Spaceborne techniques for Gravity

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DTU Space, Geodesy

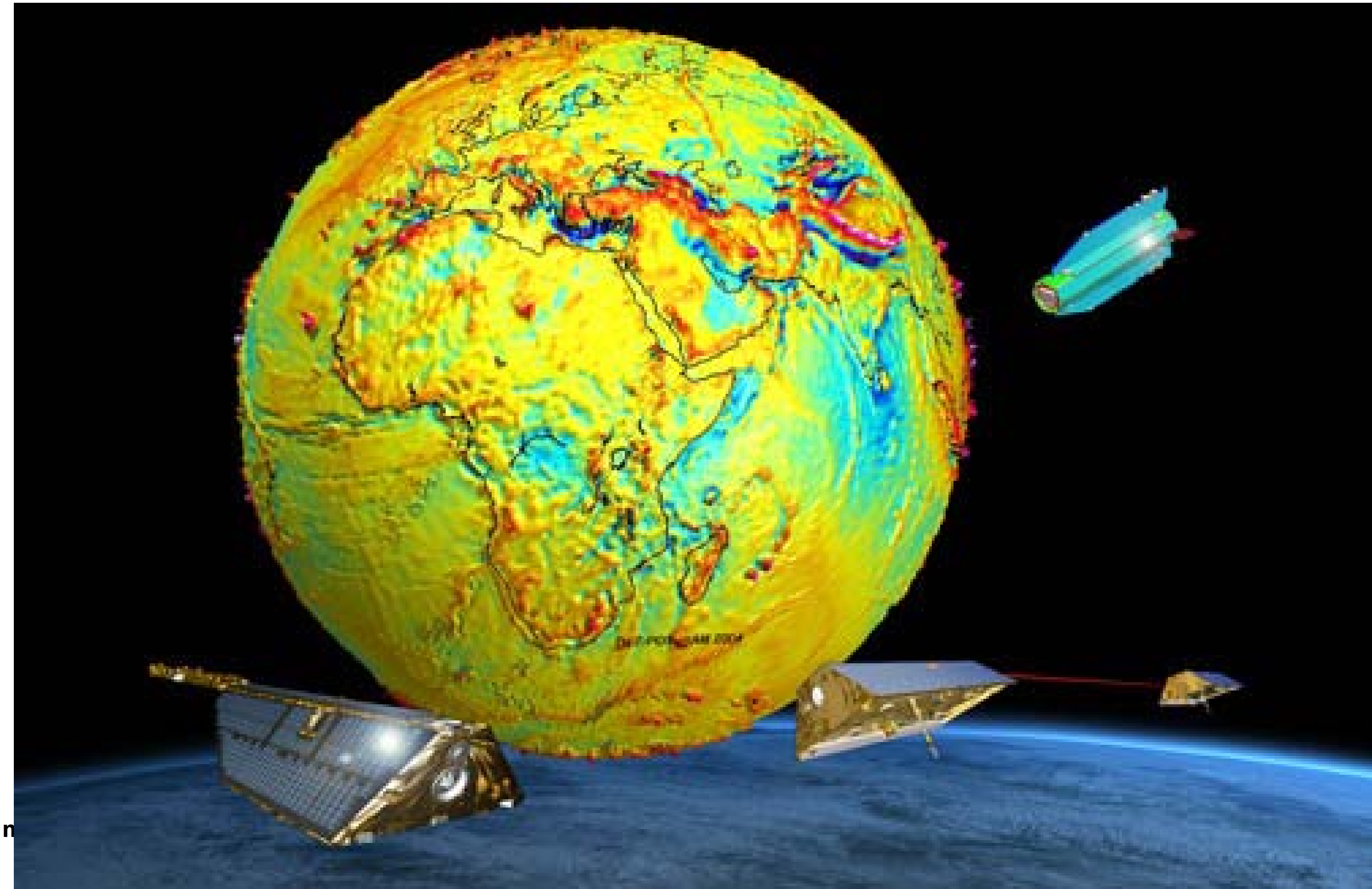
Overview

- Motivation
- The very basic……….

Gravity using satellite altimetry.

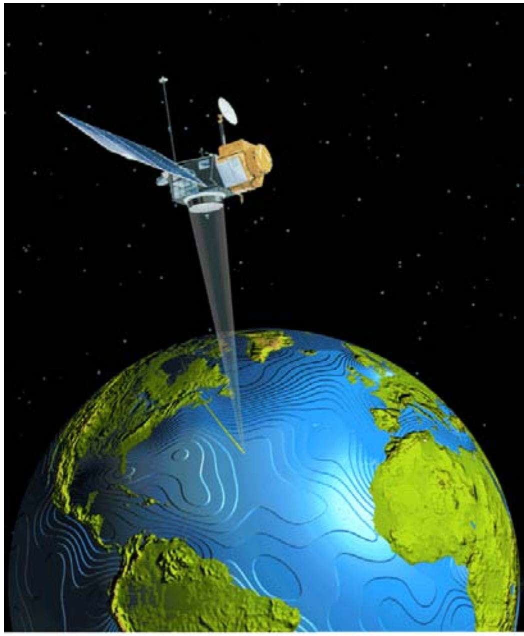
Gravity from GRACE (intersatellite ranging)

Gravity from GOCE (satellite gradiometry)



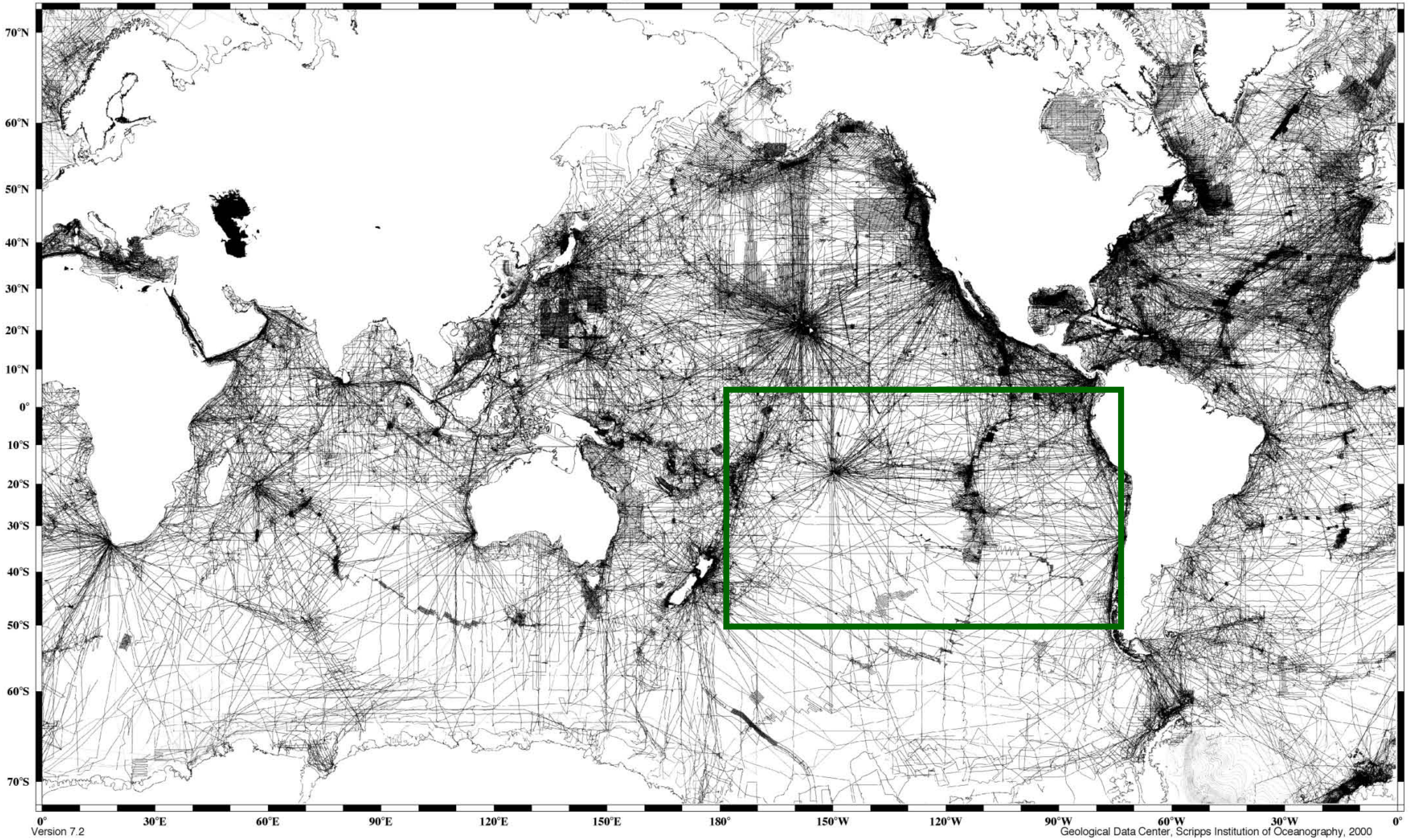
Motivation

- Why:
  - Earth Ressources
  - Earthquakes/tsunamies
  - Cheaper Sattellites
  - Better bathymetry
  - Climate research
  - Navigation /Safety



- In order to determine the gravity field of the Earth you need observations with uniform density throughout the world.
- The density of your observations determines which wavelength (and to which resolution) you can determine in the earth gravity field.
- Two thirds of the globe is covered with water, and many regions are NOT covered with marine gravity obs.

Ship Tracks


70°N
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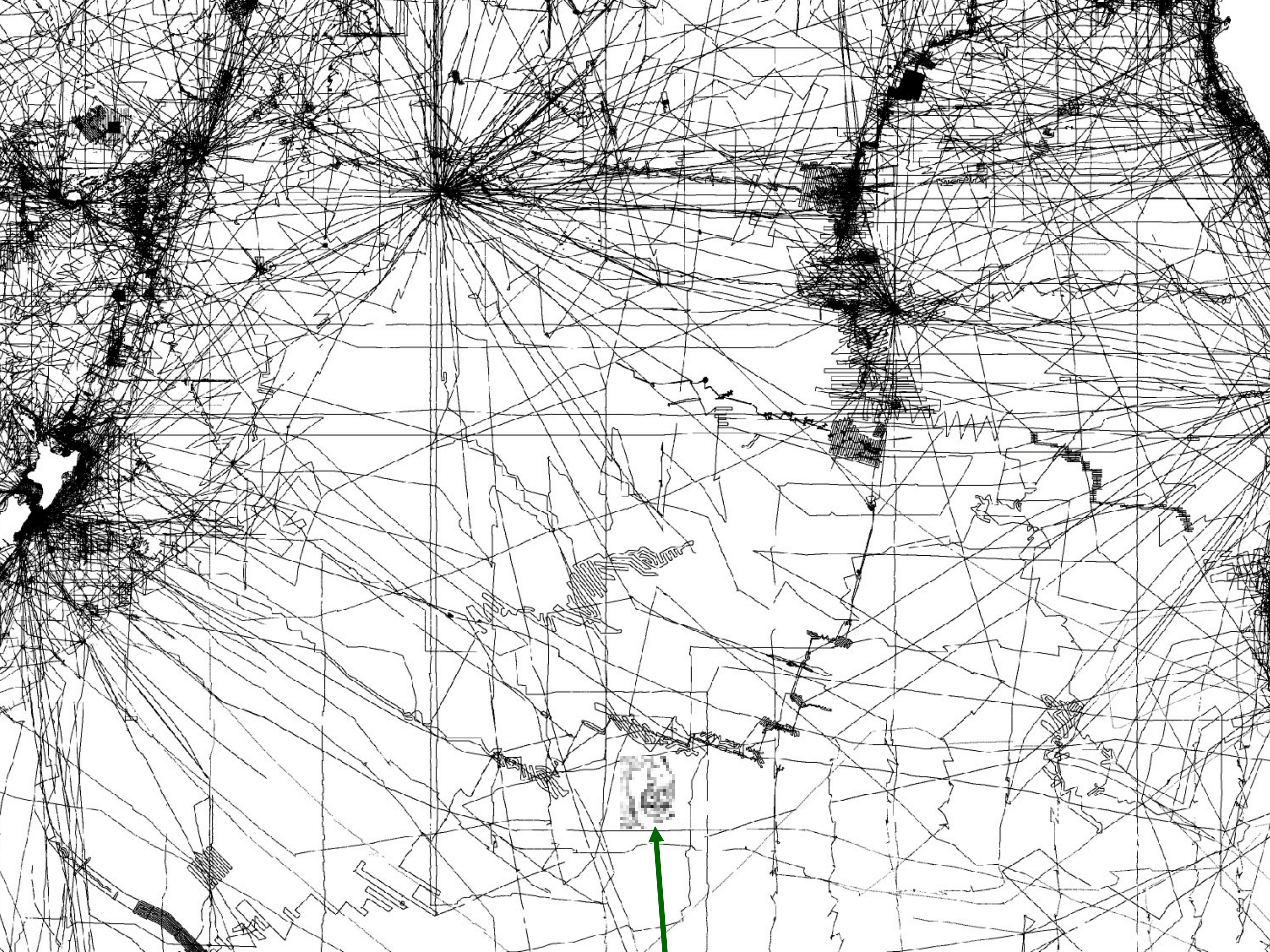
Version 7.2
Geological Data Center, Scripps Institution of Oceanography, 2000

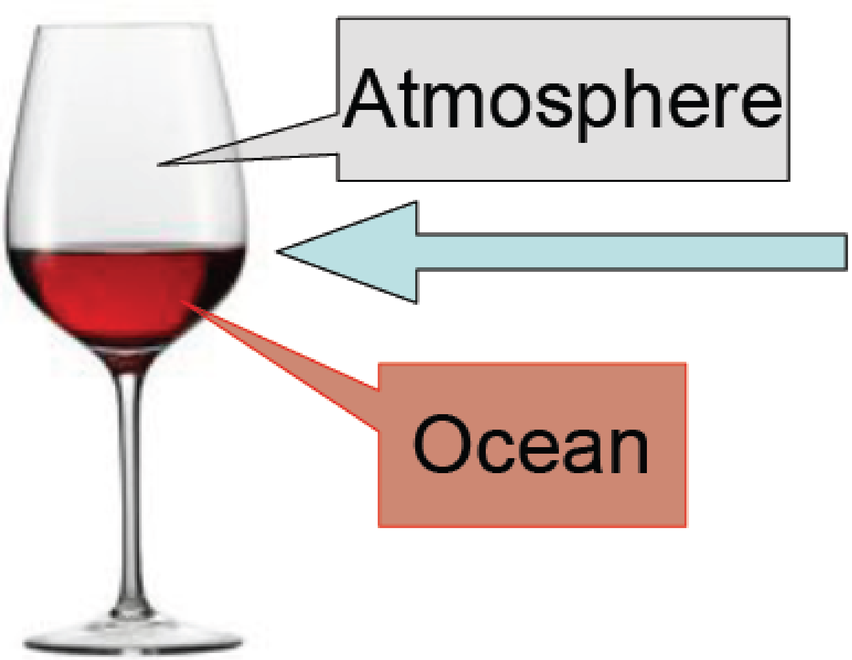


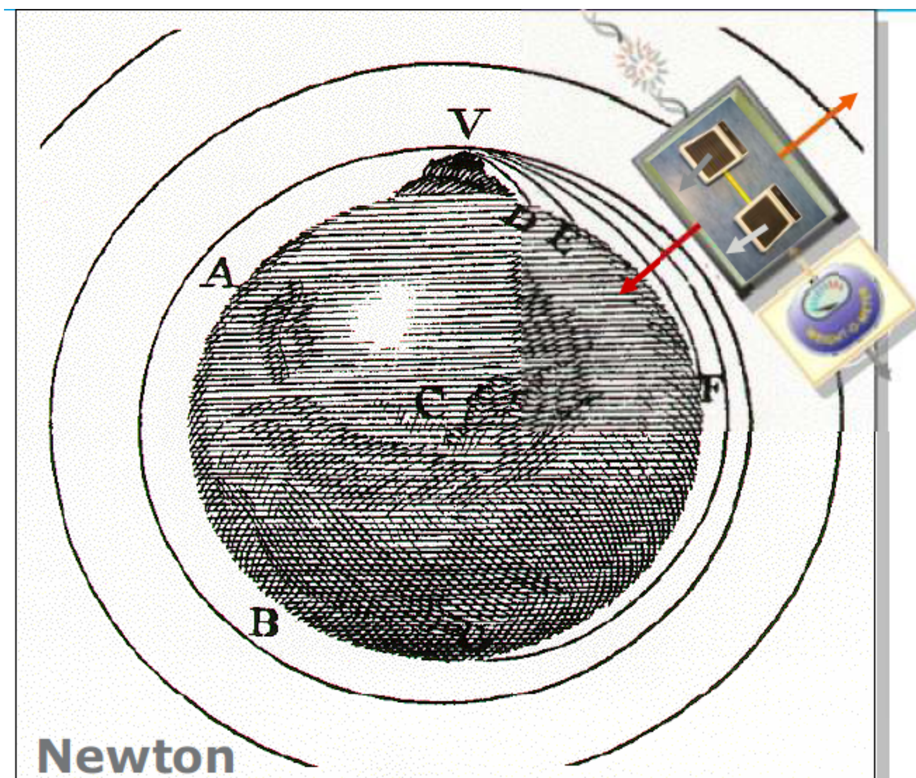
Space Measurement Techniques

- Satellite altimetry can provide information over virtually the entire Earth.
- Newton. $\vec{g} = -\frac{GM}{r^2}\vec{r}$ Notice r^2 dependence / un-ambiguity

$$\Delta g = -\frac{\partial V}{\partial r} - 2\frac{V}{r} \approx -\frac{1}{\gamma}\left(\frac{\partial N}{\partial r} + 2\frac{N}{r}\right)$$

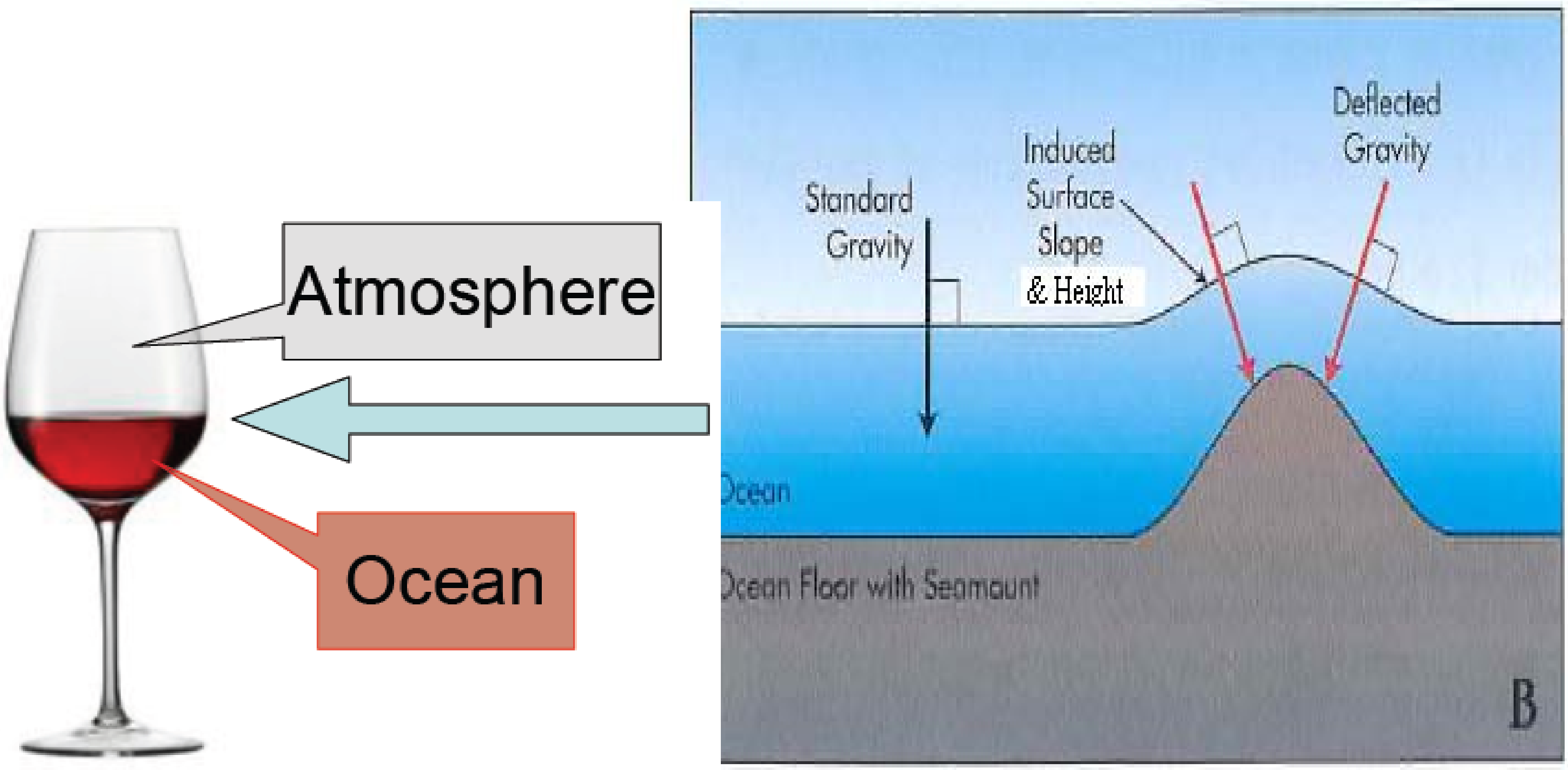
- Two principles. Observe sea level or Put scales on satellites
- Satellite Altimetry Satellite gravimetry (GRACE/GOCE)





