Earth Monitoring Satellites

Observing Earth's size and shape, Earth's gravity field and Earth's deformation in time

Applications

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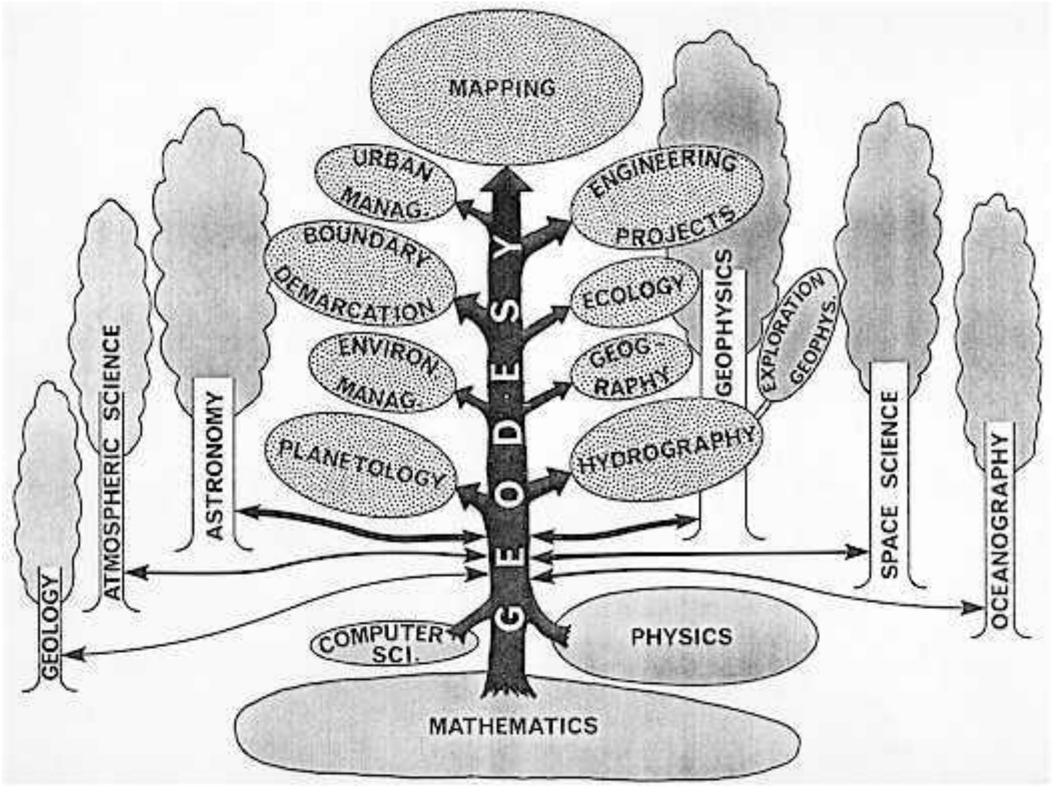
Geodesy

Geodesy is the scientific discipline that deals with the measurement and representation (Size and Shape) of the Earth, its gravitational field and its deformation and changes in time in a three-dimensional time varying space.



Courtesy: Geodesy: The concepts (Vanícek and Krakiwsky, 1986, p.45) (http://gge.unb.ca/Resources/GeodesyTutorial.pdf Page 4)

Space (Satellite) Geodesy

Three different satellite systems

1. Monitoring Size and Shape of the Earth + Monitoring Deformation of the Earth- **Satellite Positioning Systems**

2. Monitoring Oceans and Ice (Changes)- **Satellite Altimetry**

3. Monitoring Gravity Field of the Earth (Gravity and Mass changes)- **Satellite Gravimetry**

4. Other type of Earth Monitoring Satellite

Basic Definitions
Earth's figures

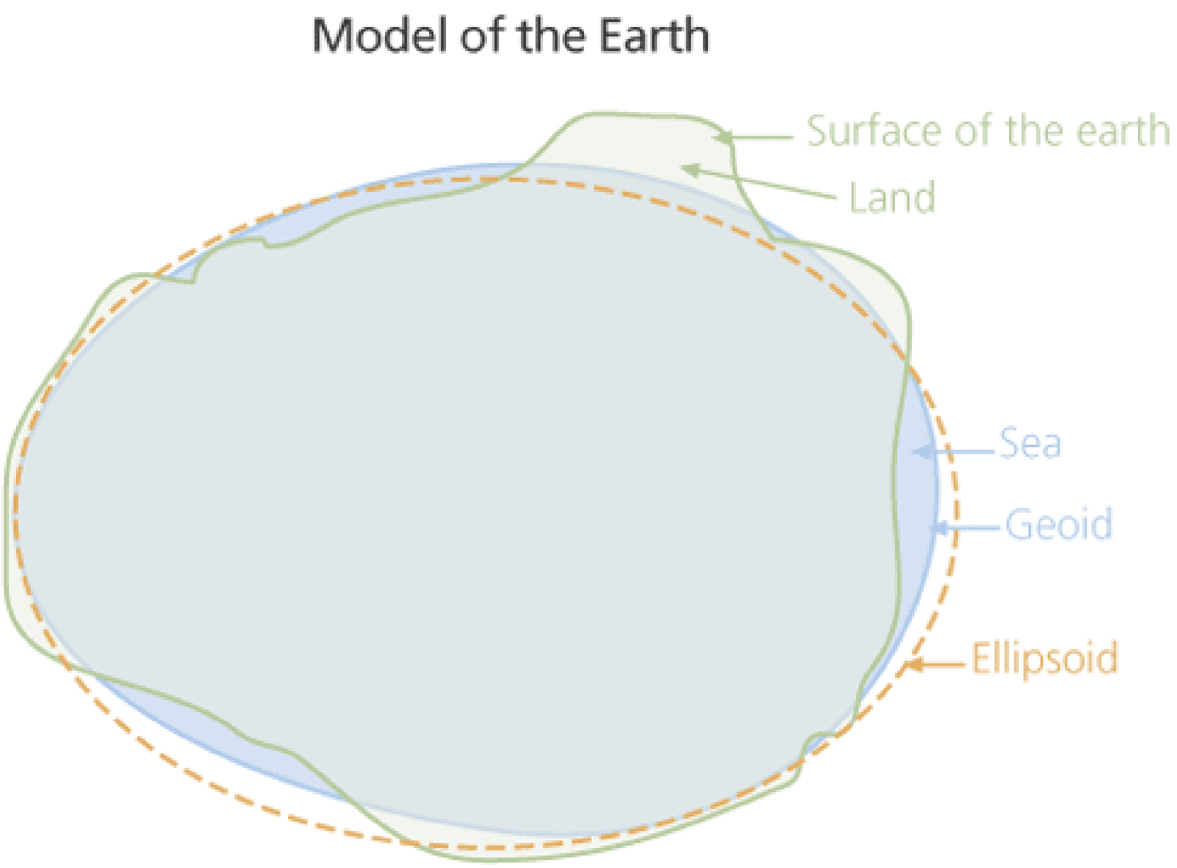
The Earth's figure is defined in different ways in Geodesy:

- **Earth's Physical shape** (the true figure of the Earth) with its very large irregularities like Mount Everest with +8000 m height and Mariana trench with -11000 m depth cannot be used for exact mathematical computations but the measurements are made on this surface.

- **Earth's Mathematical shape**, a **Reference Ellipsoid** is used to mathematically approximate the Earth's surface. Because of its relative simplicity, reference ellipsoid are used as a preferred surface for geodetic computations and the points coordinates (latitude, longitude and elevation) are defined with respect to this surface. One example of a reference ellipsoid is Geodetic Reference System (GRS80).

- **An Earth shape with relations with the two above shapes**, the **Geoid**. The geoid surface is more irregular than mathematical figure of the Earth, i.e. reference ellipsoid, but considerably smoother than the real Earth's physical surface. While the real physical surface of the Earth has excursions of +8,000 m (Mount Everest) and −11,000 m (Mariana Trench), the geoid varies by only about ±100 m about the reference ellipsoid. The geoid is the surface of an ideal global ocean in the absence of tides and currents, shaped only by gravity. Geoid coincides on average with mean sea/ocean level.

Different Figures of the Earth



Courtesy: ESRI http://www.esri.com/news/arcuser/0703/geoid1of3.html

Basic Definitions

Gravity field of the physical figure of the Earth (g) can be observed:

Gravity **g** can be observed using gravimeters, also using satellites (slide 76). A milliGal is a convenient unit for describing variations in gravity over the surface of the Earth. 1 milliGal (or mGal) = 0.00001 m/s^2, which can be compared to the total gravity on the Earth's surface of approximately 9.8 m/s^2 (or 980000 mGal).

Gravity field of the mathematical figure of the Earth (for example GRS80, see slide 4), called Normal gravity field (γ), can be computed:

Normal gravity as a function of latitude φ can be computed from:

$$\gamma(\varphi) = 978032.7(1+0.0053024\sin^2\varphi-0.0000058\sin^2 2\varphi) \text{ [mGal]}$$

http://gge.unb.ca/Resources/GeodesyTutorial.pdf

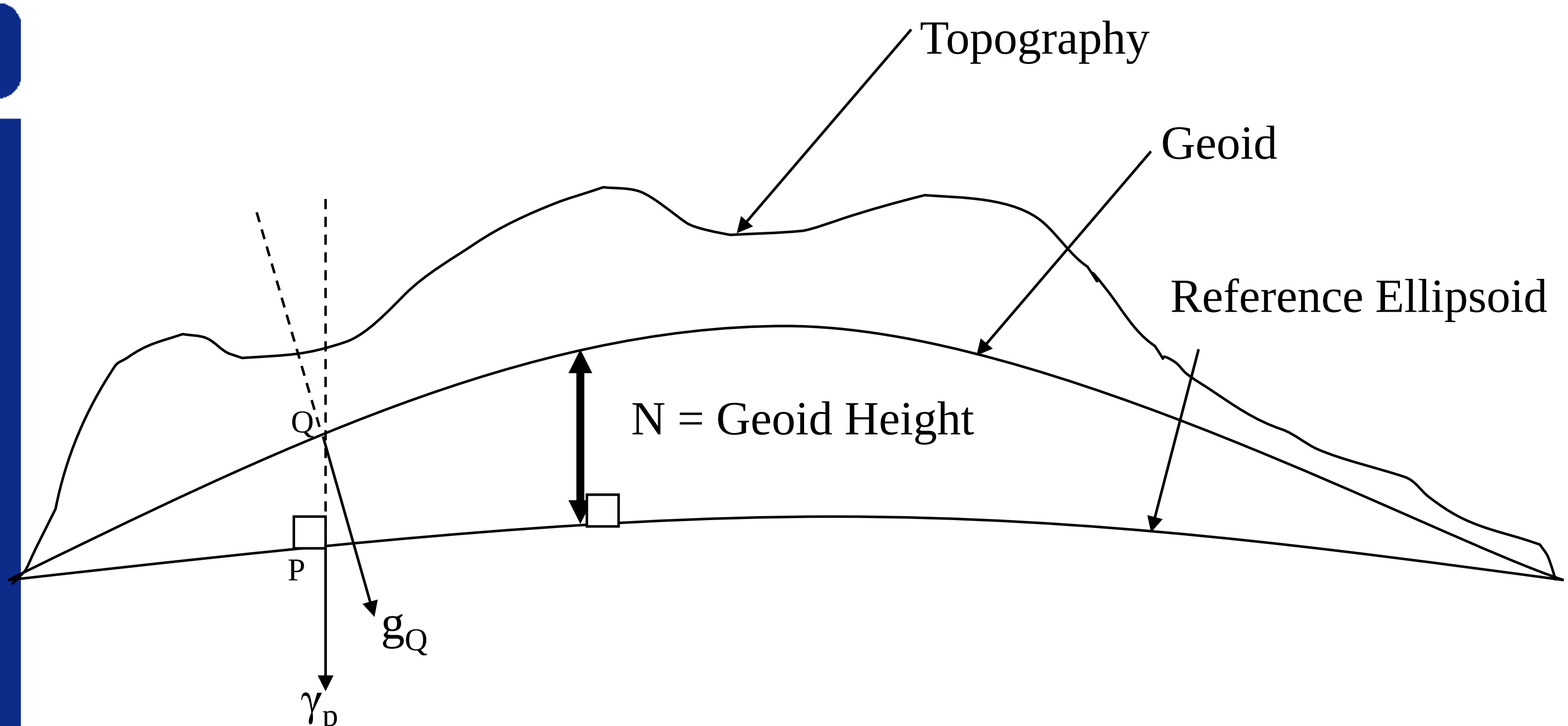
Some Observed Gravity Values

using gravimeters

Greenland (DEN)	g=982.190655 Gal
Yellowknife(CAN)	g=982.002756 Gal
Penticton(CAN)	g=980.765021 Gal
Schefferville (CAN)	g=981.317107 Gal
Int. Falls (USA)	g=980.825204 Gal
Rolla(USA)	g=979. 8975 Gal
Great Falls (USA)	g=980.1138 Gal
Tucson (USA)	g=978.8104 Gal
Fort Davis (USA)	g=978.820084 Gal
Fairbanks (USA)	g=982.198148 Gal
St. Elena Uairen (VEN)	g=977.822085 Gal
Brasilia (BRA)	g=978.048790 Gal
Tandil (ARG)	g=979.904345 Gal
Sodankyla (FIN)	g=982.3622 Gal
Wettzell (GER)	g=980.83567 Gal
Valle de Los Caidos (SPN)	g=979.884900 Gal
Antananarivo (MDG)	g=978.207626 Gal
Nanning (CHN)	g=978.750237 Gal
Beijing (CHN)	g=980.110572 Gal
Alice Springs (AUS)	g=978.630782 Gal
Yaragadee (Perth, AUS)	g=979.403662 Gal
Syowa (JPN)	g=982.524327 Gal

Courtesy: http://bgi.dtp.obs-mip.fr
http://agrav.bkg.bund.de

Geoid height and Gravity anomaly



•Gravity g is a large value, we normally reduce from g the normal gravity γ, resulting in Gravity Anomaly $\Delta g = |g_Q| - |\gamma_P|$ (There are different types of gravity anomalies depending some correction terms, among them **Free-air** gravity anomalies)

•Geoid (Heights) and Gravity anomalies are mathematically related (See slide 88).

Geoid Importance

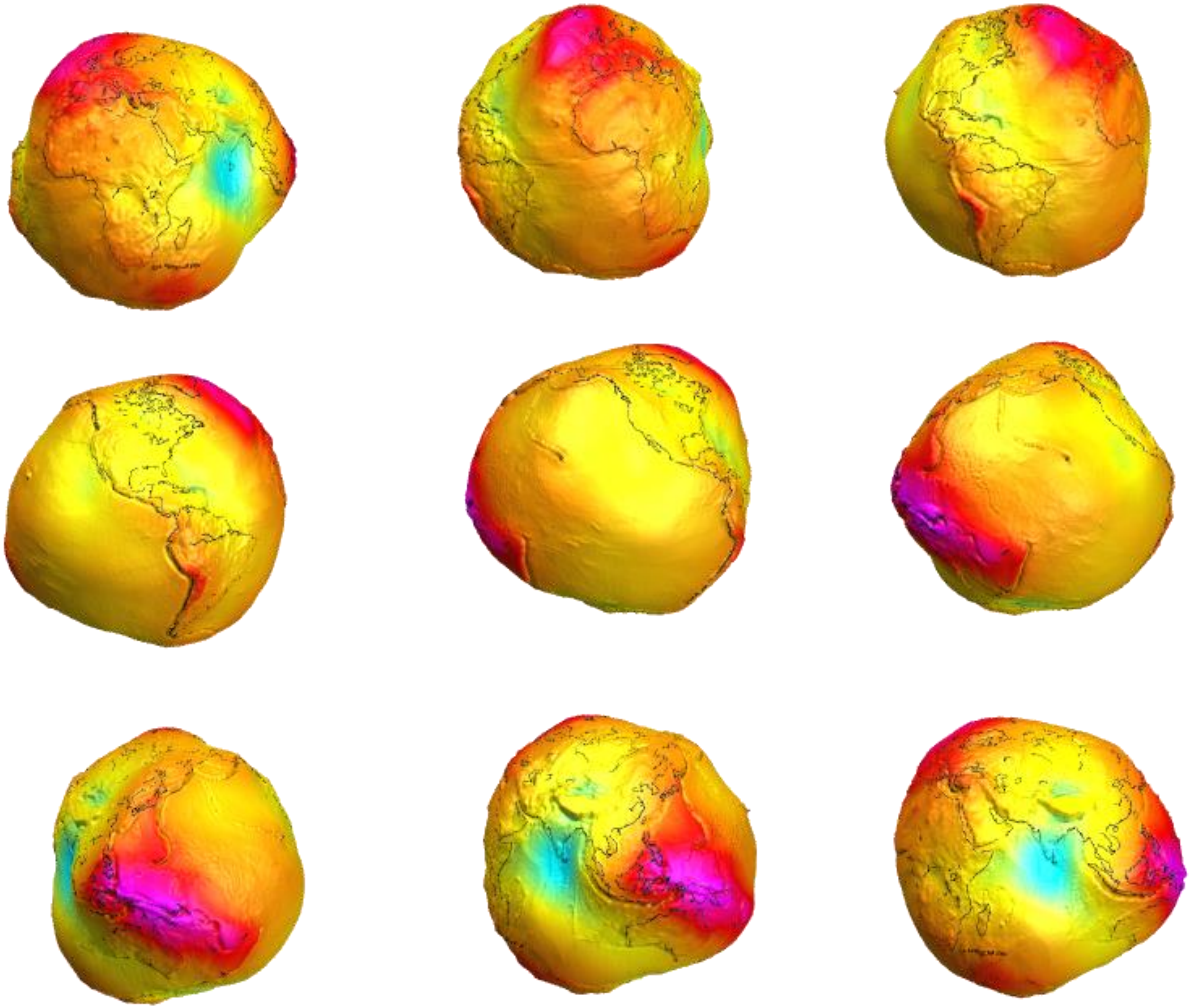
- A precise model of Earth's geoid is crucial for deriving accurate measurements of ocean circulation, sea-level change and terrestrial ice dynamics.

- The geoid is also used as a reference surface from which to map the topographical features on the planet.

- In addition, a better understanding of variations in the gravity field will lead to a deeper understanding of Earth's interior, such as the physics and dynamics associated with volcanic activity and earthquakes.

A presentation of the Geoid (Globally)

Geoid is shown here with colors and exaggerated heights from multiple point of view. The colors in the image represent deviations in height (–100 m to +100 m) from an ideal geoid. The red color represent high values and the blue represent low values.

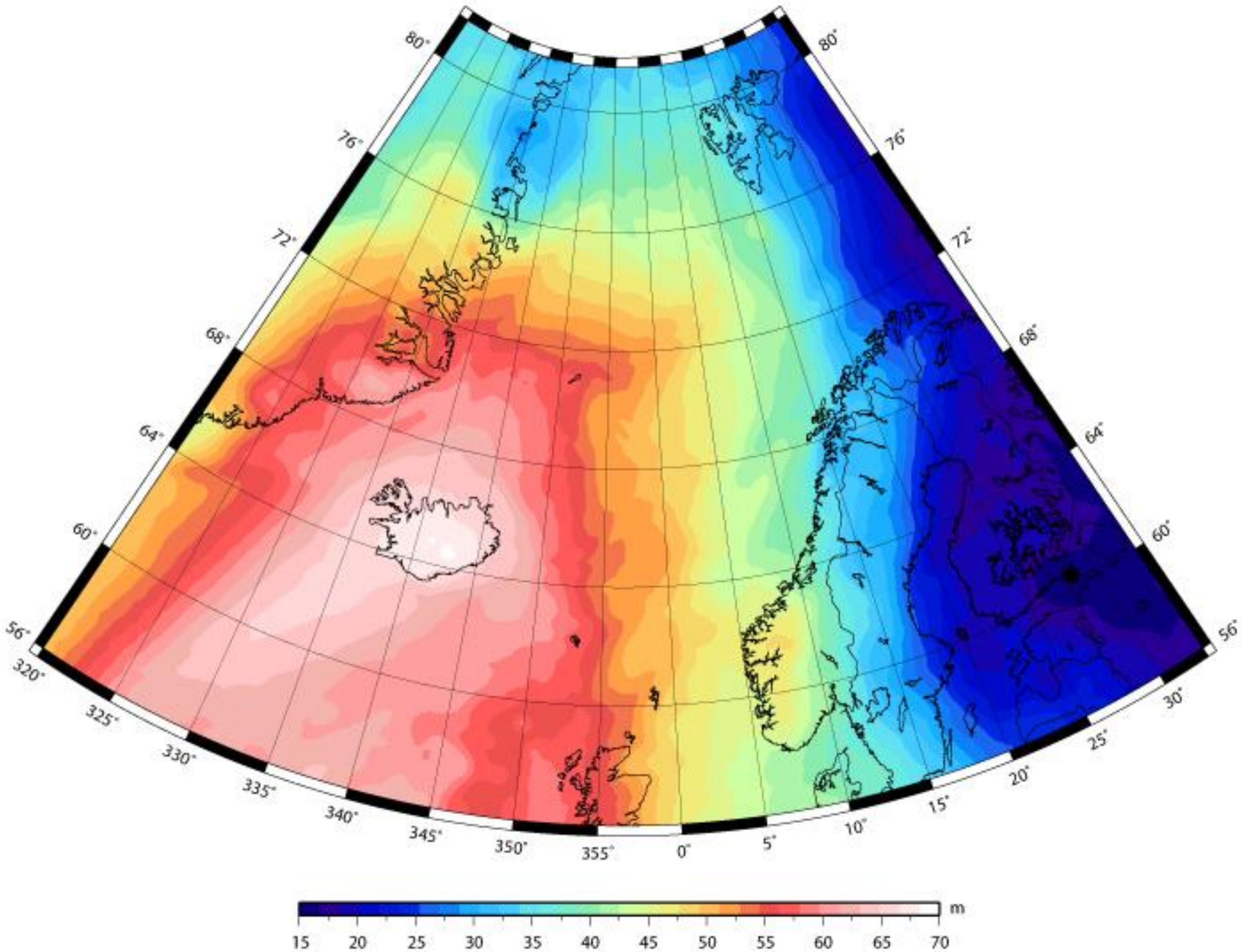


Geoid Presentation

- Geoid can be presented by its deviation (separation) from the Reference ellipsoid in units of meters as a map of geoid (see slide 8).

