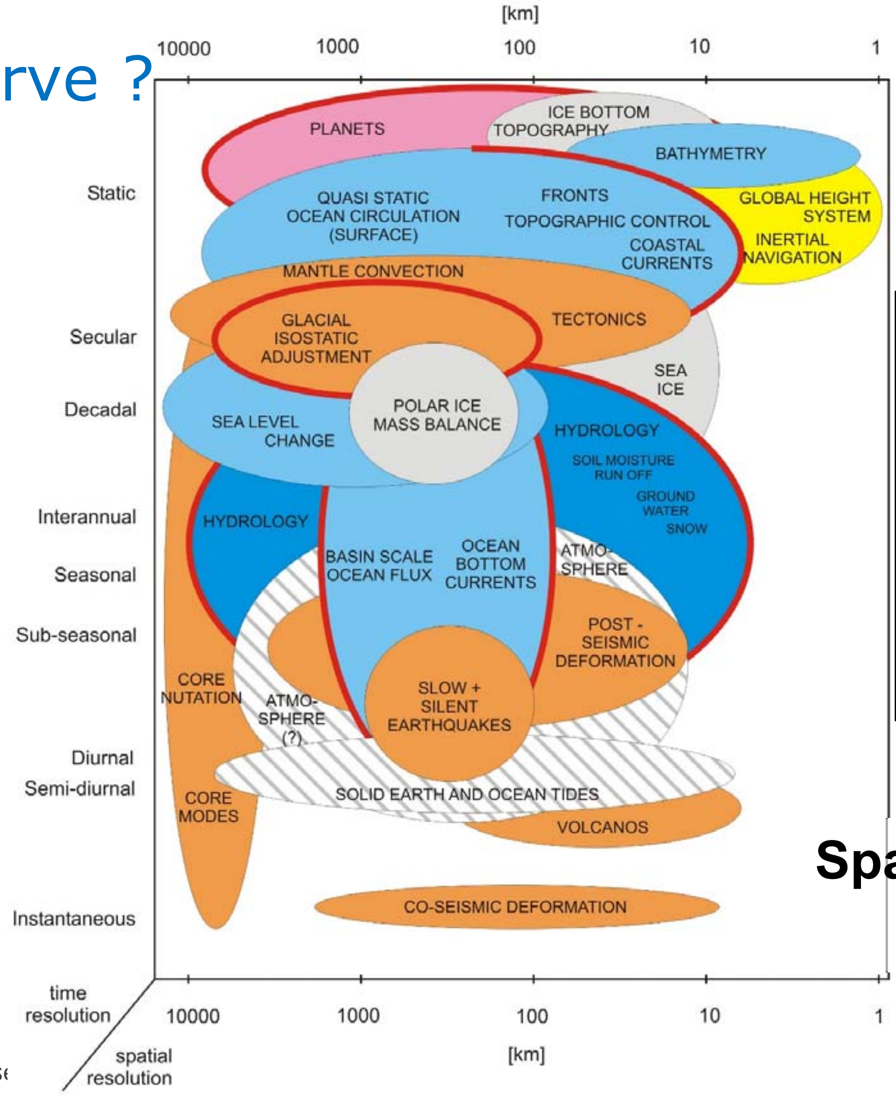
GOCE (ESA)
2009-2013

Future Gravity Satellite Mission - Design Variables

orbit altitude	high: compact SAT	low: drag measurement	very low: drag compensation		
control	none	angular	angular + linear		
dynamic range	space fixed parallel transport	local level along- cross- radial	one component		
proof masses	free floating = SST	constrained = gradiometry			
free floating: SST	hi-lo SST: GNSS + LEO	lo-lo SST: LEO cloud	lo-lo SST configuration (CART-WHEEL ect.)	lo-lo SST two LEOs	floating inside S/C
constrained: gradiometry	differental Accelerometry	rotating diff.-acc.	rotating torsional		
arm length	hi-lo SST	lo-lo SST	inside S/C		
number of gradiometric components	nine	full tensor	diagonal	Eötvös	one component
temperature	ambient	high temperature Superconductivity	low temperature Superconductivity	low temperature Cold Atom Interferometry (CAI)	

Credits R. Rummel

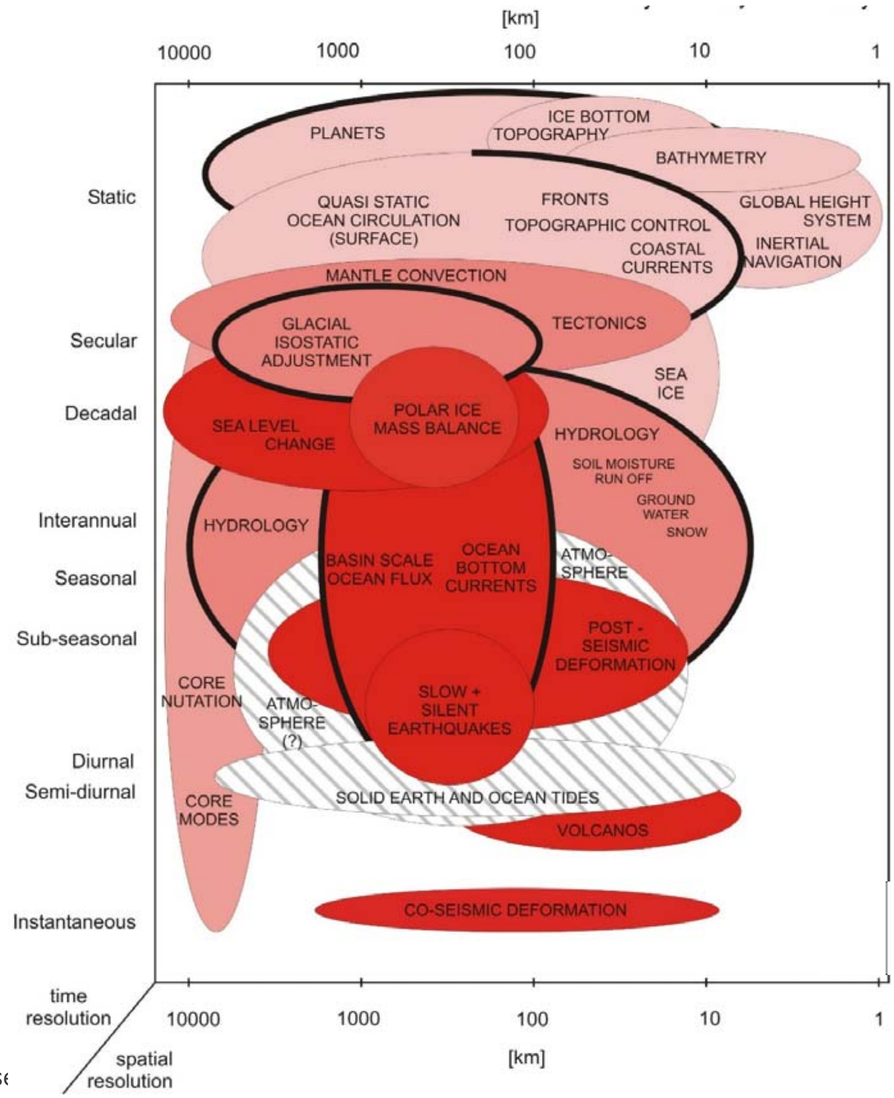
What to observe ?



- **solid Earth (brown)**
- **oceans (light blue)**
- **ice (grey)**
- **hydrology (dark blue)**
- **geodesy (yellow)**
- **planets (red)**

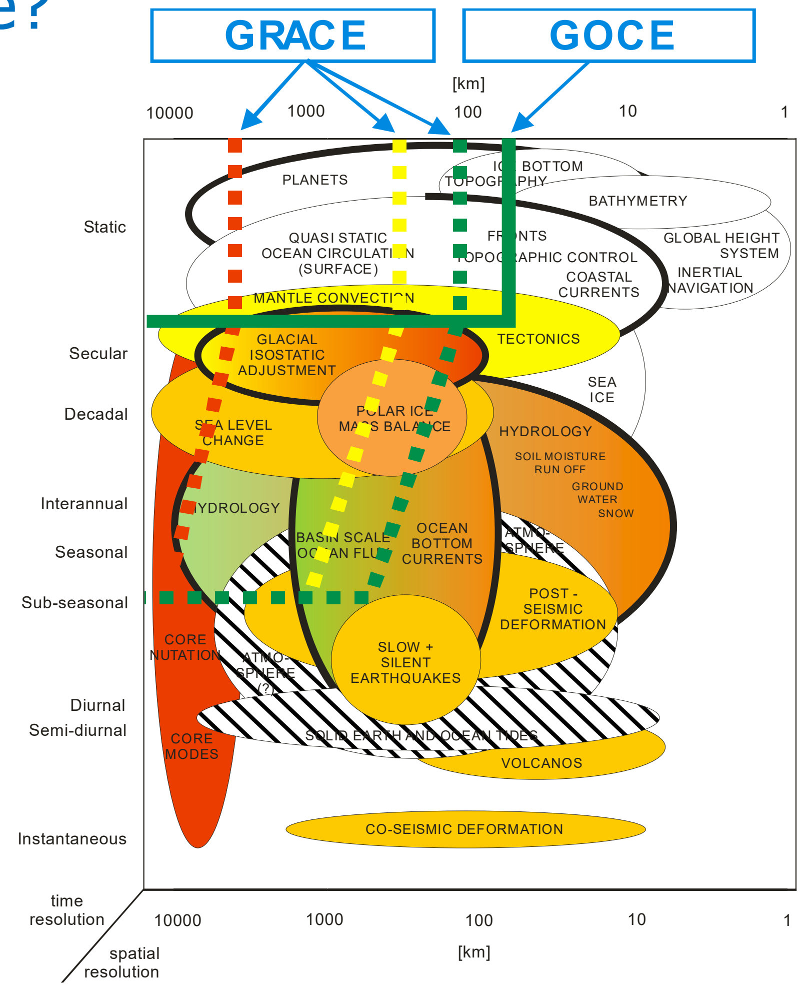
Spatial and temporal scales of geophysical processes

How long?



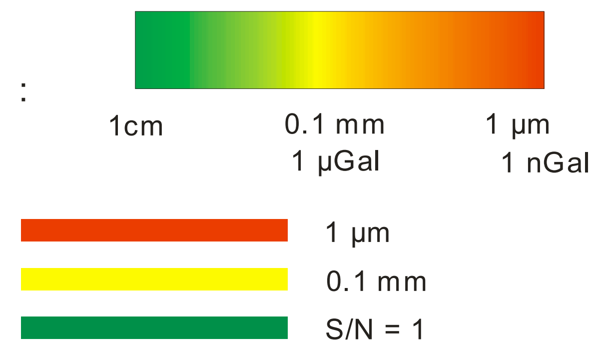
Required Mission Duration

How accurate?



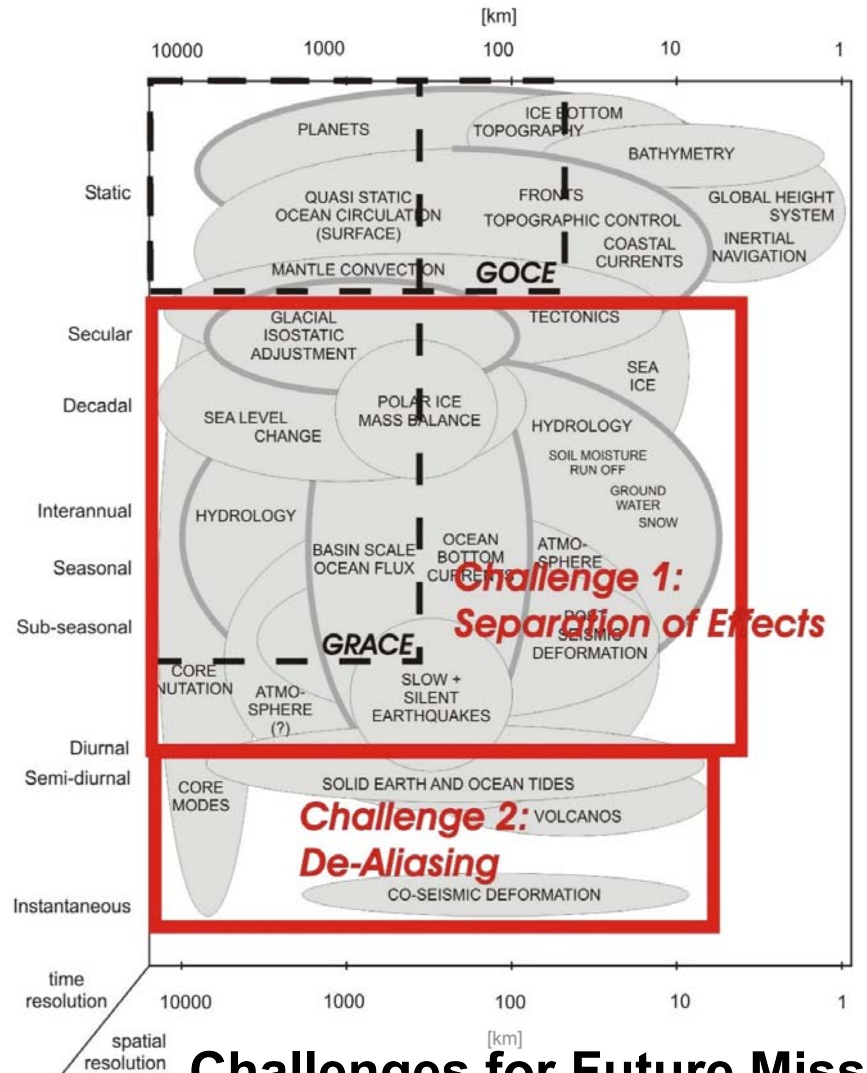
GRACE and GOCE

vs. science objectives



Things to keep in mind

- Gravity measurements contain all mass (change) effects together
- Smart space-time sampling may lead possibility to deal with 'aliasing'
- Separation based upon different spatial-temporal characteristics of sources?
- Need for correction models - but are these accurate enough?
- How to deal with tides by design?