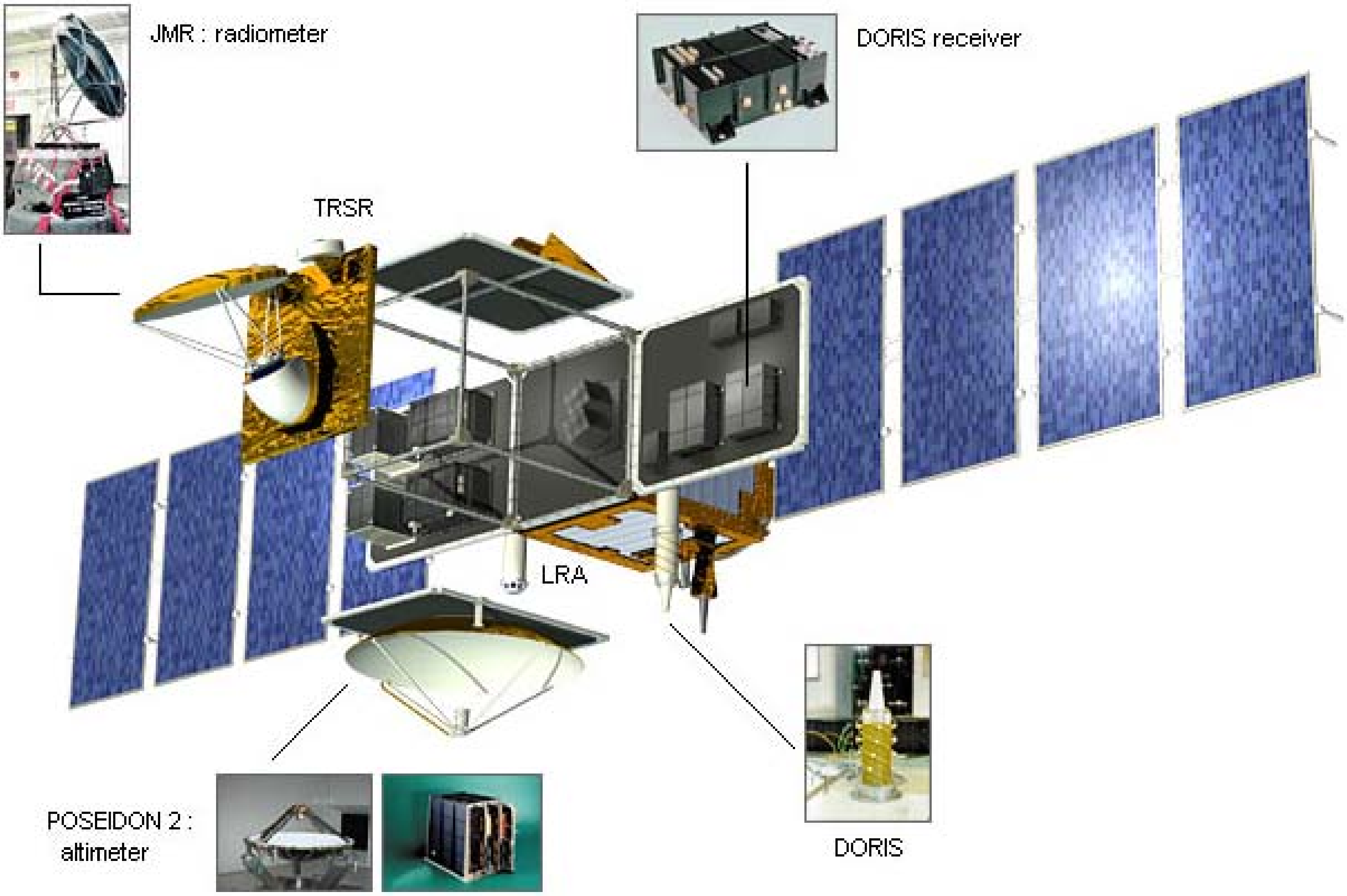
Satellite Altimetry

Measuring the sea surface height->gravity.



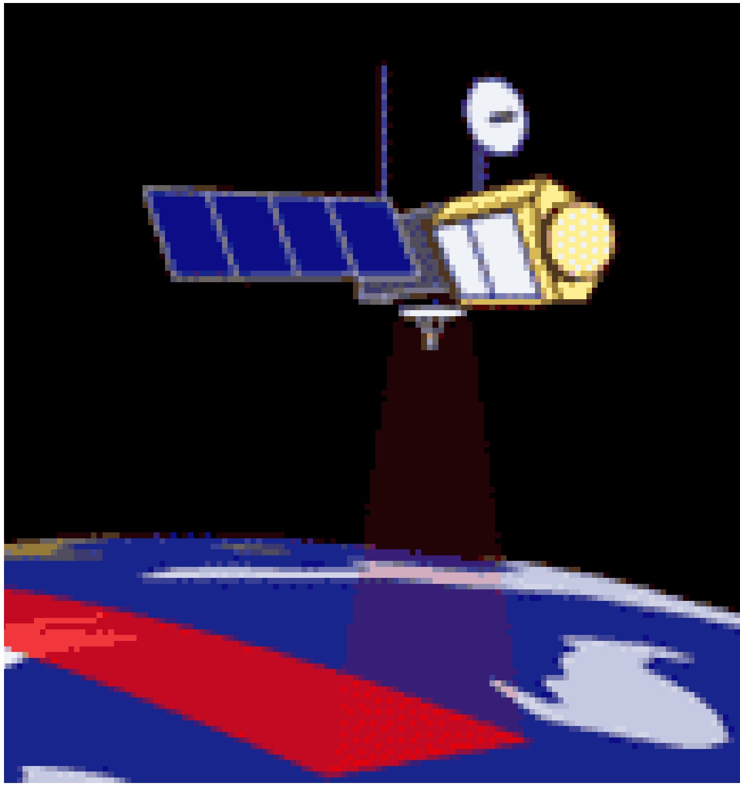
Satellite Altimetry

Altimetric Satellite (Jason, Envisat, ERS…….)



Measurement specification

Emitted Frequency (GHz)	Dual-frequency (K_u, C) - 13.575 and 5.3
Pulse Repetition Frequency (Hz)	2060 interlaced {3K_u-1C-3Ku}
Pulse duration (microseconds)	105
Bandwidth (MHz)	320 (K_u and C)
Antenna diameter (m)	1.2
Antenna beamwidth (degrees)	1.28 (K_u), 3.4 (C)
Power (W)	7
Redundancy	Yes
Specific features	Solid-State Power Amplifier. Dual-frequency for ionospheric correction, High resolution in C band (320 MHz)



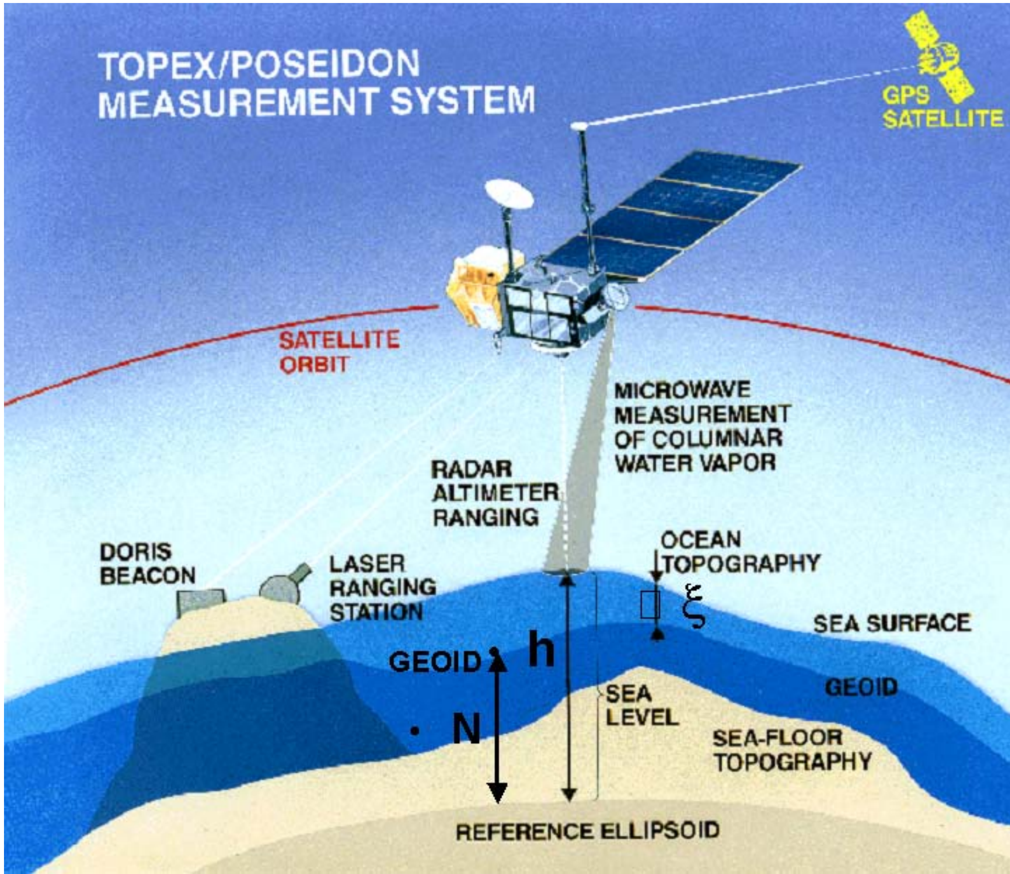
Altimetric Observations

Accurate ranging to the sea surface is

Based on accurate time-determination $d = t * c / 2$

Where c must be adjusted slighly adjusted

For passage of ionosphere and troposphere.



SSH = Height_{sat} – Range

Height_{sat} Is determinde using

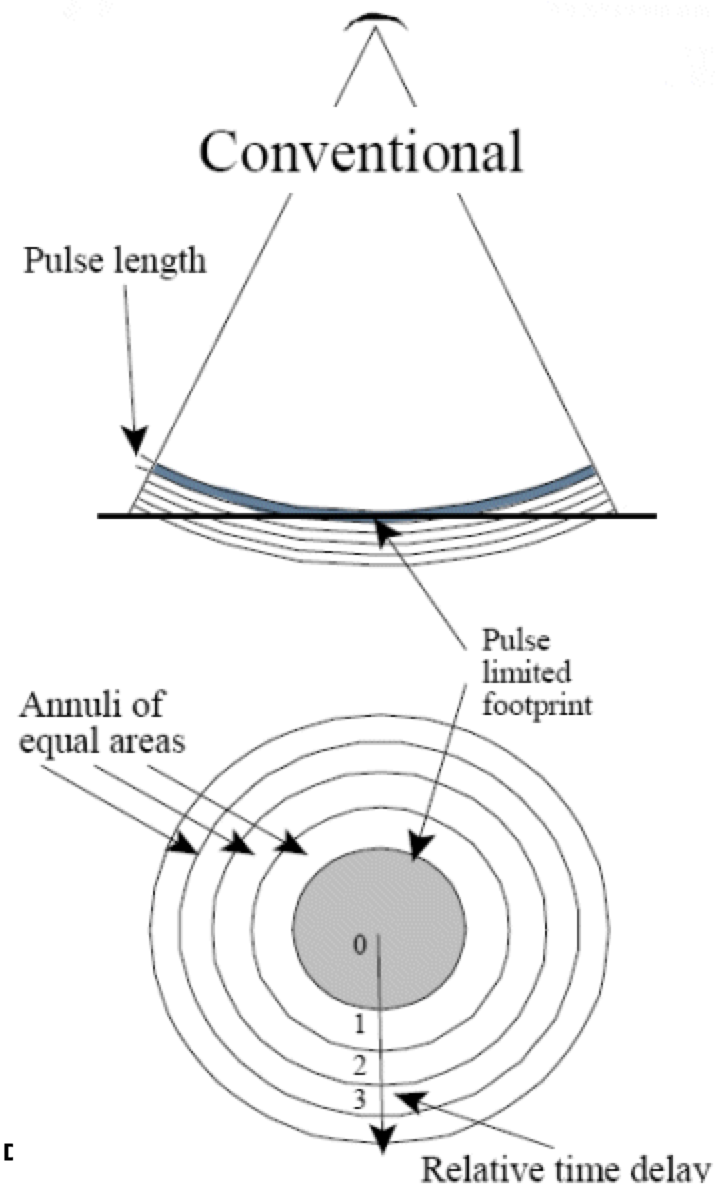
GPS or DORIS/Laser ranging

Relative to the reference ellipsoid

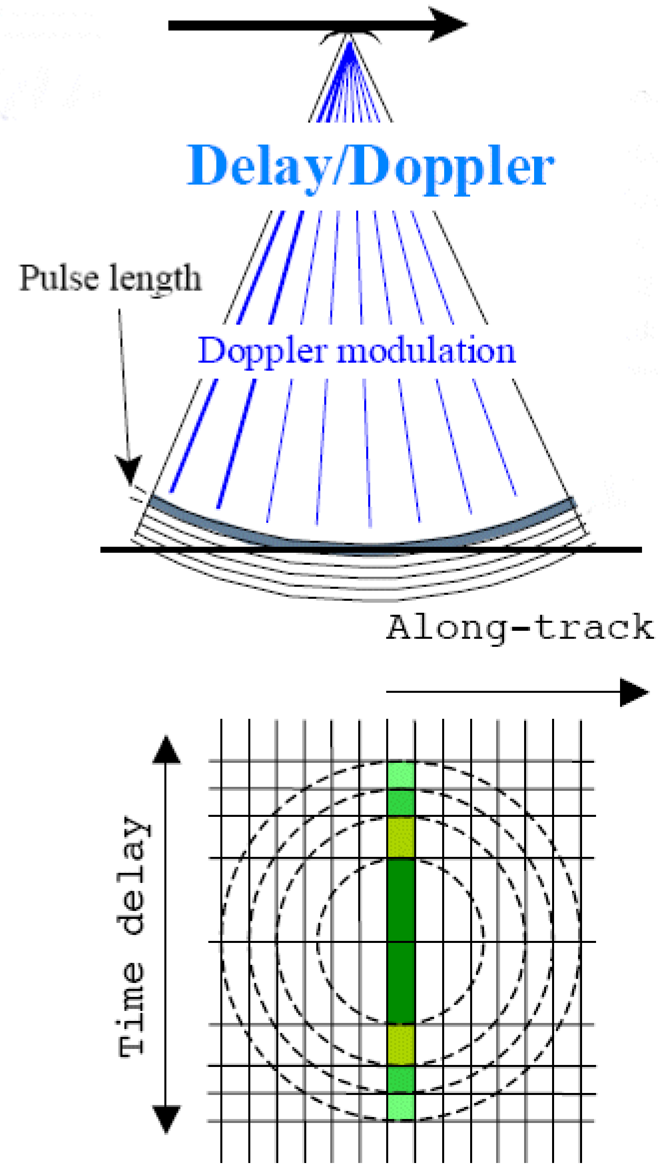
Ellipsoid is ”best” mathematical

model of the Earth Shape (WGS84)