- A map of geoid (or other parameters in geodesy like gravity anomaly, mean sea surface height) are generally presented using lines of equal values (contour maps-contour lines)

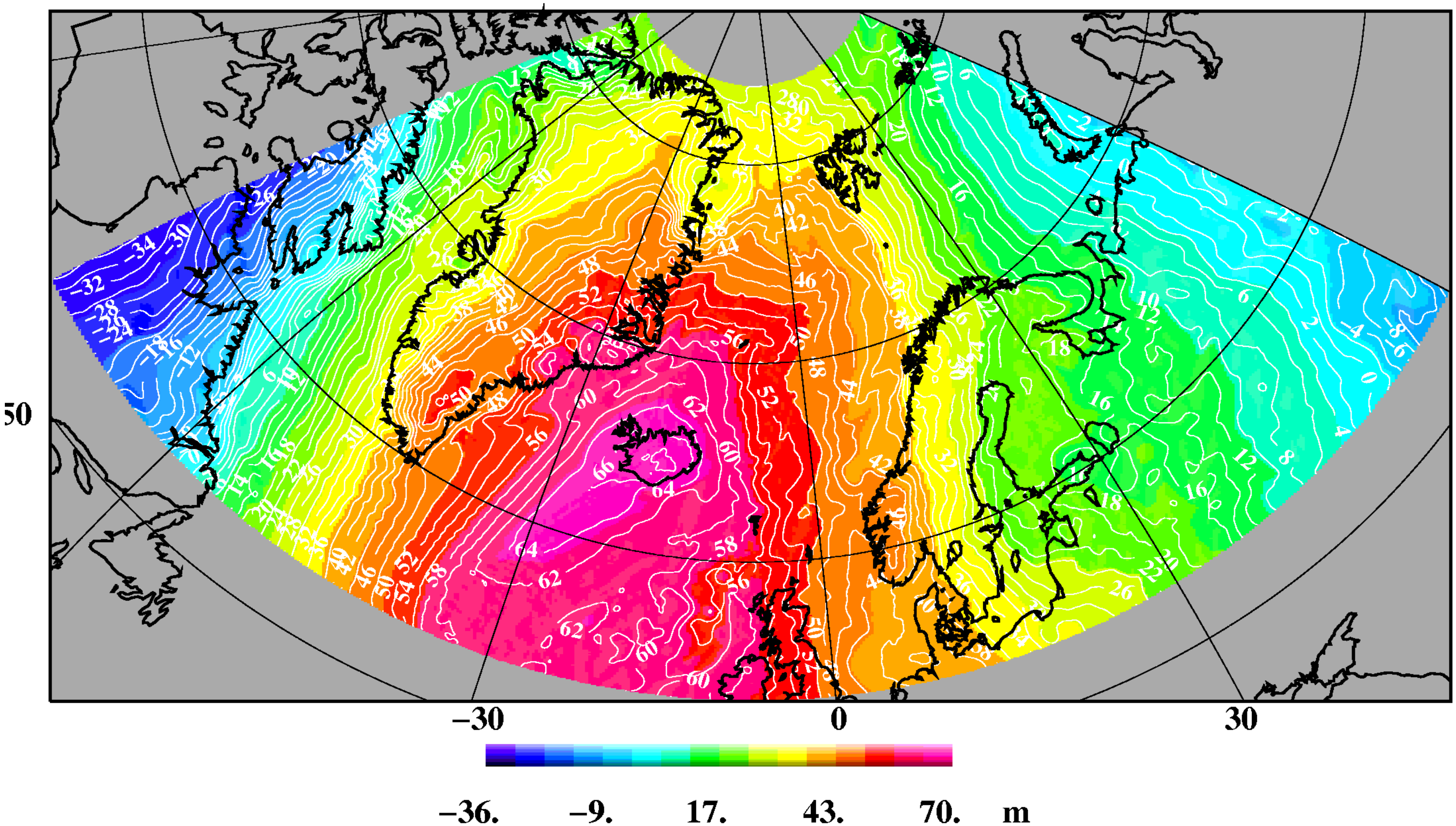
A Geoid Map



Courtesy: OCTAS project

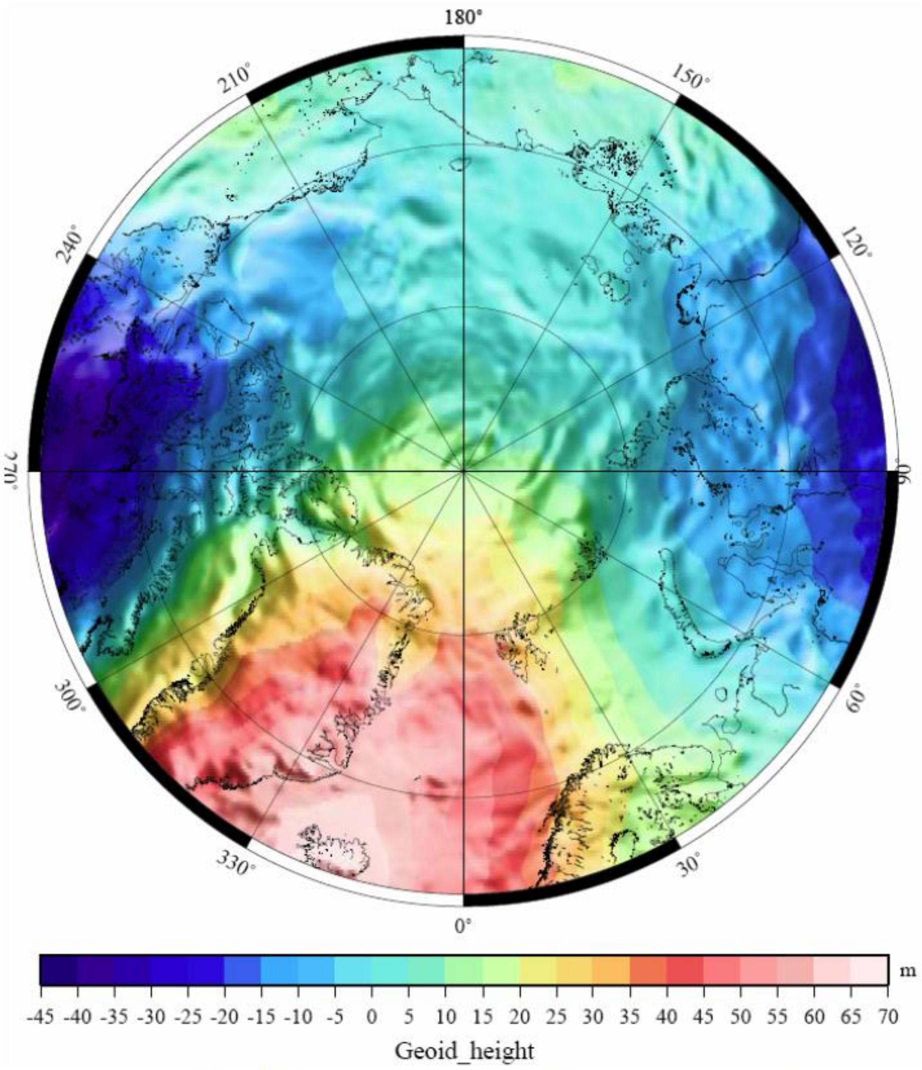
http://earth.esa.int/goce06/participants/169/pres_solheim_169.pdf

Another geoid Map



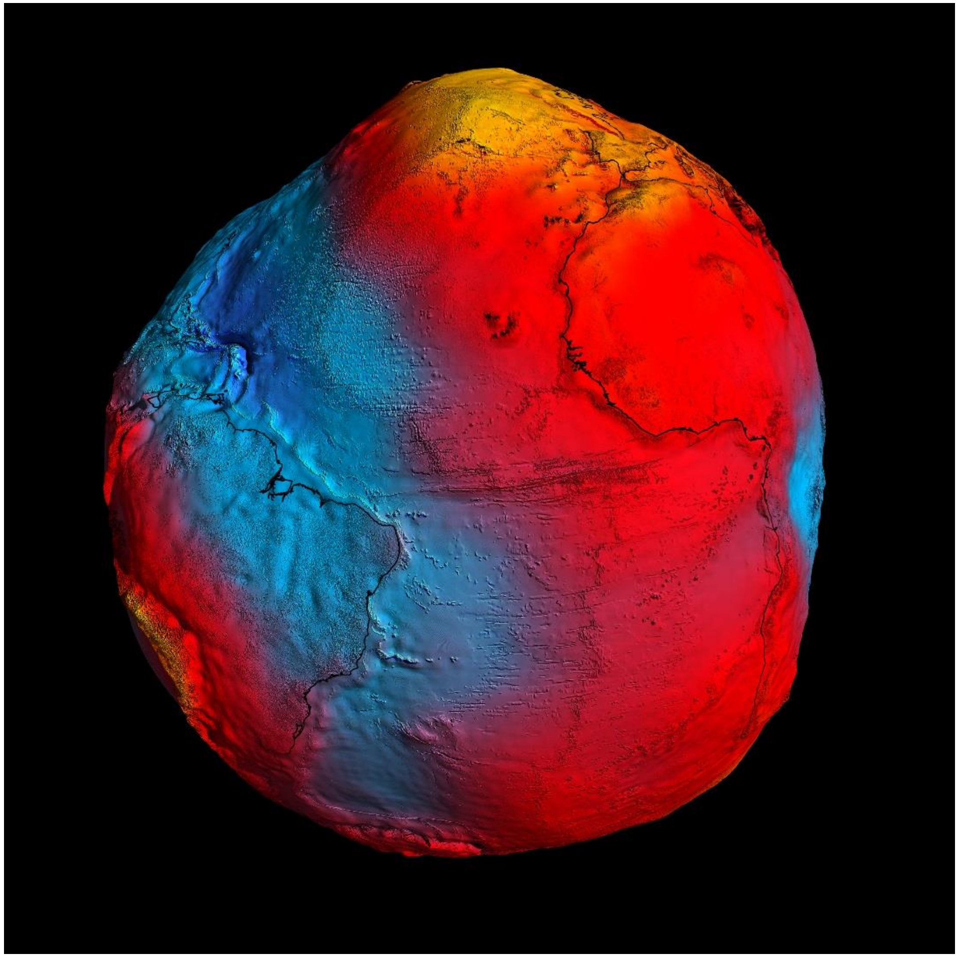
Courtesy: GOCINA Project http://gocinascience.spacecenter.dk/

Another geoid Map



Courtesy: http://esamultimedia.esa.int/docs/arcgice_venice.pdf#search=%22%20freeboard%20height%22

The most accurate model of the geoid from satellites



Courtesy: ESA/HPF/DLR
http://www.esa.int/spaceinimages/Images/2011/03/New_GOCE_geoid

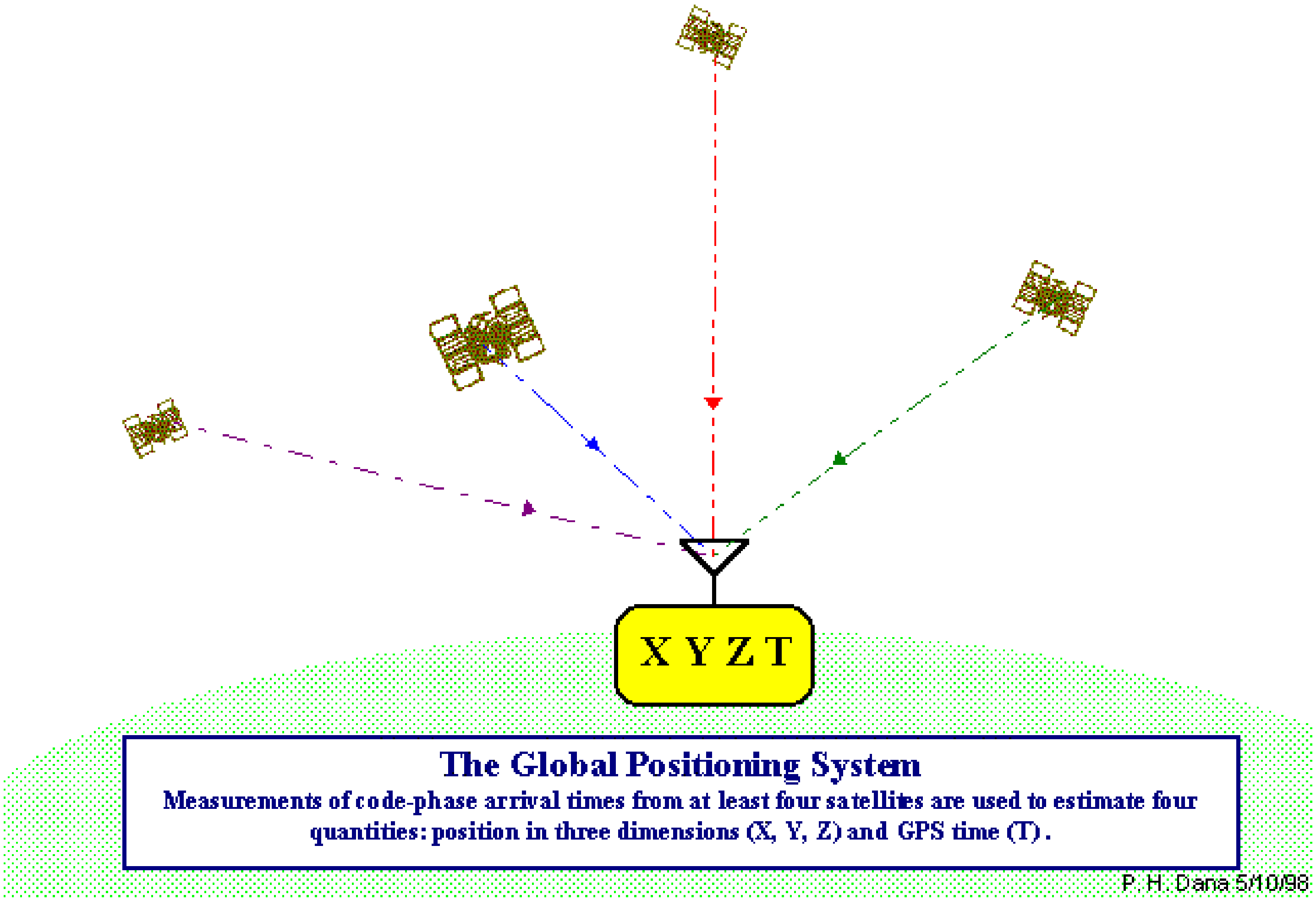
1-Satellite Positioning Systems

(Earth's Size and Shape + Deformation)

- Monitoring support is provided by various satellite missions.:
  - Global Positioning System (GPS)
    http://www.navcen.uscg.gov/?pageName=GPSmain
  - GLONASS
    http://www.glonass-ianc.rsa.ru/pls/htmldb/f?p=202:1:16752298639962070212
  - GALILEO
    http://www.glonass-ianc.rsa.ru/en/
  - Satellite Laser Ranging
    http://ilrs.gsfc.nasa.gov/
  - DORIS
    http://ids.cls.fr/

GPS Configuration

GPS Observations



http://www.colorado.edu/geography/gcraft/notes/gps/gps.html

GPS Observation equation

Simplified (Pseudo)range model from 4 satellites

$$P^1 = \left((x^1 - x)^2 + (y^1 - y)^2 + (z^1 - z)^2 \right)^{1/2} + c\,\tau - c\,\tau^1$$

$$P^2 = \left((x^2 - x)^2 + (y^2 - y)^2 + (z^2 - z)^2 \right)^{1/2} + c\,\tau - c\,\tau^2$$

$$P^3 = \left((x^3 - x)^2 + (y^3 - y)^2 + (z^3 - z)^2 \right)^{1/2} + c\,\tau - c\,\tau^3$$

$$P^4 = \left((x^4 - x)^2 + (y^4 - y)^2 + (z^4 - z)^2 \right)^{1/2} + c\,\tau - c\,\tau^4$$

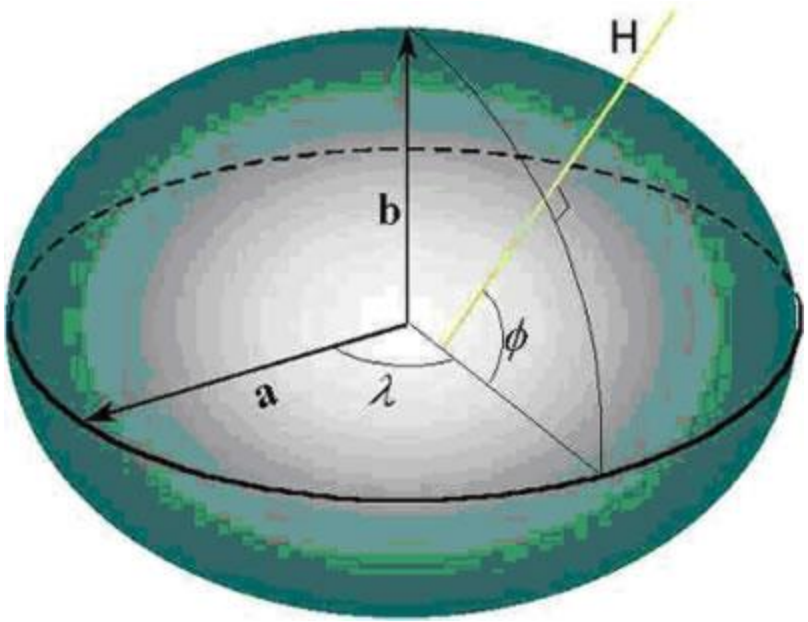
P is the actual range observation to satellites from receiver, c is the speed of light in a vacuum, (x^i, y^i, z^i) are the satellite position, (x, y, z) are the receiver position, τ is the receiver clock bias and τ^i are the satellite clock bias. All other errors are neglected in this simplified formula. Other Errors and Biases in GPS will be taken care of in proper ways.

Size and Shape of the Earth

- Geodetic datums define the size and shape of the Earth.
- Through a long history, the "figure of the Earth" was refined from flat-Earth models to spherical models. True geodetic datums were employed only after the late 1700s when measurements showed that the Earth was ellipsoidal in shape.
- Datums have evolved from those describing a spherical Earth to ellipsoidal models derived from years of satellite measurements.

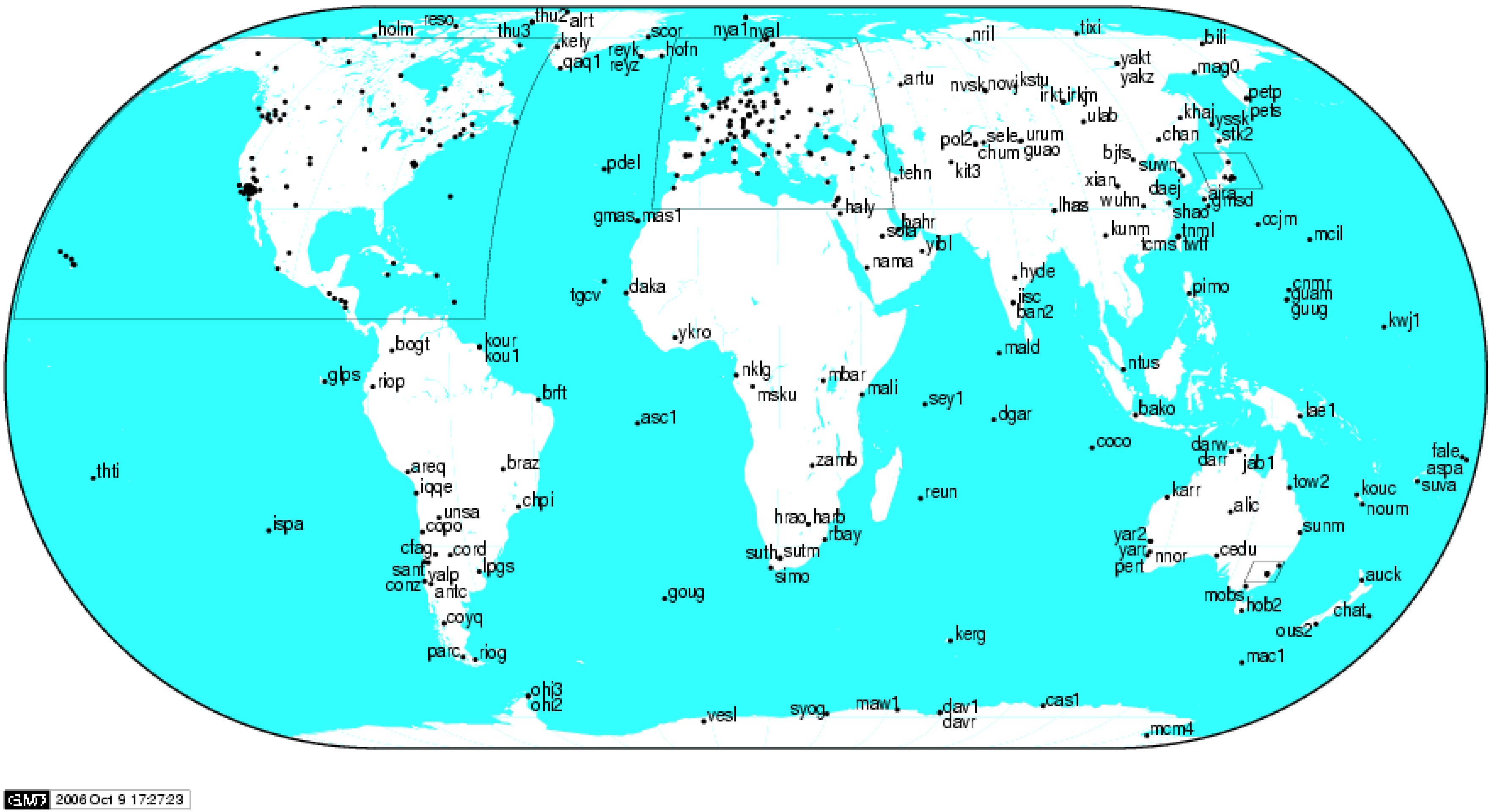
Geodetic Datum

- GPS, which is operated by the United States Department of Defense, utilizes a geocentric datum to express its positions because of its global extent. (ϕ, λ, h) or (X, Y, Z)