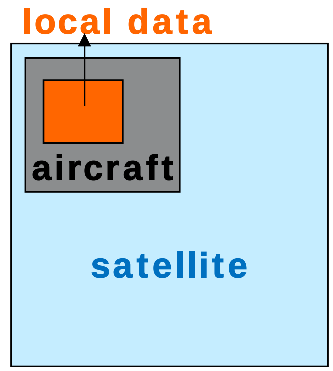


Challenges for Future Missions

Example of complementarity: geometry and gravimetry

geometry		gravimetry
GNSS, SLR, VLBI (land)	**plate tectonics**	Satellite gravimetry (also ocean)
GNSS tide gauges	**postglacial adjustment**	absolute gravimetry satellite gravimetry
GNSS	**earthquakes**	GRACE & GOCE
GNSS	**solid earth tides**	permanent gravimetry
tide gauges satellite altimetry	**ocean tides**	GRACE permanent gravimetry
GNSS radar/laser altimetry InSAR, photogrammetry.	**ice mass balance**	Satellite gravimetry Gravimetry
GNSS InSAR tide gauges	**continental hydrology**	Super conducting Gravimetry Satellite gravimety
tide gauges & GNSS radar/laser altimetry	**sea level changes**	satellite gravimetry
radar/laser altimetry	**ocean circulation**	satellite gravimetry

More things to keep in mind……the scale problem: Terrestrial, airborne and satellite data



Definition "Mission requirements"

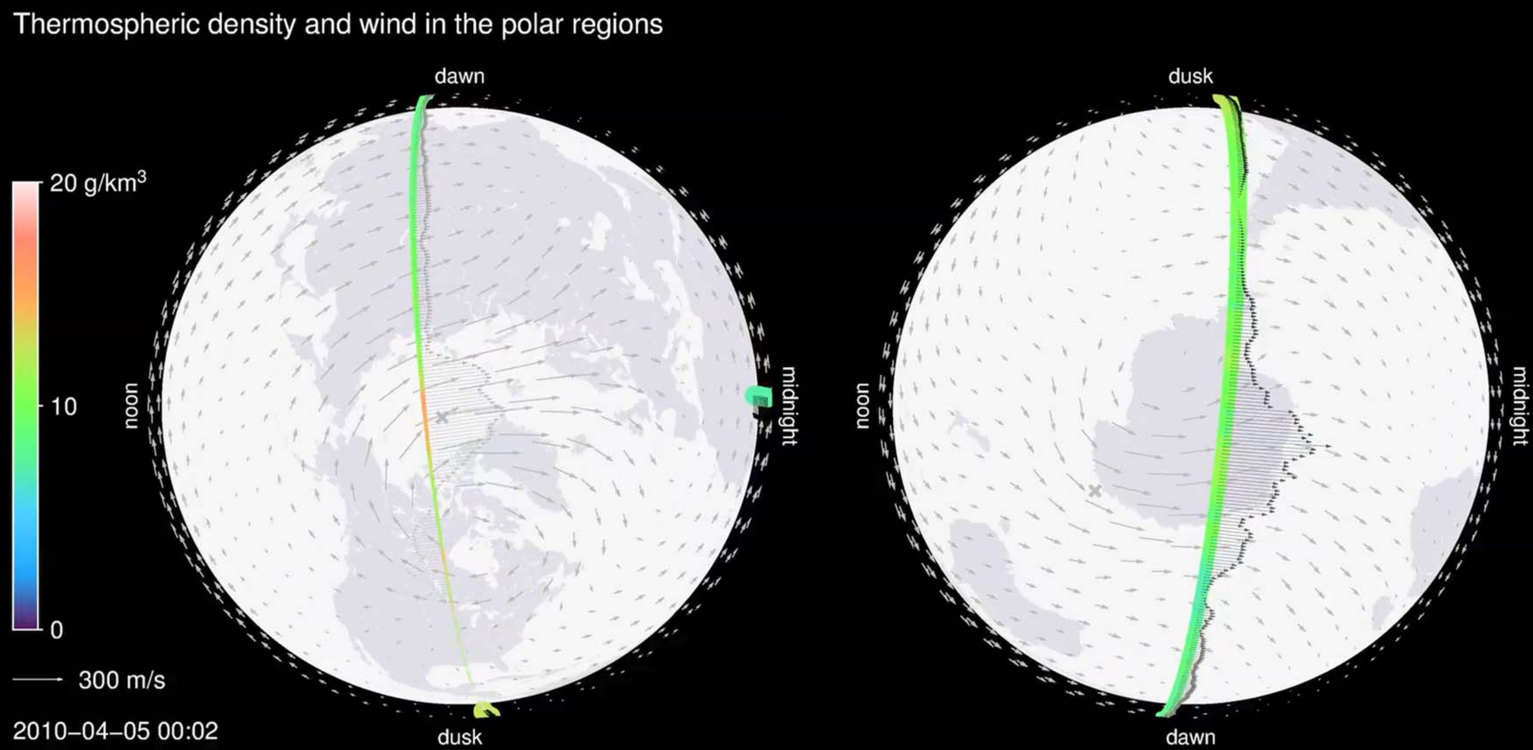
- Limit in resolution
- Complementary to airborne and local data
- Difference in quality and coverage

Re-analysis of terrestrial data needed with each new mission

"Scaleproblem" one of the main things to be resolved

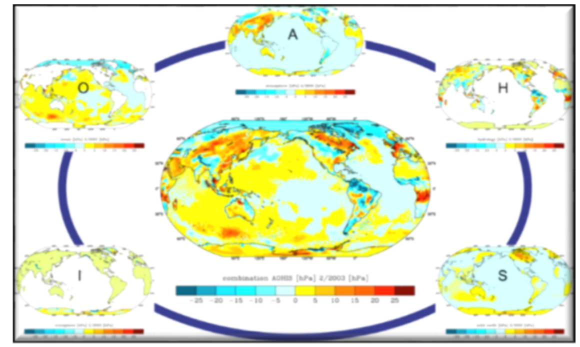
Validation and/or calibration campaigns

More science for free:
density and winds from CHAMP and GOCE



Credits: E. Doornbos

Mass Transport Model to Test Ideas



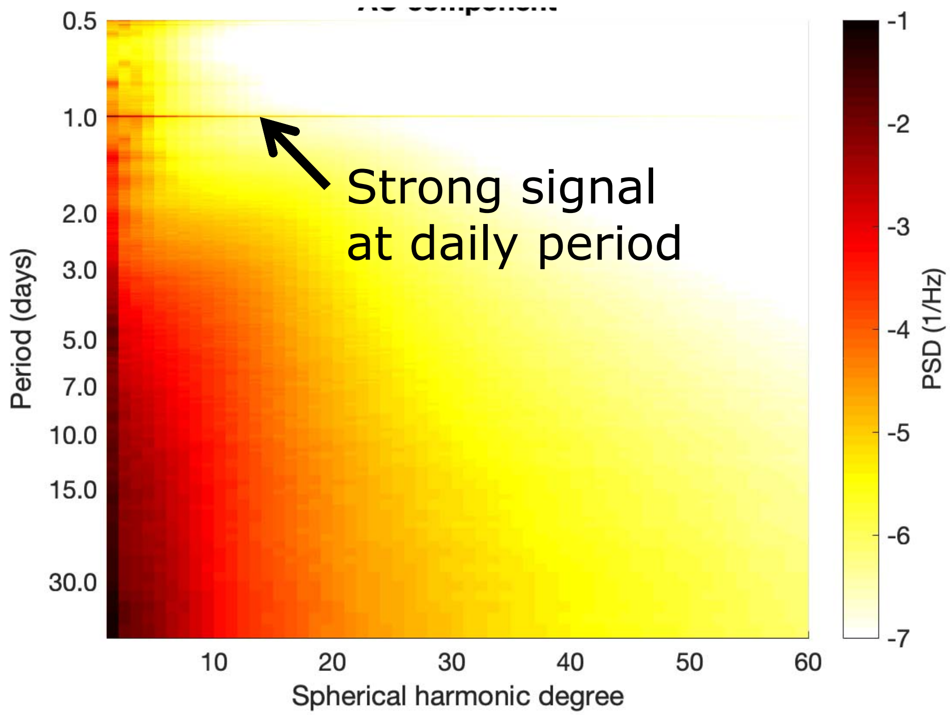
Simulated “real” world

Model free available at

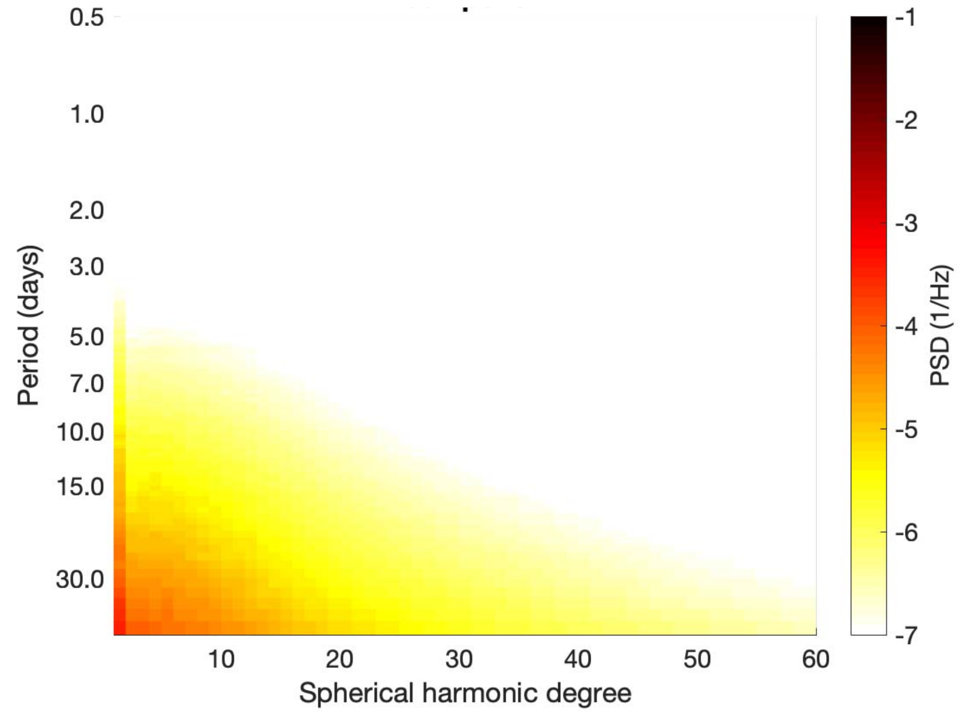
https://isdc.gfz-potsdam.de/esmdata/esaesm/

Signal characteristics from Earth System Model

Non-tidal atmosphere + ocean



Land hydrology



Remember that spherical harmonics are global functions

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What is the purpose of a future concept?