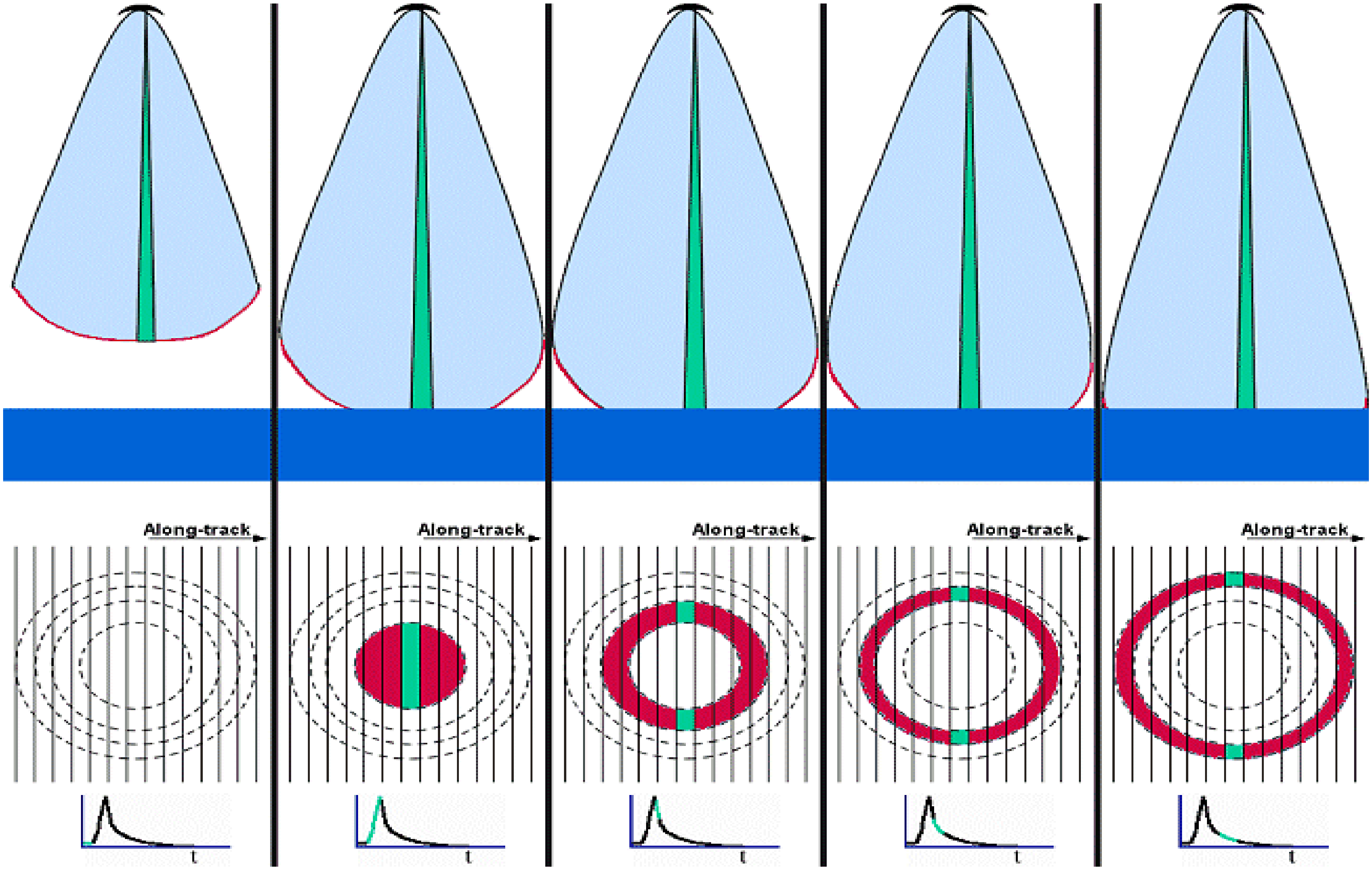
Jason/ENVISAT



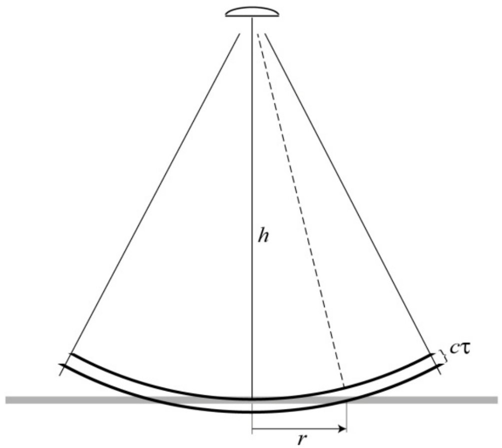
Cryosat-2, Sentinel-3

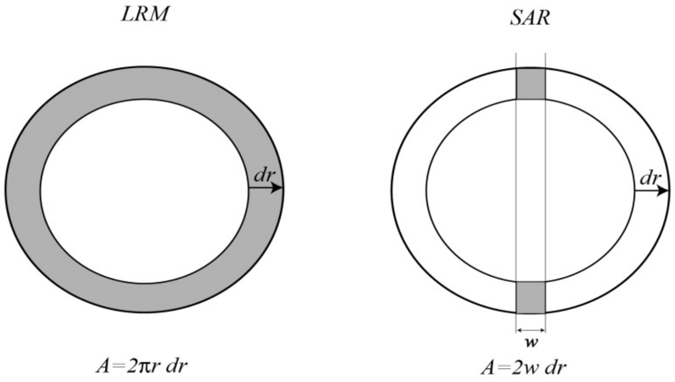


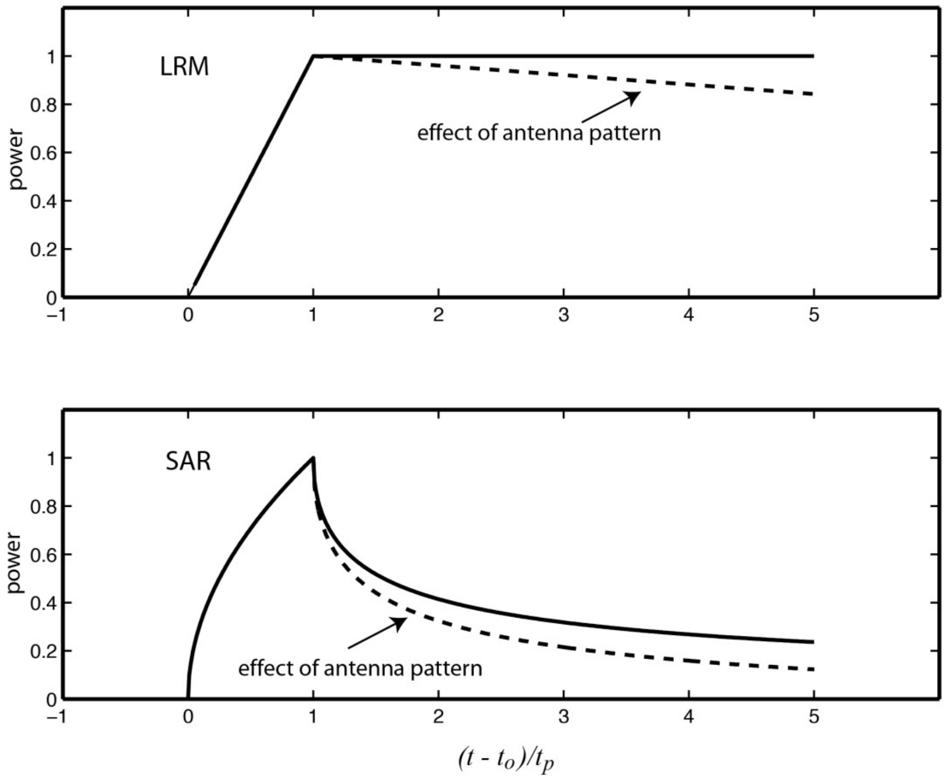
Cryosat-2, Sentinel-3. Doppler processing



flat surface response – LRM vs. SAR



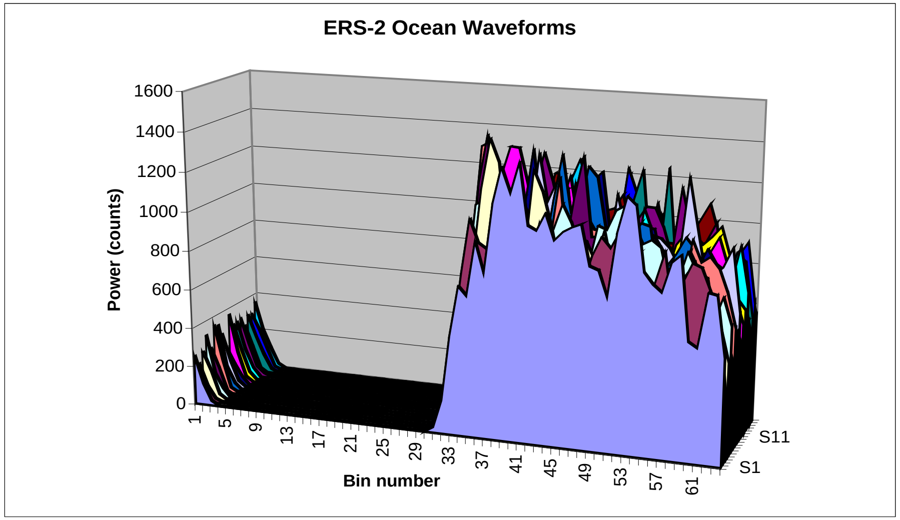




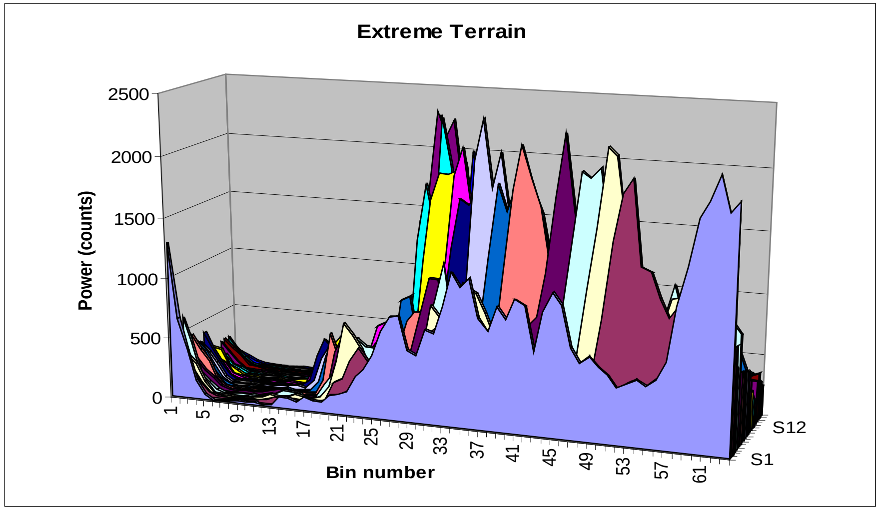
$$M(A,t_o,\sigma)=\frac{A}{2}\{1+erf(\eta)\};\qquad \eta=\frac{t_o}{\sqrt{2}\sigma}$$

Typical Echoes

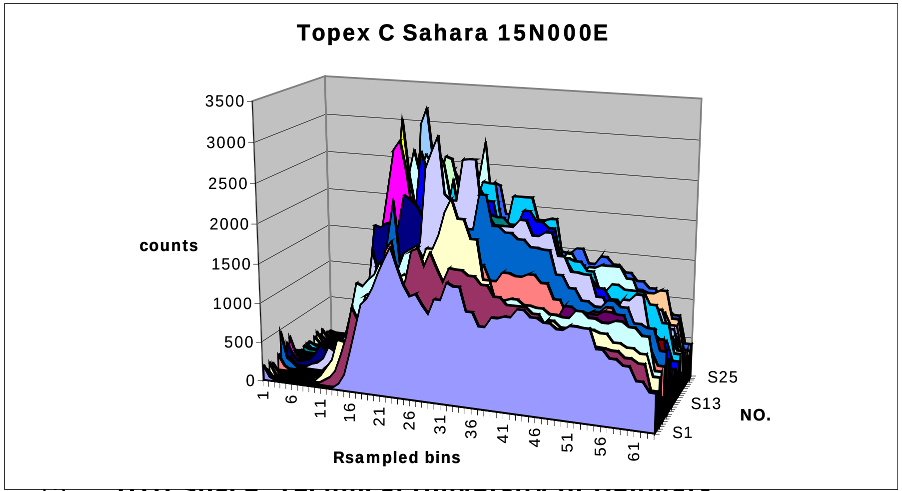
Ocean Echoes



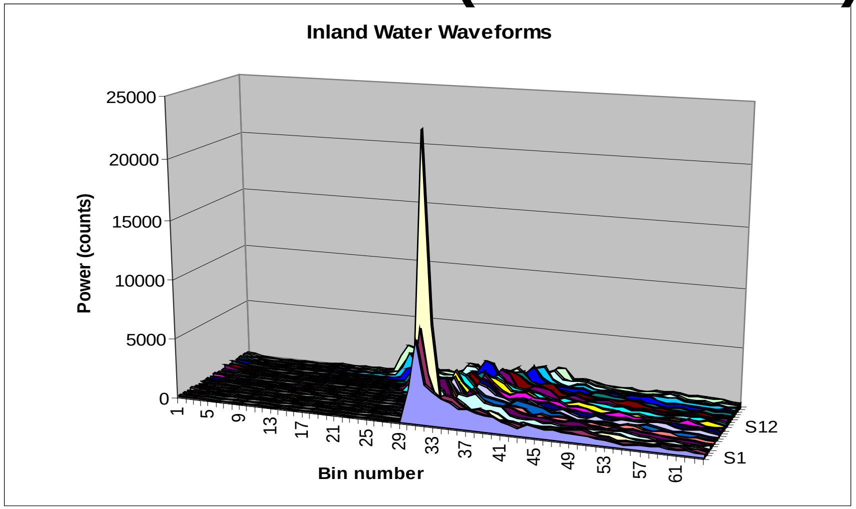
Extreme Terrain



Desert – Australia



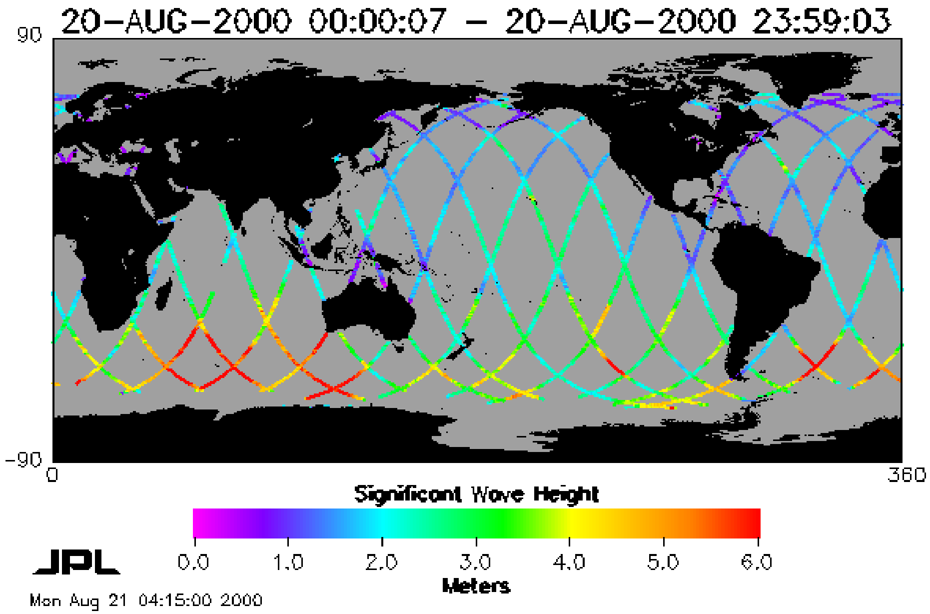
Inland Water (River – lake)



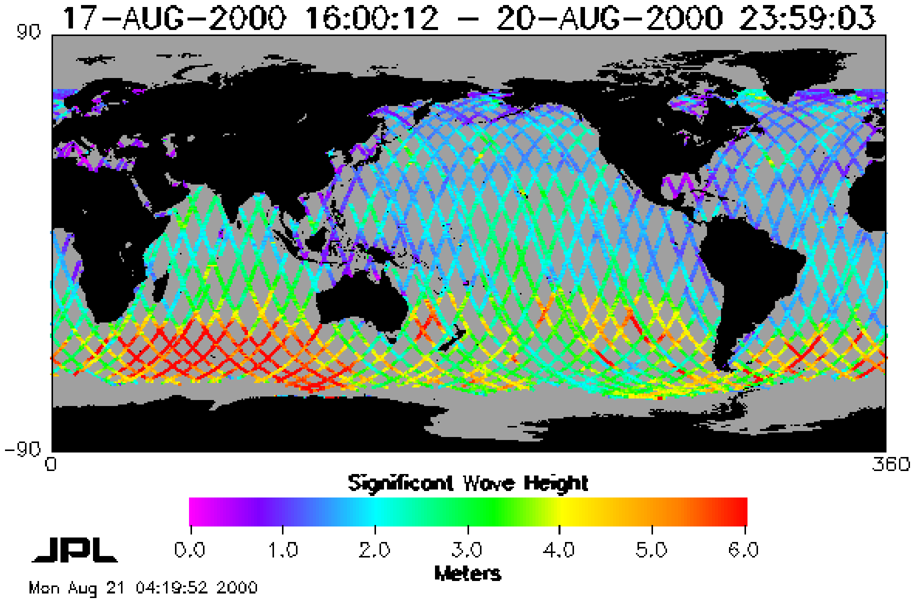
R, P. Berry, J. Freeman

When launching a satellite.

You Choose an orbit



1 Day

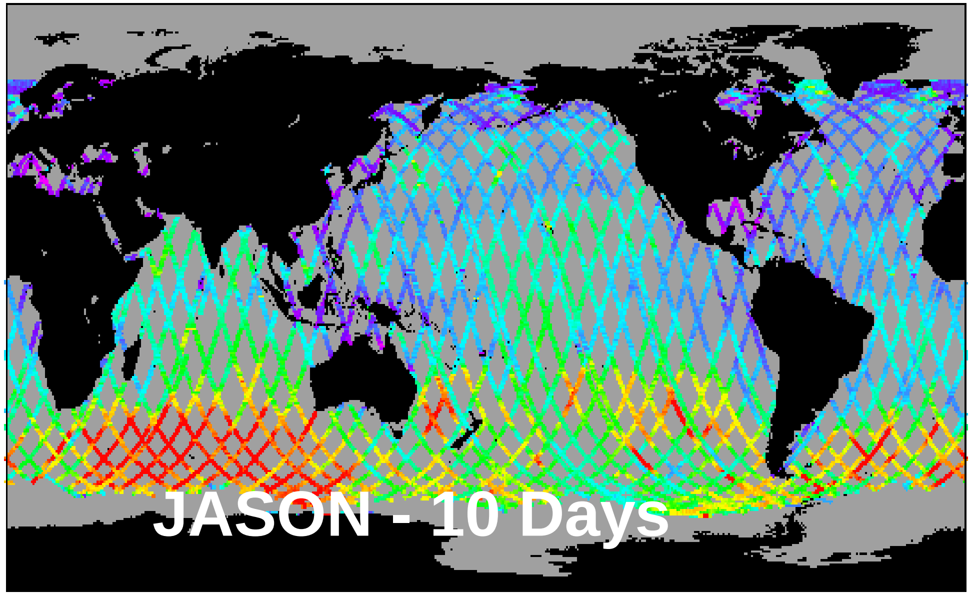


3 Days

Crossing of tracks essential for accuracy

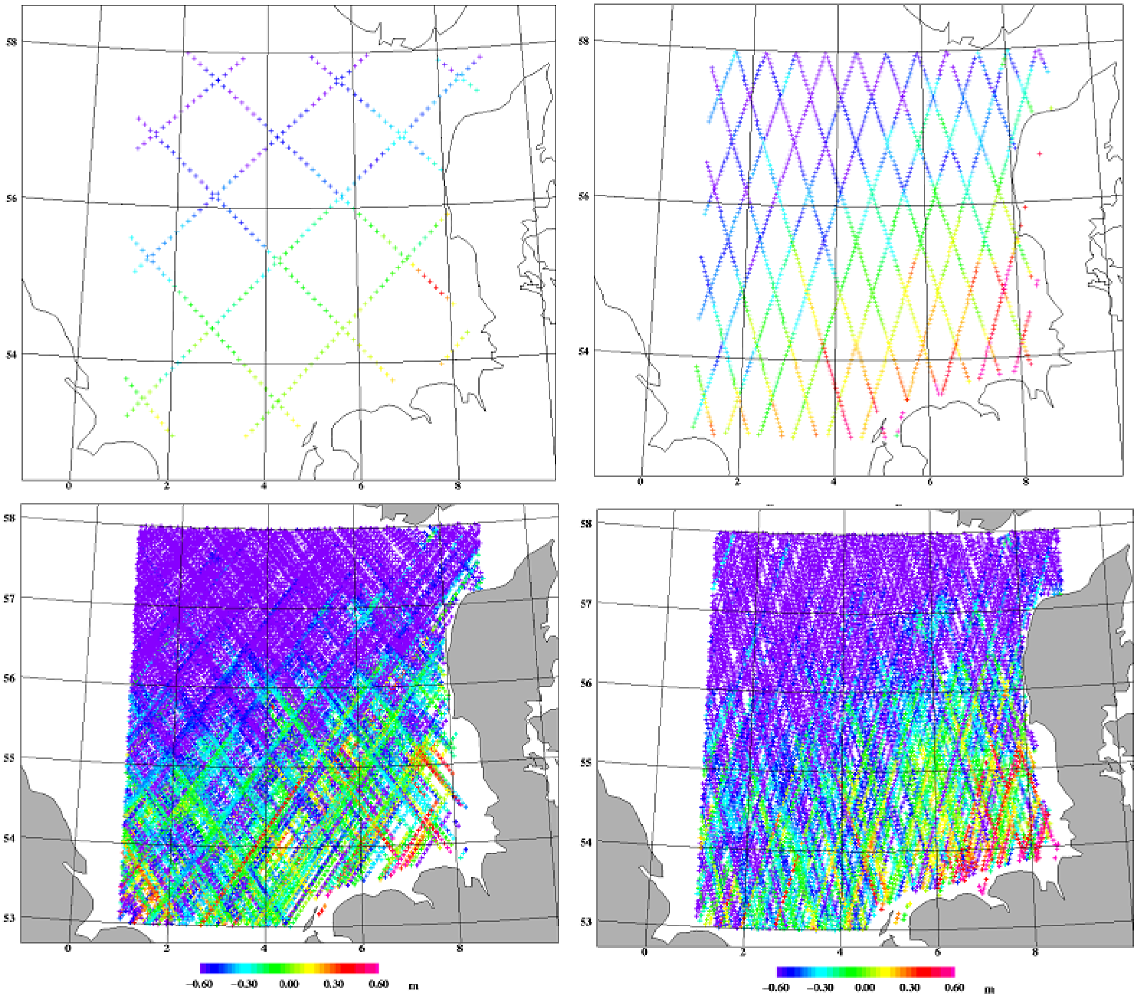
Orbit Parameters

The coverage of the sea surface depends on the orbit parameters (inclination of the orbit plane and repeat period).



	Satellite	Repeat Period	Track spacing	Inclination Coverage
Repeating (ERM)	ENVISAT/Sentinel-3	30 days	95 km	98° (+/- 82°)
	JASON 1-2-3	10 days	315 km	66.5°
Geodetic	Cryosat-2	369 days	7 km	88°

ERM – GM data.



ERM Data

TOPEX/JASON –

(280 km)

ERS/ENVISAT

(80 km)

Geodetic Missions

ERS/GEOSAT or Cryosat

(5 km track spacing)

GEOSAT+ERS GM data is ESSENTIAL for high resolution Gravity Field mapping.

Getting Gravity from Sea surface height (SSH).

Gravity does not change with time.....