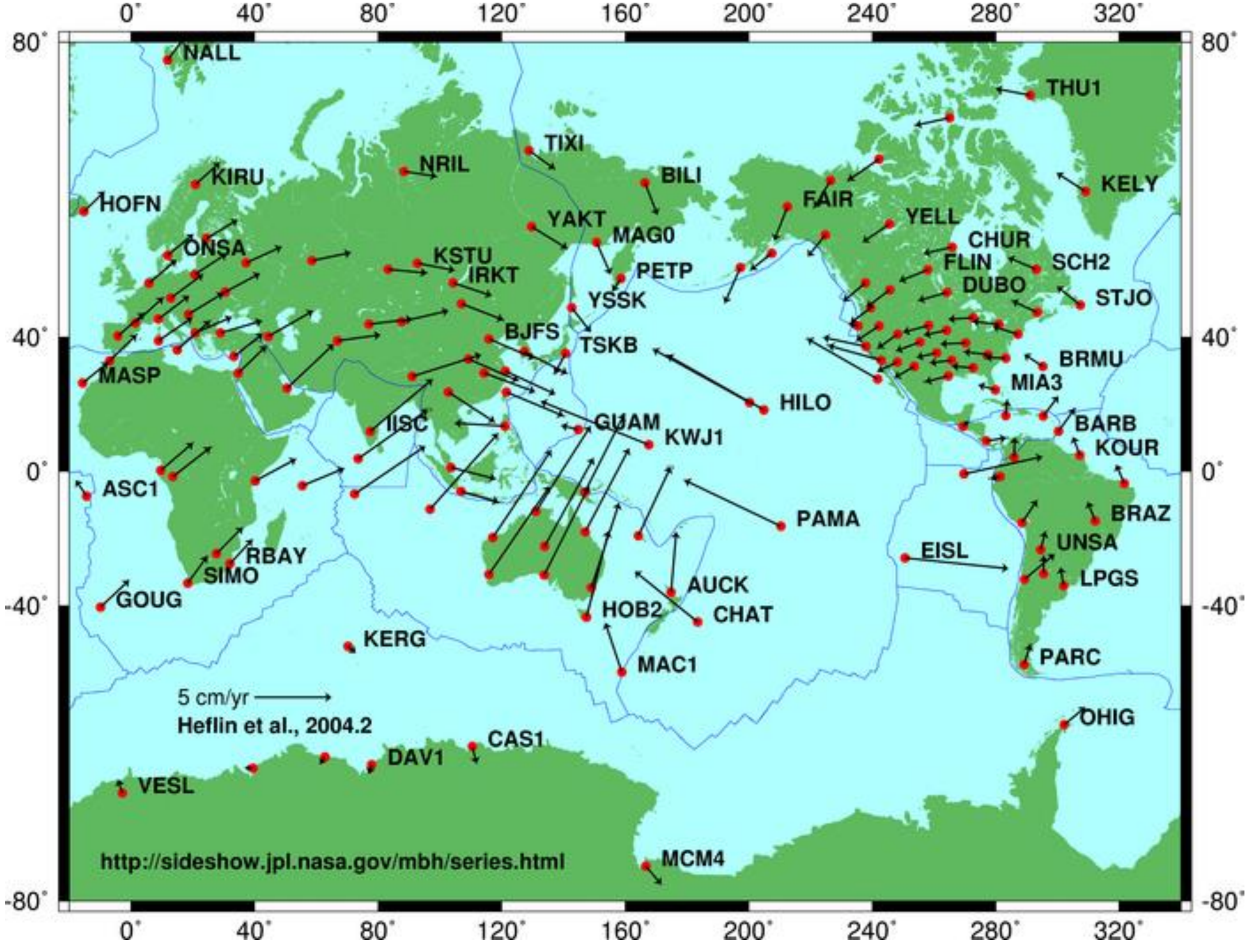
Global GNSS Stations

GNSS=Global Navigation Satellite System



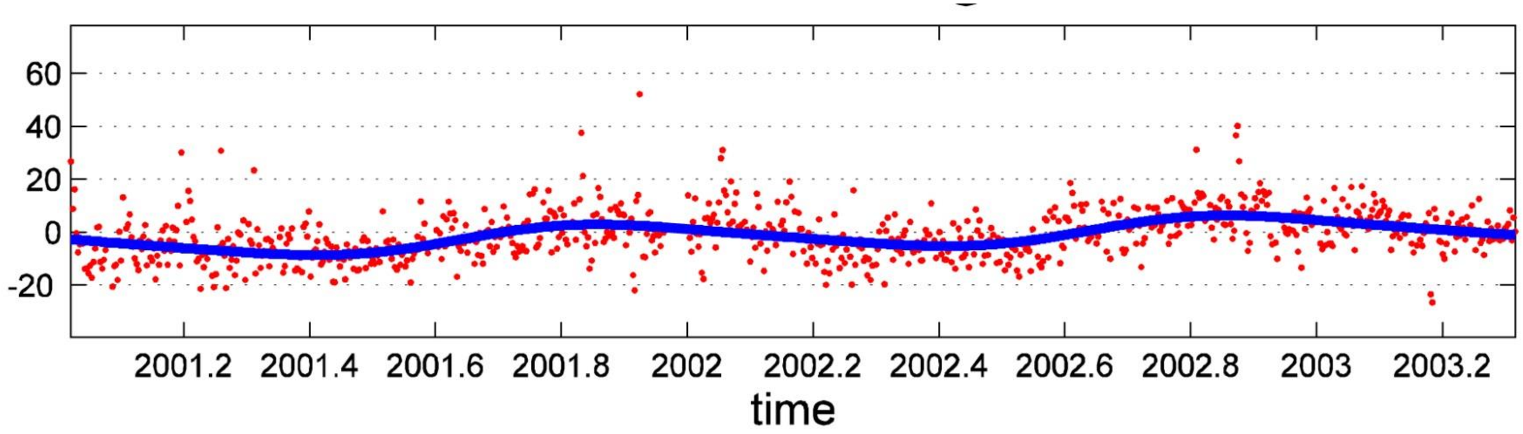
Courtesy: Global GNSS services. http://igscb.jpl.nasa.gov

Global Velocities (Deformations)



GPS TIME SERIES

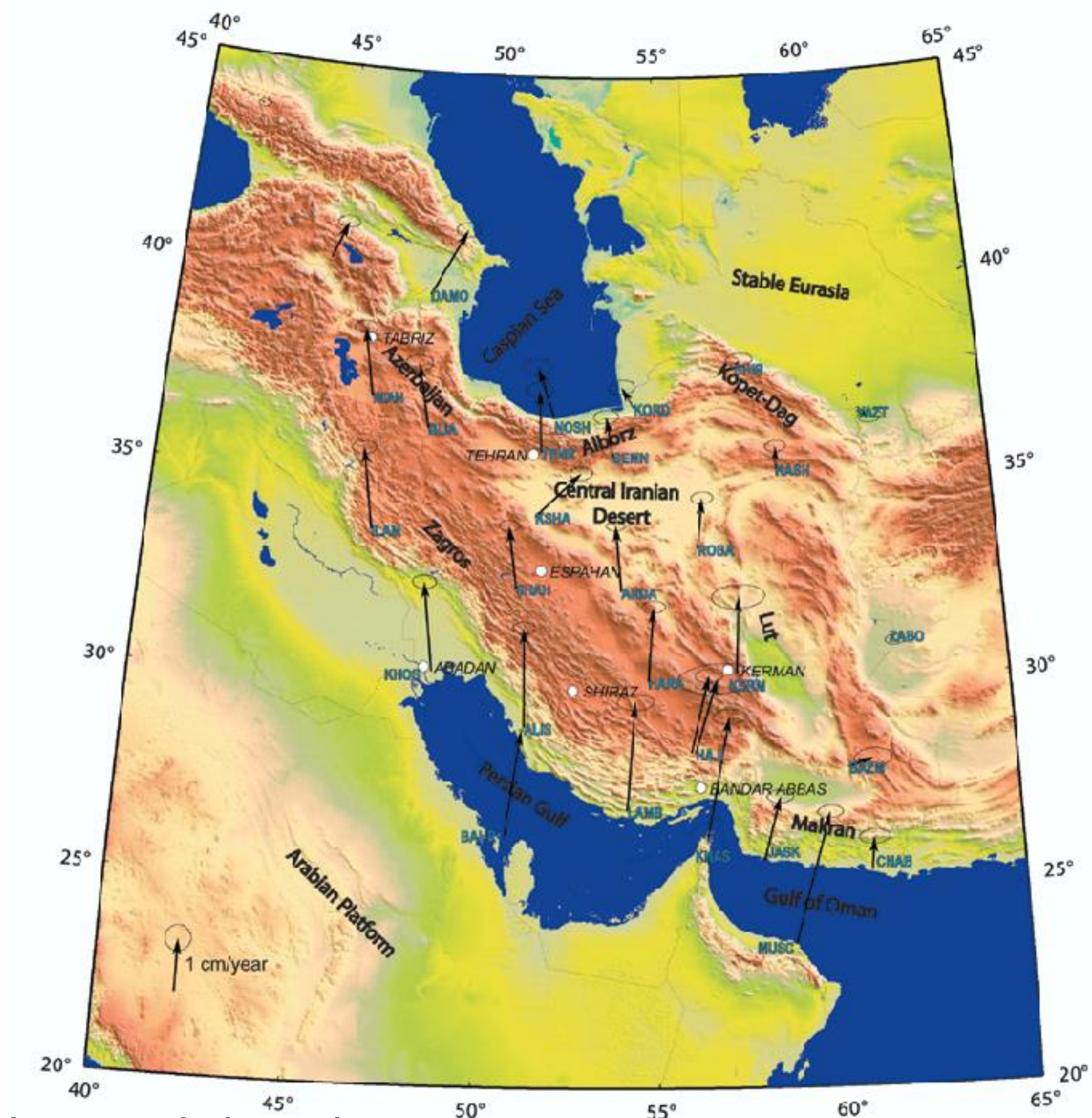
An example



The vertical axis could be one of the three coordinates in GPS: latitude, longitudes, heights, or X, Y and Z in a Cartesian coordinate system.

There are two permanent GPS stations at NTNU, Realfagbygget (Contact person Hossein Nahavandchi).

Another application of GPS data
Zagros and Alborz Projects in Iran (Deformations)



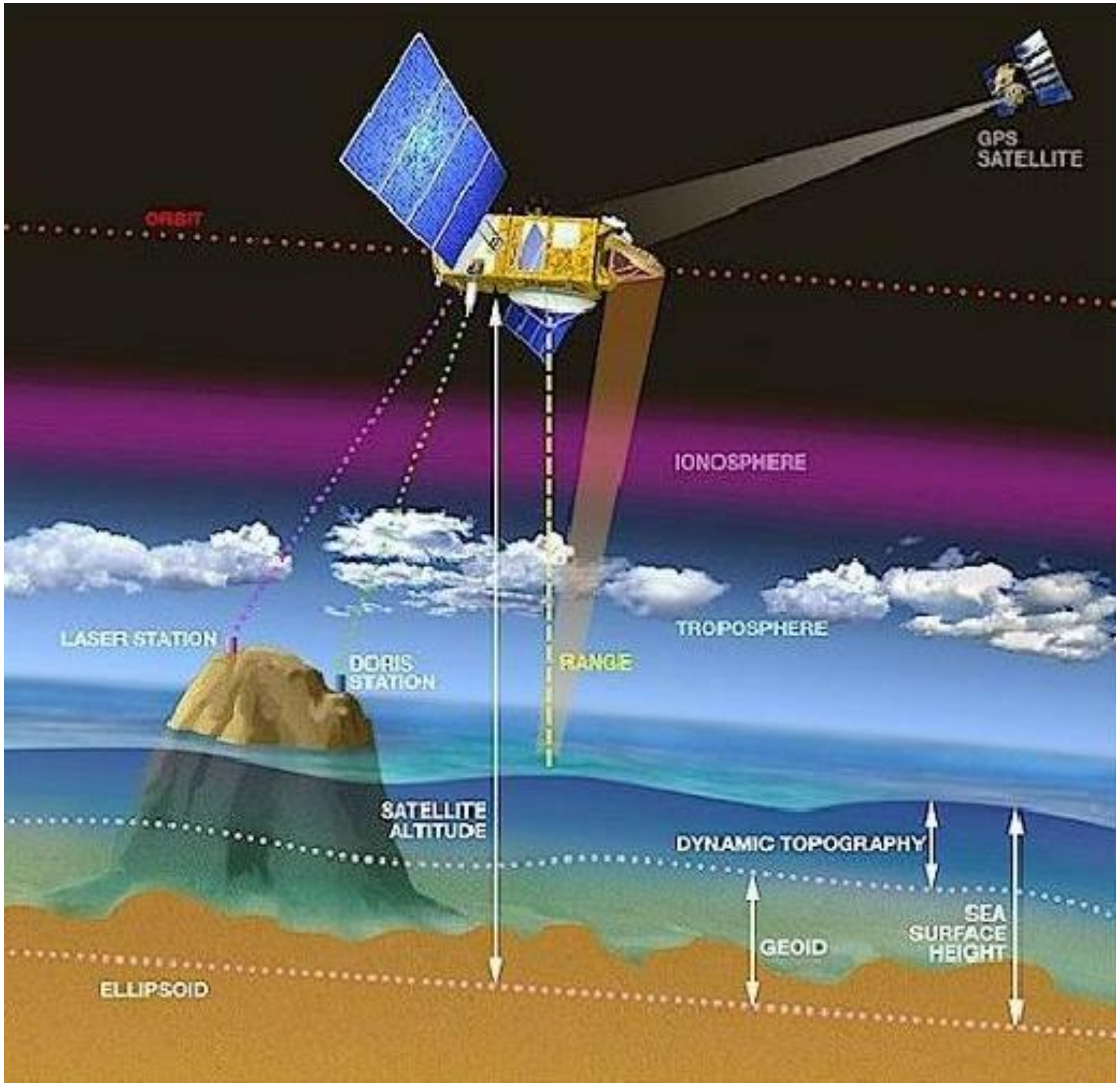
Courtesy: Nilforoushan et al. (2003)
http://www.springerlink.com/content/36xlah42b103g25q/

2- Satellite Altimetry

(Changes + Deformations)

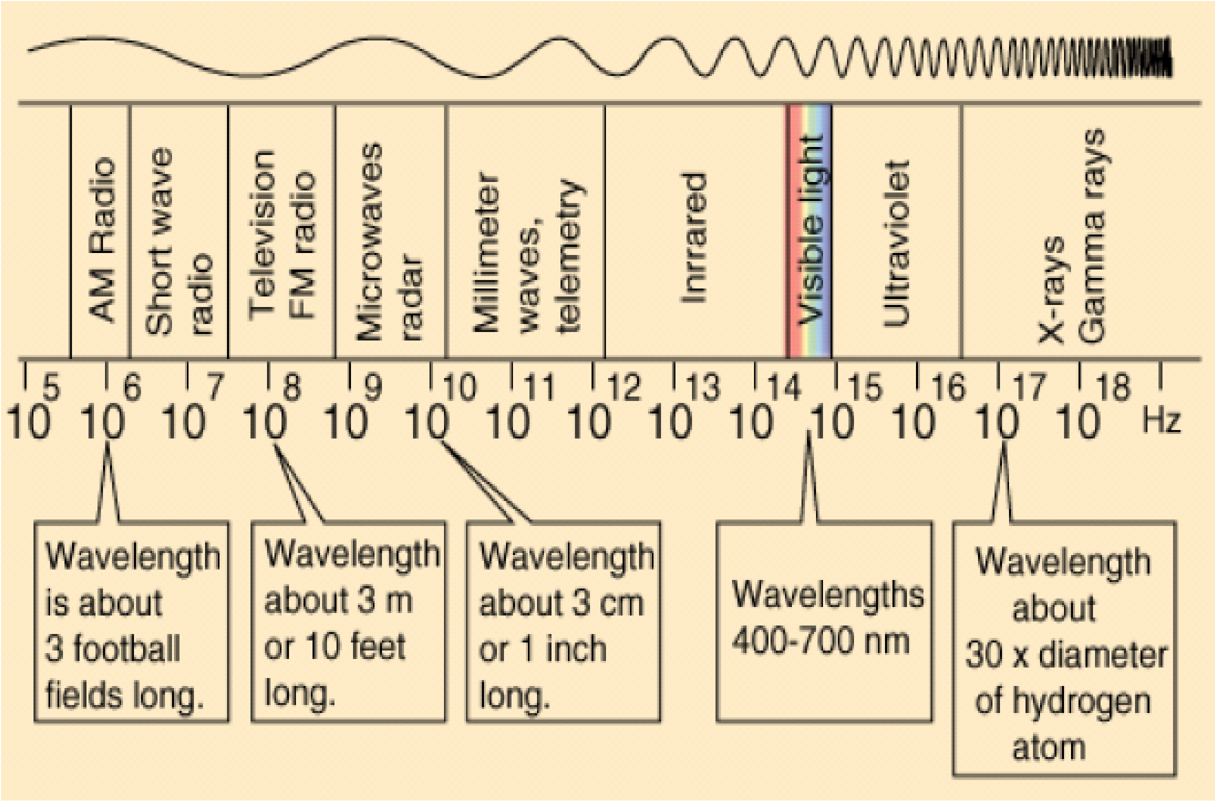
- Altimetry is the most important tool to measure global changes in the sea level.
- There are different satellite radar altimeters starting with GEOS-3 in 1975.
- Satellite altimetry determines the global sea surface height
- The mean sea surface height is determined from the sea surface heights
- The mean sea surface height plays an important role in geodetic, geophysical, and oceanographic research.

Satellite Altimetry Principle



Courtesy: CNES http://www.cnes.fr/web/CNES-en/7114-home-cnes.php

Electromagnetic wave travel with the speed of the light



Courtesy: Shum and Braun, Satellite Altimetry and Gravimetry Course. Contact Hossein Nahavandchi

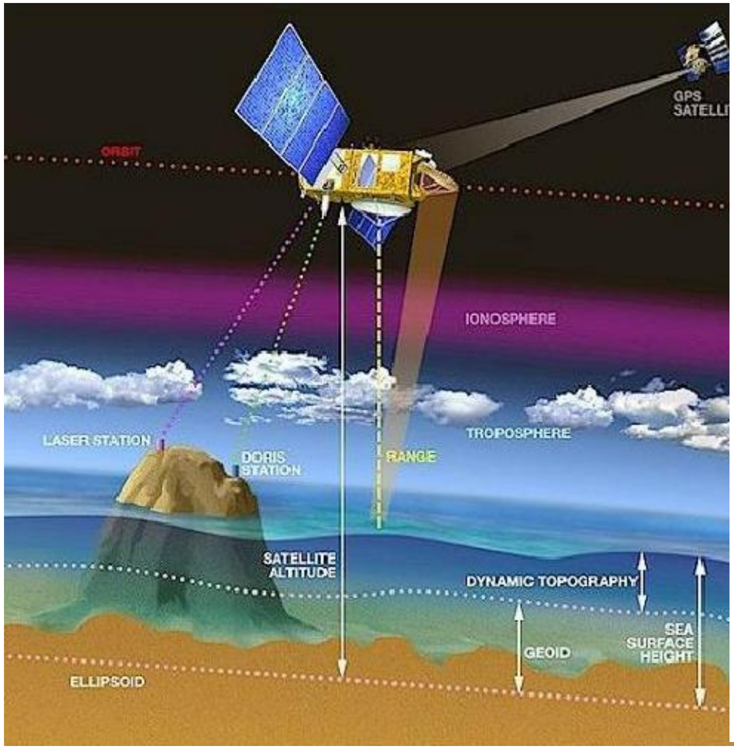
Satellite Altimetry Observations

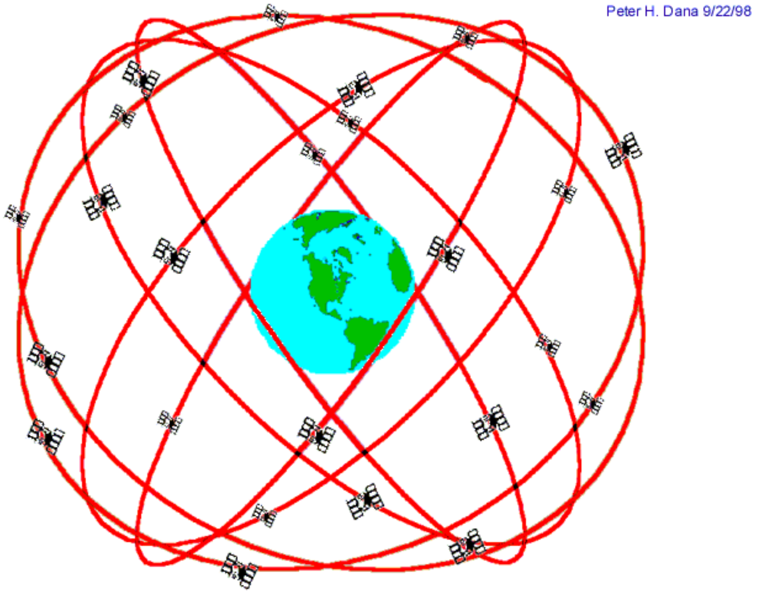
Once we know the travel time and the velocity, we can derive the distance between satellite and Earth Surface. To derive the topography, we need to know the position of the satellite at the time of measurement, the orbit, which can be determined from :

- GPS
- DORIS
- Satellite Laser Ranging (SLR)

GPS

Satellite Altimetry orbit determination





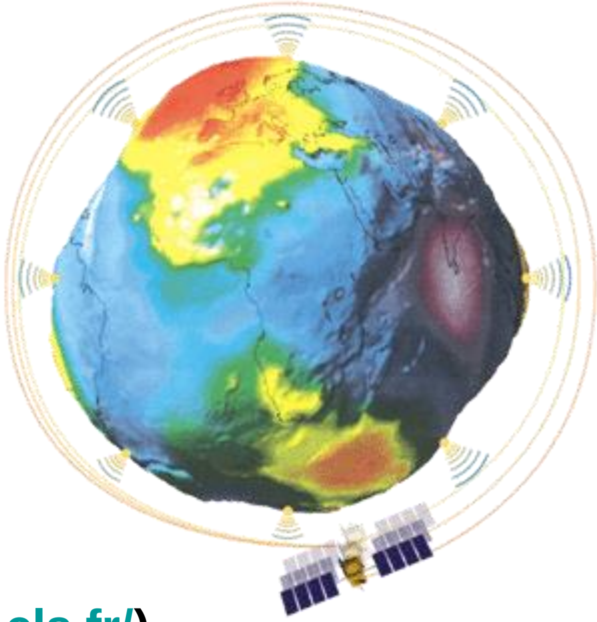
Courtesy: Peter Dana
http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

Courtesy: CNES
http://www.cnes.fr/web/CNES-en/7114-home-cnes.php

DORIS

Satellite Altimetry orbit determination

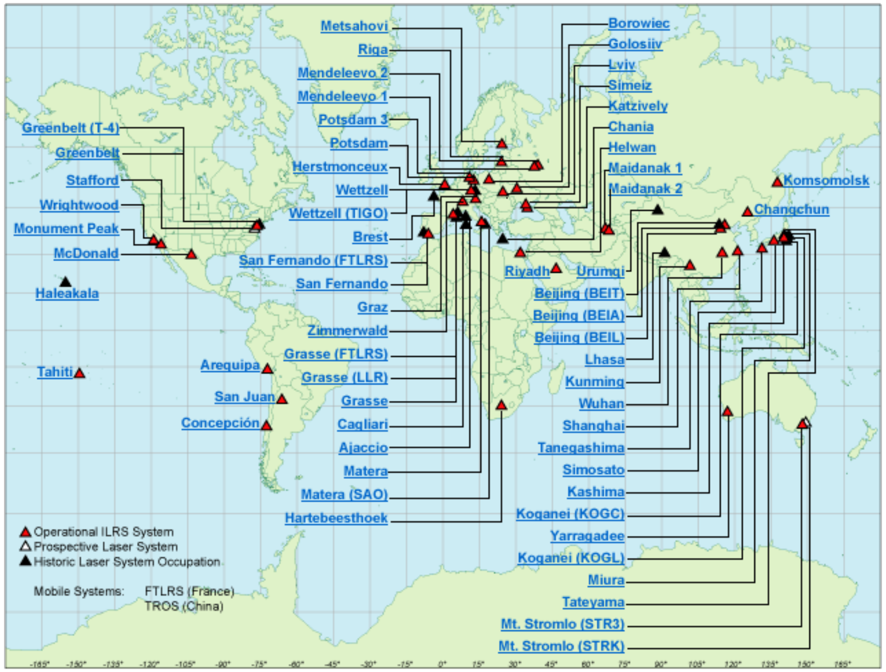
The DORIS system is based on the principle of the Doppler effect. This is the effect that causes the frequency of a wave to shift when a transmitter and receiver are in motion relative to one another. Consequently, the frequency of the received signal is not the same as that of the transmitted signal. The frequency increases as the two objects get closer and decreases as they move apart. The DORIS system transmits and receives radiofrequency waves. The receiver is on the satellite and the transmitters are ground beacons. Every 10 seconds, it measures the Doppler shift in the frequency of radio signals transmitted by beacons at 400 MHz and 2 GHz. Doris can give the position of a satellite because it compares a model of orbit (giving position and velocity) with its measurements. DORIS ultimate aim is to achieve an accuracy of one centimeter.