- Mass transport as observable for Earth System modelling (including atmosphere)
- Mission for cryosphere change detection and modelling of mass balance
- Measurement of the hydrological cycle: short and long term changes (catchment size)
- Ocean mass changes: sea level and ocean circulation changes (barotropic, basin-scale, ocean circulation)
- Solid Earth Geophysics: Global Isostatic Adjustment and seismic deformations

Mass change from gravity for ………

From continuity to sustained observations

Increase of time resolution

Target 1 month → 3-4 days

Increase of spatial resolution

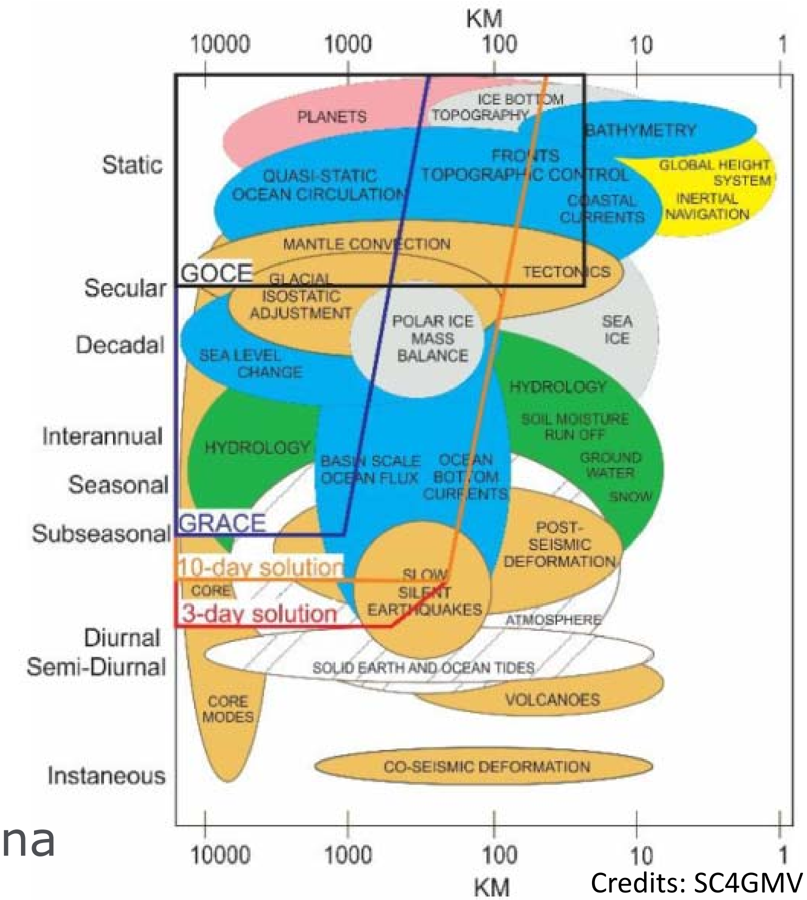
Target 600 km → < 300 km

Solve problem of undersampling

Fast mass changes in ocean and atmosphere

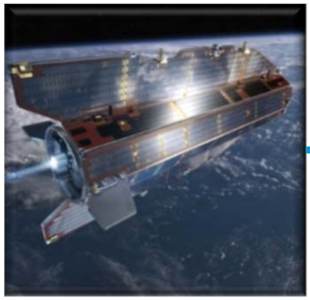
30+ years time series for climatology

Disentangle natural and anthropogenic phenomena



Credits: SC4GMV

Learning from GOCE and GRACE: examples

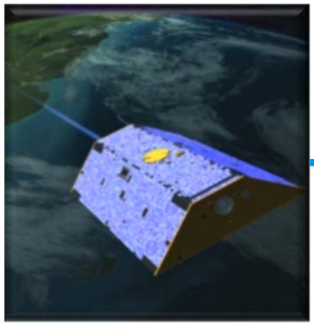


Drag free system and control

Stable structure

Accelerometer & Thermal control

Future SST

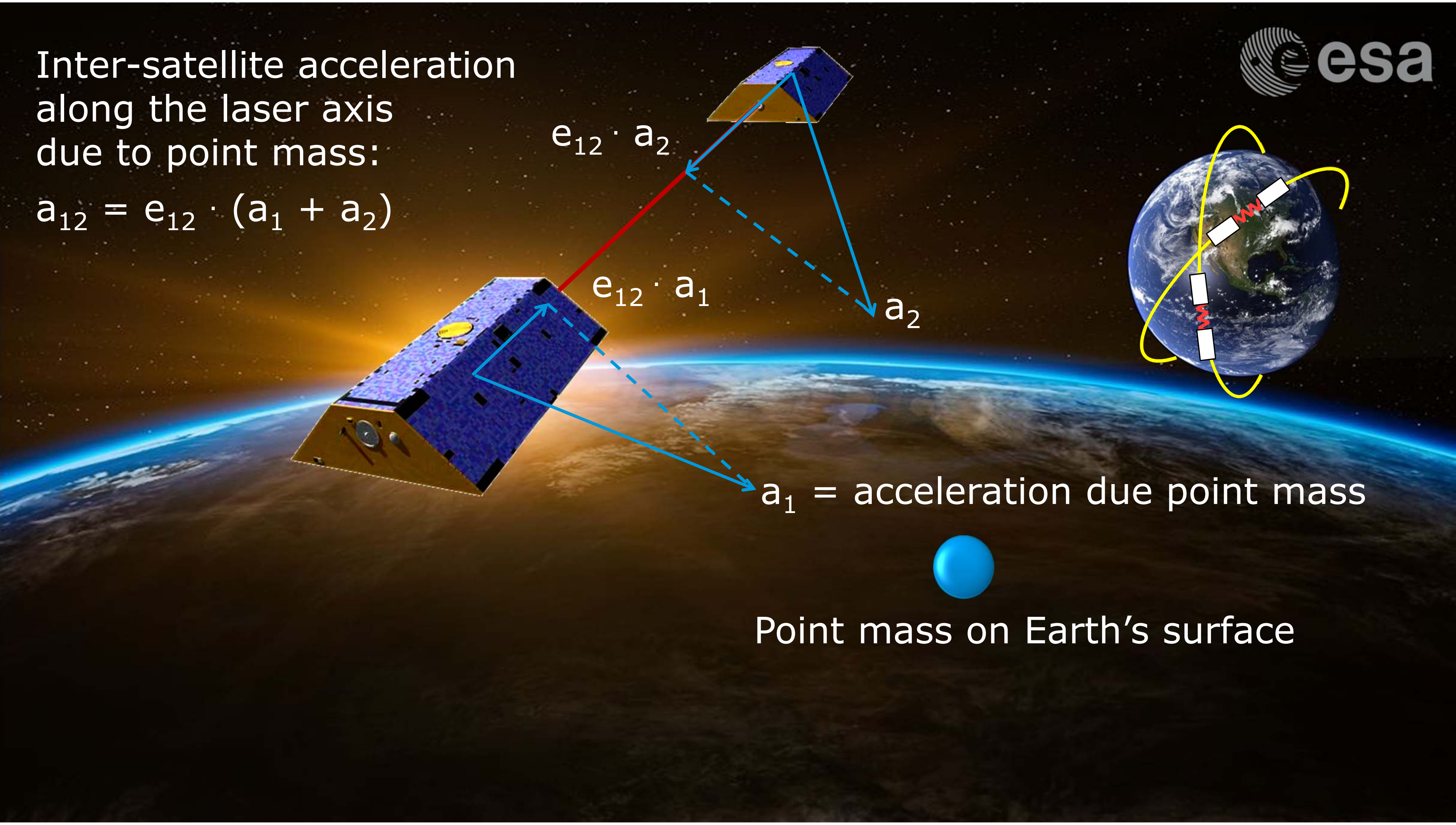


Low-low SST concept

Laser SST demonstration (FO)

Processing chain

Continue time series


Inter-satellite acceleration
along the laser axis
due to point mass:
$a_{12} = e_{12} \cdot (a_1 + a_2)$
$e_{12} \cdot a_2$
$e_{12} \cdot a_1$
a_2
a_1 = acceleration due point mass
Point mass on Earth's surface

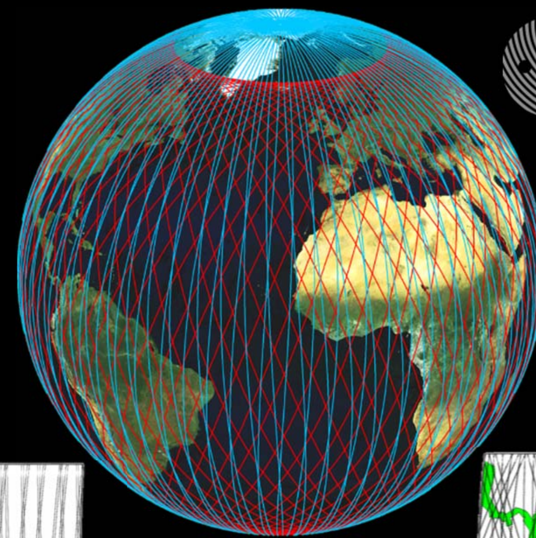
Double pair constellation

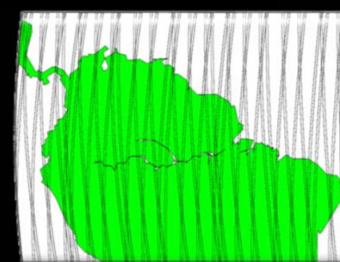
Optimising sampling between two satellite pairs result in comparable quality results for each time interval over mission lifetime

This is desired for services

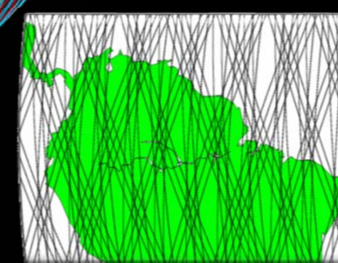
One pair: near-polar at 340-380km

One pair: inclined between 60-70 degrees at 340-380 km

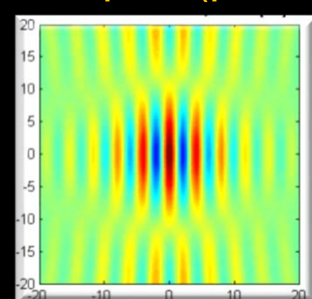


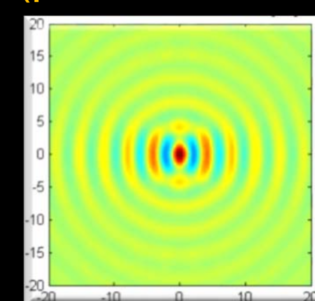


One pair (polar)



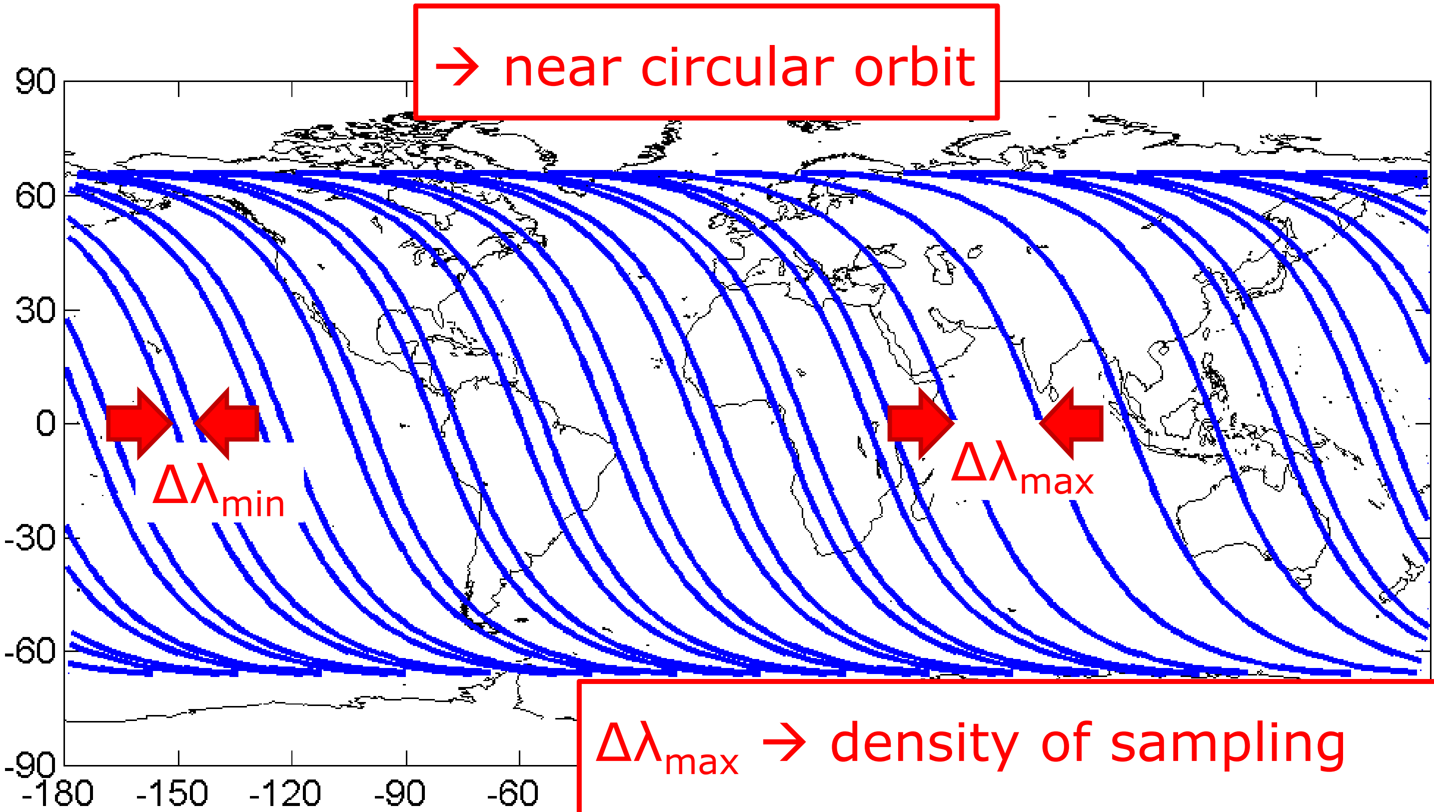
Two pairs (polar + I=63°)