So SSH must agree when tracks crosses…… Crossover adjustment

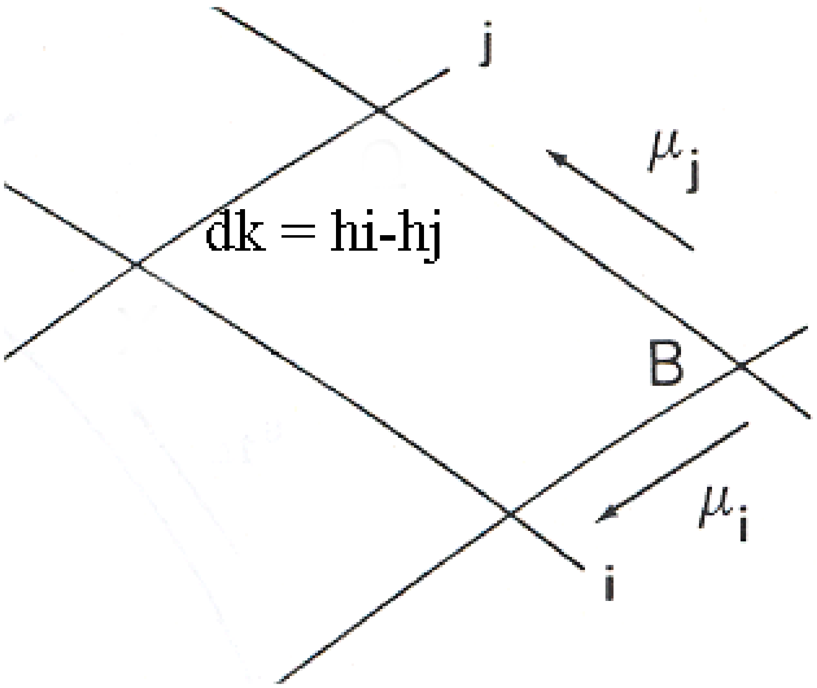
- $\underline{d_k = h_i - h_j}$
- $\underline{d} = A\underline{x} + v$
- where $\underline{x}$ is vector containing the unknown parameters for the

  track-related errors.

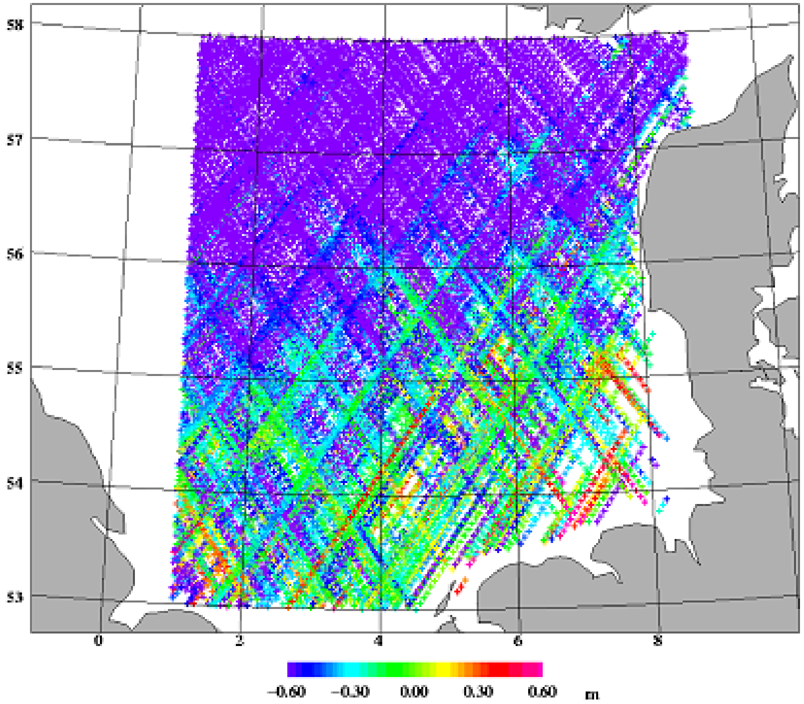
  v is residuals that we wish to minimize
- Least Squares Solution to this is

$$\underline{x} = (A^T C_d^{-1} A + cc^T)^{-1} A^T C_c^{-1} \underline{d}$$

- Constraint is needed $\mathbf{c}^T \underline{x} = 0$
- Case of bias – mean bias is zero



Before


58
57
56
55
54
53
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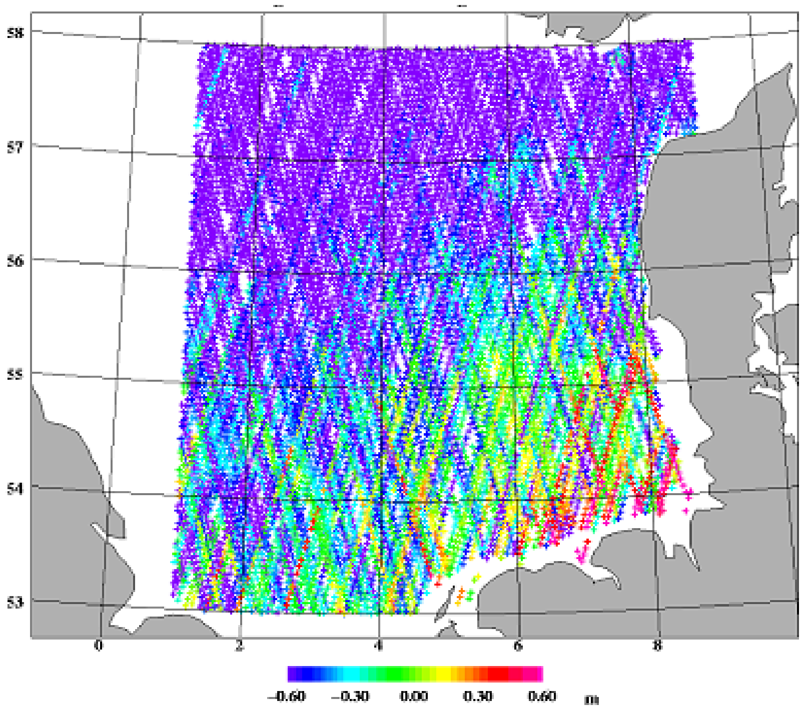
2
4
6
8
-0.60 -0.30 0.00 0.30 0.60 m


58
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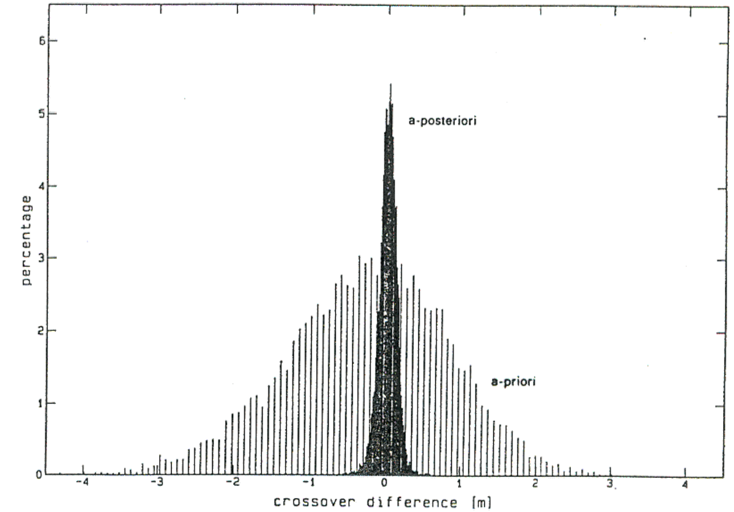
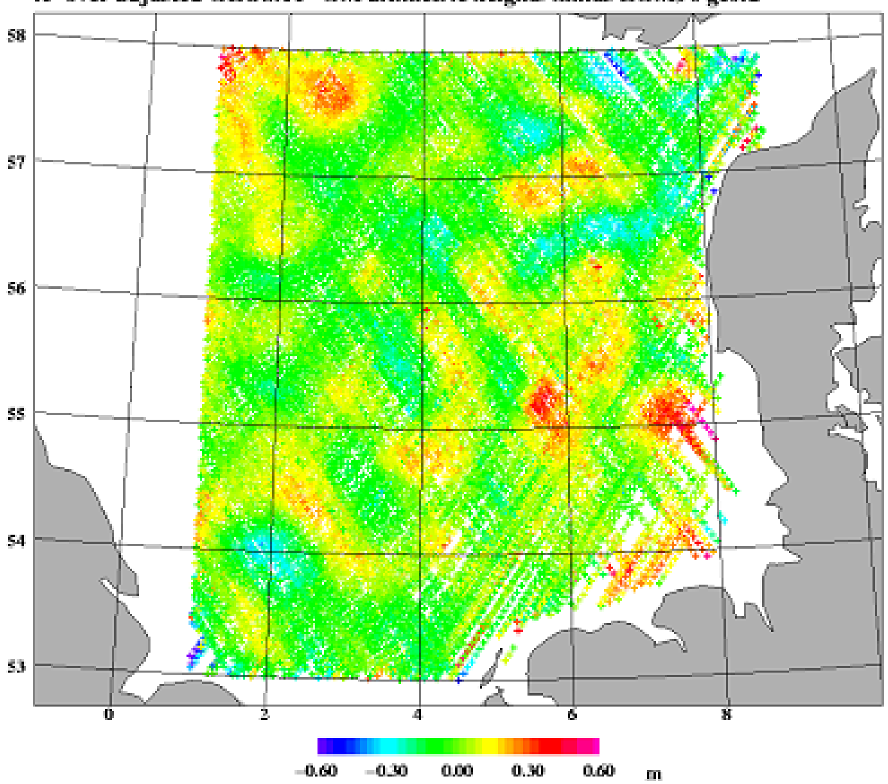
2
4
6
8
-0.60 -0.30 0.00 0.30 0.60 m

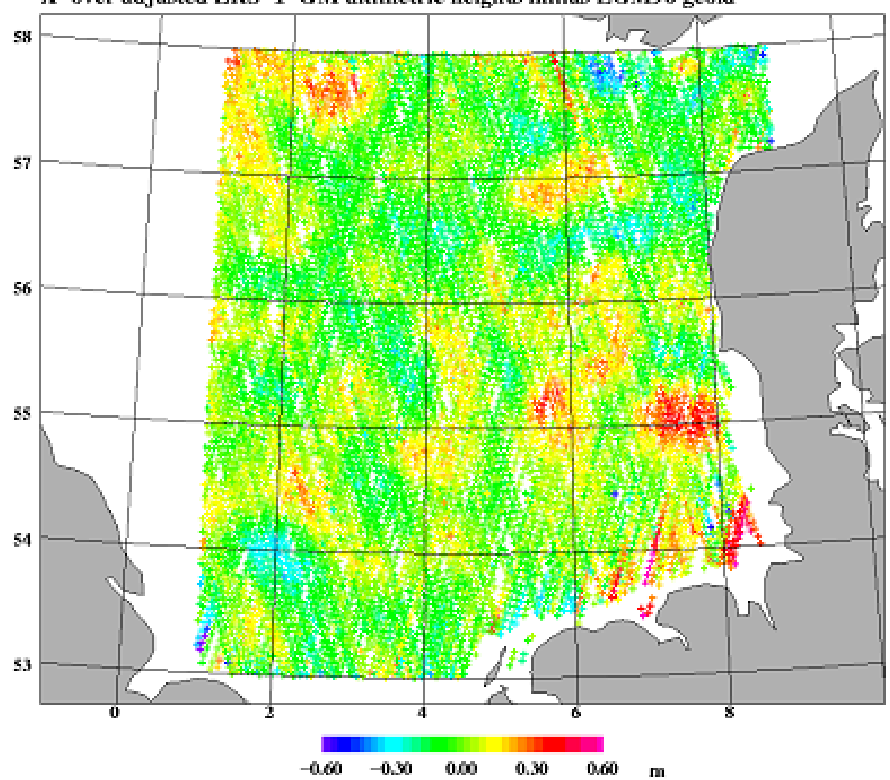
After Crossover



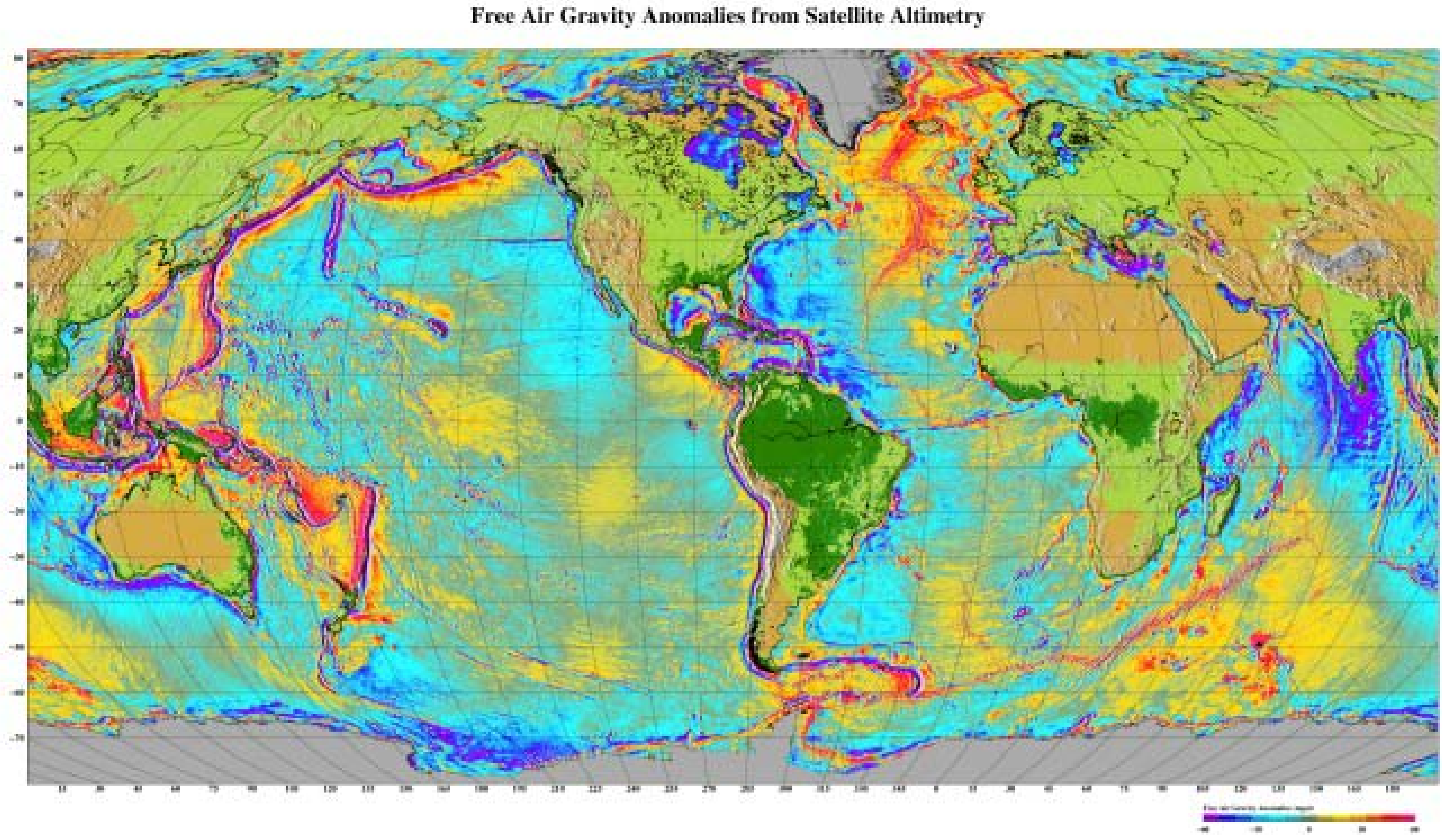
X−over adjusted GEOSAT−GM altimetric heights minus EGM96 geoid

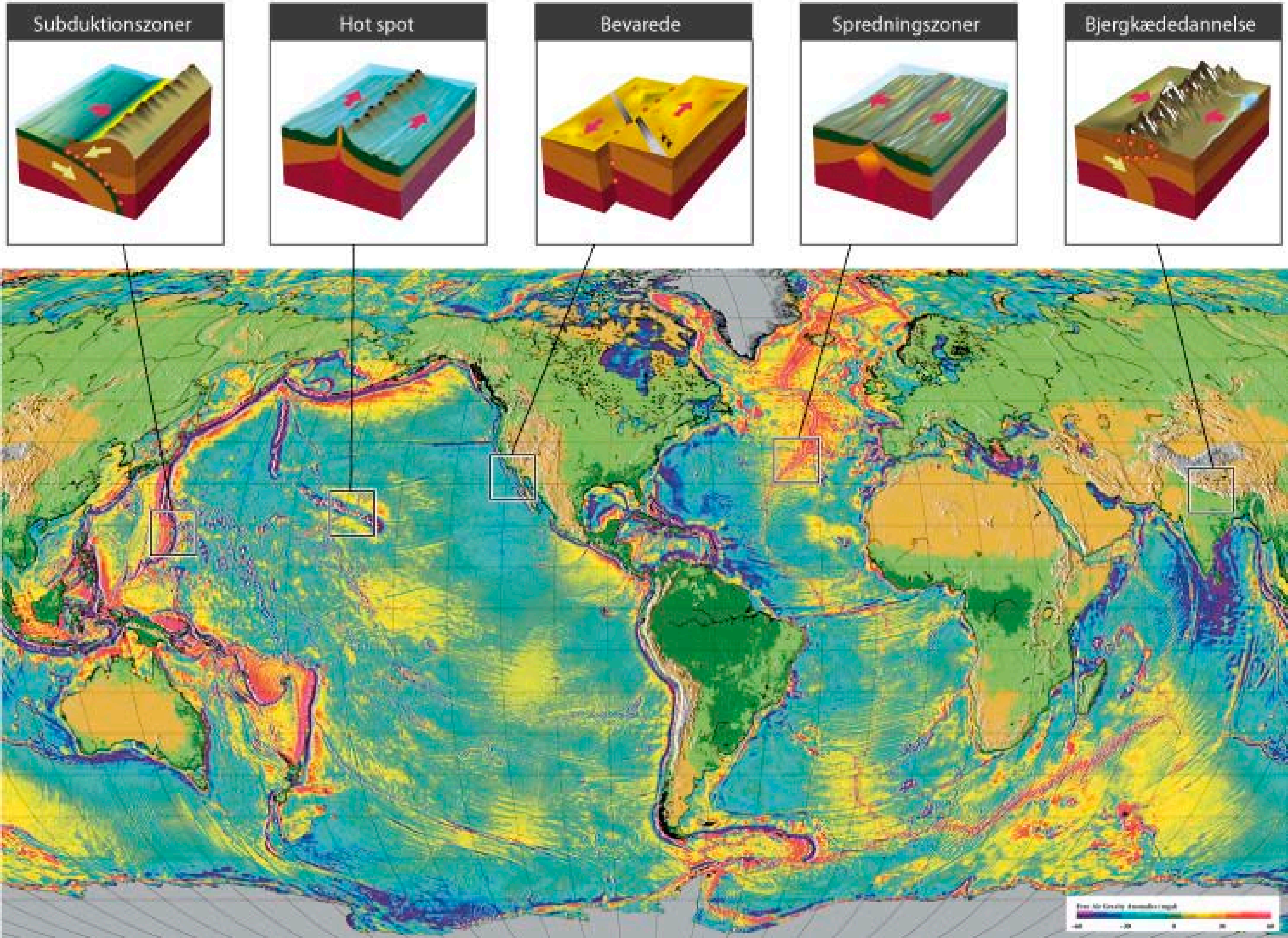


X−over adjusted ERS−1−GM altimetric heights minus EGM96 geoid

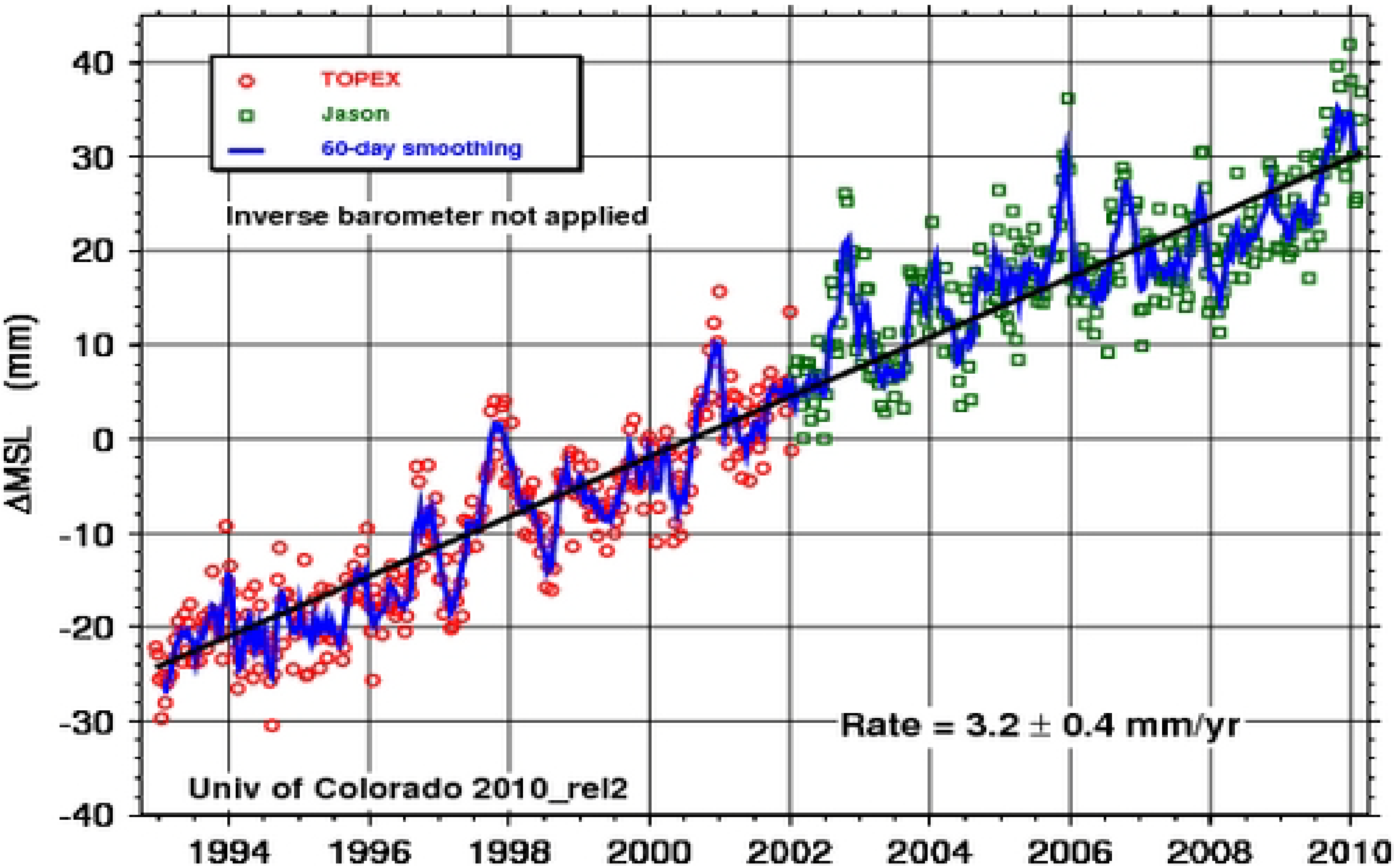


DTU10 1 min global marine gravity grid.