Courtesy International DORIS Service (http://ids.cls.fr/)

SLR

- Satellite laser ranging uses lasers to measure ranges from ground stations to satellite borne retro-reflectors to the millimeter level.



Potsdam 2

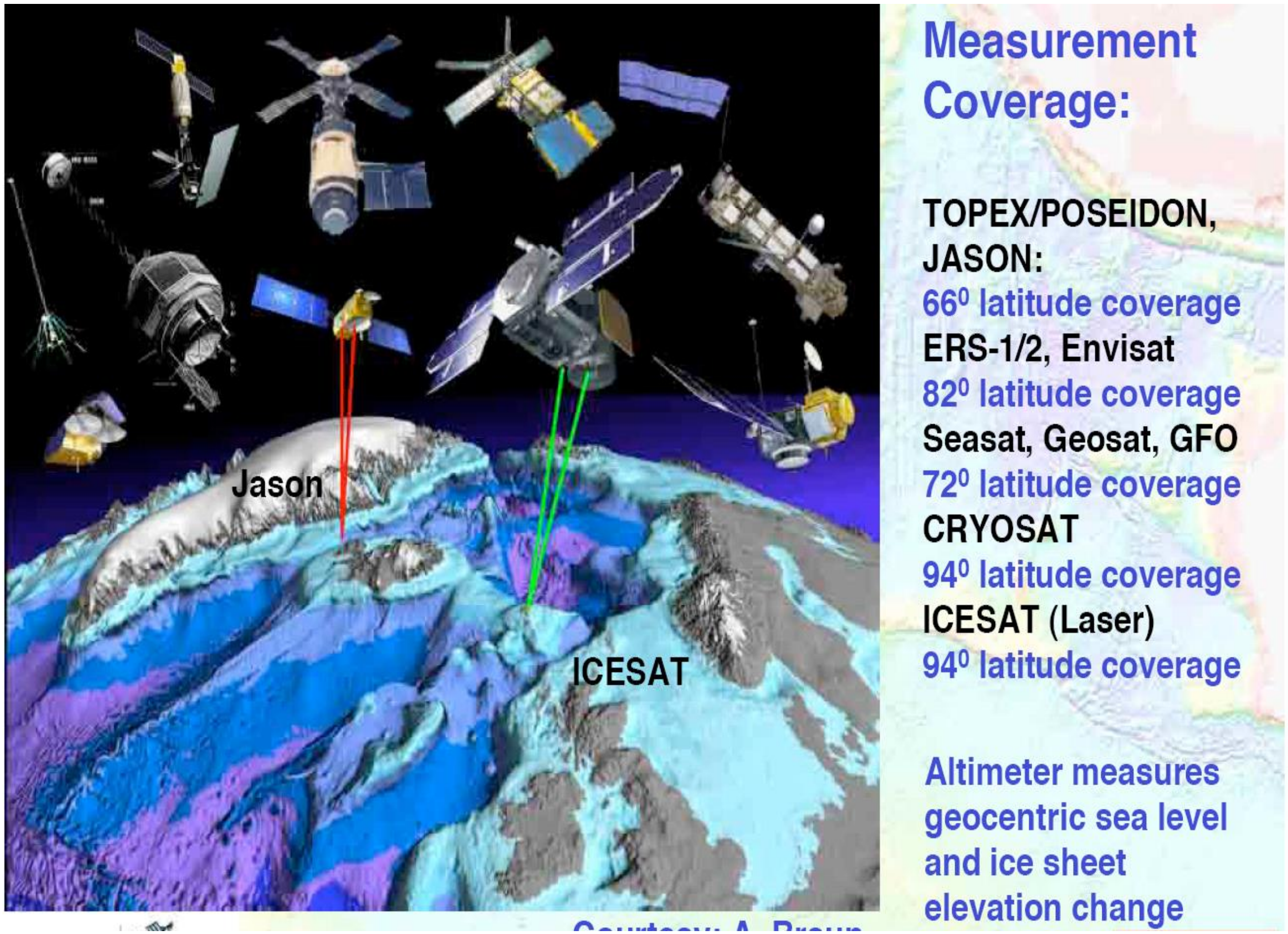
Curtesy: International Laser Ranging Service (http://ilrs.gsfc.nasa.gov/)

What Changes the orbit?

- Earth’s Gravity Field
- Third body gravitational attraction from the Sun, Moon and other planets
- Atmospheric Drag
- Direct Solar radiation Pressure
- Indirect Solar Radiation reflected from the Earth’s surface (Albedo effect)

http://grgs.obs-mip.fr/content/download/1056/7184/file/Celestial_mechanics_beutler.pdf

Satellite Altimetry Missions



Courtesy: Shum and Braun, Satellite Altimetry and Gravimetry Course. Contact Hossein Nahavandchi.

Satellite Altimetry Missions

Satellite	Agency	Launch	Altitude	Altimeter	Frequency used	Repetitivity	Inclination	Error budget (Open ocean)
Skylab	NASA	1973	435 km	S193		?	50°	Range: 1 m; Orbit: ~500 cm
GEOS 3	NASA	1974	845 km	ALT			115°	Range: 25 cm; Orbit: ~500 cm
Seasat	NASA	1978	800 km	ALT	Ku-band	17 days?	108°	Range: 5 cm; Orbit: ~100 cm
Geosat	US Navy	1985	800 km		Ku-band	17 days	108	Range: 4 cm; Orbit: 30-50 cm
ERS-1	ESA	1991	785 km	RA	Ku-band	35 days (3 days ice phase, 168 days geodetic phase)	98.5°	Range: 3 cm; Orbit: 8-15 cm
Topex/ Poseidon	NASA / CNES	1992	1336 km	Topex Poseidon-1	Ku and C-band Ku-band	10 days	66°	Range: 2 cm; Orbit: 2-3 cm

Satellite Altimetry Missions

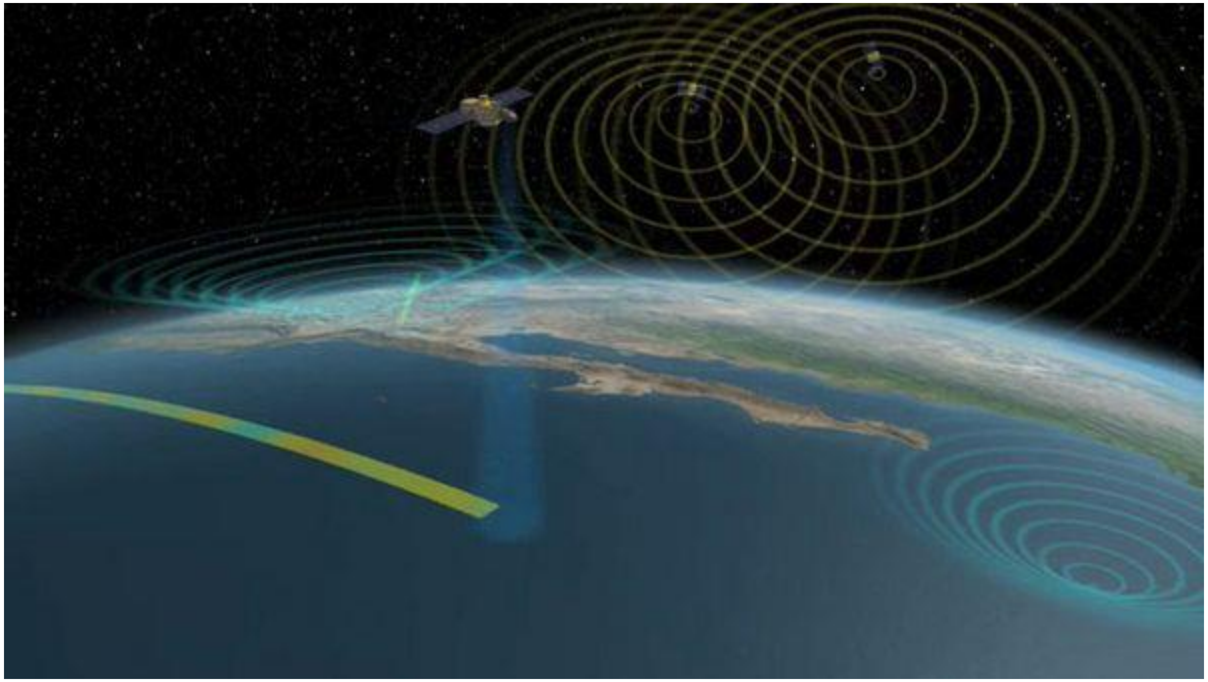
ERS-2	ESA	1995	785 km	RA	Ku-band	35 days	98.5°	Range: 3 cm; Orbit: 7-8 cm
GFO	US Navy / NOAA	1998	800 km	GFO-RA	Ku-band	17 days	108°	Range: 3.5 cm; Orbit: ? cm
Jason-1	CNES / NASA	2001	1336 km	Poseidon-2	Ku and C-band	10 days	66°	Range: 2 cm; Orbit: 2-3 cm
Envisat	ESA	2002	800 km	RA-2	Ku and S-band	35 days	98.5°	Range: 2-3 cm ; Orbit: 2-3 cm
OSTM/Jason-2	CNES / NASA / Eumetsat /NOAA	2008	1336 km	Poseidon-3	Ku and C-band	10 days	66°	Range: 2.5 cm; Orbit: 2-3 cm
Cryosat-2	ESA	2010	717 km	SIRAL	Ku-band	369 days	92°	Range: 2-3 cm; Orbit: 2-3 cm

Satellite Altimetry Missions

HY-2	China	2011	971 km		Ku and C-band	14/168 days	99.3°	Range: 4 cm;
Saral	ISRO / CNES	2012	800 km	AltiKa	Ka-band	35 days	98.55°	
Sentinel 3	ESA	2014	814 km	SRAL	Ku and C-band	27 days	98.5º	
Jason-3	CNES / NASA/ Eumetsat/ NOAA	2014	1336	Poseidon-3B	Ku and C-band	10 days	66º	
Jason-CS	ESA/ CNES / NASA/ Eumetsat/ NOAA	2017	1336	New altimeter		10 days	66º	
SWOT	CNES / NASA/	2020	970		Ka-band Radar Interferometer	22 days	78º	Range: 1 cm;

http://www.aviso.oceanobs.com

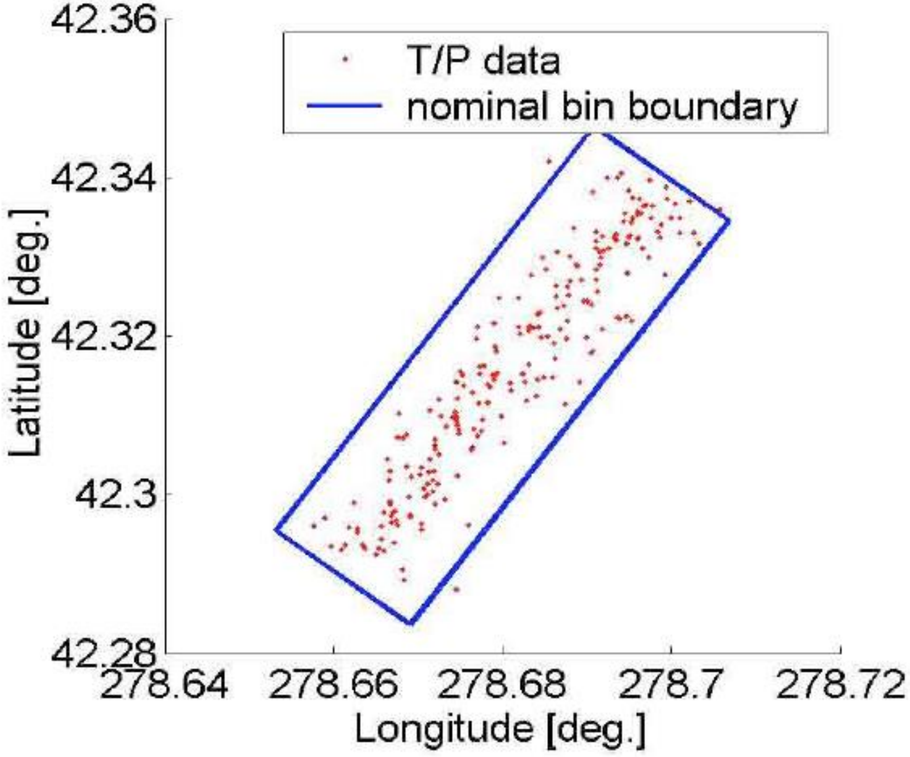
Satellite Altimetry Movie



Courtesy: NASA/JPL-Caltech **http://sealevel.jpl.nasa.gov/gallery/videos/**

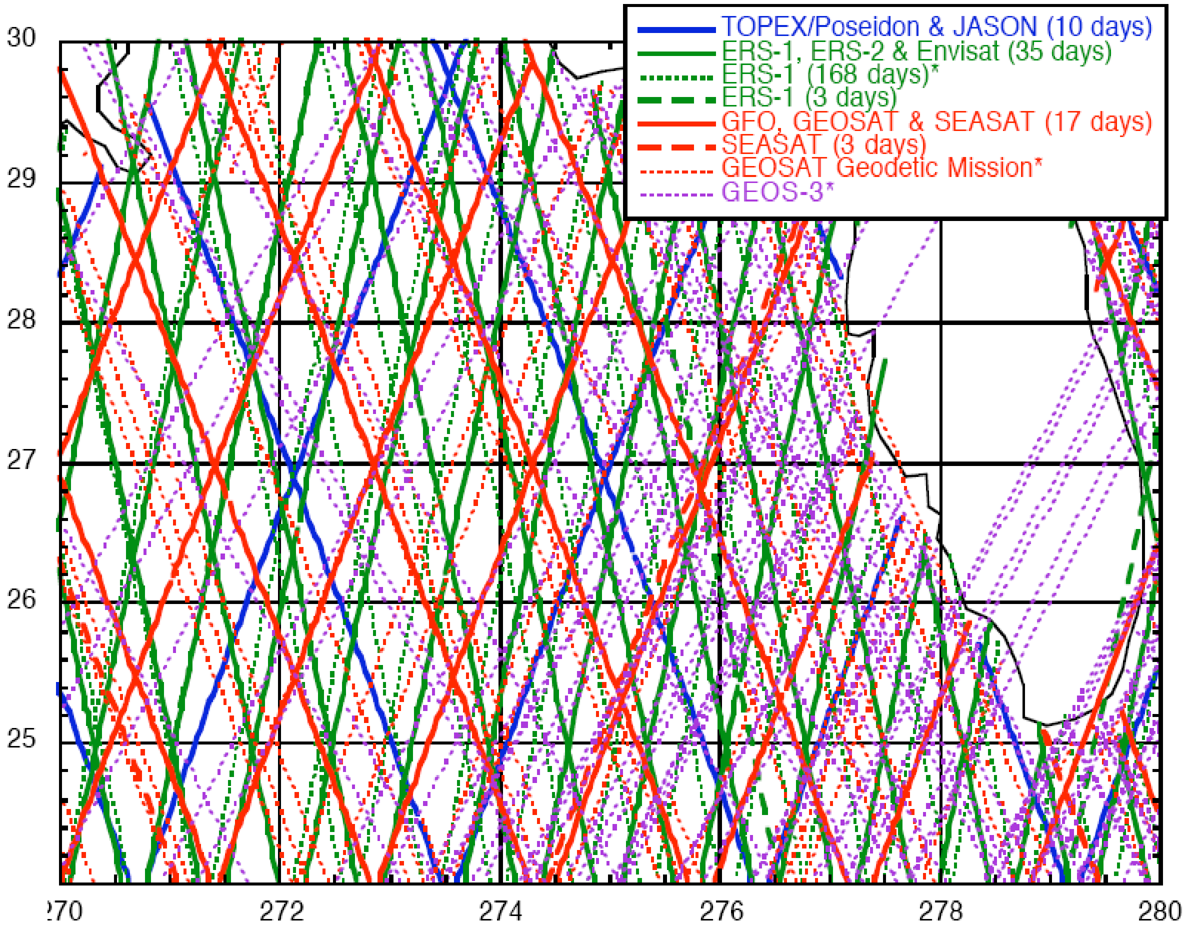
Satellite altimetry data points registered in a Bin

The ground track of satellite altimeters does not repeat exactly because of the perturbations and orbital maneuvers, and the fact that the time for the satellite to orbit the Earth is not exactly constant, therefore, Sea Surface Height (SSH) measurements are not repeated at exactly the same location every time, but within a small area, or bin.



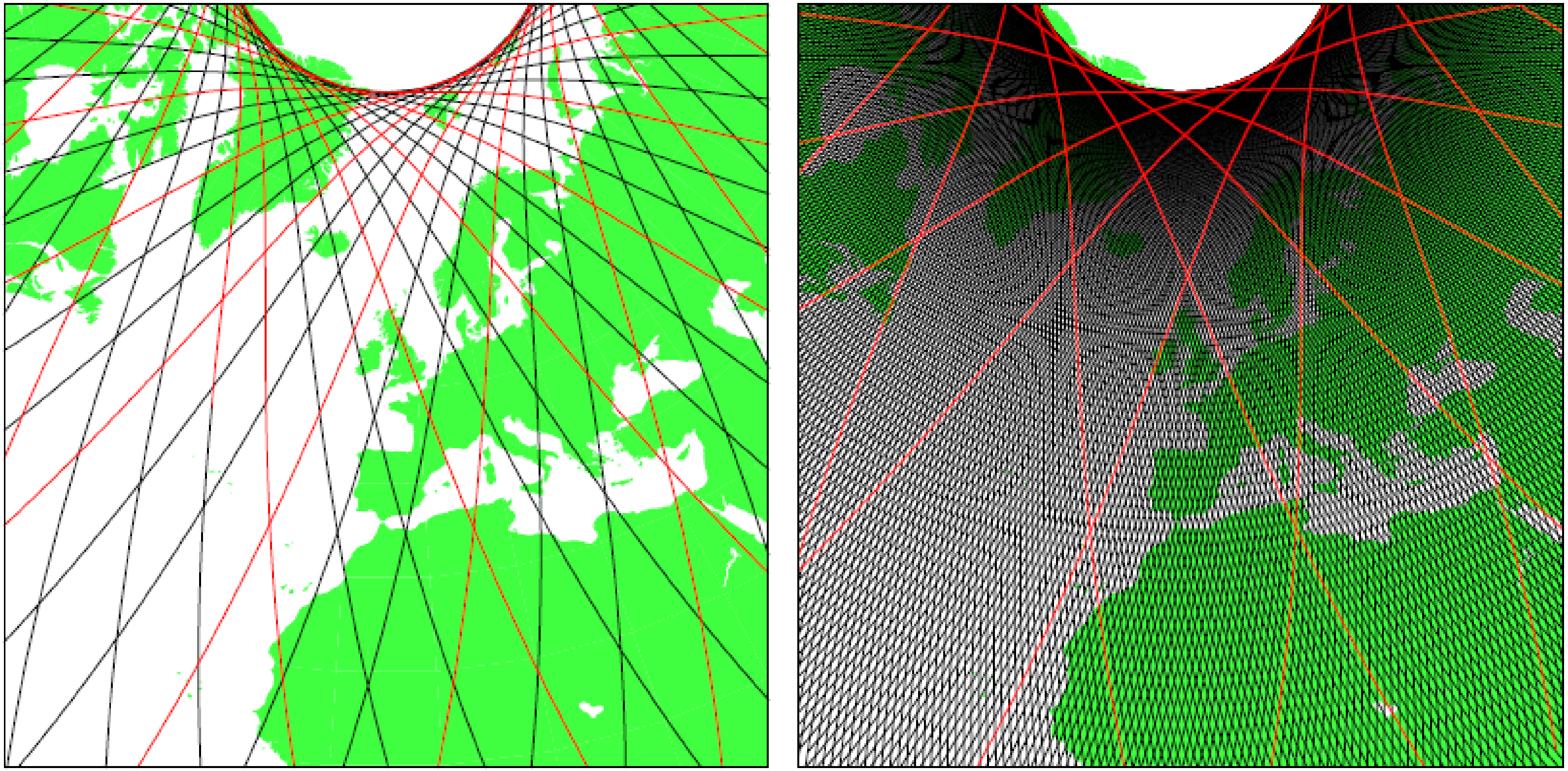
Courtesy: Shum and Braun, Satellite Altimetry and Gravimetry Course. Contact Hossein Nahavandchi.