Credits: P. Visser

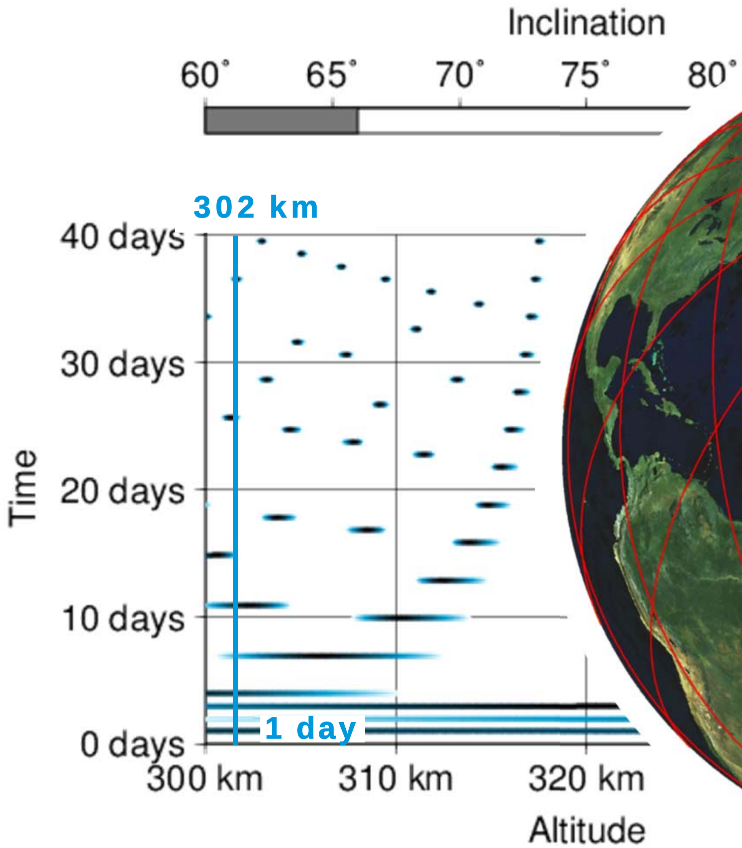
Sampling in space and time

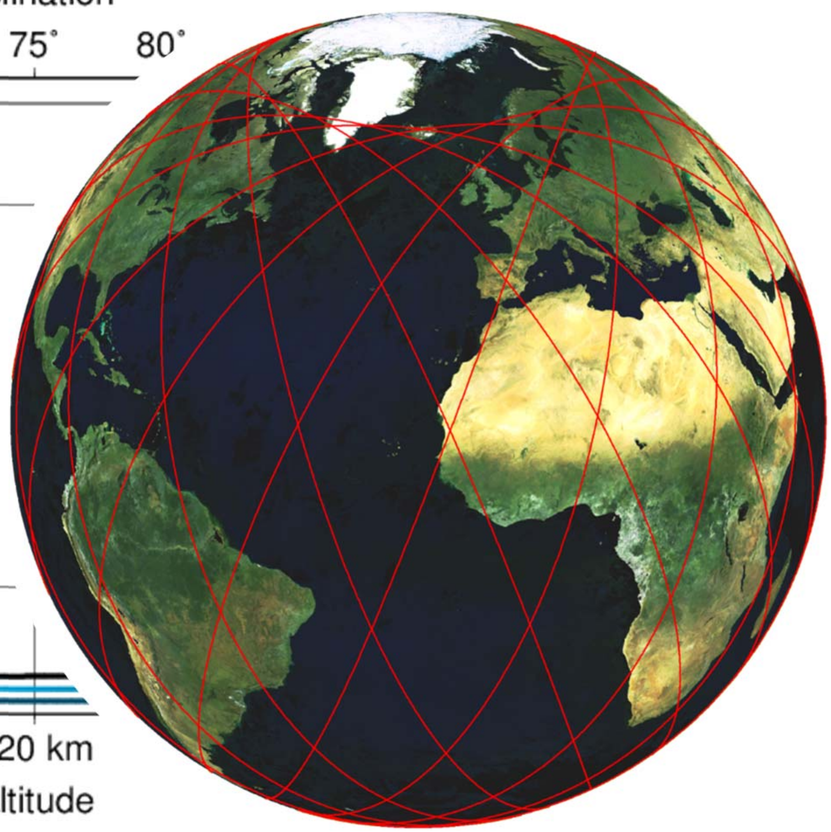


$\Delta\lambda_{max}$ → density of sampling

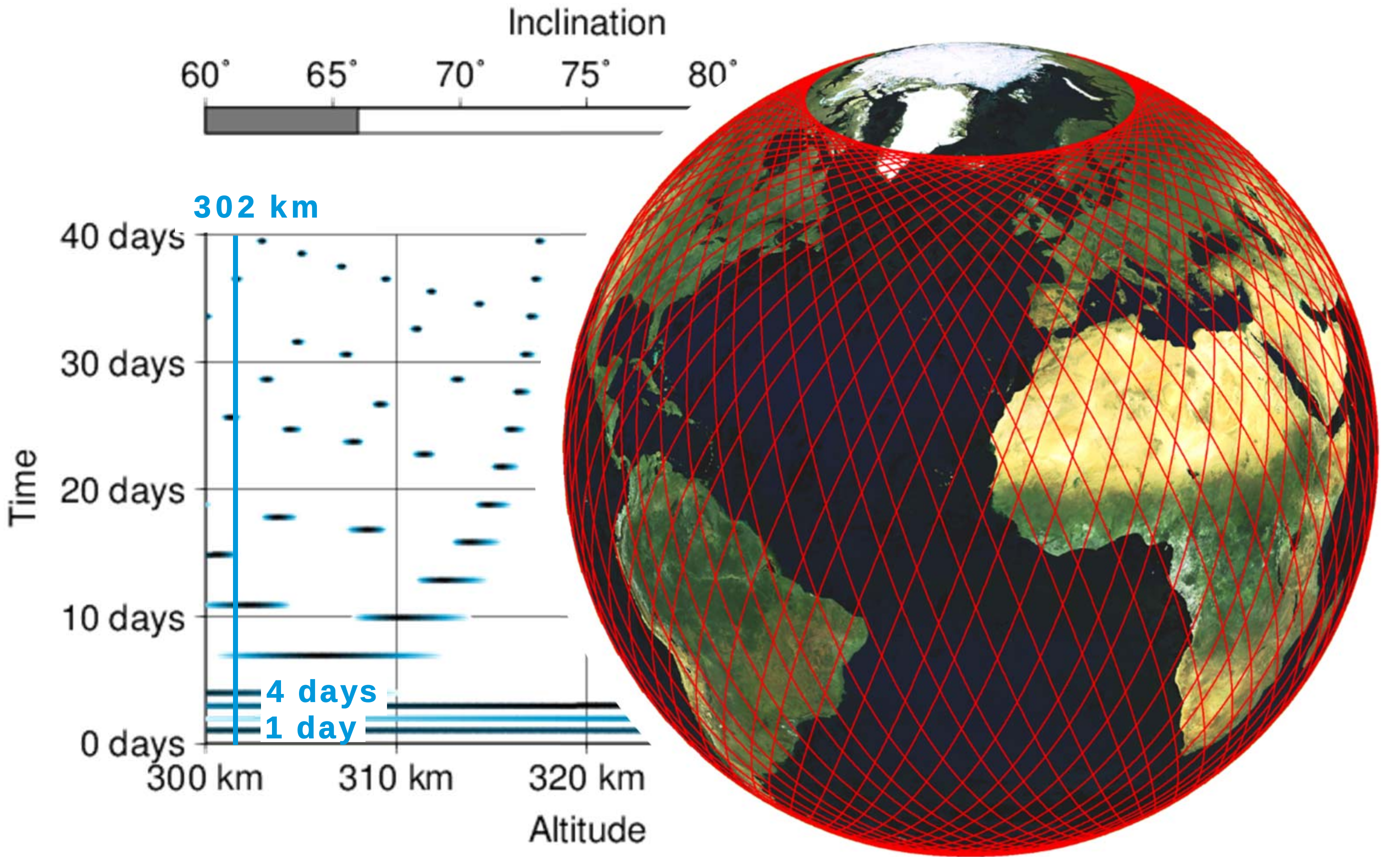
$\Delta\lambda_{max}$ / $\Delta\lambda_{min}$ → homogeneity of sampling