Subduktionszoner
Hot spot
Bevarede
Spredningszoner
Bjergkædedannelse

But you can use altimetry for many purposes



Satellite Altimetry.
Summary - Limitations / Possibilities

- Altimetry opserves the surface of the ocean (geodesy and oceanography)

- Satellites altimetry observes repeatedly under all weather conditions

- Satellite altimetry measures the ”gravity related quantity at the sea surface”
- This is very close to the sources – so you get very high spatial resolution.....

- Altimetry maps wavelength between 20 an 100 km of the gravity field.
- -> How do we get the longer wavelength parts of the gravity field....

- Satellite altimetry observes along predefined ground tracks at predefined intervals. Orbital issues are important to consider. No observations ”at will”.

- There will be polar Gap around the North Pole with no coverage

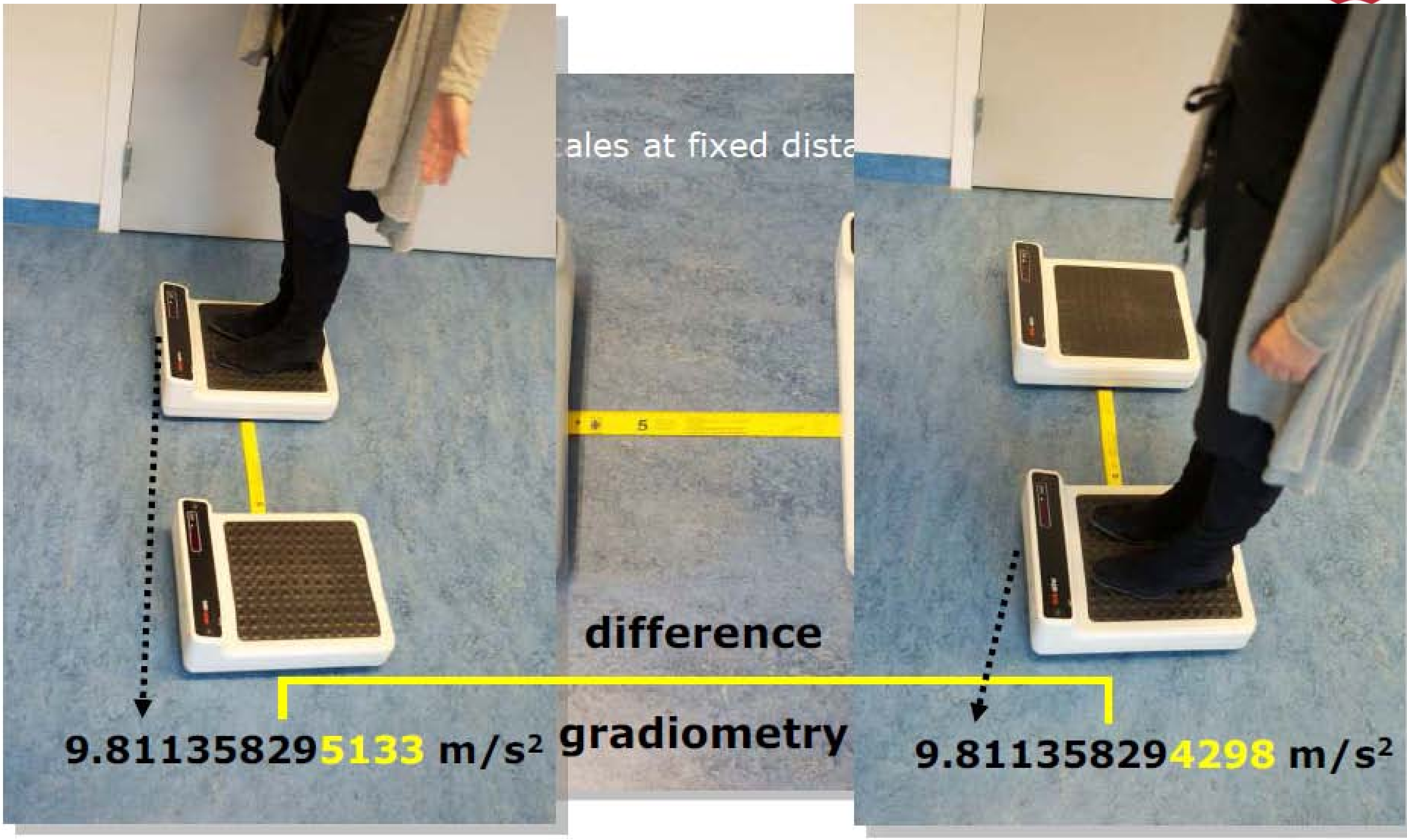
Lets go for the longer wavelength >200 km.

- Now its adequate to measure in space, but height of satellite
- Determine which wavelength can be measured.

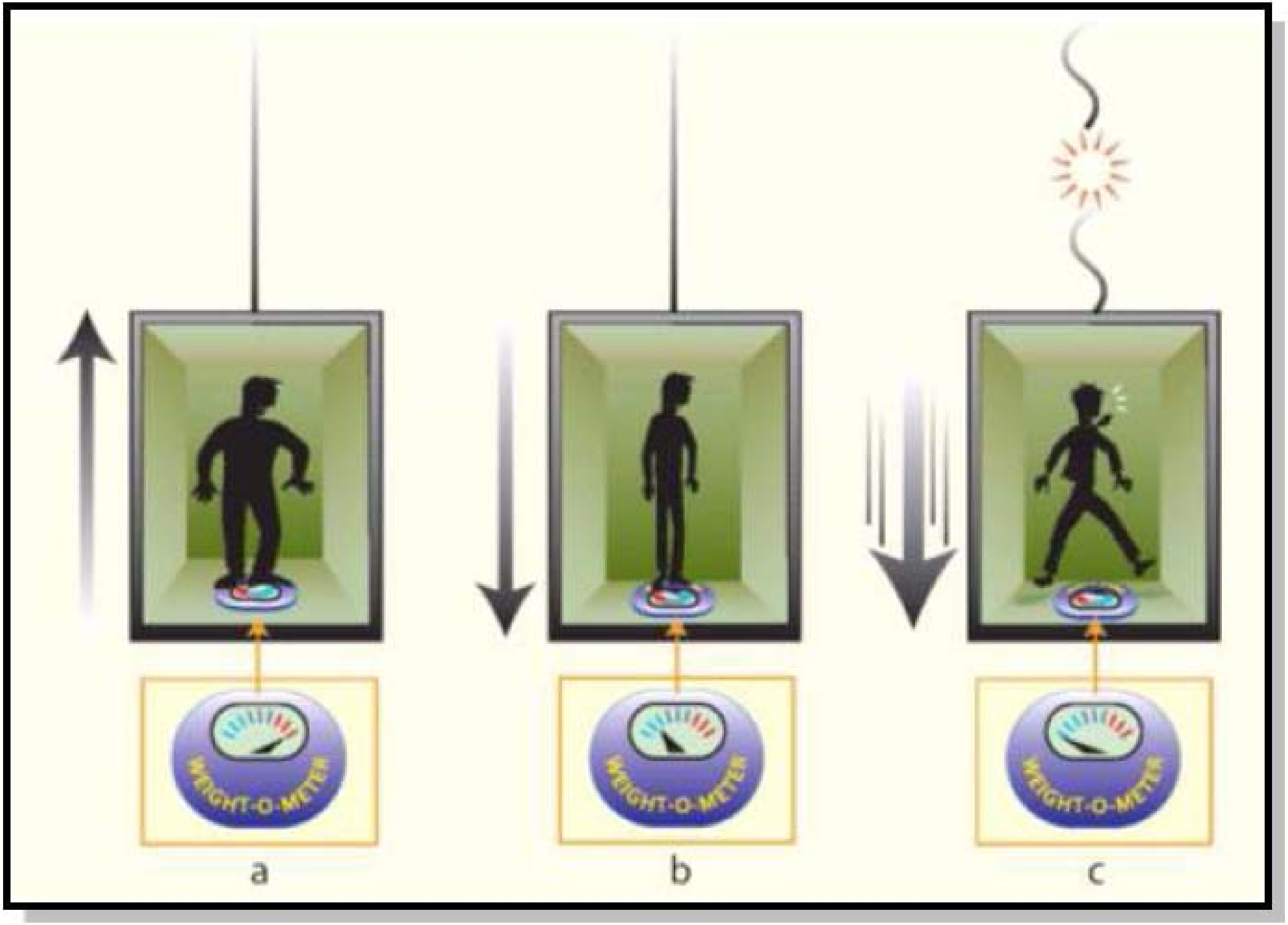
- Rule of thumb. Resolution equals height

Satellite Gravimetry

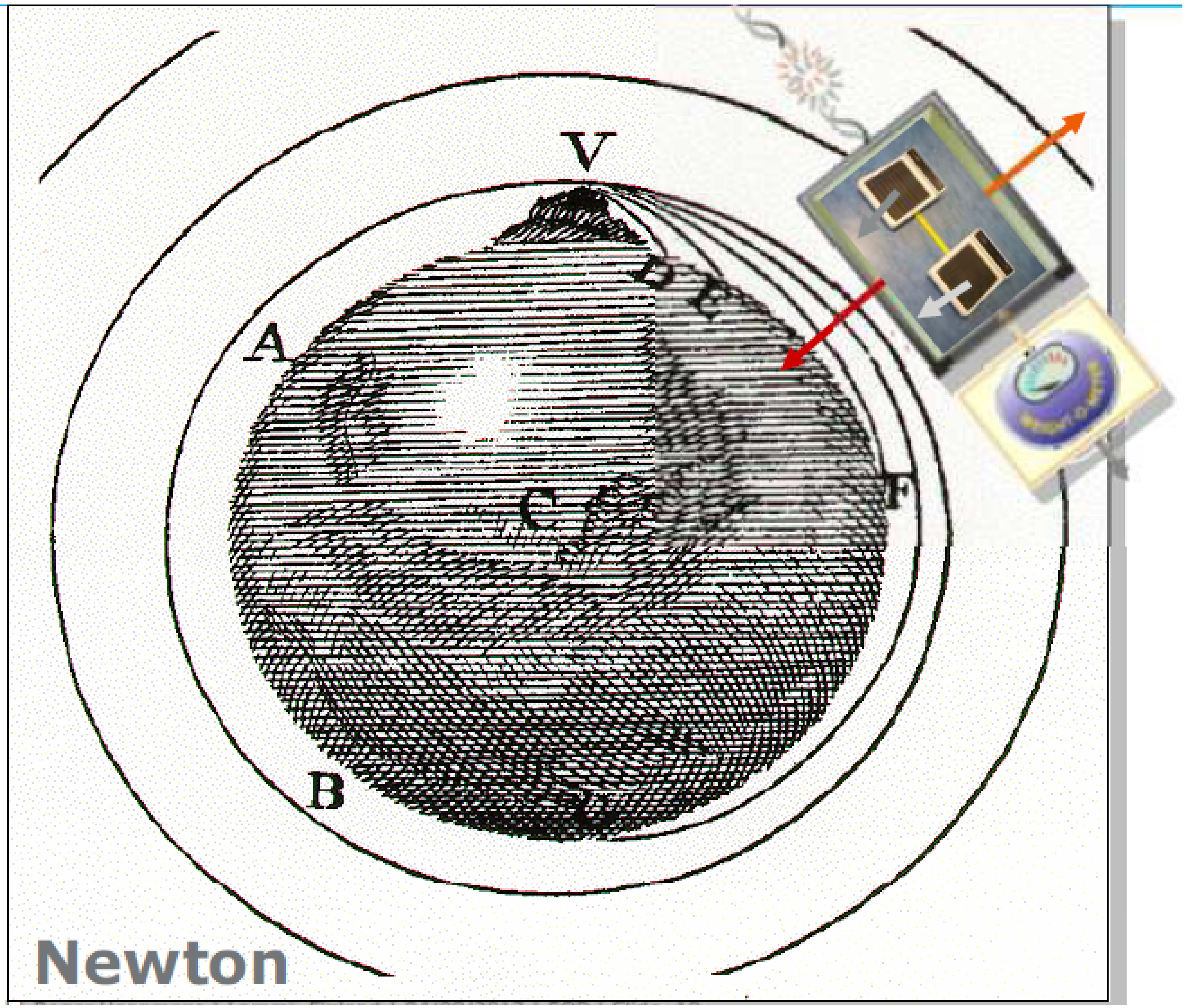
GRACE AND GOCE


ales at fixed dista
5
difference
9.811358295133 m/s²
gradiometry
9.811358294298 m/s²

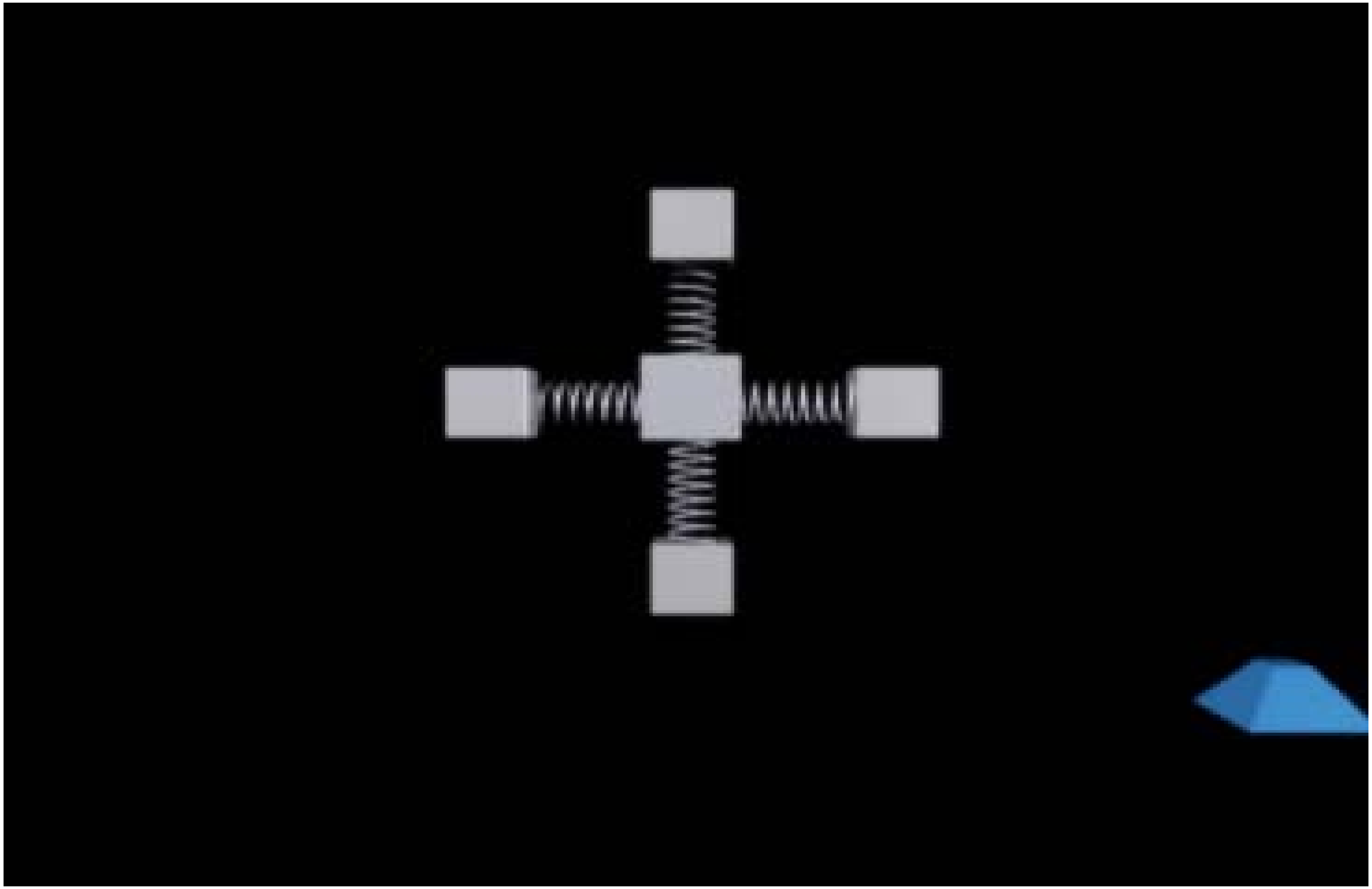
Scales in motion........



Gravity and satellite orbits
GOCE is launched in 250 km orbit…….