Ground Tracks in Global Models



Courtesy: Shum and Braun, Satellite Altimetry and Gravimetry Course. Contact Hossein Nahavandchi.

Ground Tracks

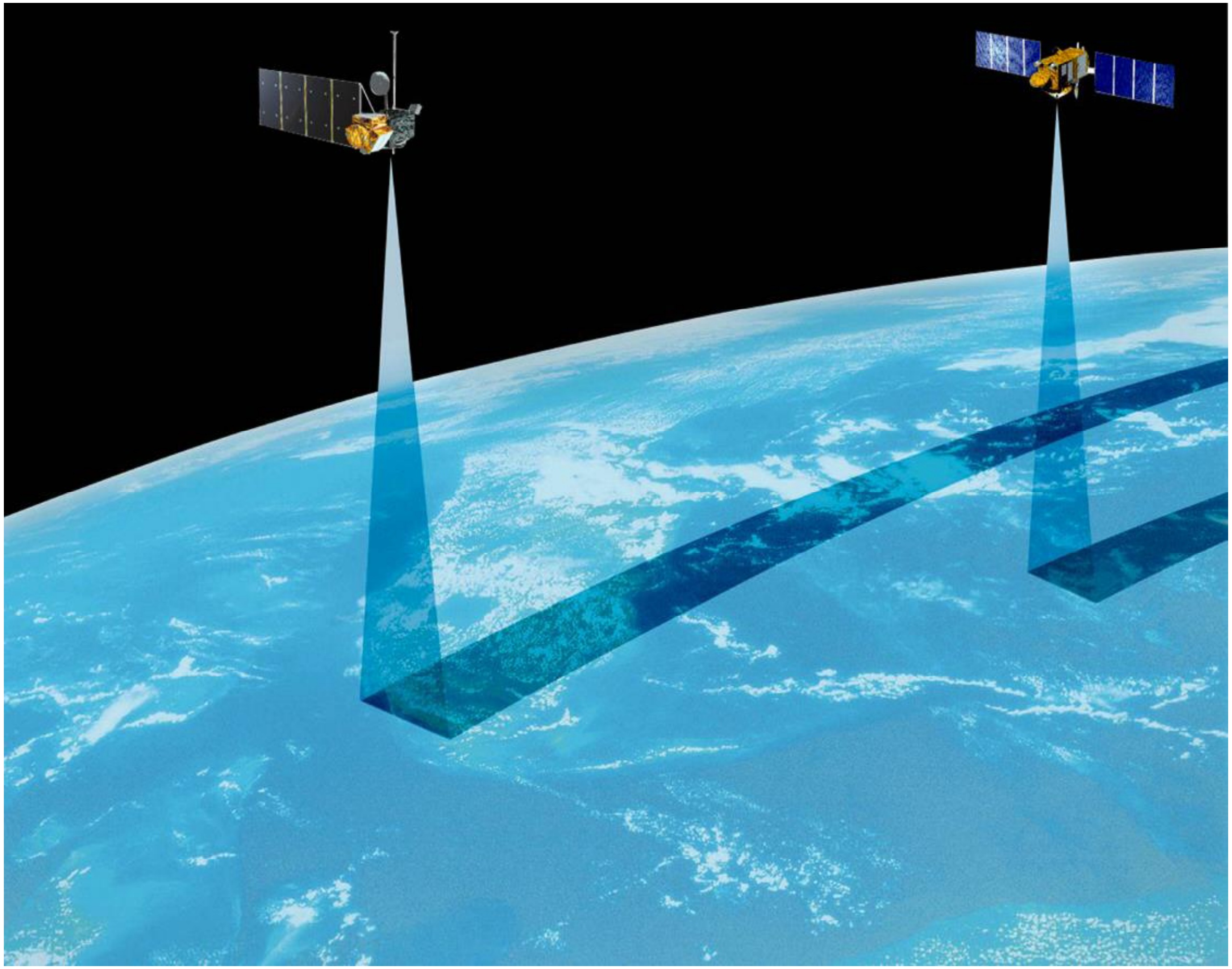


3-day repeat orbit 35-day repeat orbit

Courtesy: Marc Naeije, Delft university of Technology, Faculty of Aerospace Engineering

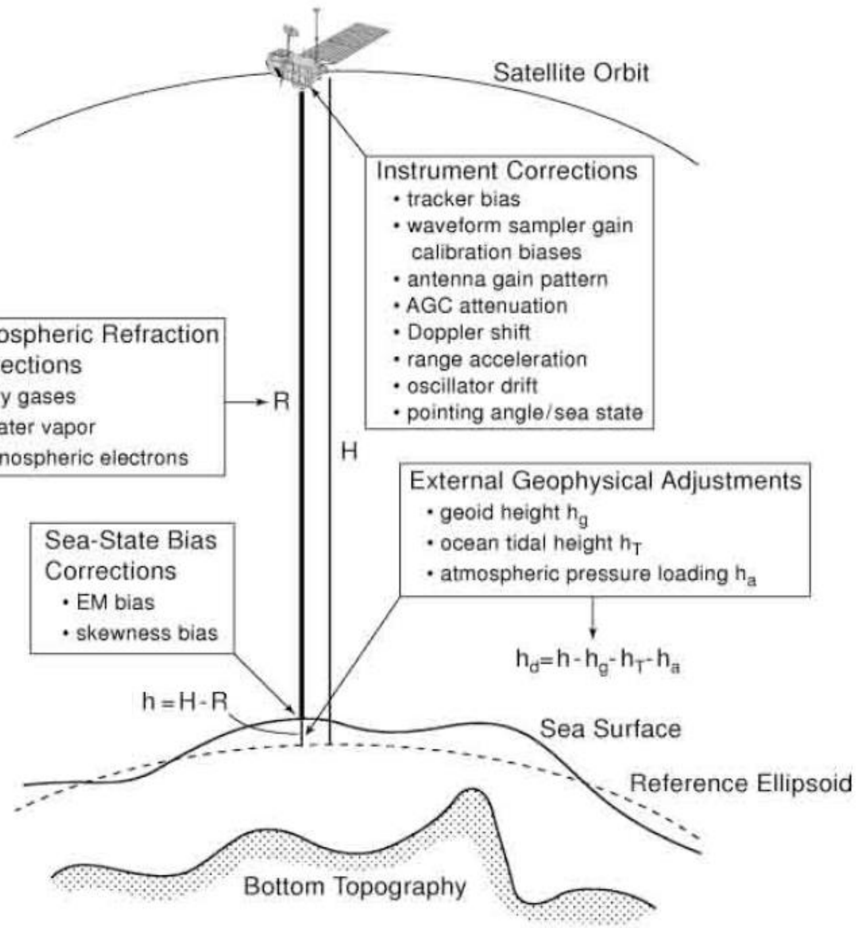
http://www.deos.tudelft.nl/seamerges/docs/SMkickoff_SALT.pdf

Satellite Altimetry Tracks



Courtesy: Nerem et al., GRACE Hydrology Workshop, 2004
http://bprc.osu.edu/water/Meetings_WATERHM/SubMesoscale_April2008/presentations-day2/Nerem.ppt

Sea Surface Heights from Altimetry



Courtesy: Chelton et al. [2001]

Chelton D.B., J.C. Ries, B.J. Haines, L.L. Fu, P. Callahan, 2001: Satellite altimetry, in Satellite altimetry and earth sciences, ed. L.L. Fu and A. Cazanave. Academic Press, NY, 57-64.

Sea Surface Height

$$h_{ssh} = (h_{orbit} - h_{alt} - h_{insru} - h_{ssb} - h_{dry} - h_{wet} - h_{iono} \\ - h_{tides} - h_{ib}) + b + e$$

where

h_{orbit}	the altitude of altimeter orbit;
h_{alt}	the raw altimeter range;
h_{insru}	the total of the instrument corrections;
h_{ssb}	the sea state bias correction;
h_{dry}	the dry troposphere correction;
h_{wet}	the wet troposphere correction;
h_{ion}	the ionosphere correction;
h_{tides}	the ocean tide correction, solid Earth tide correction and the pole tide correction;
h_{ib}	the inverted barometer correction;
b	the altimeter bias;
e	the contribution of random and systematic errors.

Mean Sea Surface

Having sea surface heights we can calculate Mean Sea Surface Height, or Mean Sea Surface (MSS) from satellite altimetry observations

Applications

Satellite altimetry has applications in oceanography, geophysics, geodesy, glaciology, atmospheric and space science: **Climate Change Studies**.

http://topex-www.jpl.nasa.gov/

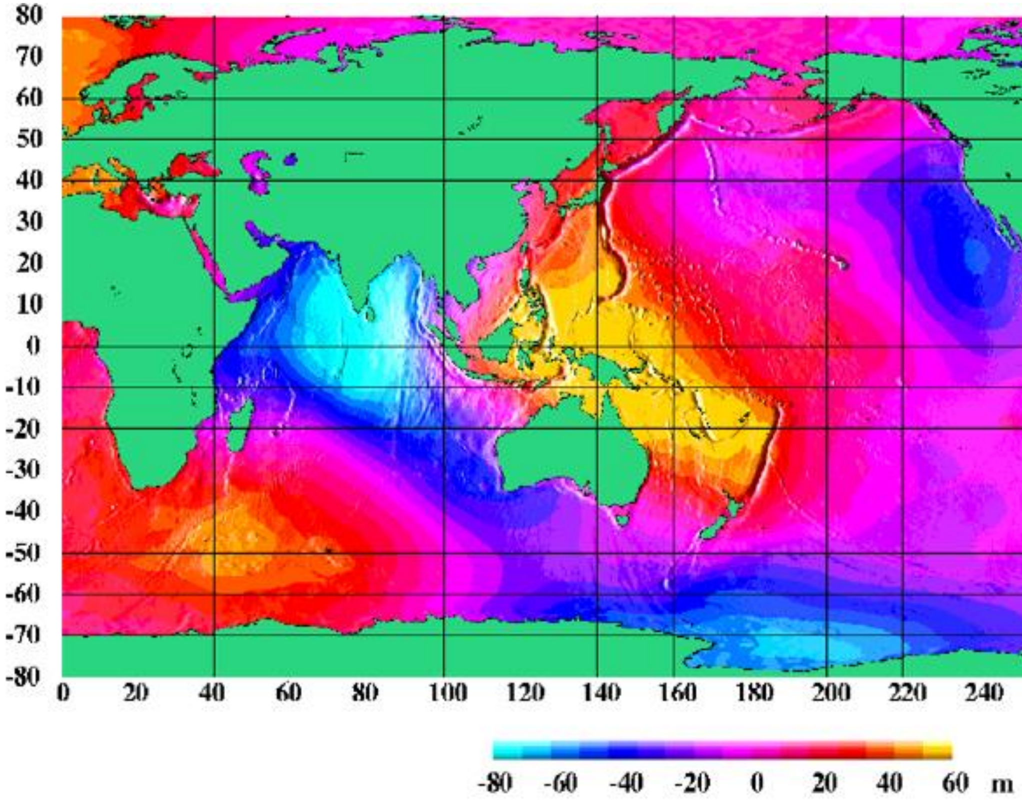
http://www.aviso.oceanobs.com/en/applications/index.html

Applications

- Parameters like Mean Sea Surface Heights, the Geoidal height, the Gravity Anomalies are very important parameters for other disciplines than Geodesy.

- We provide these parameters for, for example, oceanographers and geophysicist.

Mean sea surface height
from satellite Altimetry



Knudsen and Andersen, KMS

Geoid Heights and Gravity

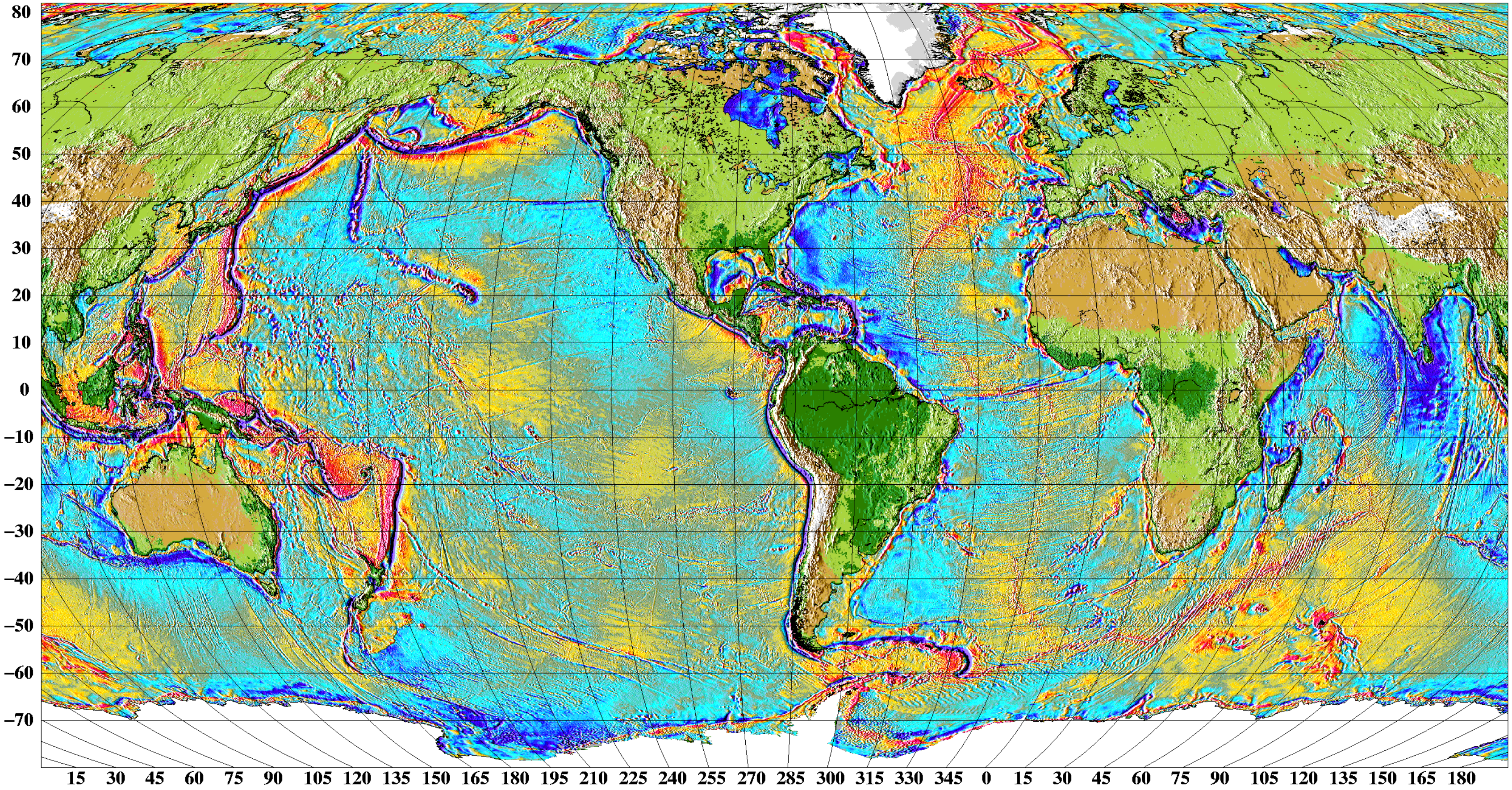
- The Geoid and Mean Sea Surface heights are related mathematically with the gravity anomalies.

- Having computed the geoidal heights and Mean Sea Surface heights, one can compute the gravity anomalies over oceans (Marine gravity anomaly)

Marine Gravity anomaly

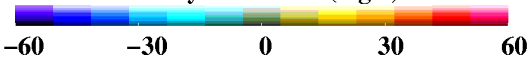
NTNU

Free Air Gravity Anomalies from Satellite Altimetry



Produced by:
Ole B. Andersen and Per Knudsen – Denmark
oa,pk@kms.dk, research.kms.dk/GRAVITY

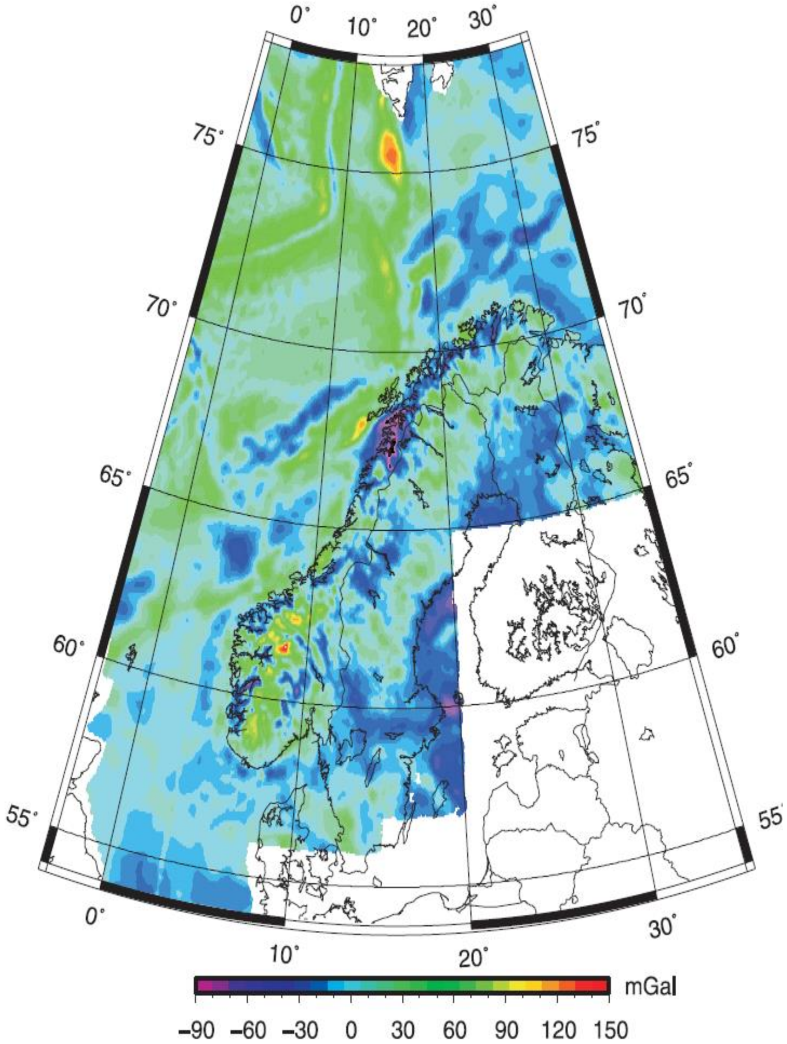
Free Air Gravity Anomalies (mgal)



Kort & Matrikelstyrelsen

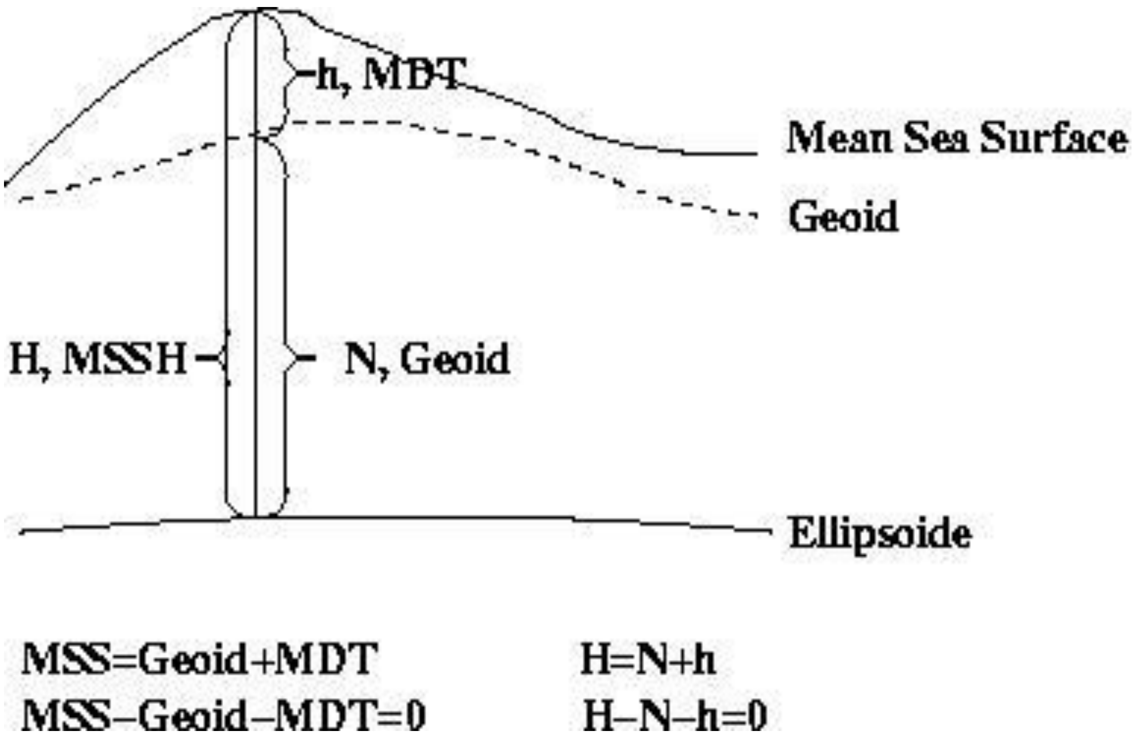
Marine Gravity Anomaly

Marine gravity anomalies from Satellite Altimetry data are shown over areas covered by Water. Over land, terrestrial gravity data are used in the Figure.



Courtesy: Soltanpour and Nahavandchi, NTNU.