Sampling in space and time

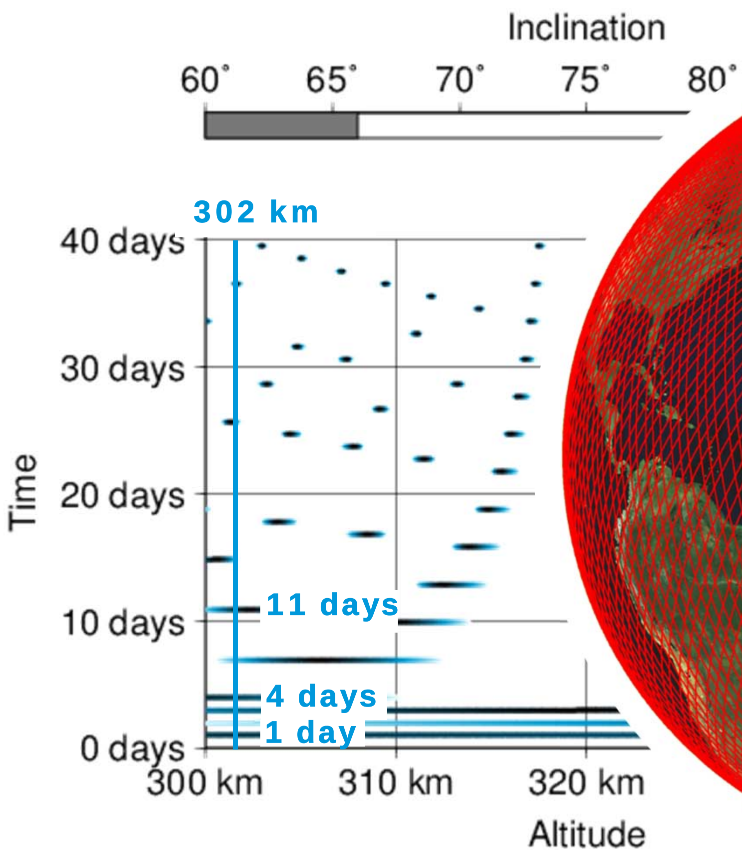


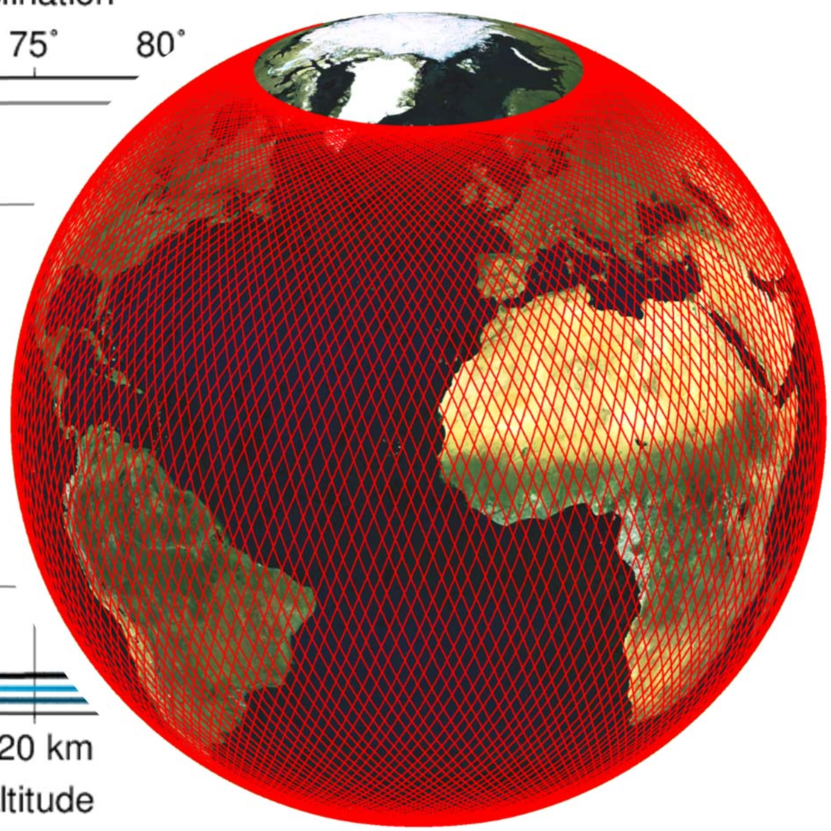


Sampling in space and time

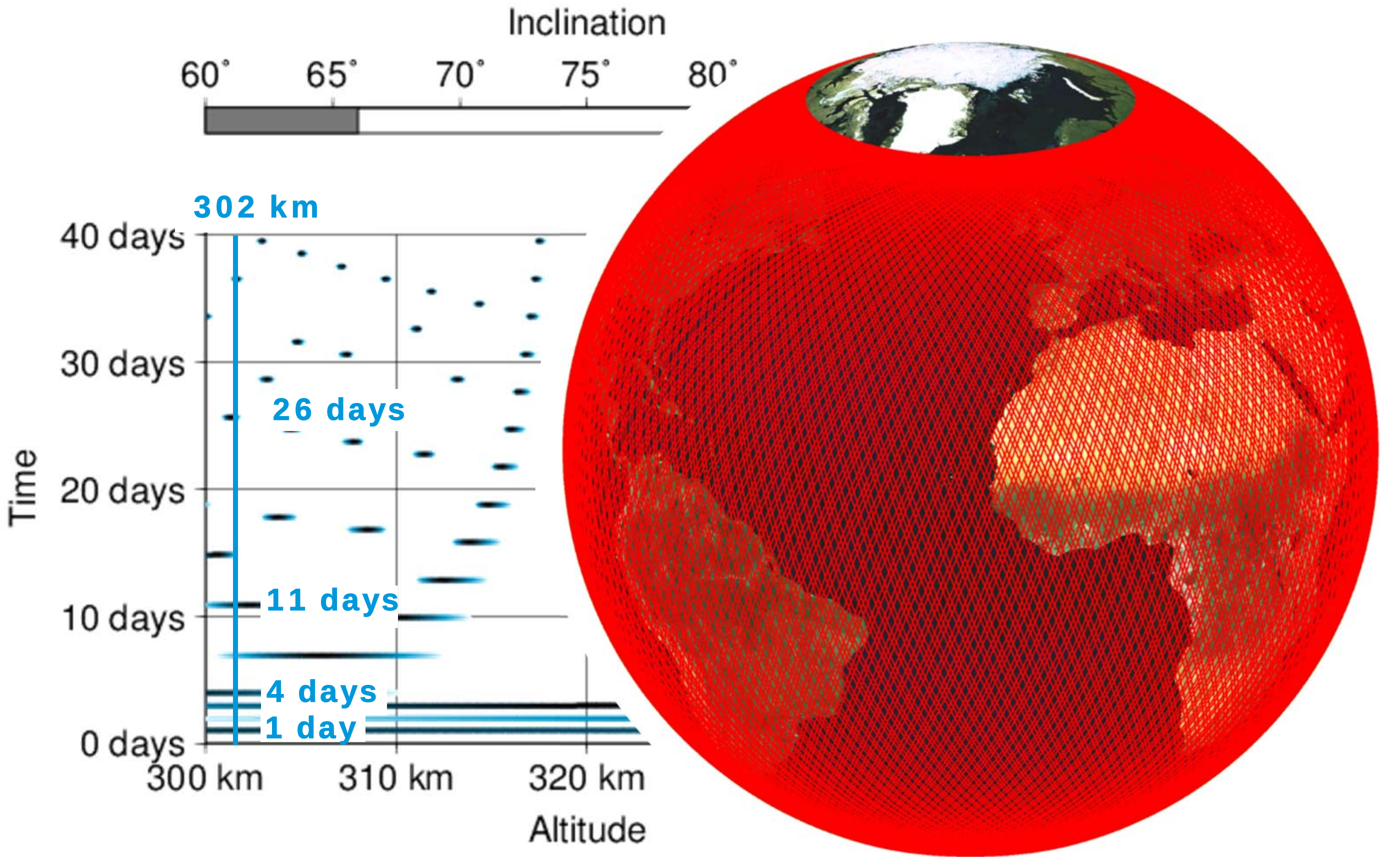


Sampling in space and time

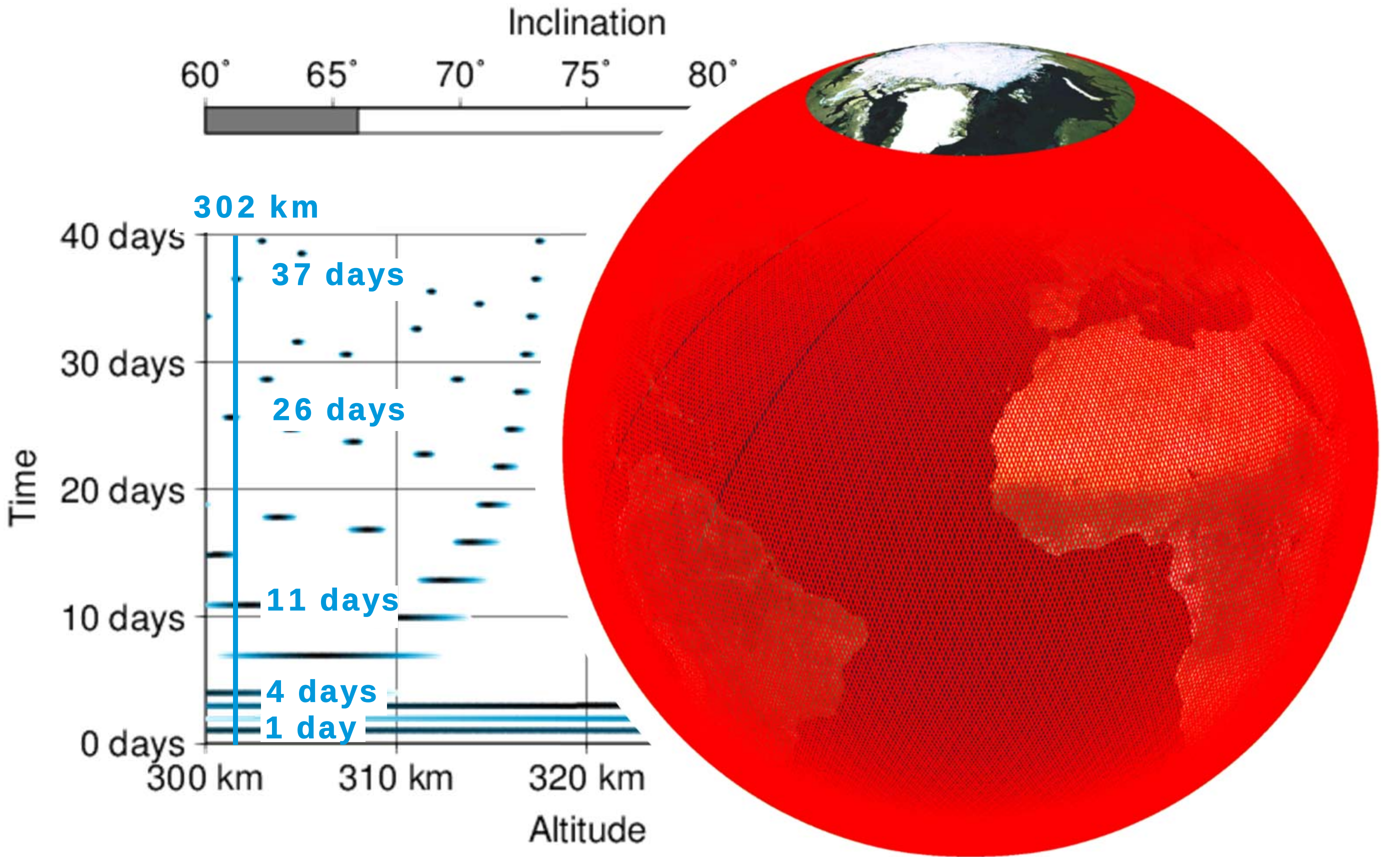




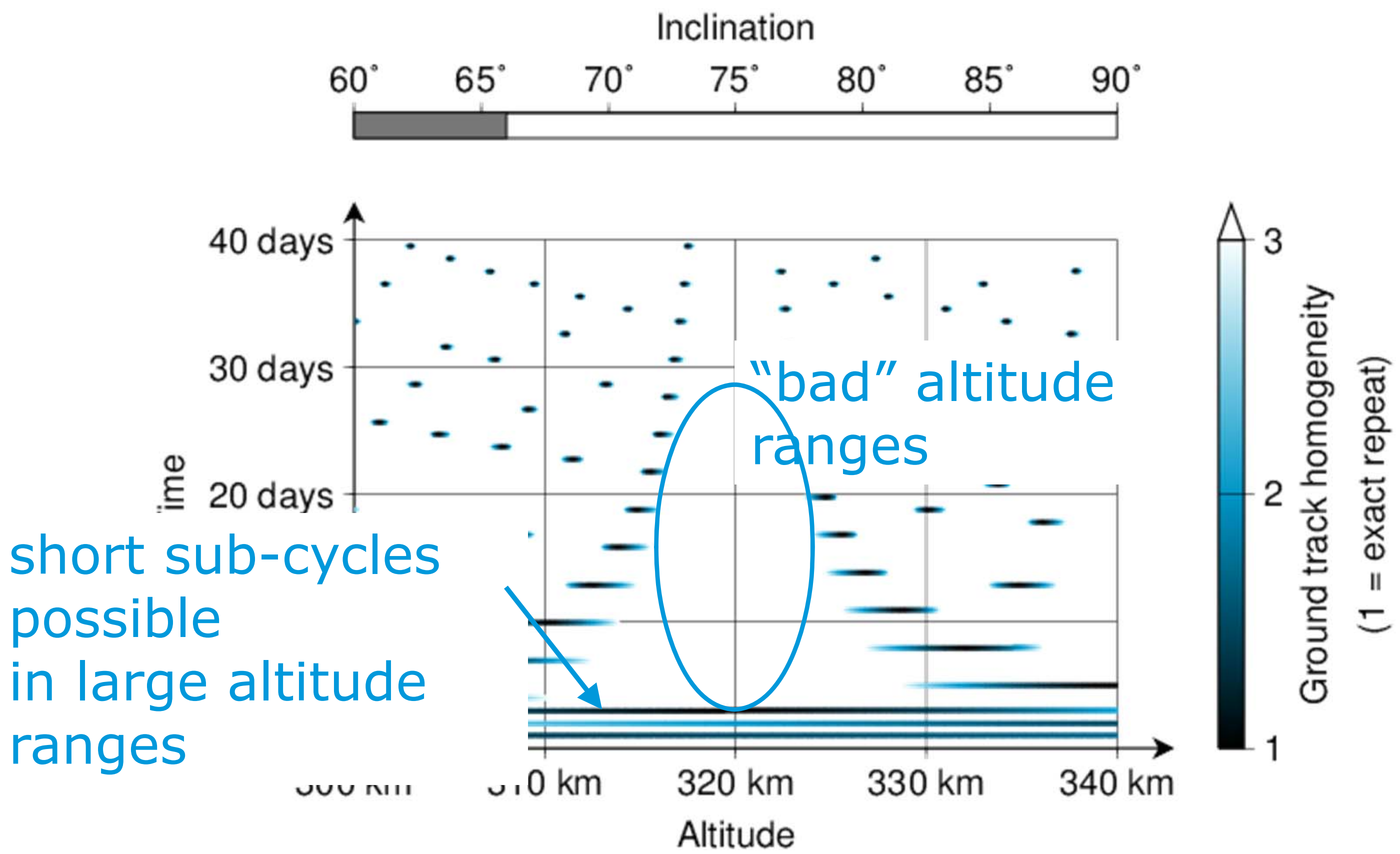
Sampling in space and time