Gradiometry



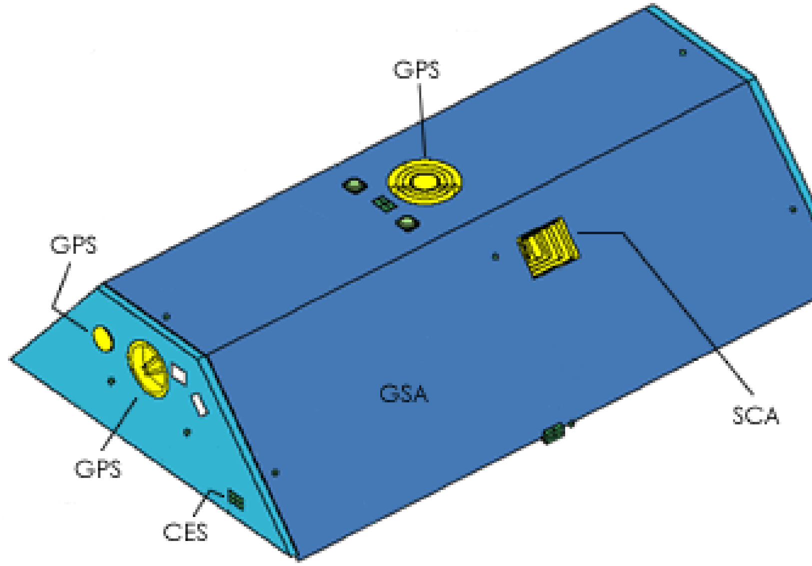
GRACE Formation Flying Satellites

KBR+USO Ranging (JPL/SSL/APL)

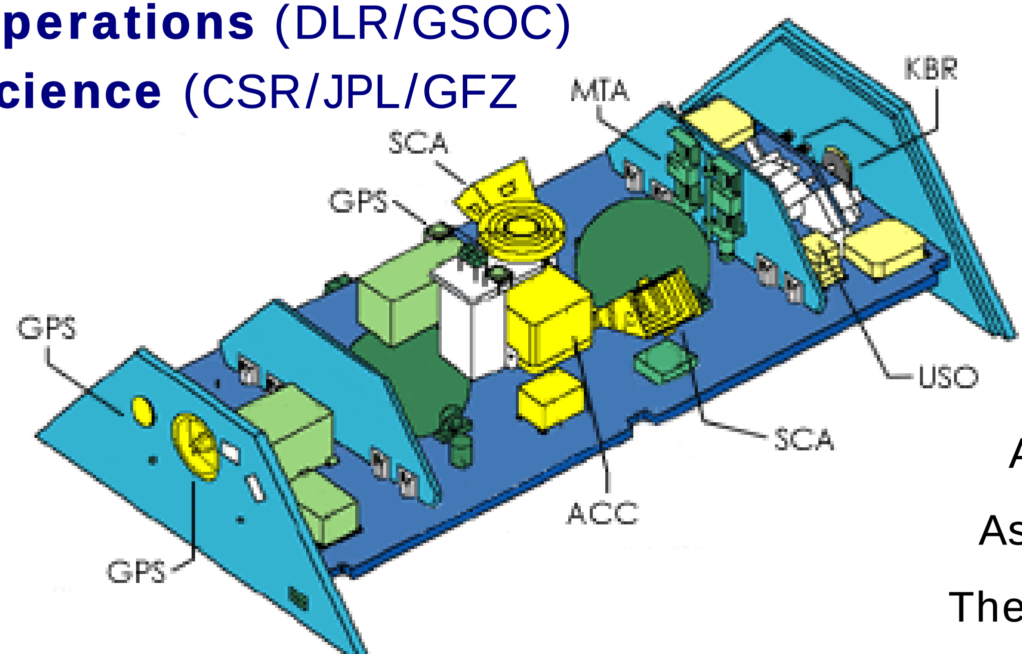
ACC SuperSTAR Accelerometer (ONERA)

SCA Star Cameras (DTU)

GPS Receiver (JPL)



- **Satellite** (JPL/Astrium)
- **Launcher** (DLR/Eurockot)
- **Operations** (DLR/GSOC)
- **Science** (CSR/JPL/GFZ



In essence.

The two satellites become the scale

And you use orbit pertubation

As measurements.

There aint no moving parts in satellite

Launch GRACE (look for DTU Starcameras)

- QT - LAUNCH

Orbit

Launched: March 17, 2002

Initial Altitude: 500 km

Current Altitude: 456 km (30 m/d)

Inclination: 89 deg

Eccentricity: ~0.001

Distance: ~220 km

Nominal Mission : 5 years

Non-Repeat Ground Track, Earth Pointed, 3-Axis Stable

2005 GRACE 1-2 Orbit Switch

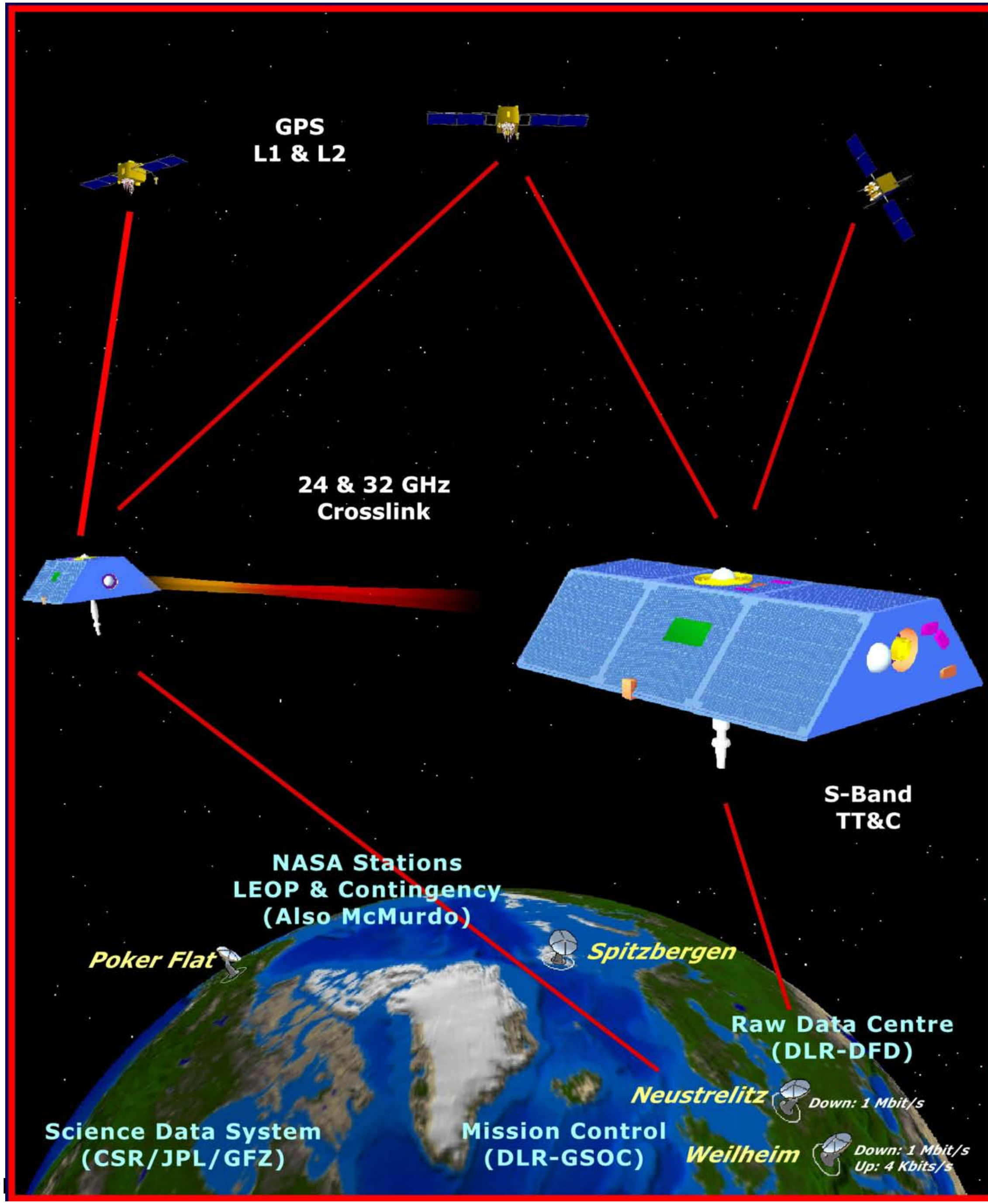
Mission Lifetime

5 Years

Extended to 9 Years

Future

GRACE-Follow On



GRACE over LAND (QTIME)

- QT - Land

GRACE measurement technique

The two satellites act like a very big scale because of ORBIT pertubation……

Orbit pertubation/ranging is measured by KBR ranging

Accuracy currently 2 Micrometer

1/100 thickness of a hair

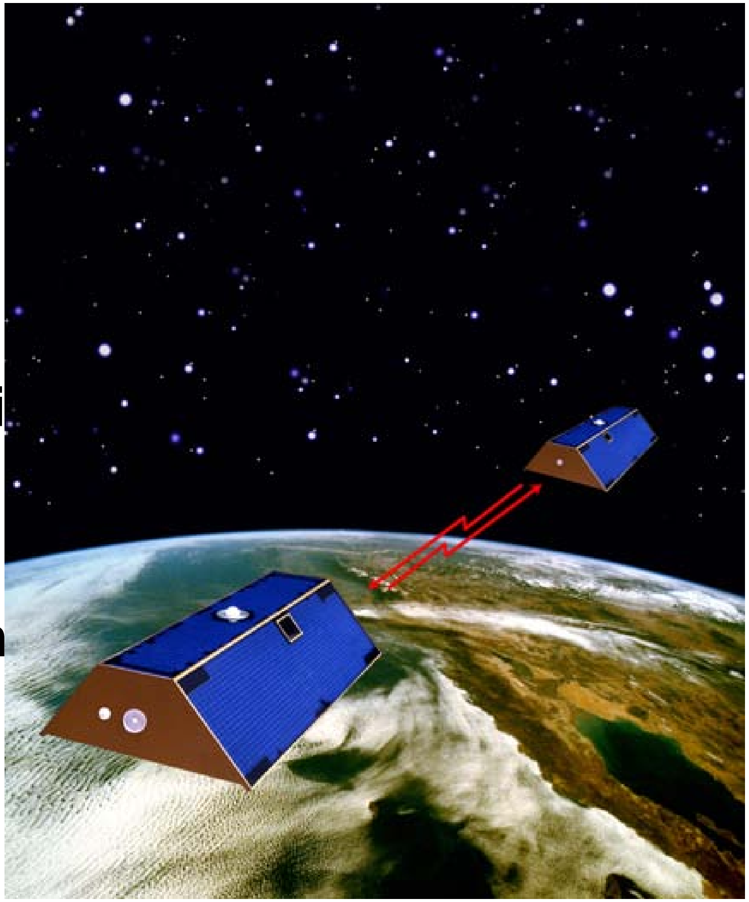
Better than diameter of blood cell

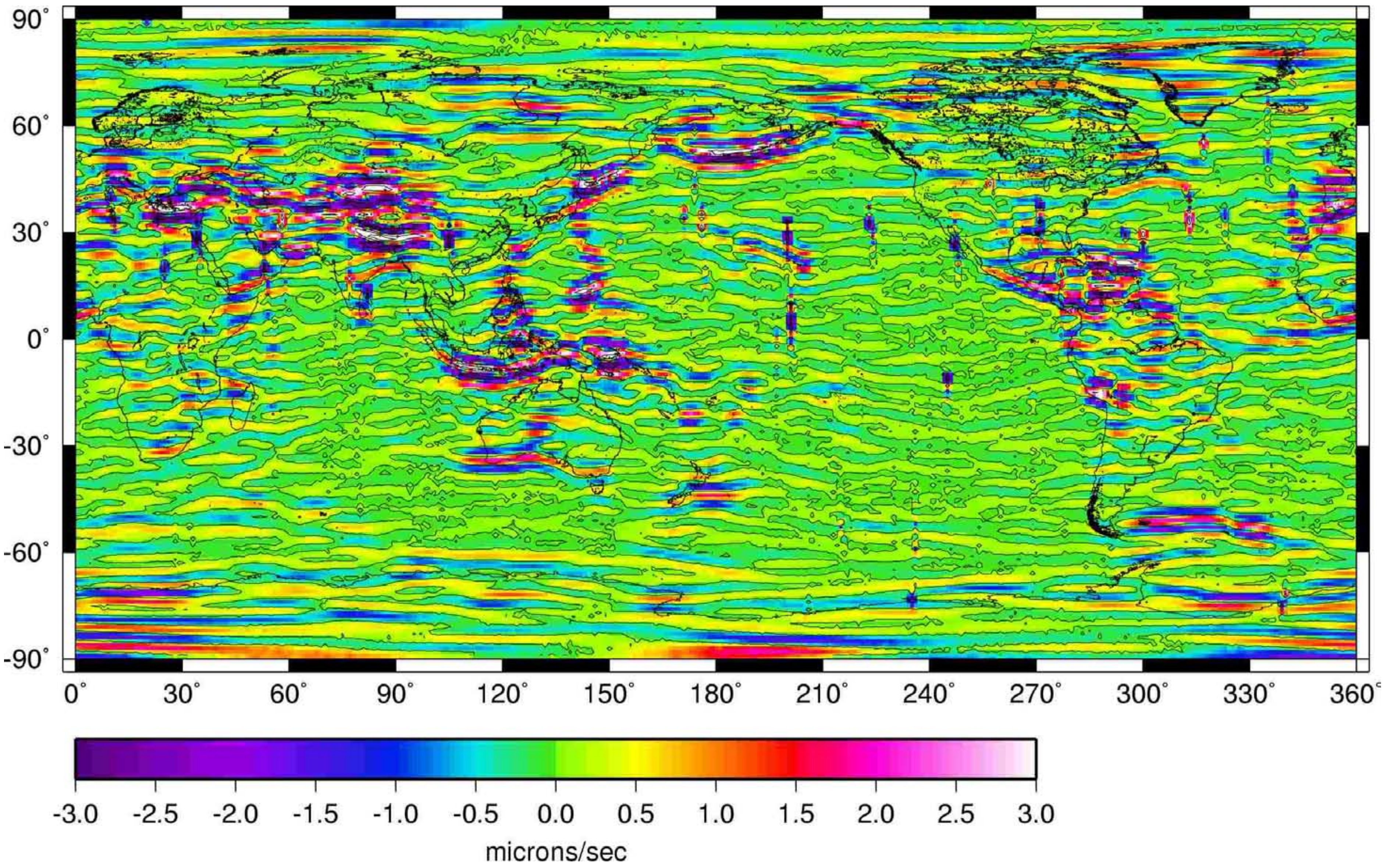
Delivers 10-Day / Monthly gravity fi

From 2002 Onwards

Study gravity field changes with tim

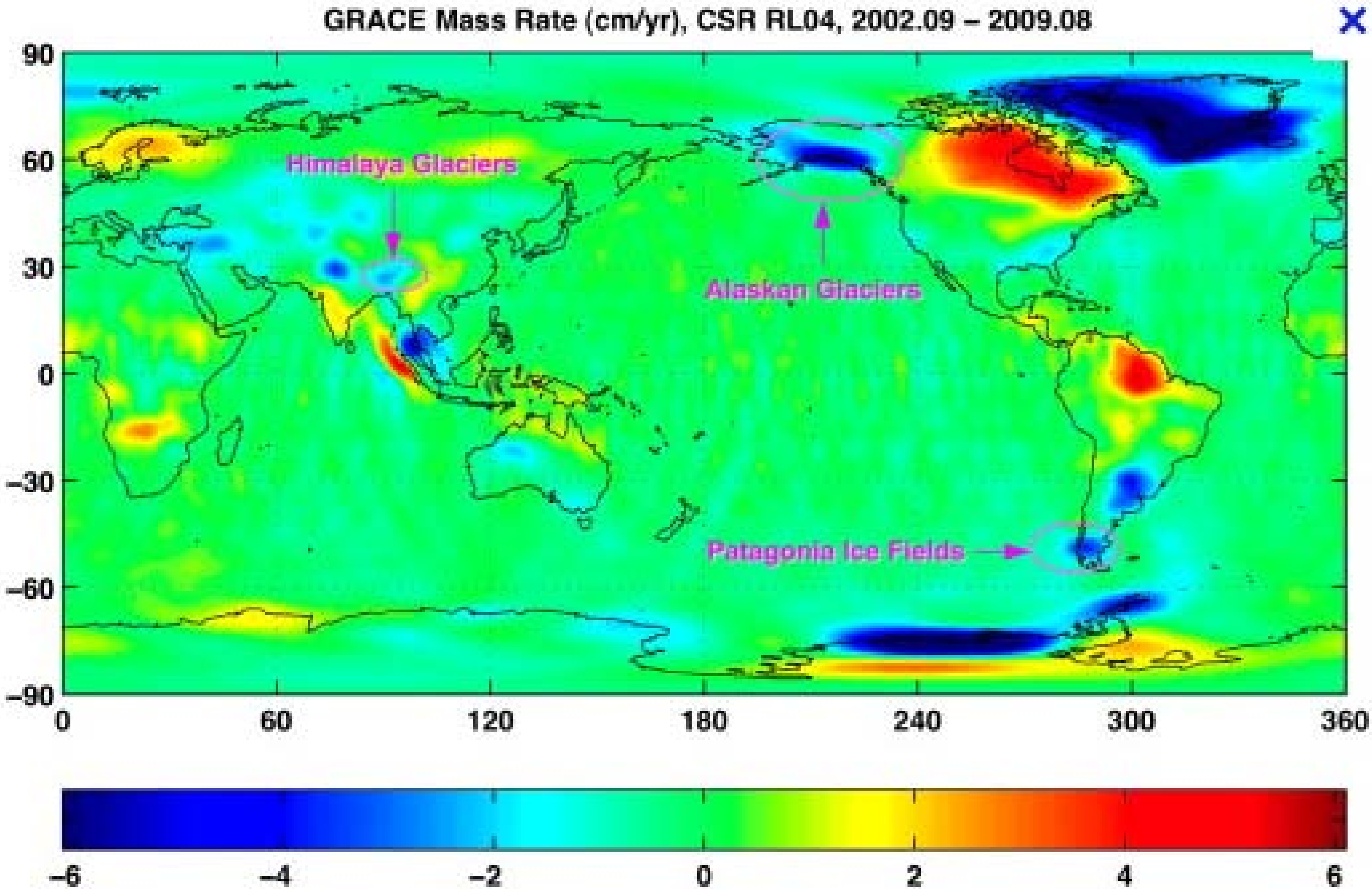
Limit in resolution 400 km

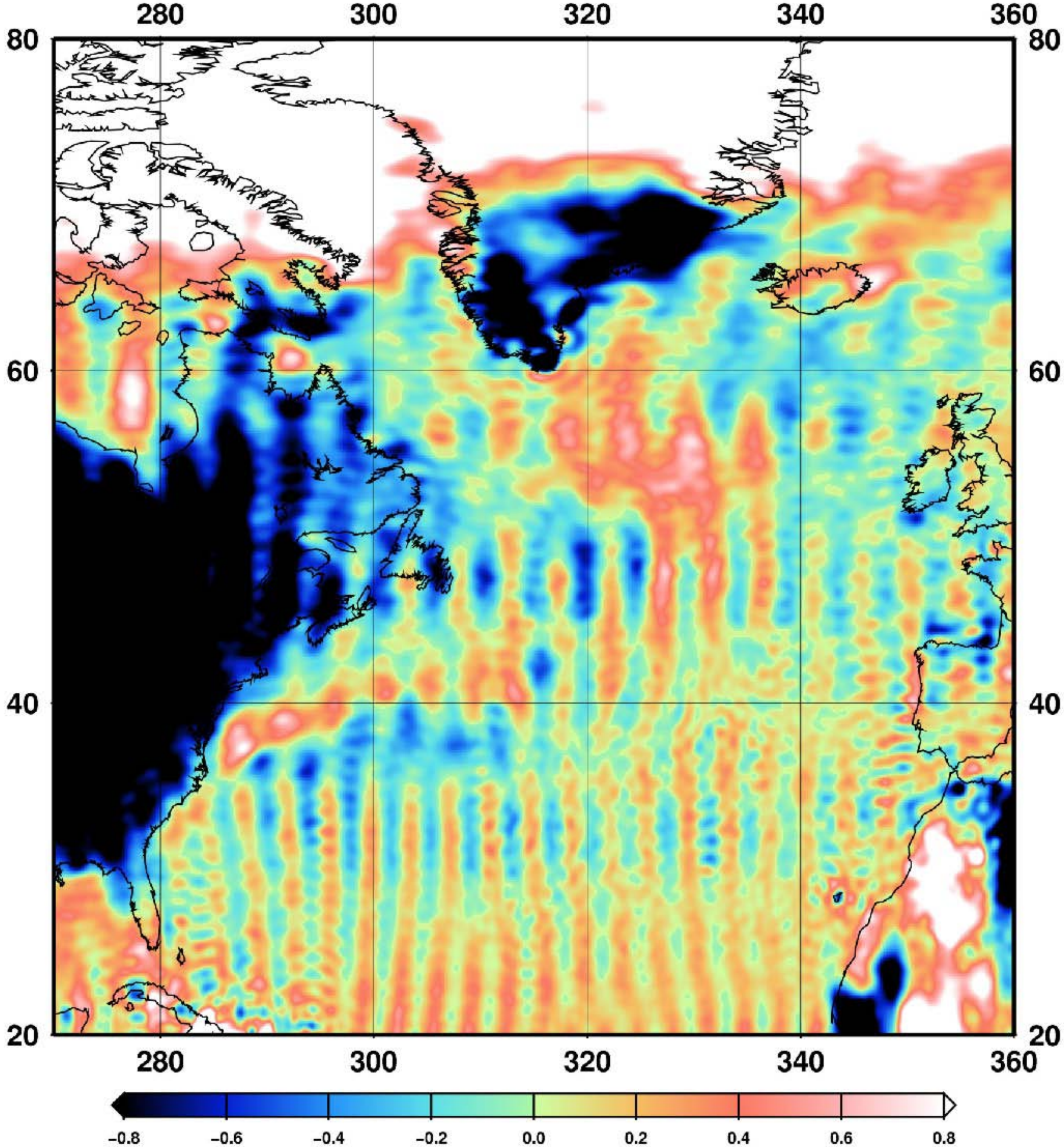




Grace can derive a gravity field every month...... > Does gravity change ?????