Satellite Altimetry Applications



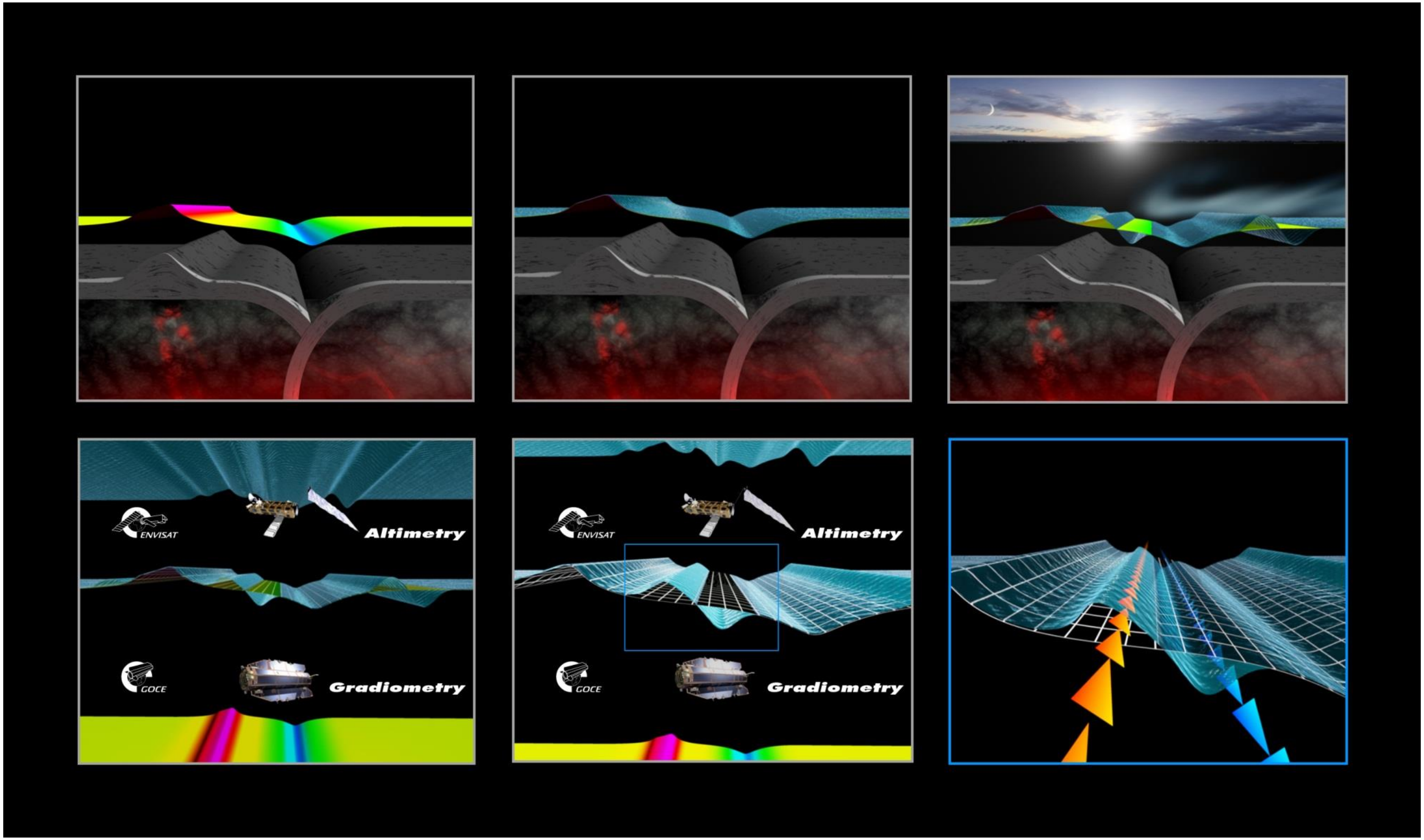
If we determine, MSS from altimetry data, Geoid height N from Gravimetry data (comes later), and MDT from oceanography data, then we have a good possibility to investigate the Ocean Circulation ⟹ **GOCINA** and **OCTAS** projects.

Ocean Circulation and Transport

For Ocean circulation and transport studies, one needs:

- A Mean Dynamic Topography model, MDT
- A high precision geoid model, N
- A Mean Sea Surface model, MSS

Ocean Circulation and Transport



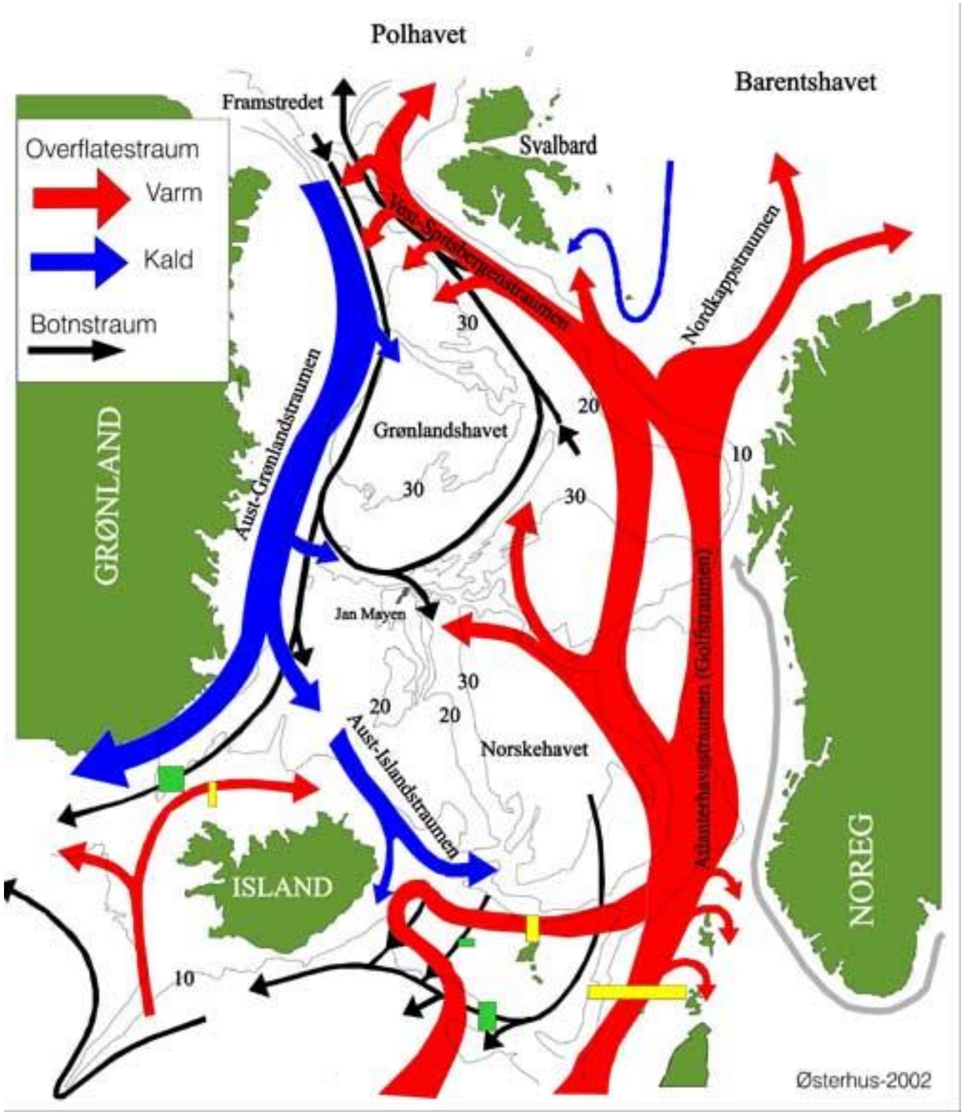
The combination of sea-surface height mapped by altimeters and the knowledge of the precise ocean geoid that will improve our understanding of surface currents and lead to a better knowledge of general ocean circulation patterns - crucial for understanding climate change.

Courtesy: ESA http://www.esa.int/esaLP/ESA4ZK1VMOC_LPgoce_0.html

North Atlantic Ocean Circulation
General

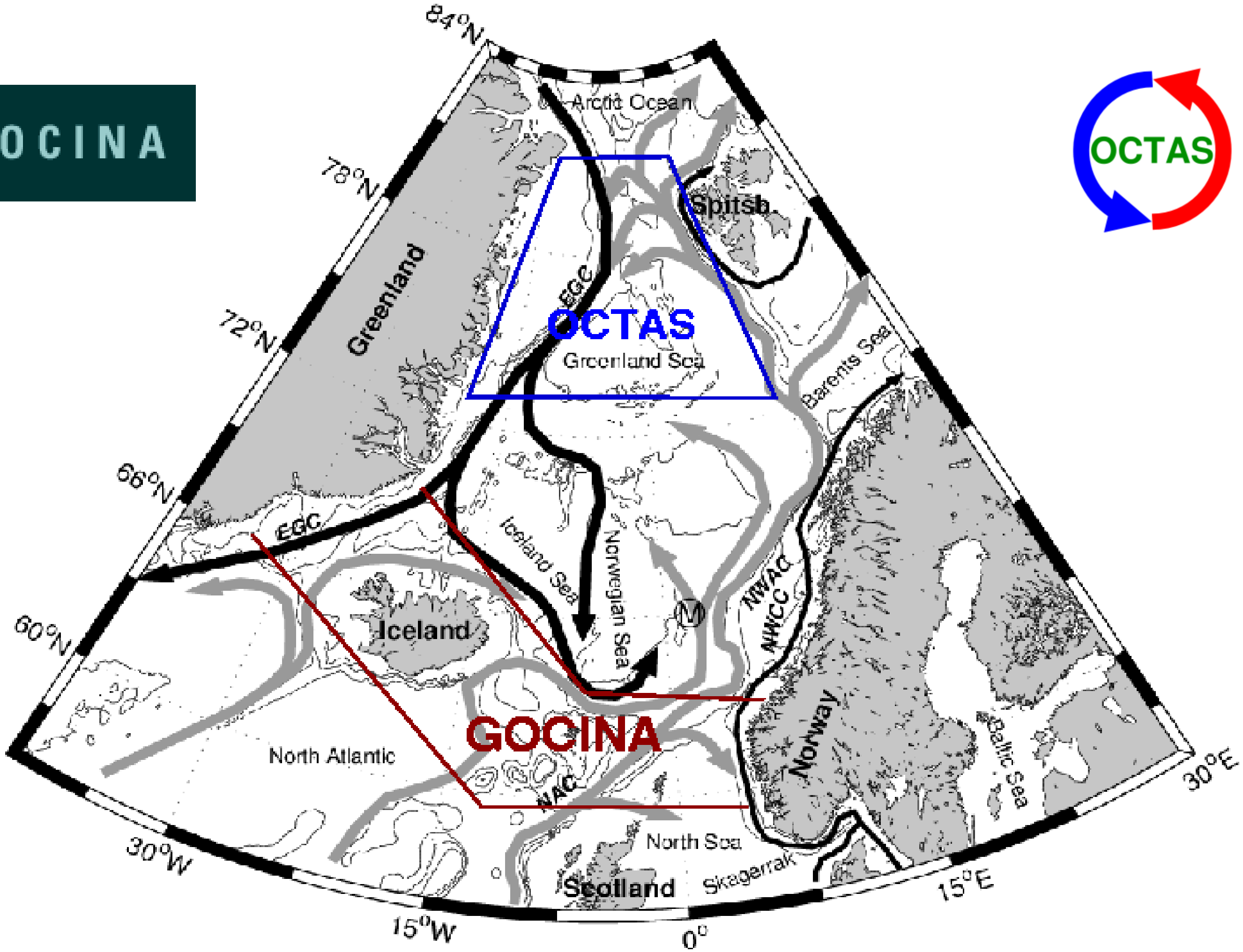
Credit: HENNING DALHOFF / SCIENCE PHOTO LIBRARY

North Atlantic Ocean Circulation
In more details



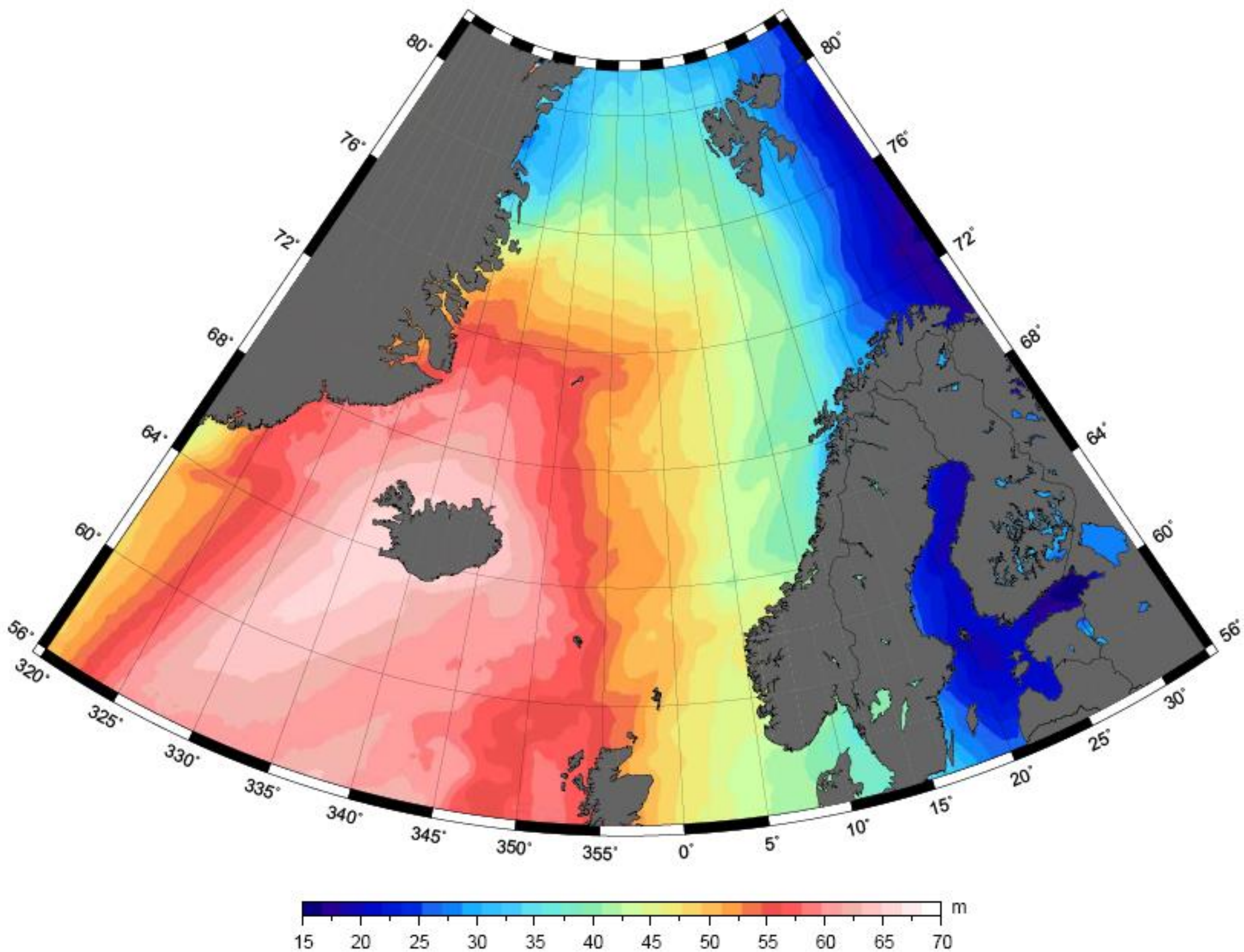
Illustrasjon: Svein Østerhus

OCTAS and GOCINA Projects



http://earth.esa.int/goce06/participants/169/pres_solheim_169.pdf
http://gocinascience.spacecenter.dk/

OCTAS MSS Model

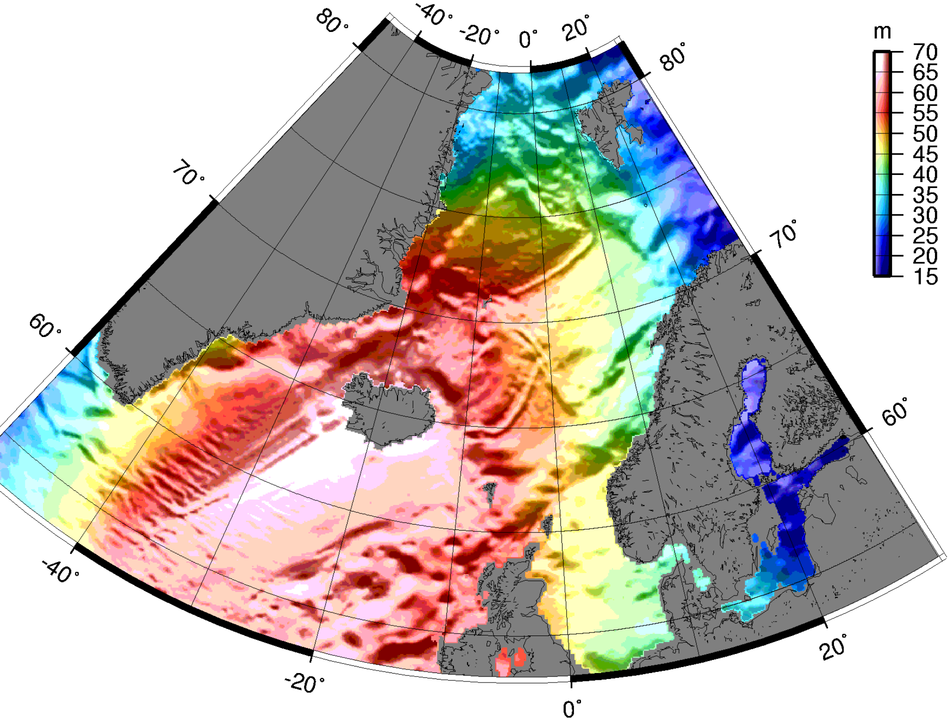


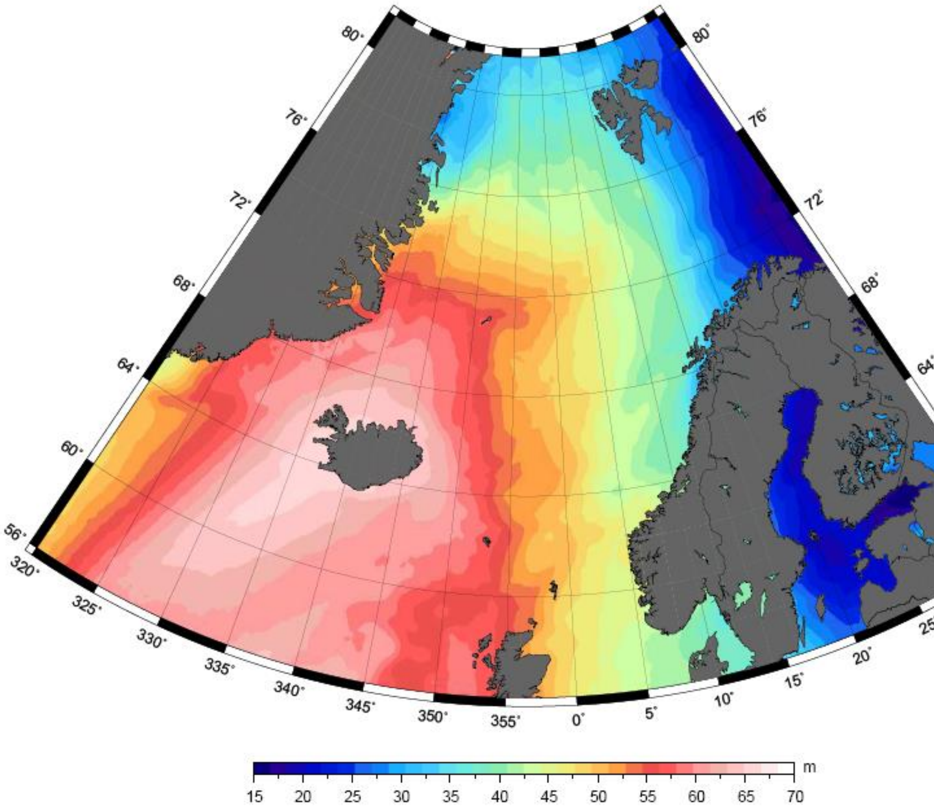
Courtesy: Ghazavi and Nahavandchi, NTNU.