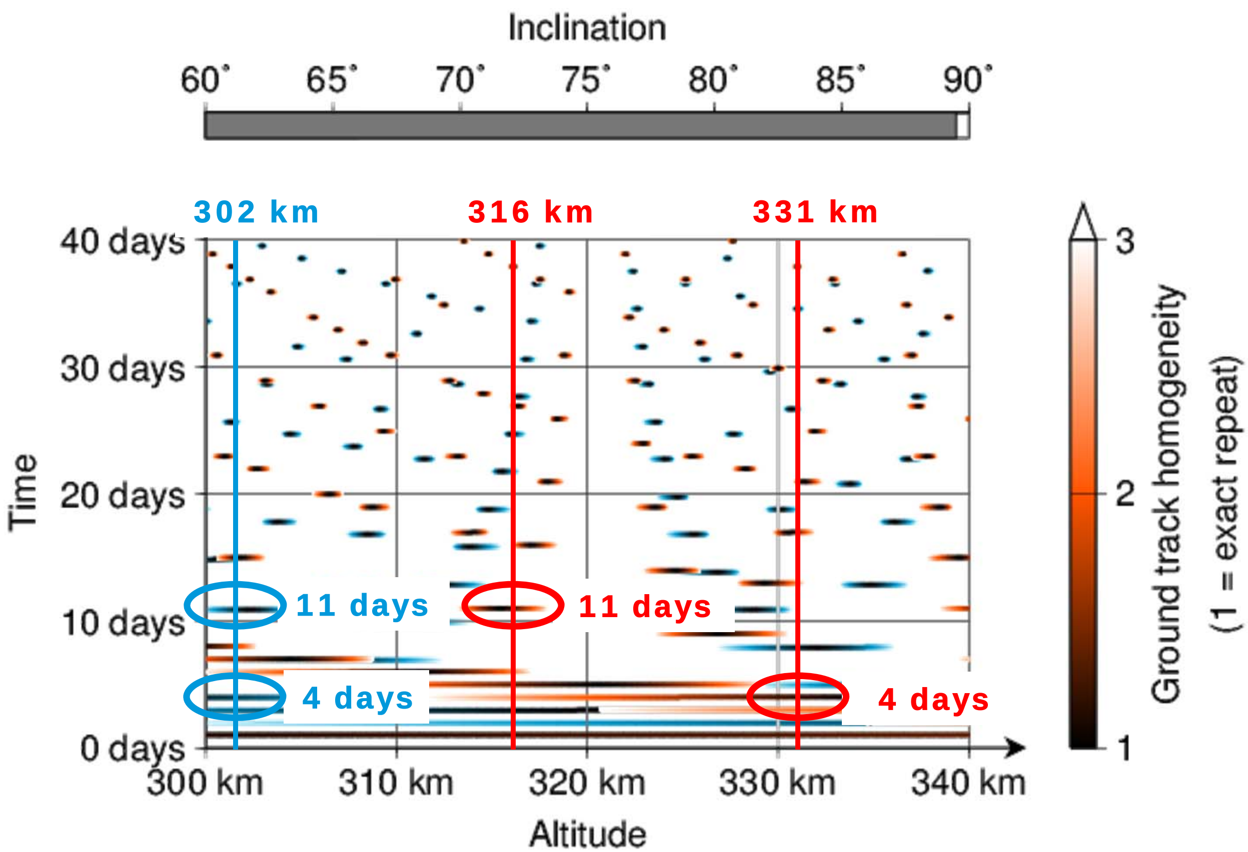
Sampling in space and time



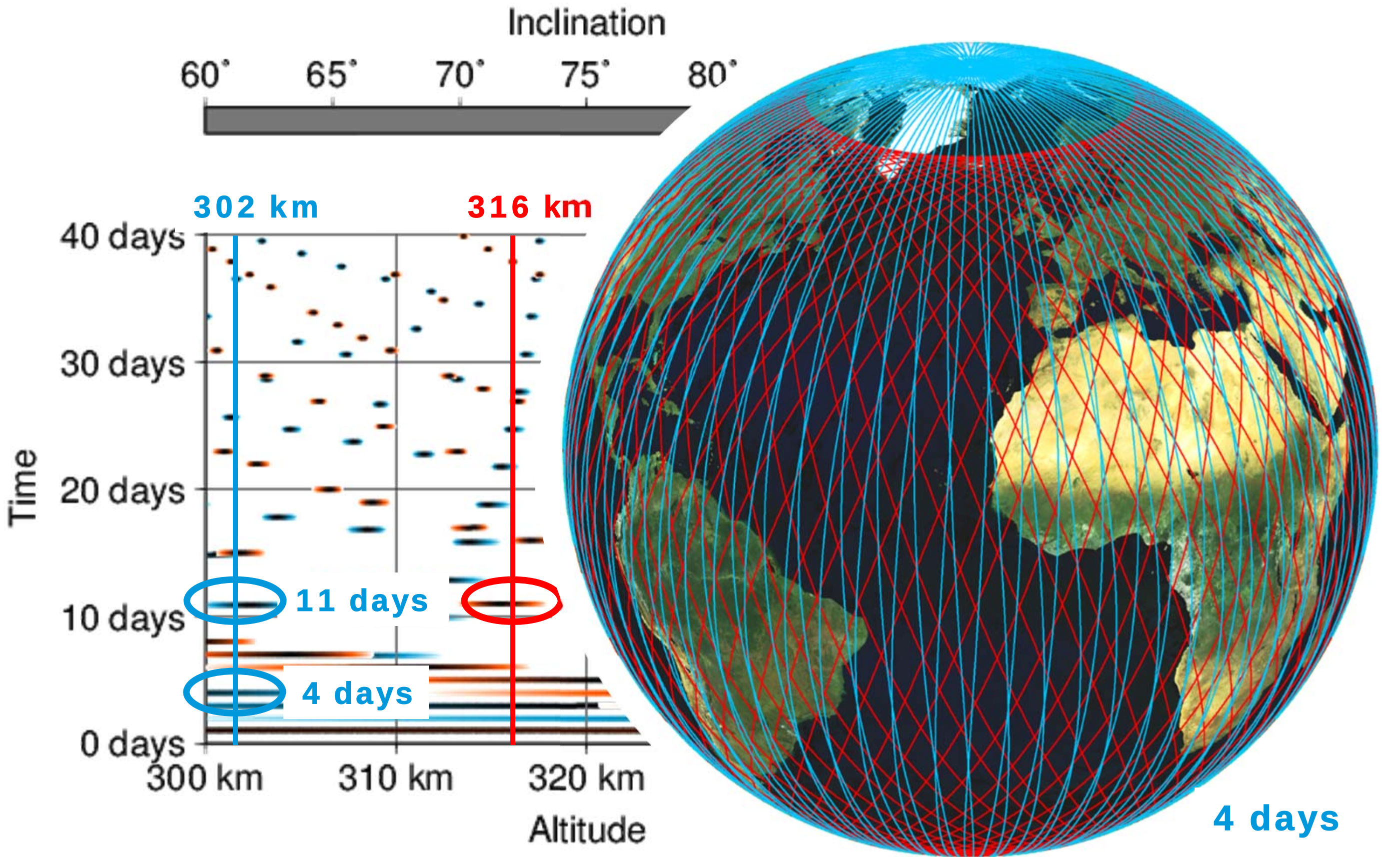
Sampling in space and time



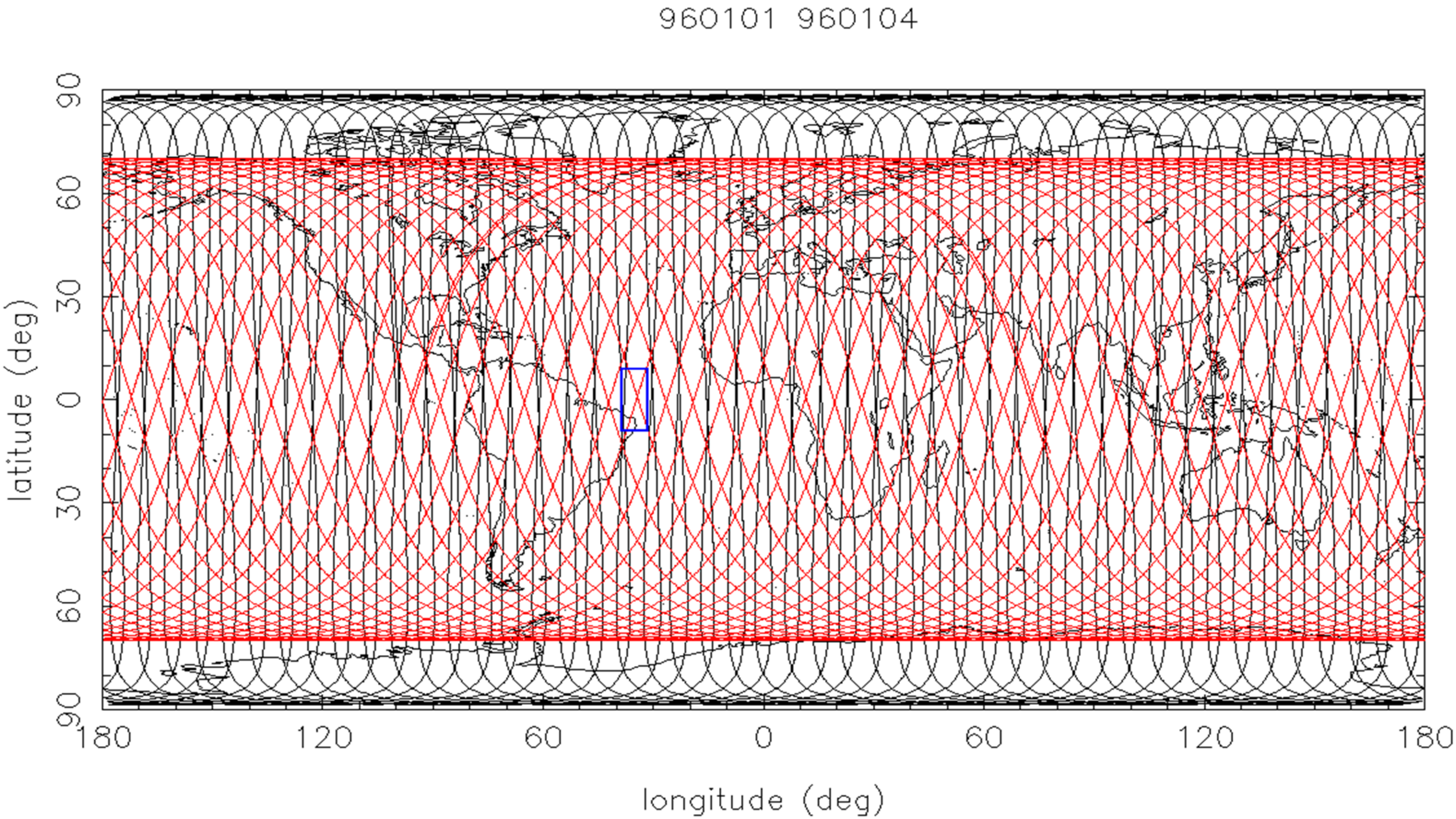
Sampling in space and time



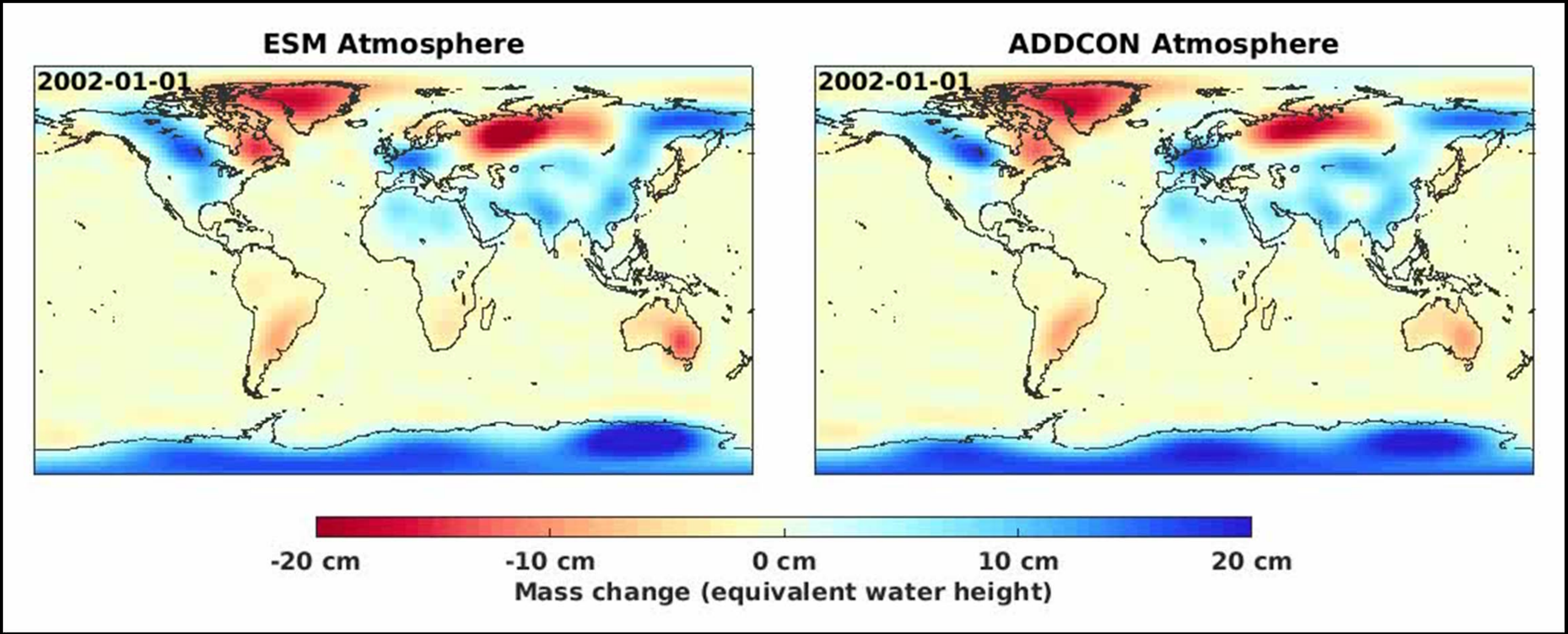
Sampling in space and time



Drifting ground tracks → Eastward near 3 days