Whats fantastic about GRACE is that it can measure how gravity is changing because our planet is changing.





DTU

However GRACE

Has one big problem.

Because GRACE

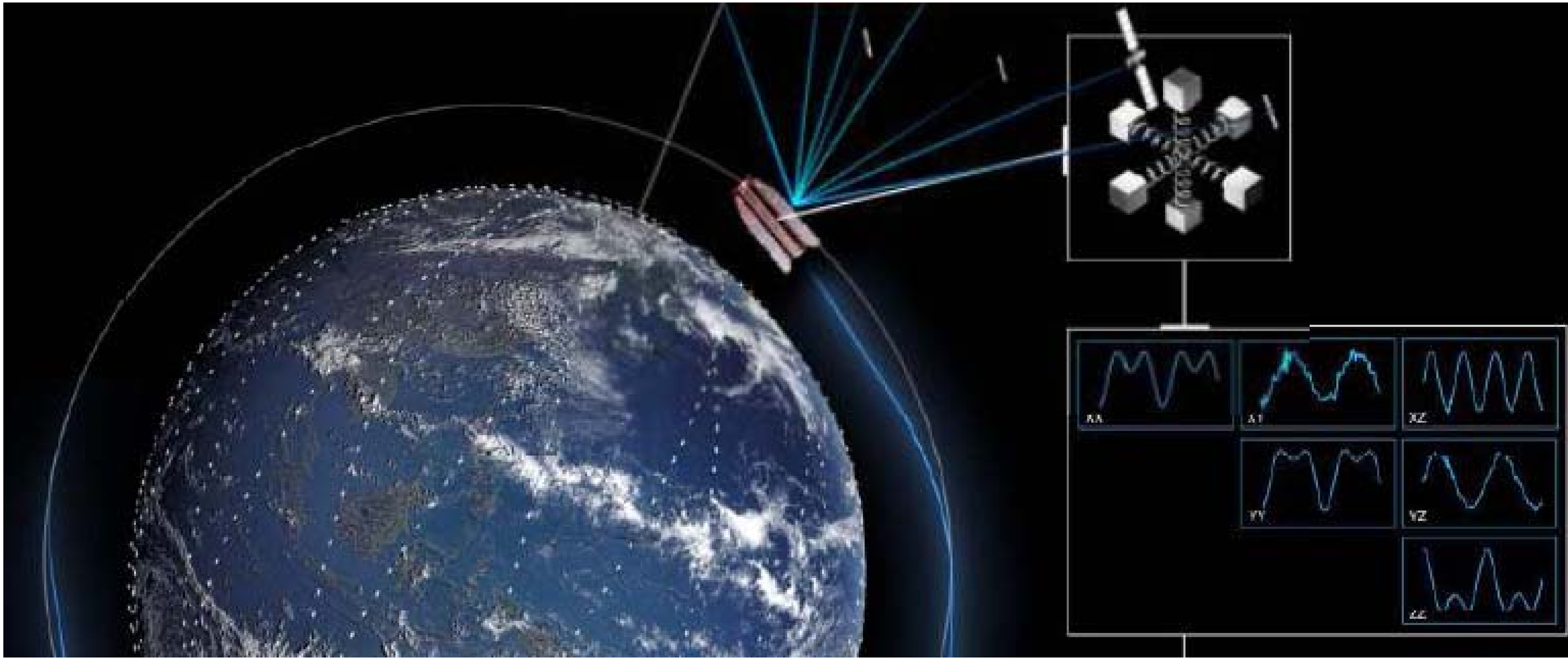
Flies north-south

It doesnt measure

East west accurately –

What do we do......

ESA Launch GOCE in 2010



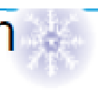
Measure gravity / accelerations -> no moving parts

Extreme stability->fabulous engeneering achievement

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

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

Get a feeling for what GOCE can do…….

0.2 gram 

Super-tanker acceleration
due to attracting snowflake:

$0.000000000002\ m/s^2$

smallest acceleration measurable
in space by GOCE

1 000 000 metric tonnes

GPS positioning of GOCE in orbit

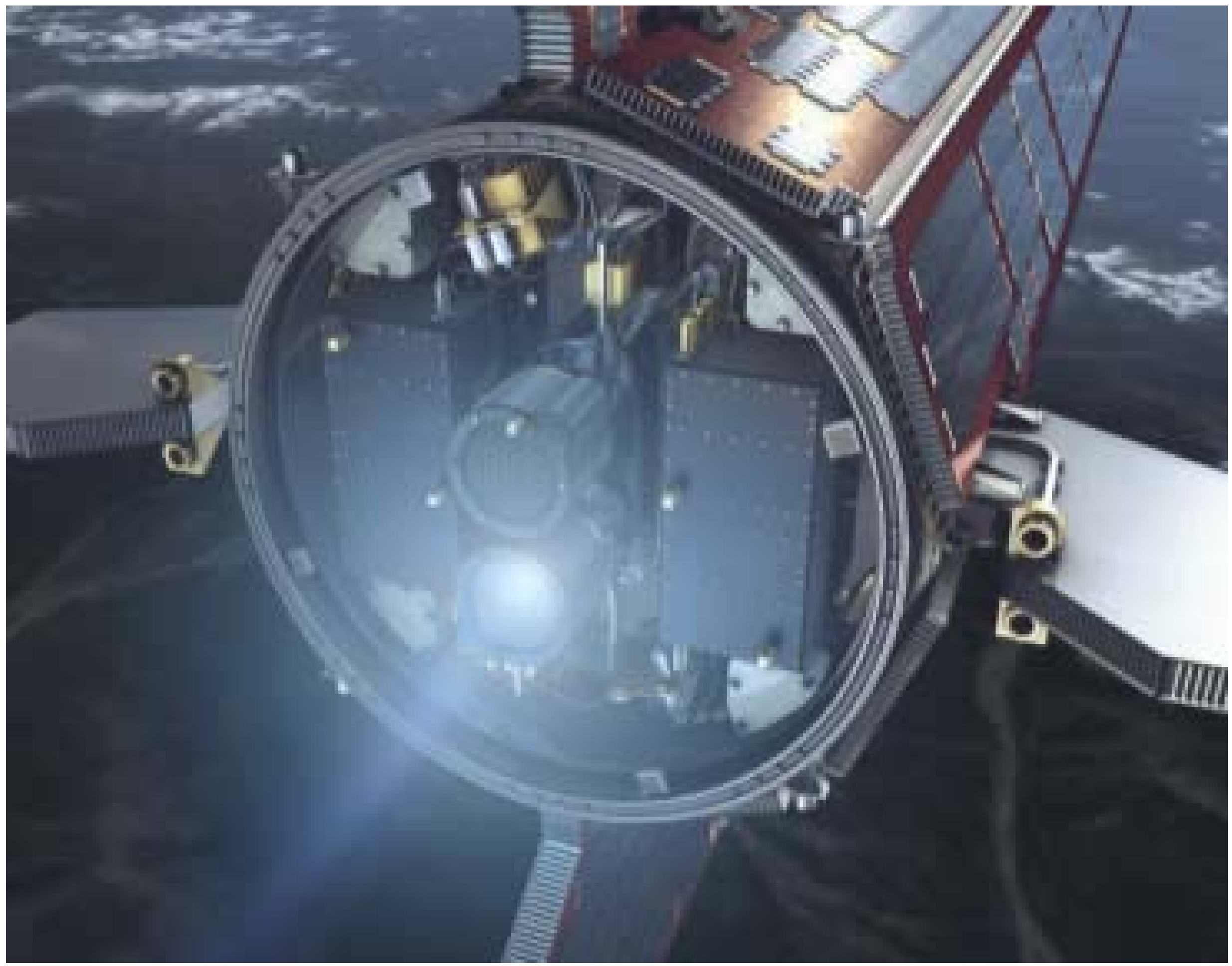
Sun-synchronous, 61 day repeat orbit at 256 km altitude

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

Gradiometer needs 'quiet environment'

Flying low –>Atmosphere disturbes the Free Fall

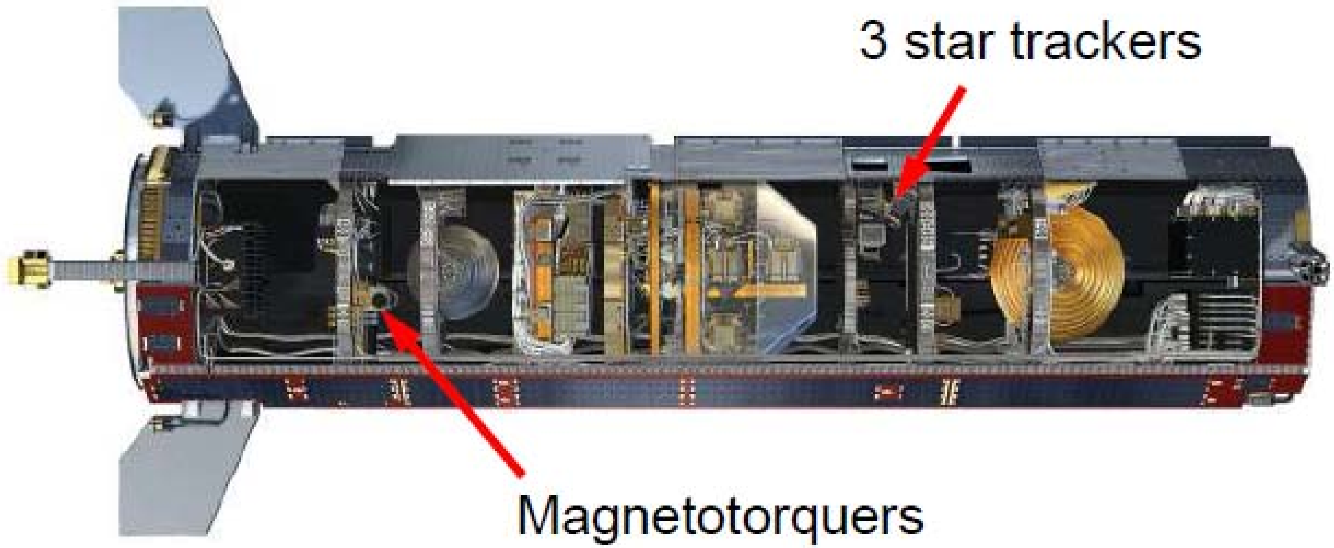
Counteracting the atmospheric drag…..



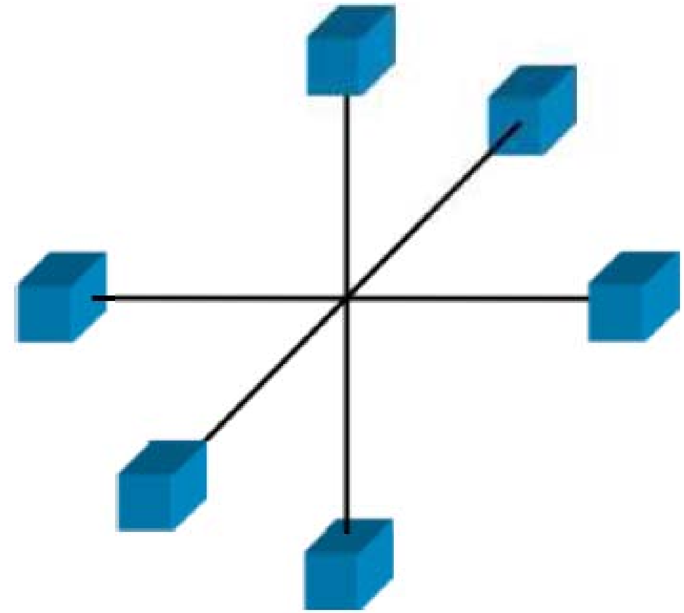
Navigating GOCE - DTU startrack/camera

Attitude

- Attitude control by magnetotorquers
  - Sun- and nadir-pointing
  - No control about yaw axis at magnetic poles and roll axis at magnetic equator
- Attitude measured by three star trackers
  - Capture also angular rates and angular accelerations

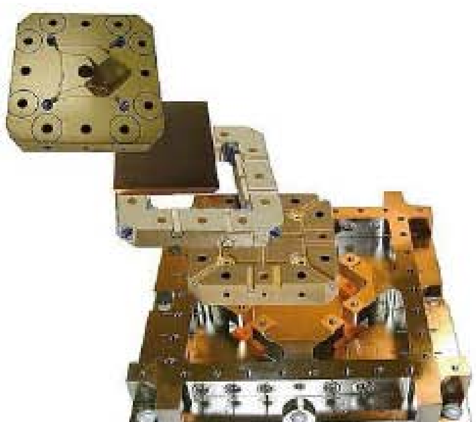


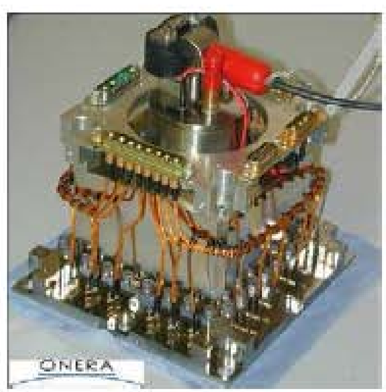
GOCE Gradiometer

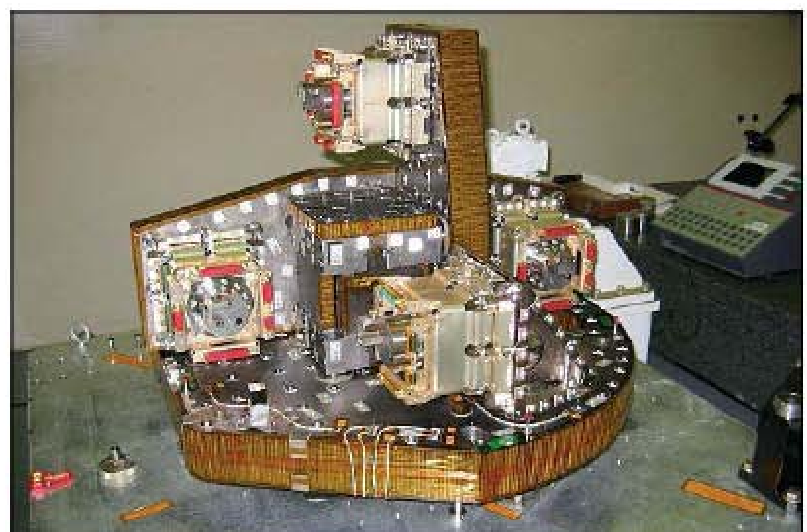


Gradiometer = 6 Accelerometers

- 100 times more sensitive than any accelerometer previously flown
- Proof-mass is kept levitated at the center of a slightly larger cage by applying control-voltages to electrodes on the inner walls of the cage
- Control-voltages are representative for accelerations experienced by accelerometer
- Dimensions of proof-mass = 4 x 4 x 1 cm
- 2 ultra-sensitive axes + 1 less sensitive axis







GOCE accelerometer measurements

$$a = -[V]\cdot r + (\omega \times (\omega \times r)) - (\dot{\omega} \times r) + (2\omega \times \dot{r}) + \ddot{r} + d - s \ldots m$$

gradient | centrifugal acceleration | angular acceleration | Coriolis | cage | drag | self gravity | magnetic coupling

Forming common and differential accelerations:

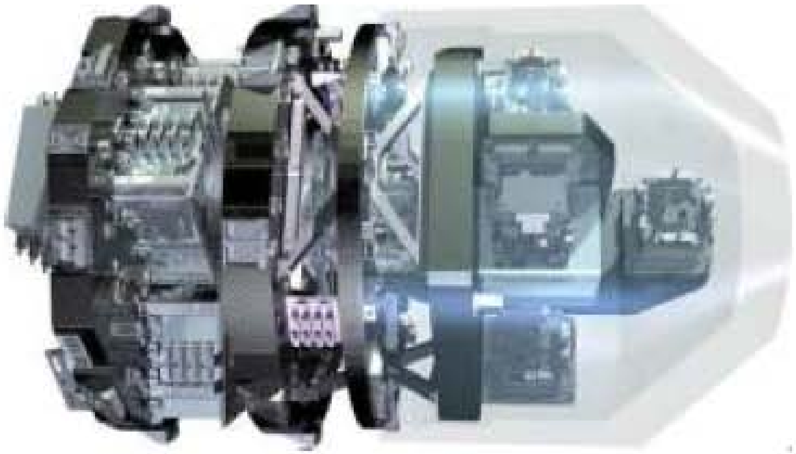
- Common relates to drag and winds
- Differential relates to gravity gradients rotating around the Earth