http://versita.metapress.com/content/r378625241077772/fulltext.pdf

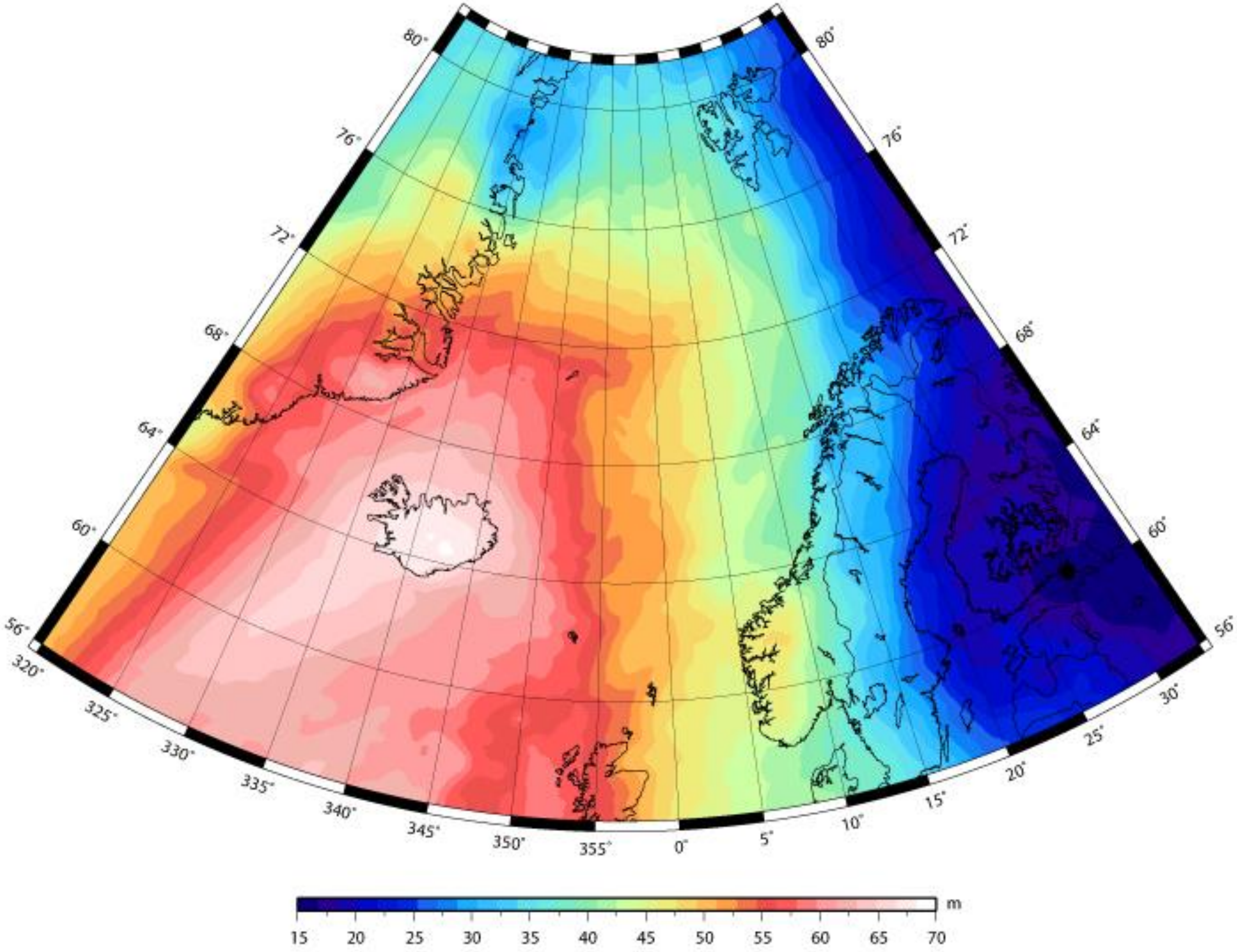
COMPARISON

MSS Models





OCTAS Geoid Model

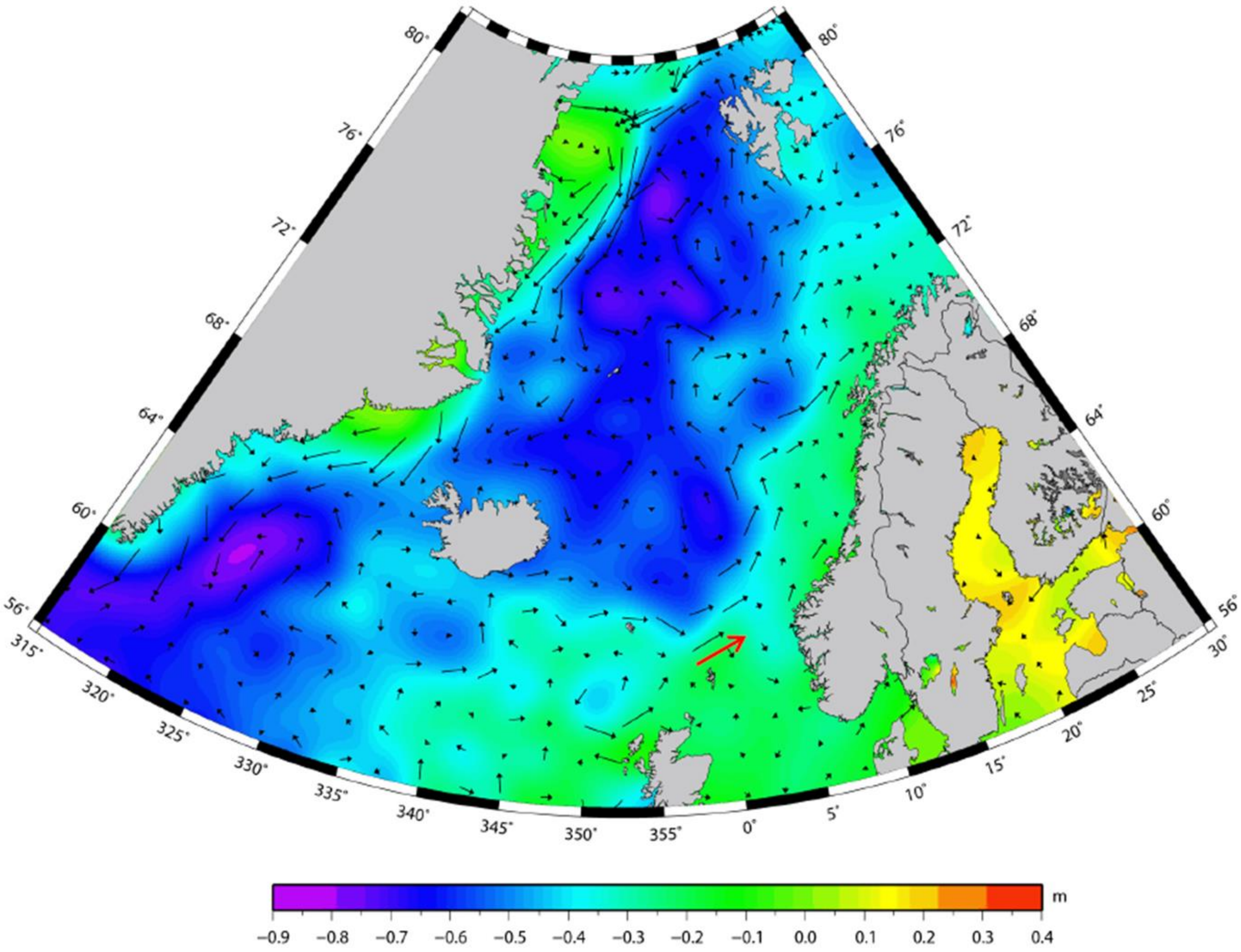


Courtesy: Omang Et al. OCTAS project.

http://earth.esa.int/goce06/participants/169/pres_solheim_169.pdf

OCTAS MDT Model

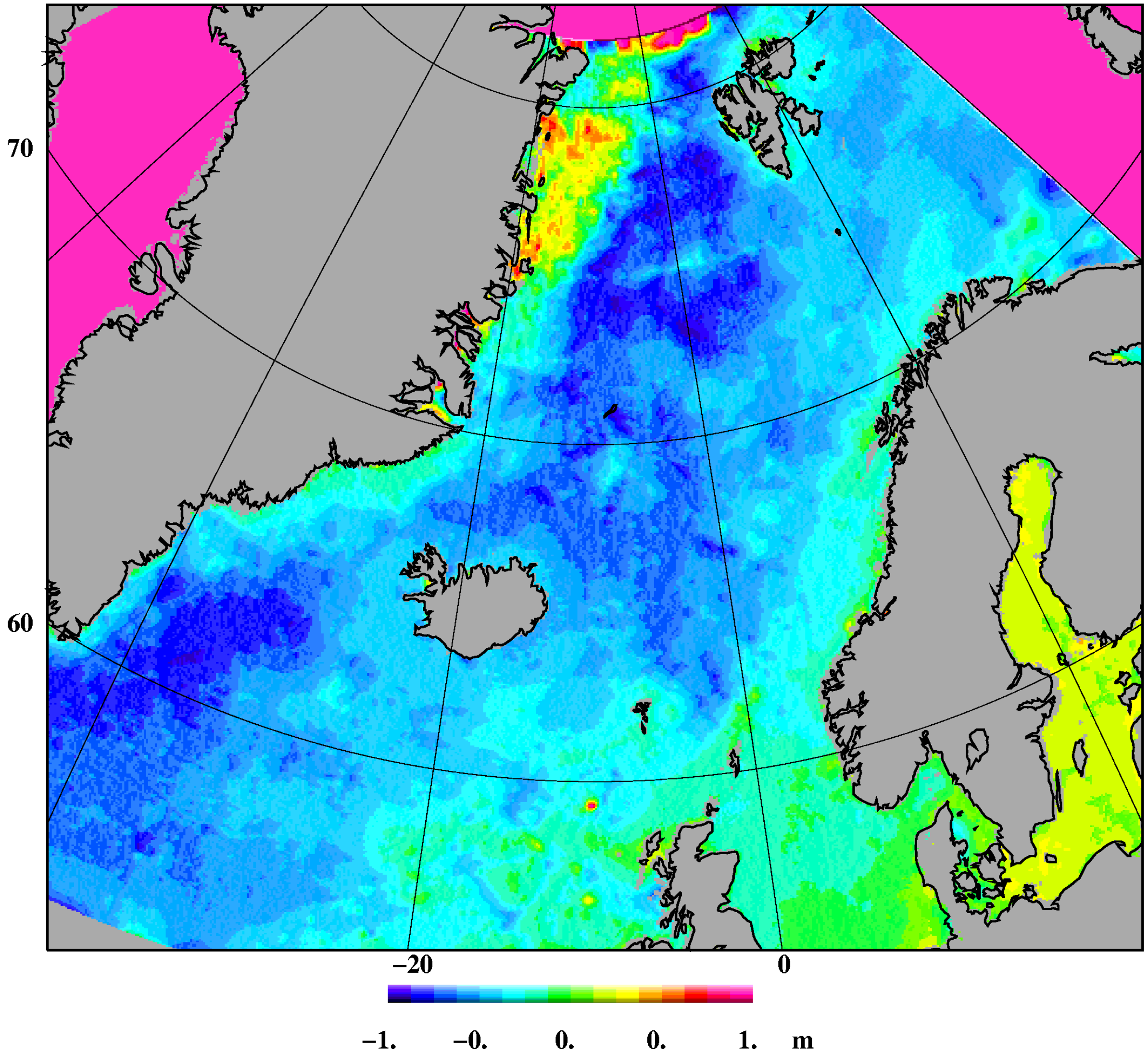
MDT=MSS-GEOID



Courtesy: Ghazavi and Nahavandchi, NTNU.

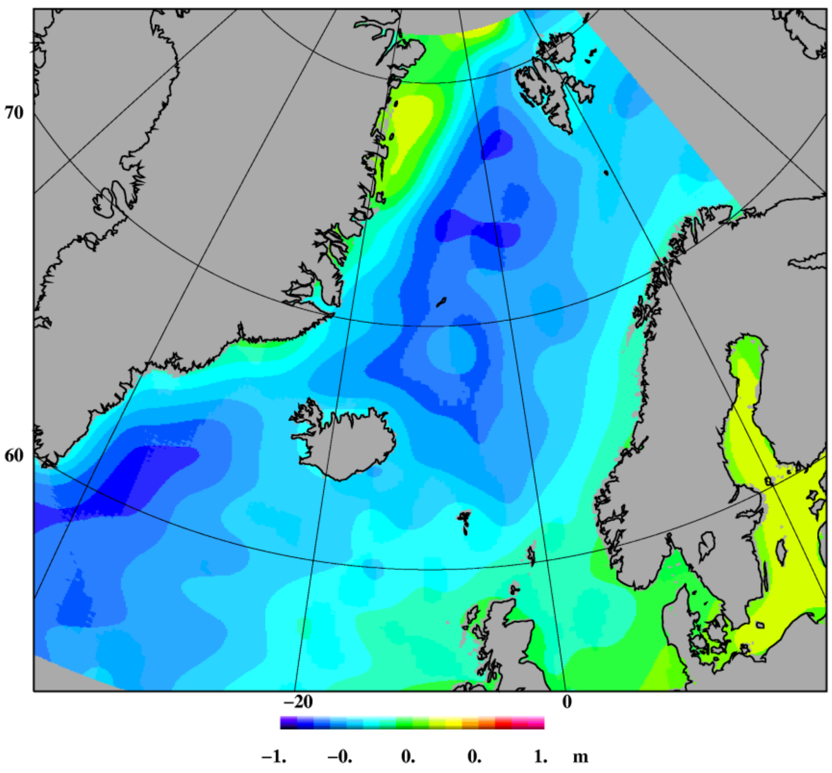
http://versita.metapress.com/content/r378625241077772/fulltext.pdf

Another MDT

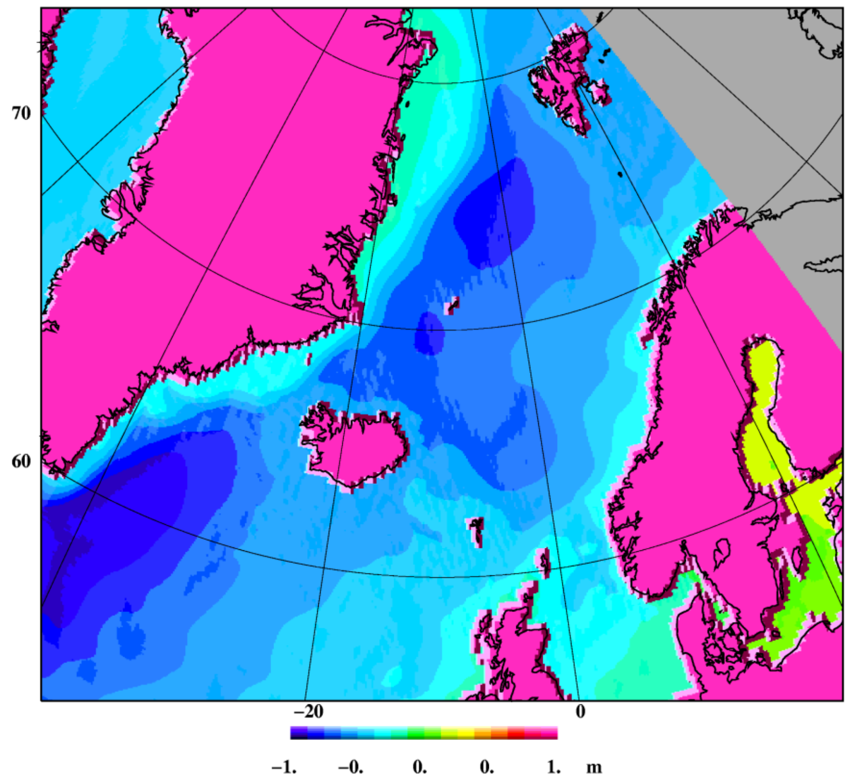


http://gocinascience.spacecenter.dk/

Comparison with oceanographic MDT models



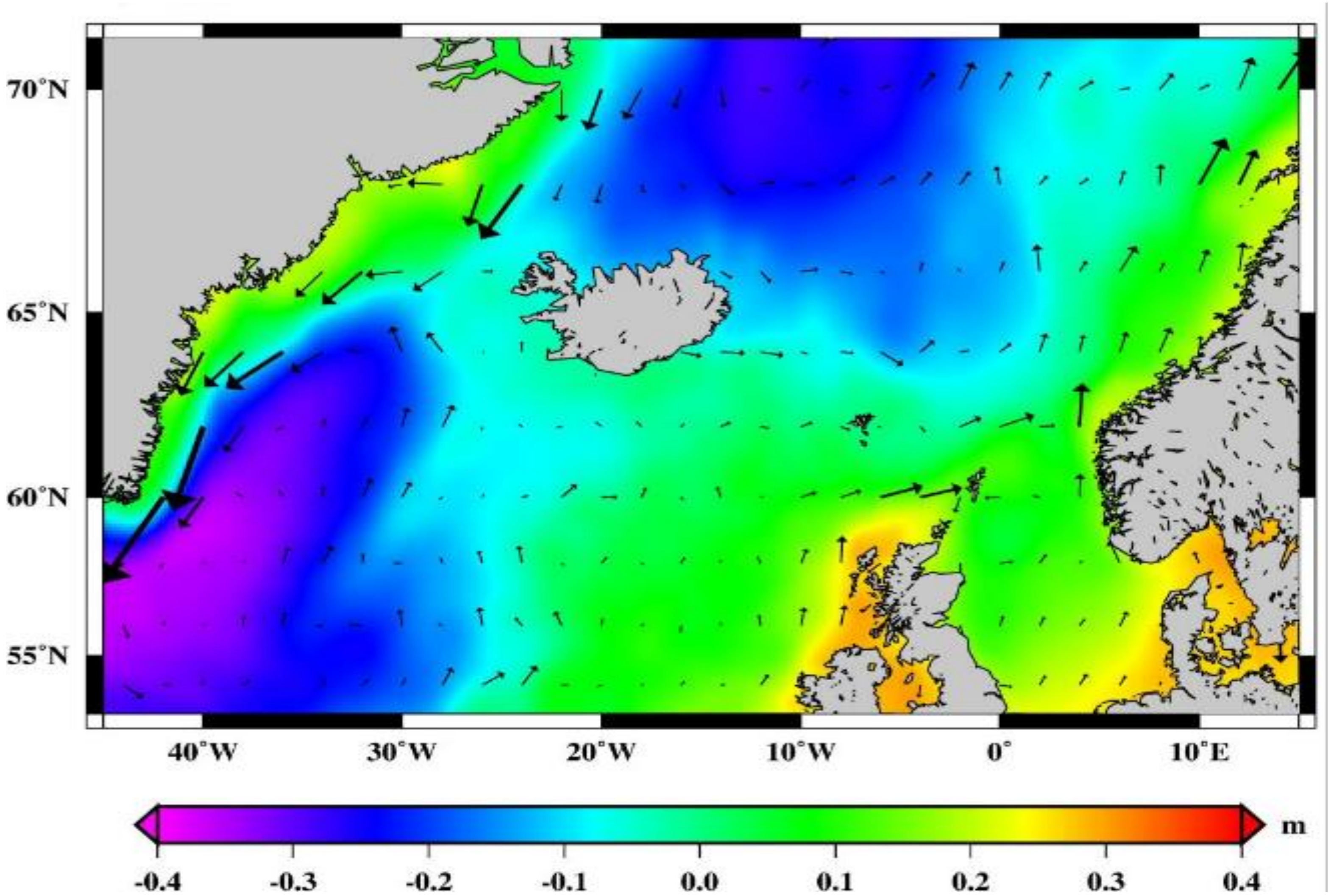
MDT from MSS-Geoid



Oceanographic model

http://gocinascience.spacecenter.dk/

Mean Dynamic Topography and the Currents (GOCINA Project)

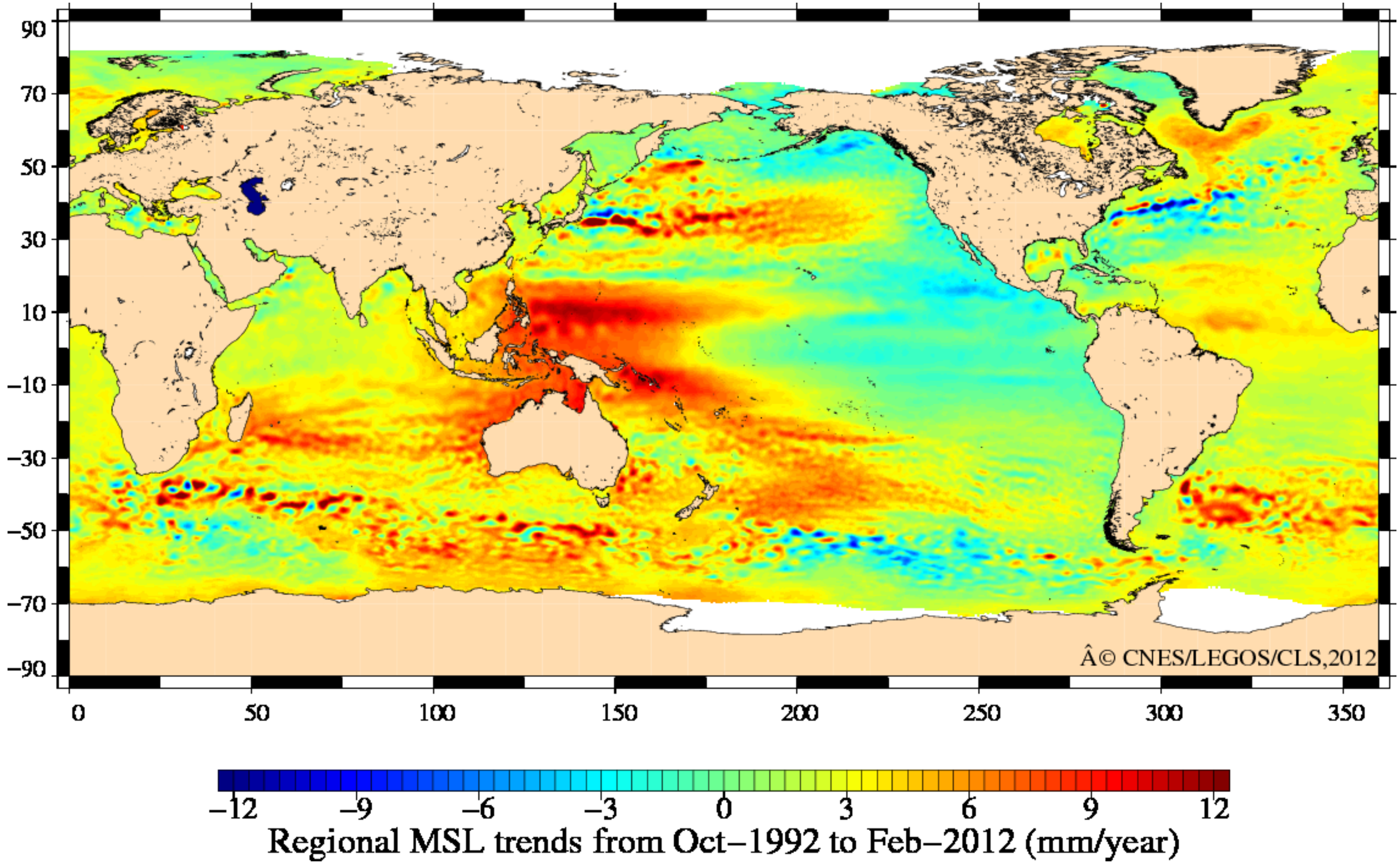


http://gocinascience.spacecenter.dk/

Other types of Application

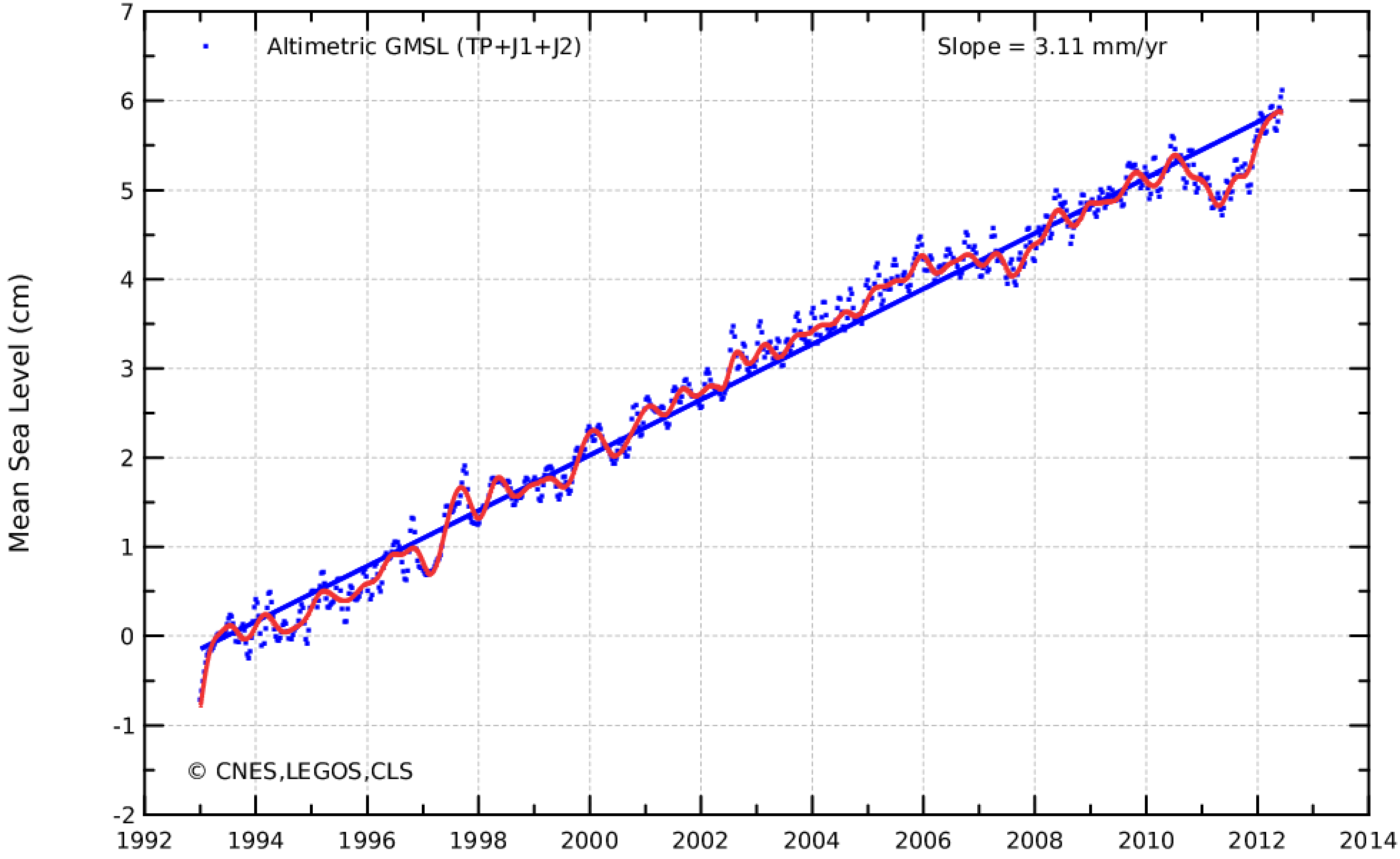
Altimetry satellites measure the sea surface heights. From these measurements we can calculate sea-level changes, as the satellite altimetry missions repeatedly observe the Earth’s oceans. Global sea level changes and sea level trends can then be computed.