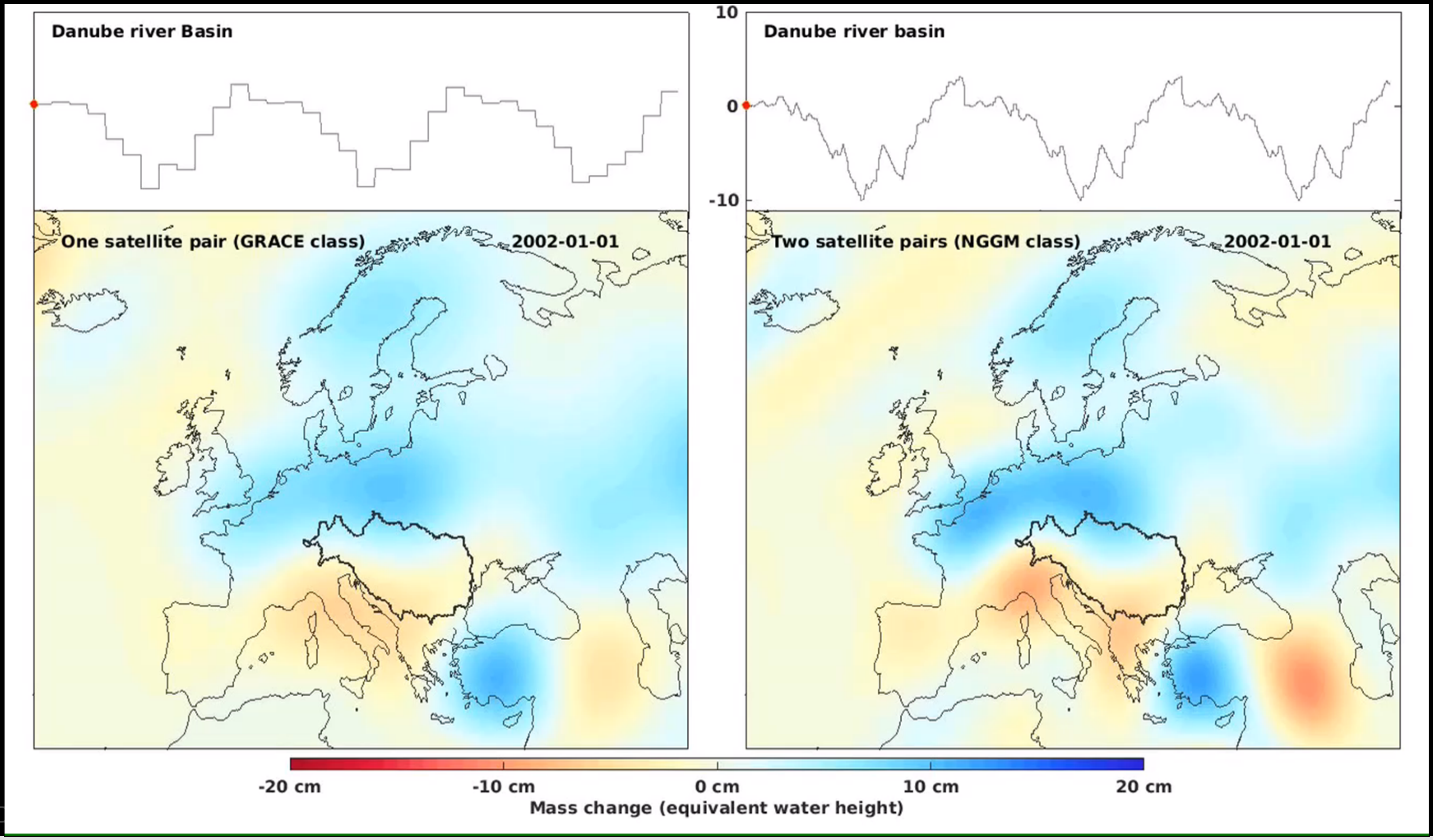


Example of simulation results 1 day large scale



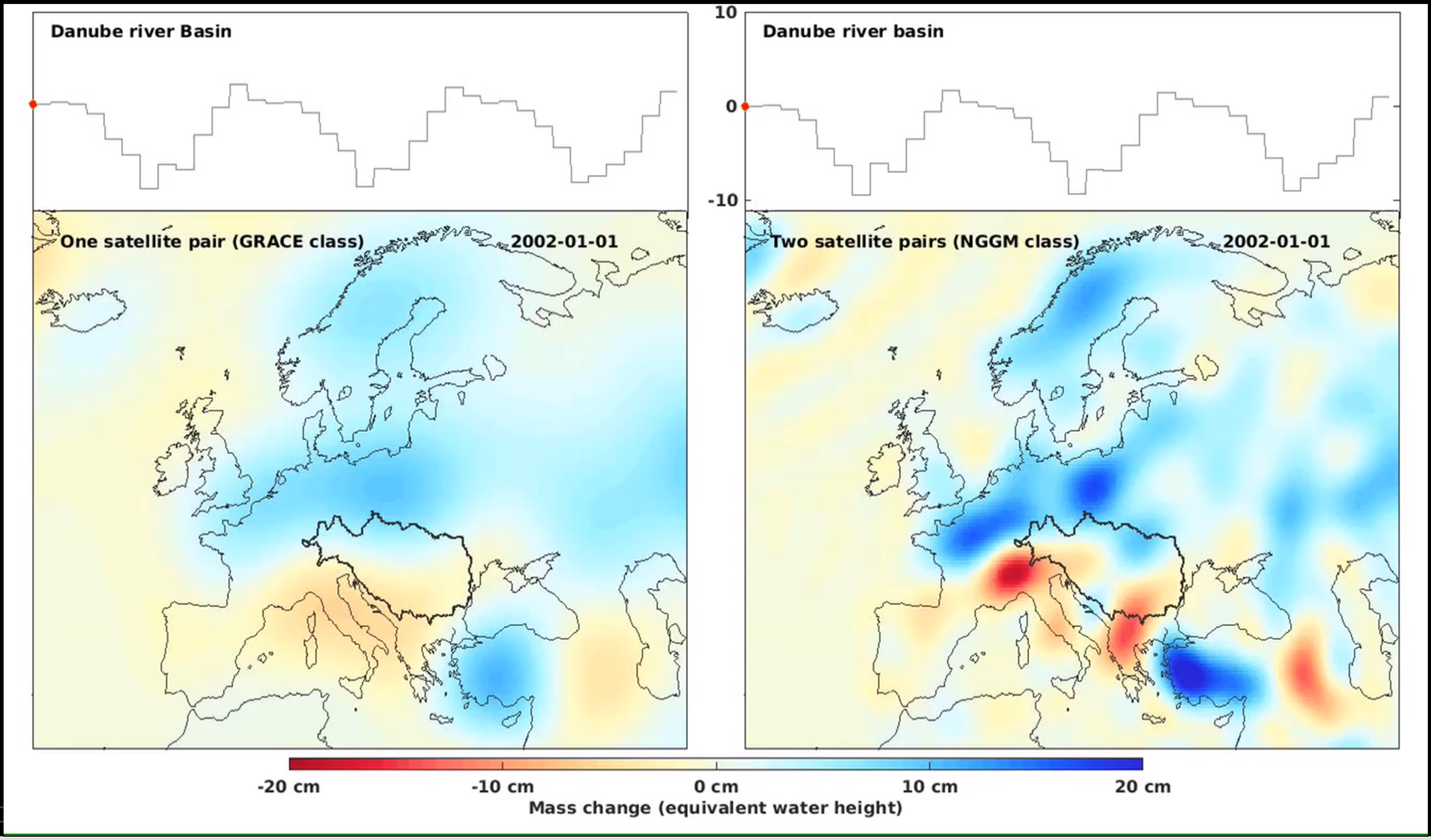
Example of simulation results over Europe

30 days "GRACE" type 3 days double pair



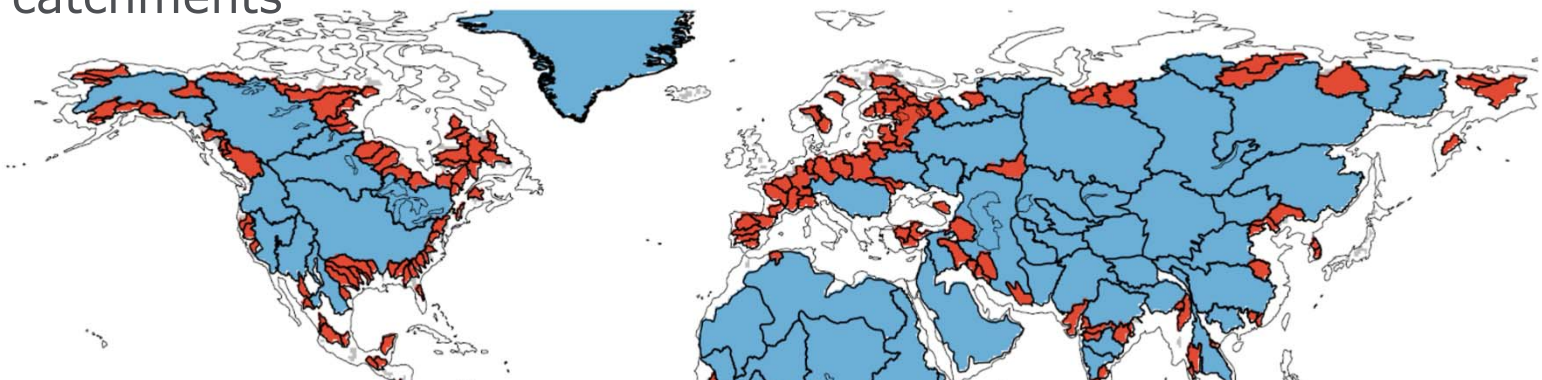
Example of simulation results over Europe