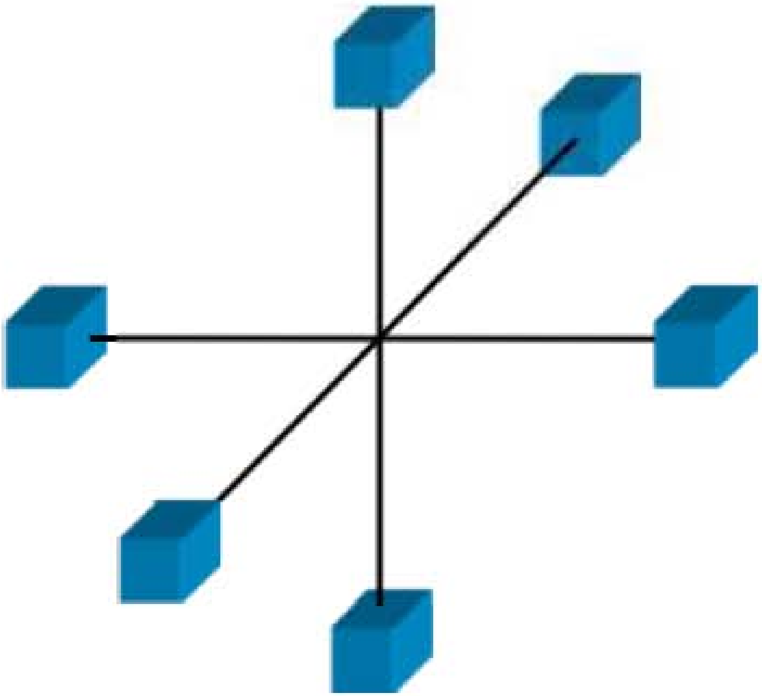
-> use information from star trackers

Gravity gradiometry

Gradiometer = 6 Accelerometers, each accelerometer measures

$$a_i = -(V - \Omega^2 - \dot{\Omega})r_i + d$$



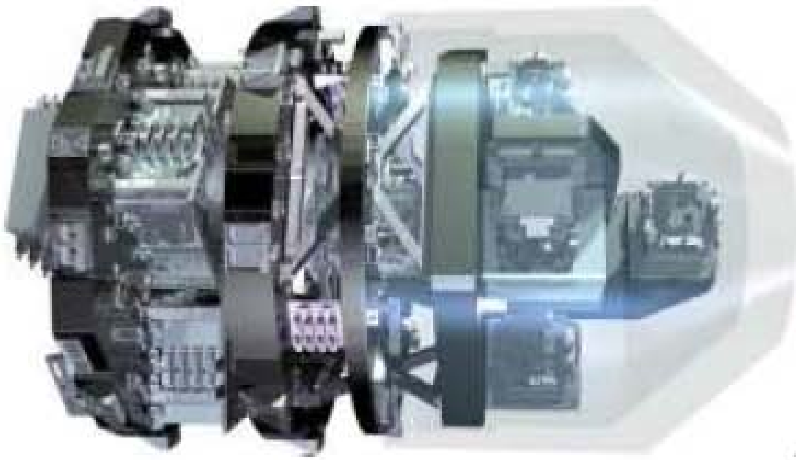


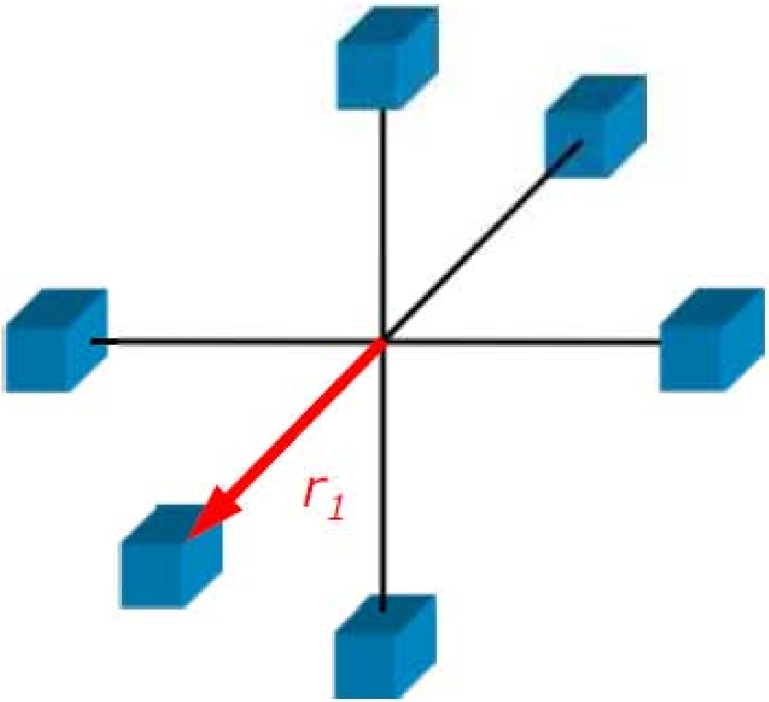
Gravity gradiometry

Gradiometer = 6 Accelerometers, each accelerometer measures

$$a_i = -(V - \Omega^2 - \dot{\Omega})r_i + d$$

position of accelerometer



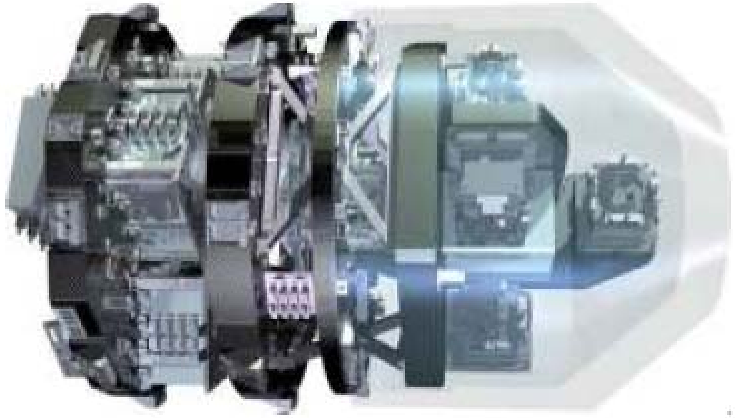


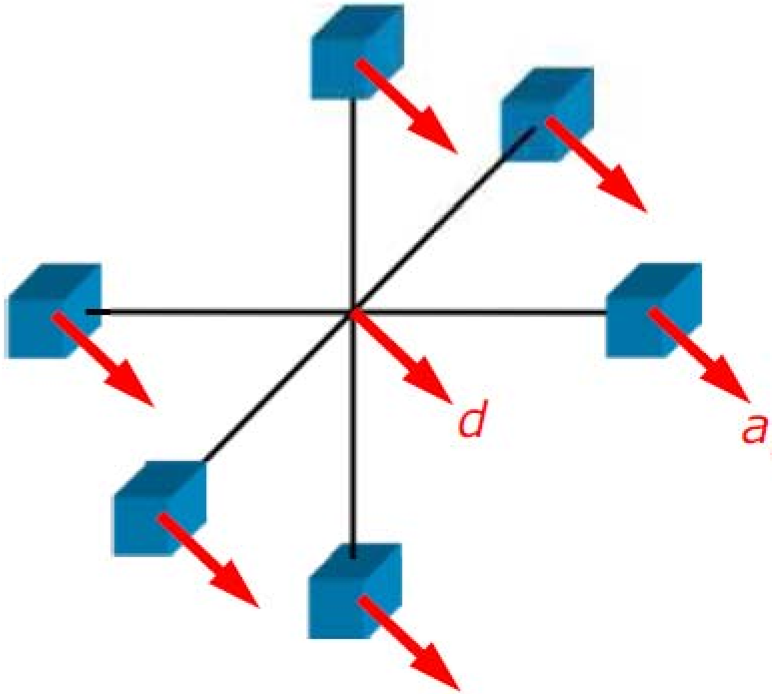
Gravity gradiometry

Gradiometer = 6 Accelerometers, each accelerometer measures

$$a_i = -(V - \Omega^2 - \dot{\Omega})r_i + \boxed{d}$$

linear acceleration of satellite



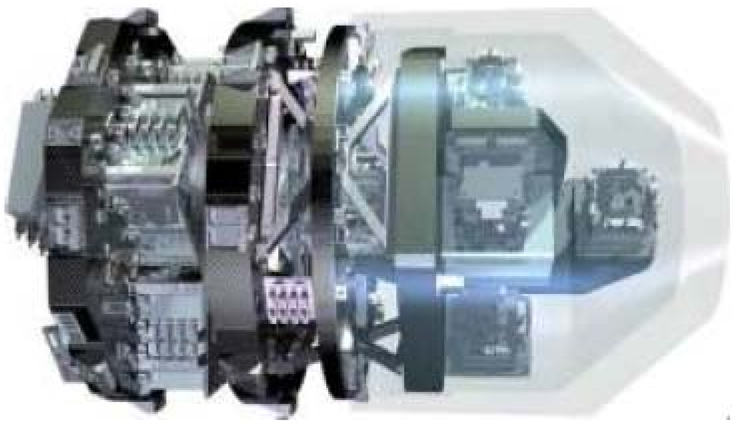


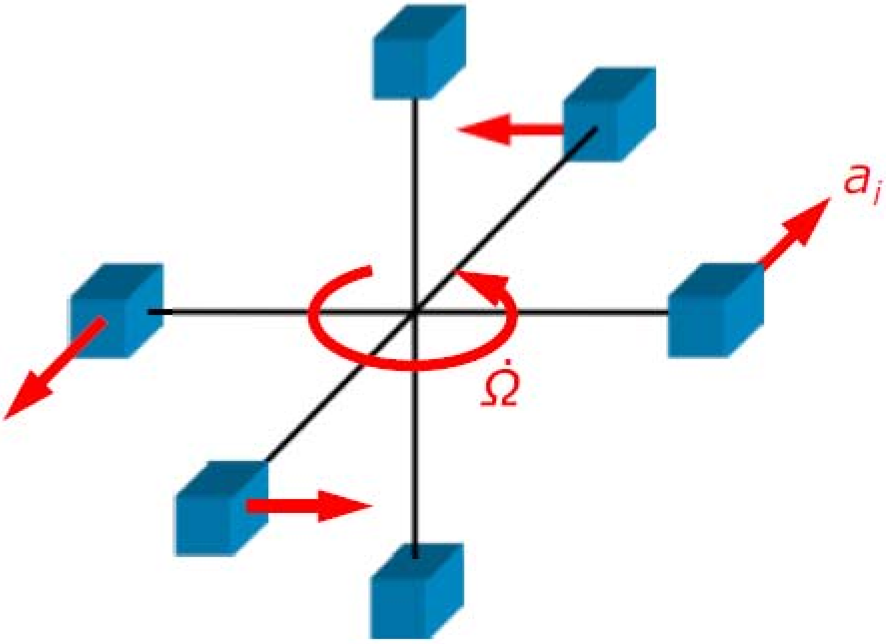
Gravity gradiometry

Gradiometer = 6 Accelerometers, each accelerometer measures

$$a_i = -(V - \Omega^2 - \dot{\Omega})r_i + d$$

angular acceleration of satellite



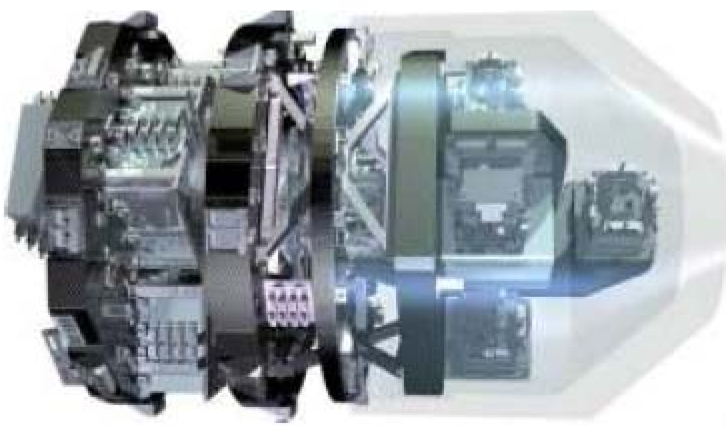


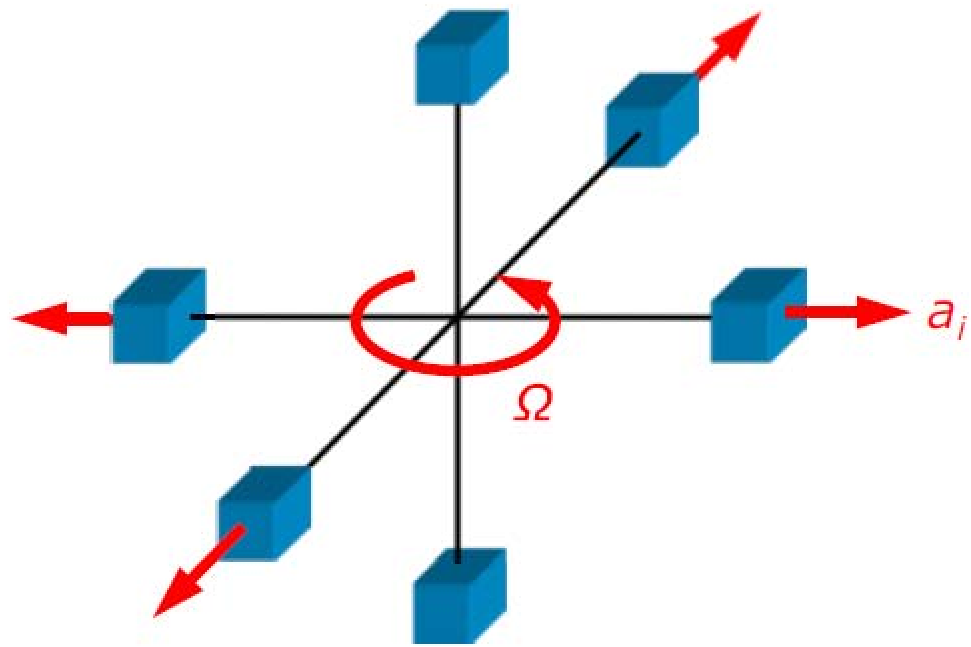
Gravity gradiometry

Gradiometer = 6 Accelerometers, each accelerometer measures

$$a_i = -(V - \boxed{\Omega^2} - \dot{\Omega})r_i + d$$

centrifugal acceleration
caused by satellite rotation



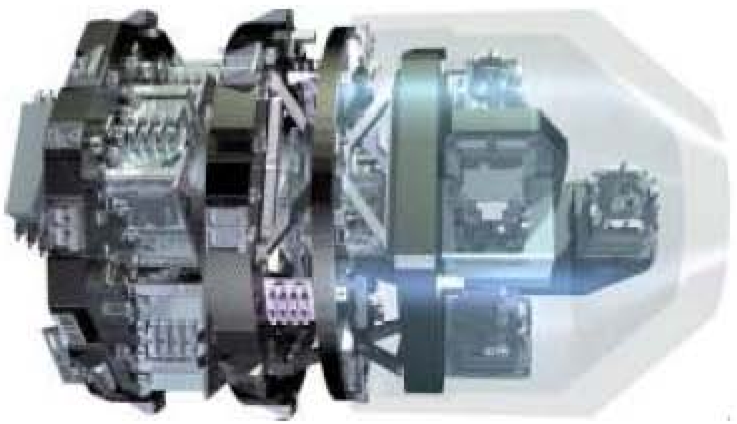


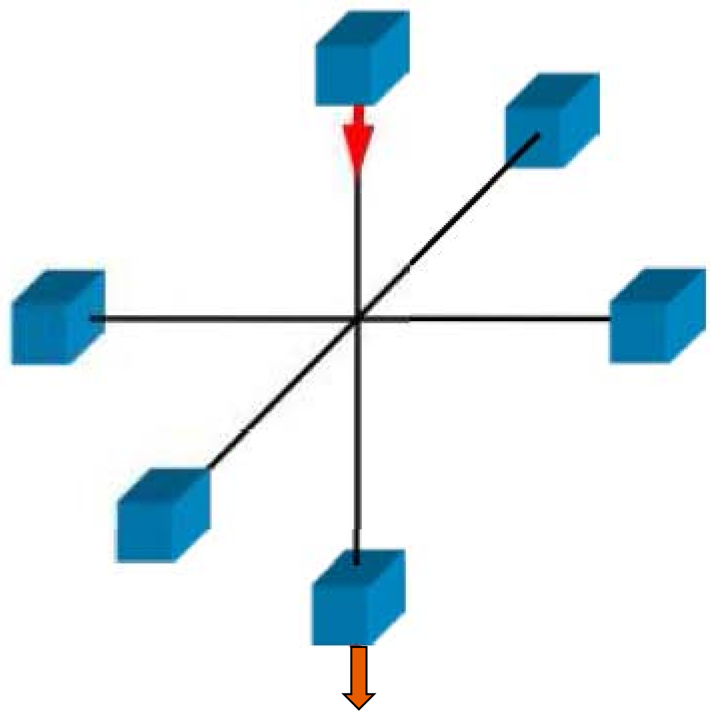
Gravity gradiometry

Gradiometer = 6 Accelerometers, each accelerometer measures

$$a_i = -(V - \Omega^2 - \dot{\Omega}) r_i + d$$

gravity gradient between accelerometers





Form common sums and differences....

1. **Common mode rejection** (for accelerometer pair on one gradiometer arm)

$$a_{cij} = \frac{1}{2}(a_i + a_j) \approx d$$ *common mode acceleration*

$$a_{dij} = \frac{1}{2}(a_i - a_j) = -\frac{1}{2}(V - \Omega^2 - \dot{\Omega})(r_i - r_j)$$ *differential mode acceleration*

2. **Separation of symmetric and anti-symmetric parts of**

$$A_d = \begin{bmatrix} a_{d14} & a_{d25} & a_{d36} \end{bmatrix} \qquad L = \begin{bmatrix} r_1 - r_4 & r_2 - r_5 & r_3 - r_6 \end{bmatrix}$$

$$A_d L^{-1} - L^{-T} A_d^T = \dot{\Omega}$$ *angular acceleration*

$$A_d L^{-1} + L^{-T} A_d^T = -V + \Omega^2$$ *gravity gradient + centrifugal acceleration*

Getting the gravity potential

3. Separation of centrifugal accelerations

$$V = \boxed{\Omega^2} - (A_d L^{-1} + L^{-T} A_d^T)$$

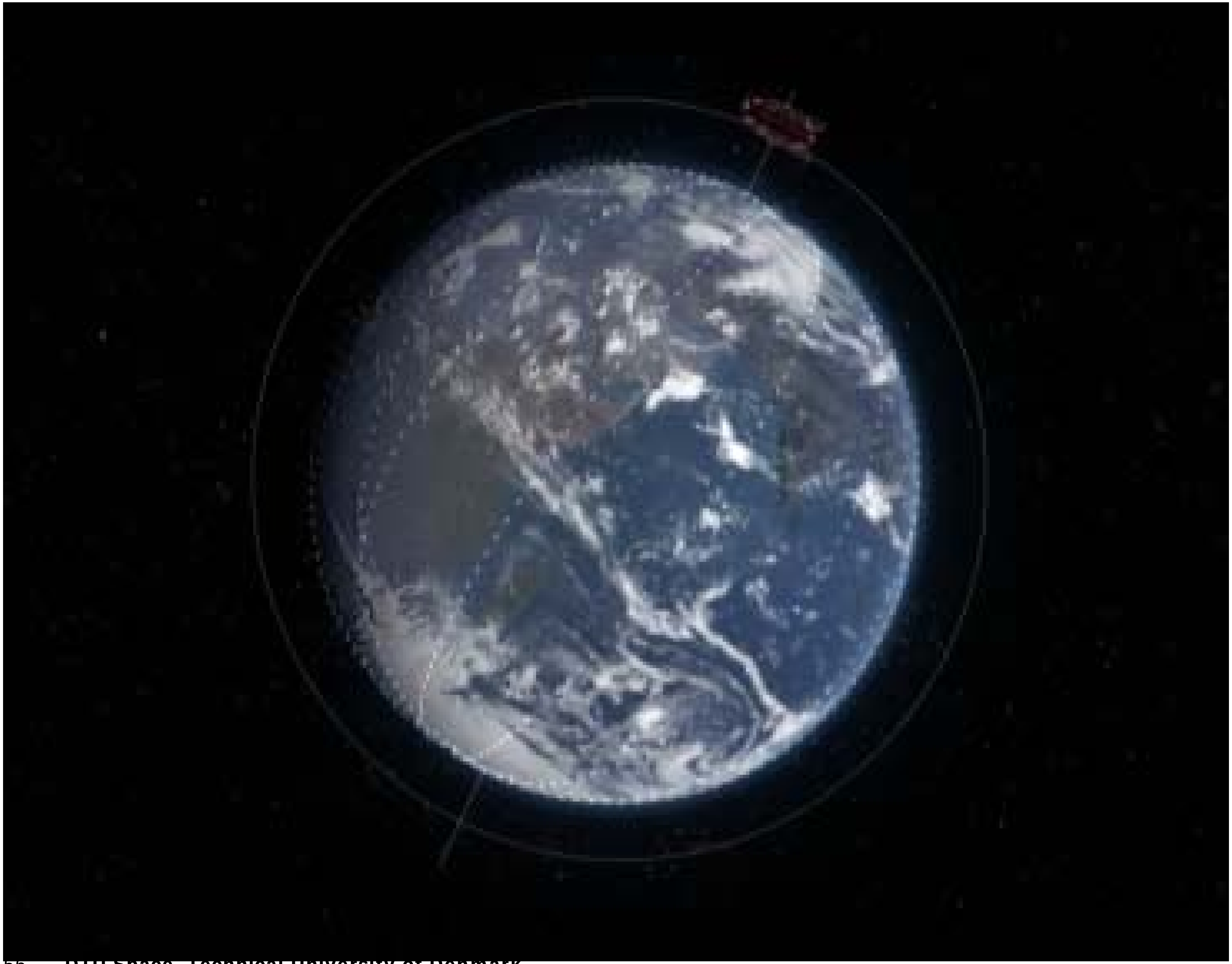
Star trackers provide angular rate as first derivative in time of inertial attitude

Gradiometer provide the angular acceleration

$$-\dot{R}R^T = \Omega_{STR} \Rightarrow \text{angular rate reconstruction} \Leftarrow \int \dot{\Omega}_{GRAD} dt = \int A_d L^{-1} - L^{-T} A_d^T dt$$

$$\Downarrow$$

$$\Omega$$



Summarizing

Satellite gradiometry gives us the long wavelenght of the gravity field as
They measure the gravity field / potential in space hundreds of km away

Satellite alitmetry gives us detailed information on the shorter wavelength
Of the gravity field by measureing the sea surface, but can not give us
Information about longer wavelength due to sea surface variations....

We still have a long way to go......
GRACE Follow On or GRACE 2 will use lasers that are 100 times more accurate.