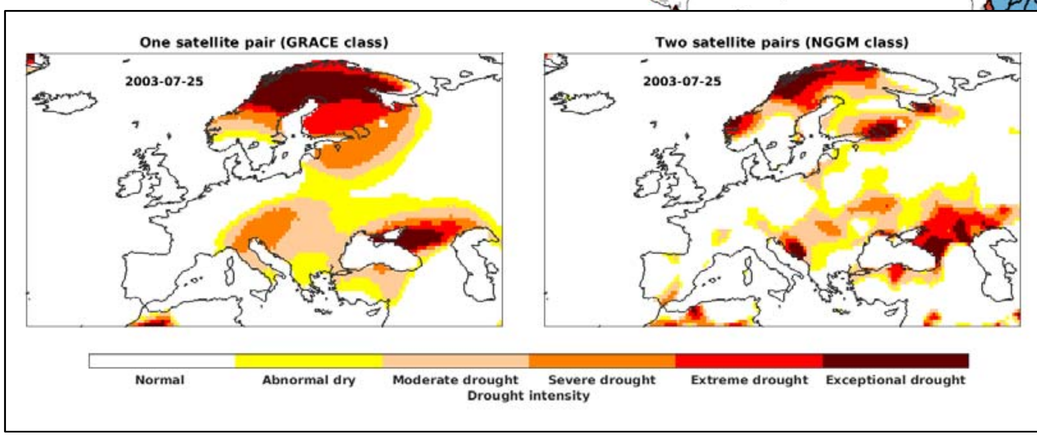
30 days "GRACE" type — 30 days double pair

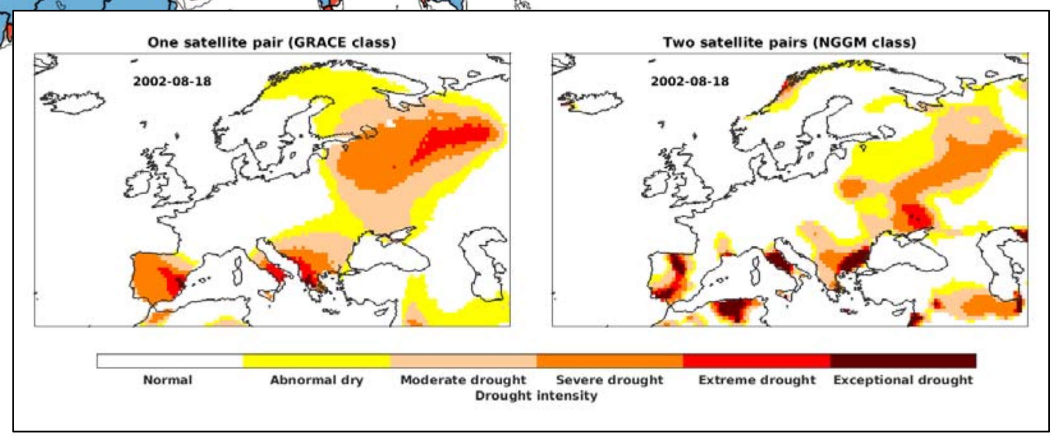


Possible results for hydrology: better closure of the water cycle?

observable catchments







Outline of the presentation

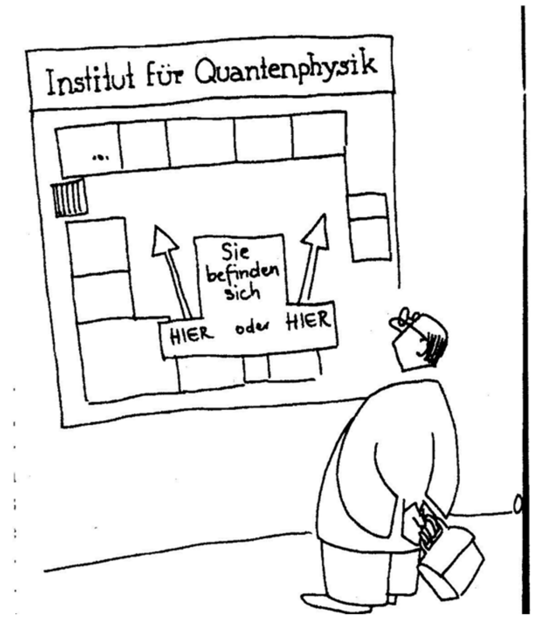
- Introduction to gravity and measurements
- What can we learn from GOCE ?
- What are important parameters for a gravity mission?
- Existing ideas for future gravity missions
- New ideas for future gravity missions

Where are we heading?

Atomic clocks reach relative accuracies of about 10^{-18}:

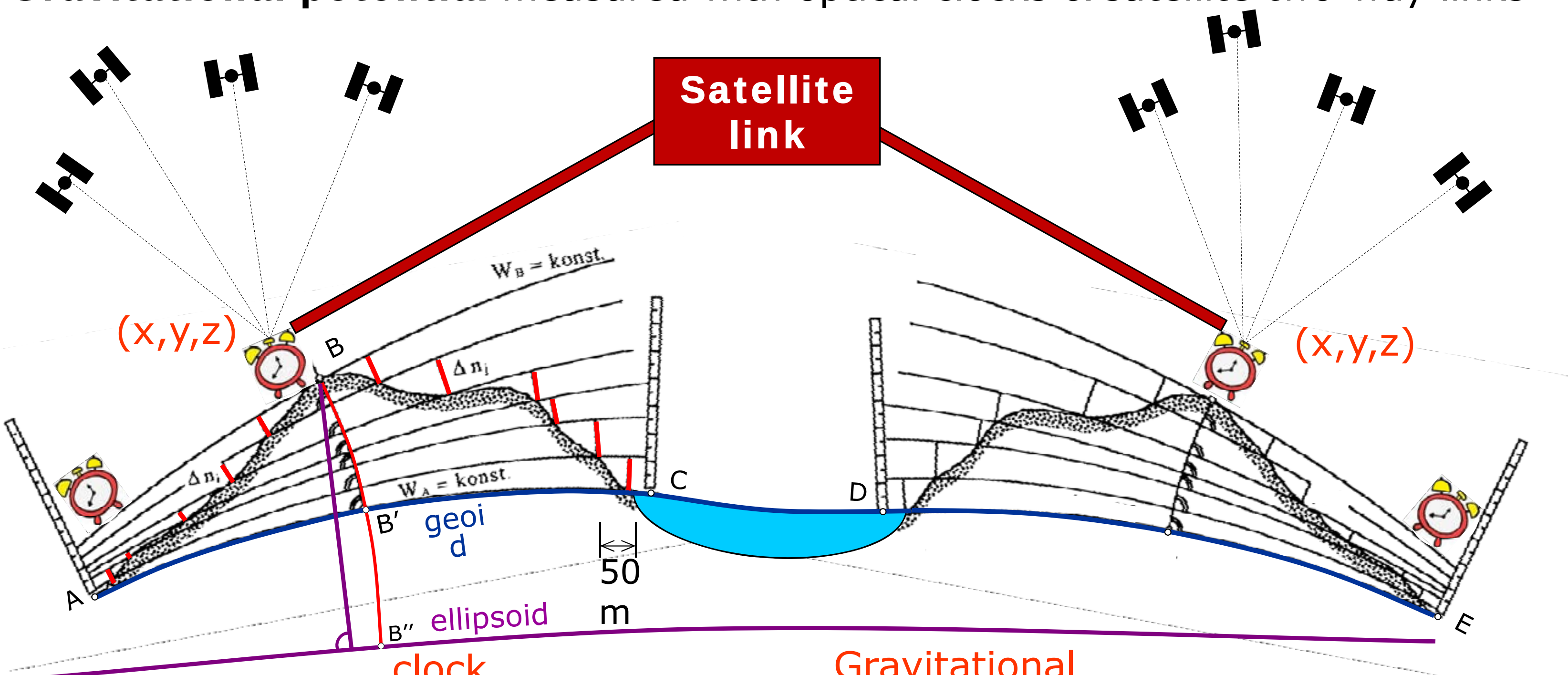
- Measure direct potential differences with clocks (Einstein)
- Replace spirit leveling by clocks with a “cm accuracy” or better
- Flying clocks usefull?

Harrison
1 first sea chronometer



Relativistic Geodesy:
unify geometry (GNSS) & gravitational positioning

Geometry measured with GPS
Gravitational potential measured with optical clocks & satellite two-way links



$\nu_B/\nu_A = \Delta T_A/\Delta T_B = 1 + (V_B - V_A)/c^2$

(Credits: D. Svehla)

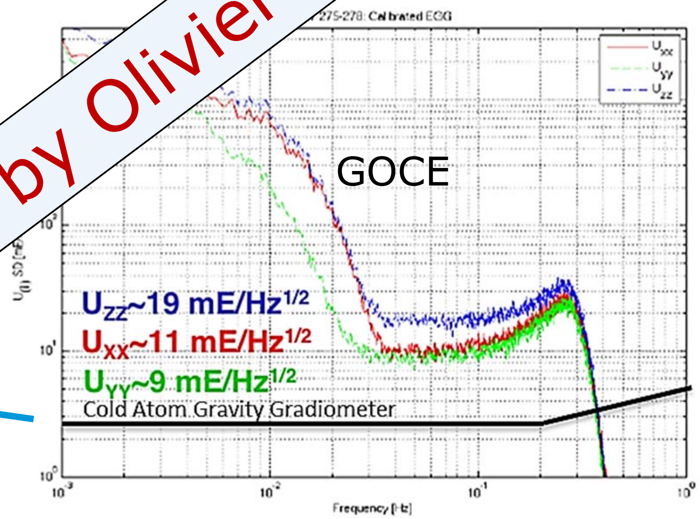
Qauntum sensors: Cold Atom Interferometry

Cold Atom Interferometers: towards a gradiometer

Can this be used for studying time-variations?

Multiple satellites in polar orbits

Replace laser ranging satellites: 2^{nd} generat

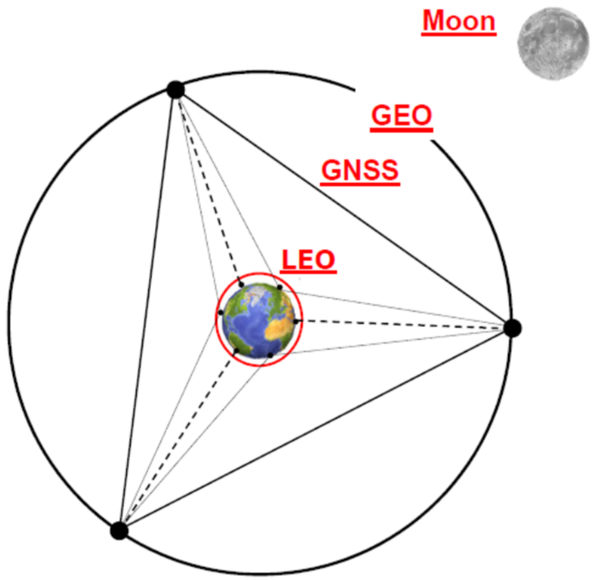


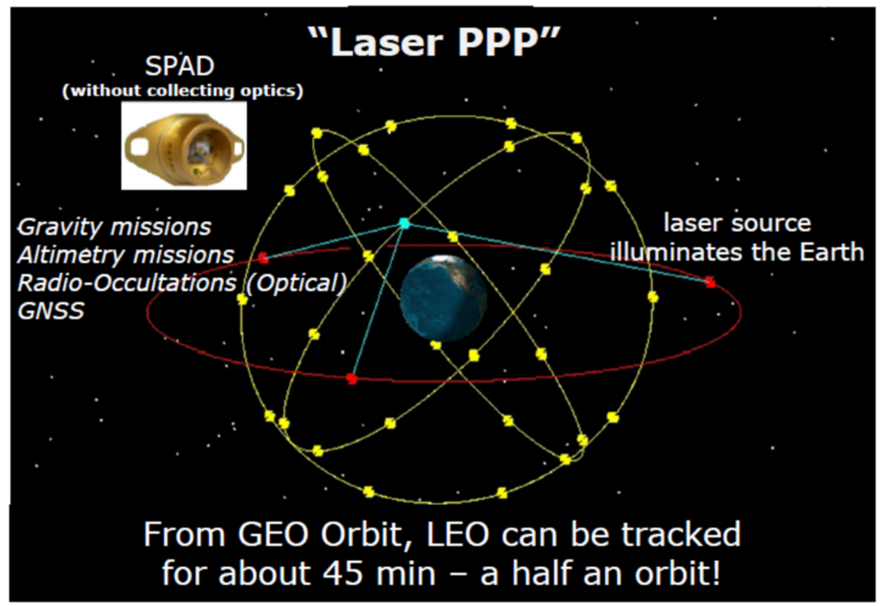
Credits: O. Carraz, ESA

Lecture on monday by Olivier Carraz

New ideas; old concepts: smaller satellites option?

- Laser Precise Point Positioning from geostationary satellites (e.g. with reference clocks)
- GEO-GNSS and GEO-LEO satellite monitoring in “free” fall or with drag/wind measurements (like GETRIS or MOBILE concepts).





(Svehla et al. 2007)

Questions ?

"Don't take this lesson too seriously because tomorrow's lesson will contradict what you've learned today."