Sea level trend



Credits CLS/Cnes/Legos
http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/

Global sea level change from satellite altimetry



http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/
http://www.cnes.fr/web/CNES-en/7114-home-cnes.php
http://www.cls.fr/welcome_en.html

Radar versus Laser Altimetry

Radar Altimetry versus Laser Altimetry

- Footprint 2-20 km versus 40-70 m
- Vertical accuracy <5cm versus <10cm
- Weather independent versus weather dependent (clouds)
- Robust versus energy consuming (not-robust)
- Long history (18 years) versus short missions only

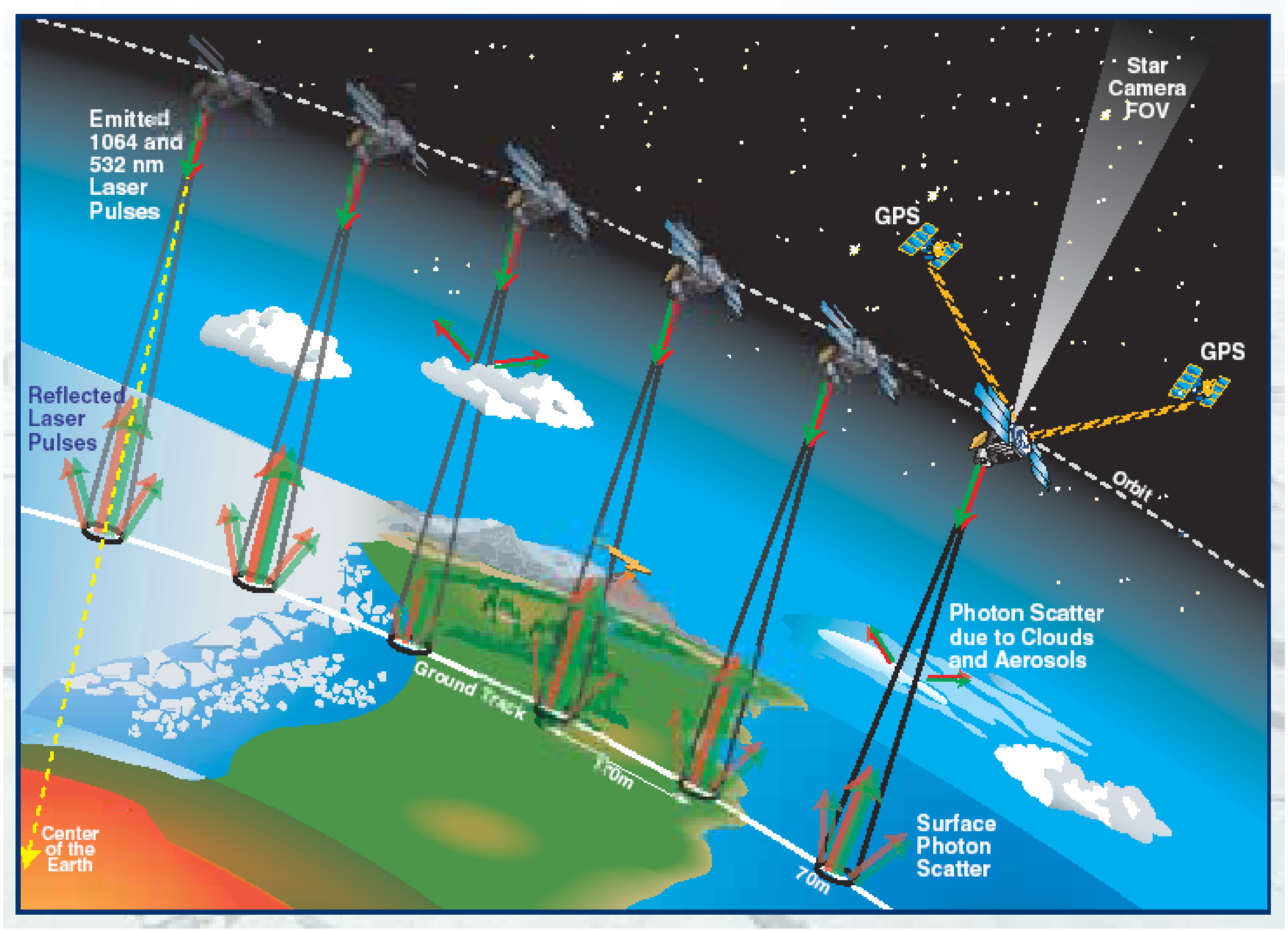
Radar altimetry operates on most altimetry missions and works over water and ice (and land??) but laser altimetry operates on ICESat and works over water, ice and land

ICESat

- First laser altimeter in space for Earth observation
- Important contributions to global climate change, ice mass change, sea level change, digital elevation models, and hydrology
- 3 lasers onboard- 1064-532 nanometer
- Laser pulse rate 40 Hz- footprint spacing=170 m
- Footprint diameter= 70 m
- Inclination= 94 degree, near circular orbit in altitude of 600 km
- Position accuracy 20-50 m
- GPS receiver and star trackers for navigation

http://icesat.gsfc.nasa.gov/

ICESat

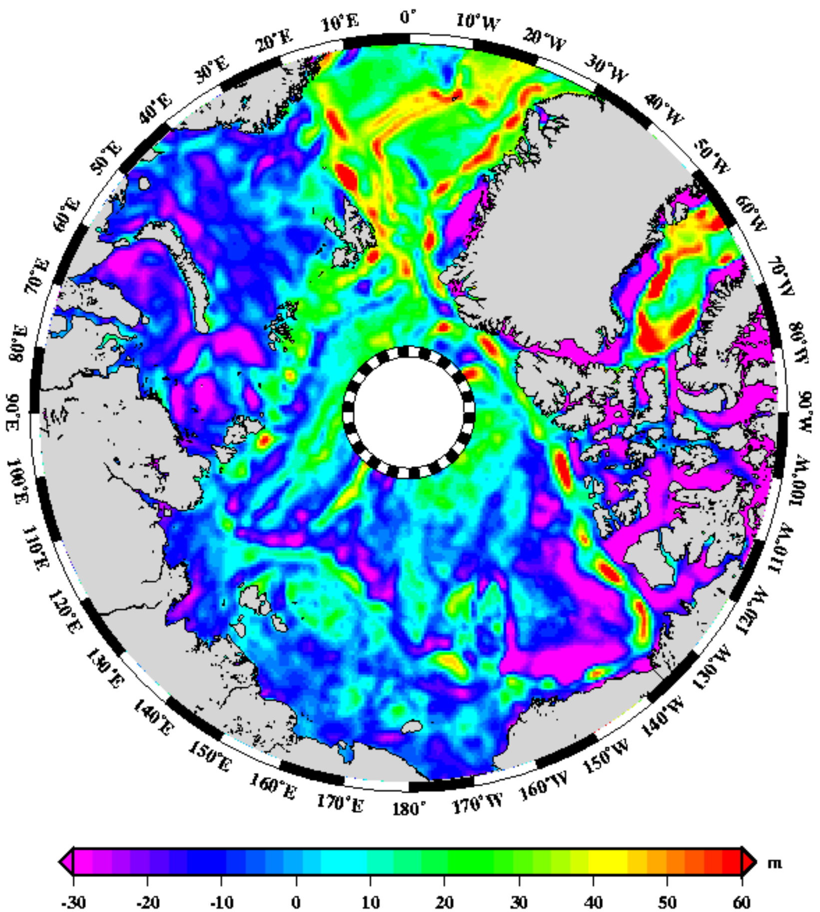


http://icesat.gsfc.nasa.gov/

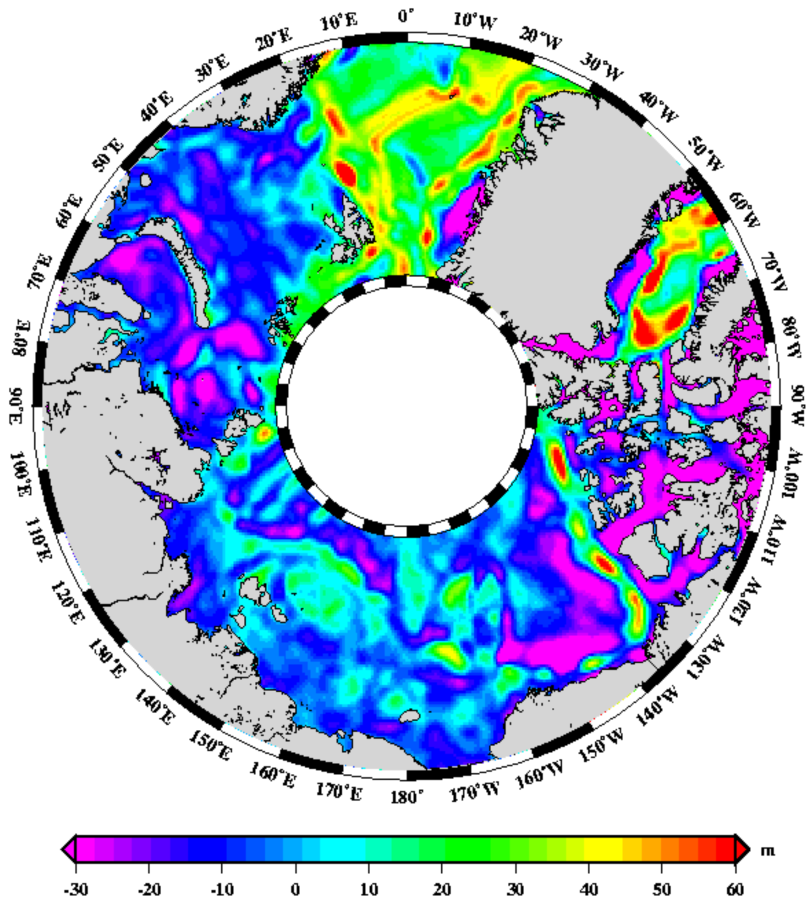
ICESat Gravity anomaly

Arctic Gravity field

ICESAT



ERS

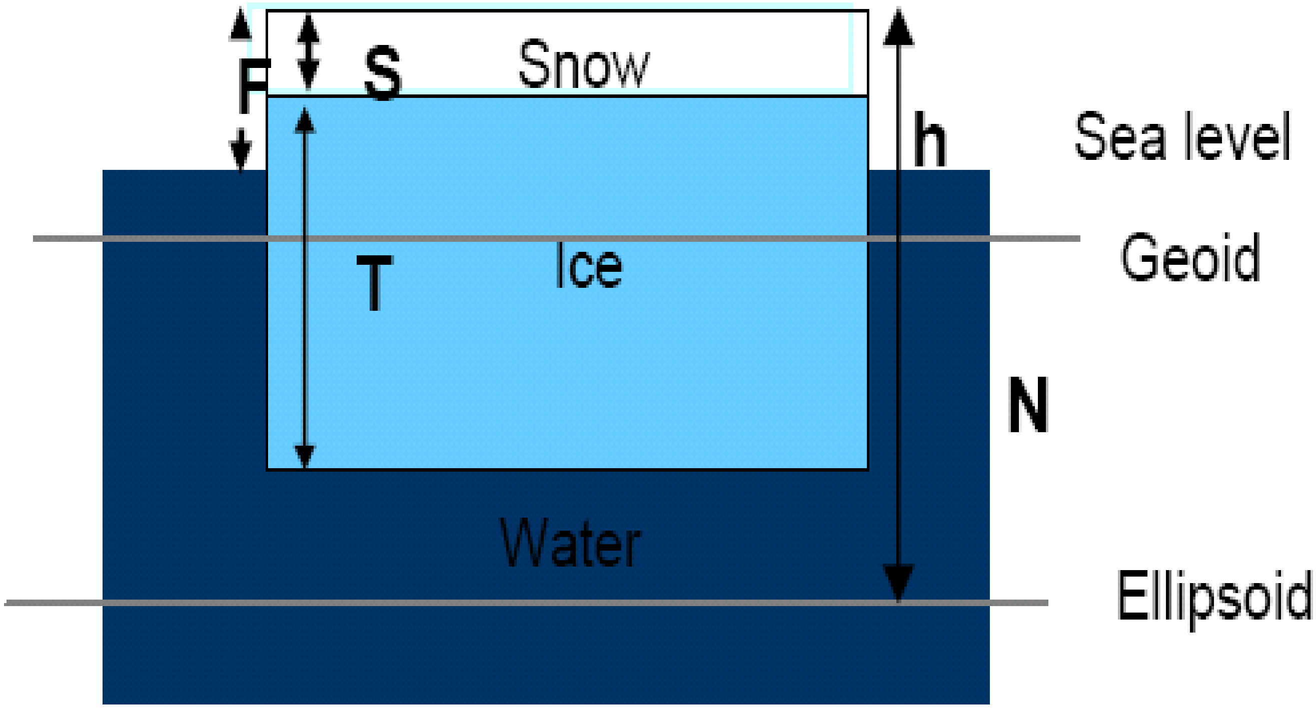


Comparisons of the ICESat mapping of gravity field with very long-period mission of ERS show good consistency.

Courtesy: O.B. Anderson, OCTAS study course. Contact Hossein Nahavandchi.

Sea ice freeboard height

F in figure

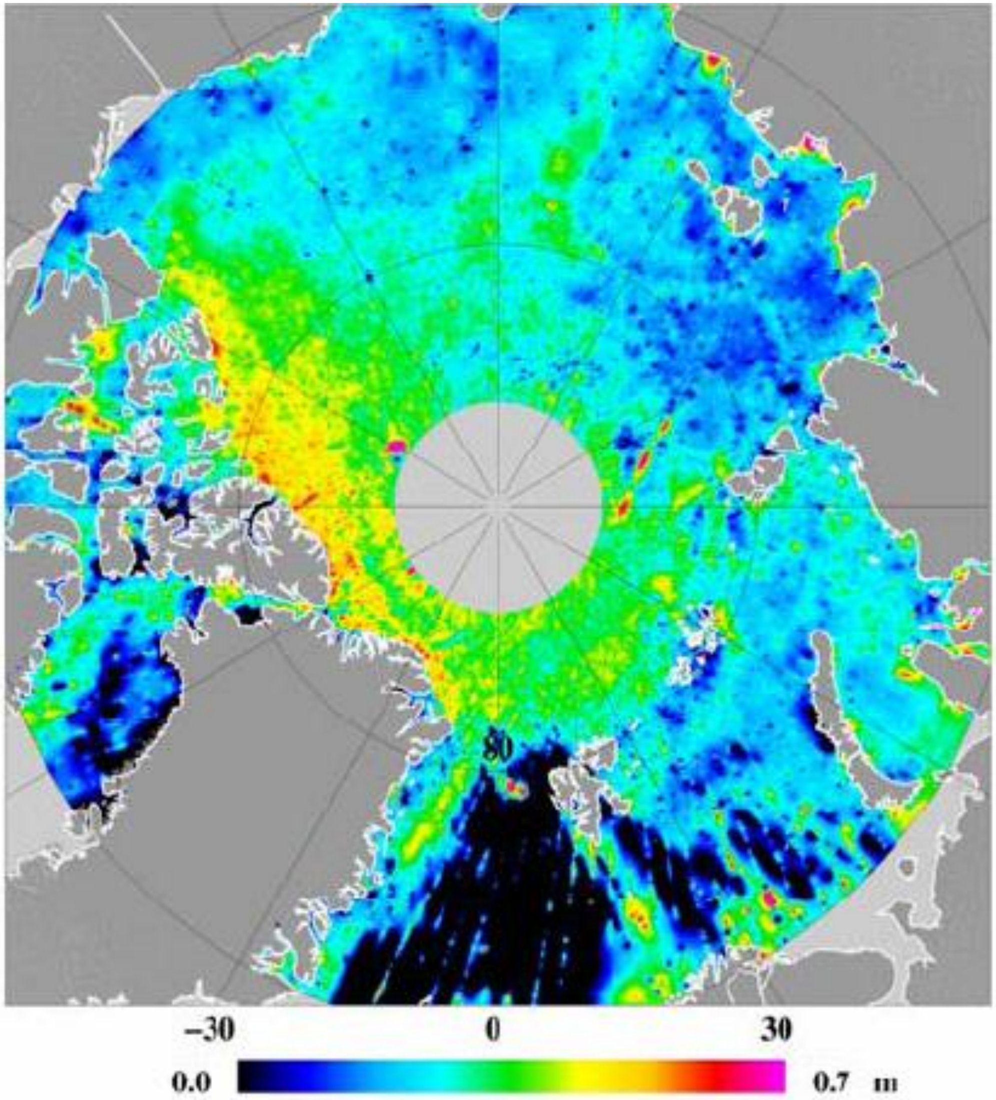


Having computed the sea-ice freeboard height, and under assumptions of isostatic balance of the ice floe in the water, and assumptions on snow, ice and water density, one may calculate the sea ice thickness T.

$$F = h - N - MDT + e$$

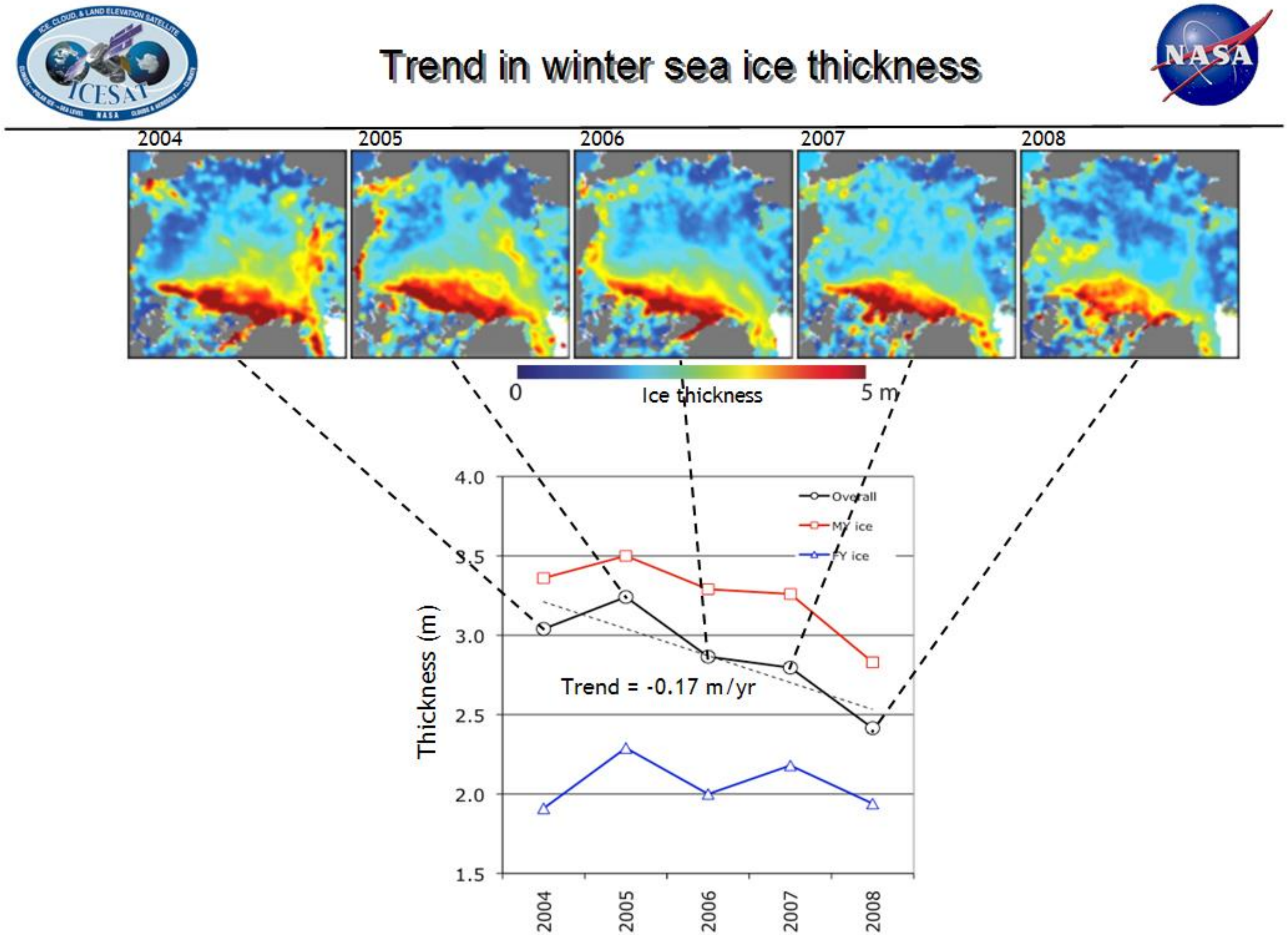
Courtesy: http://esamultimedia.esa.int/docs/arcgice_venice.pdf#search=%22%20freeboard%20height%22

ICESat Arctic Sea ice freeboard height



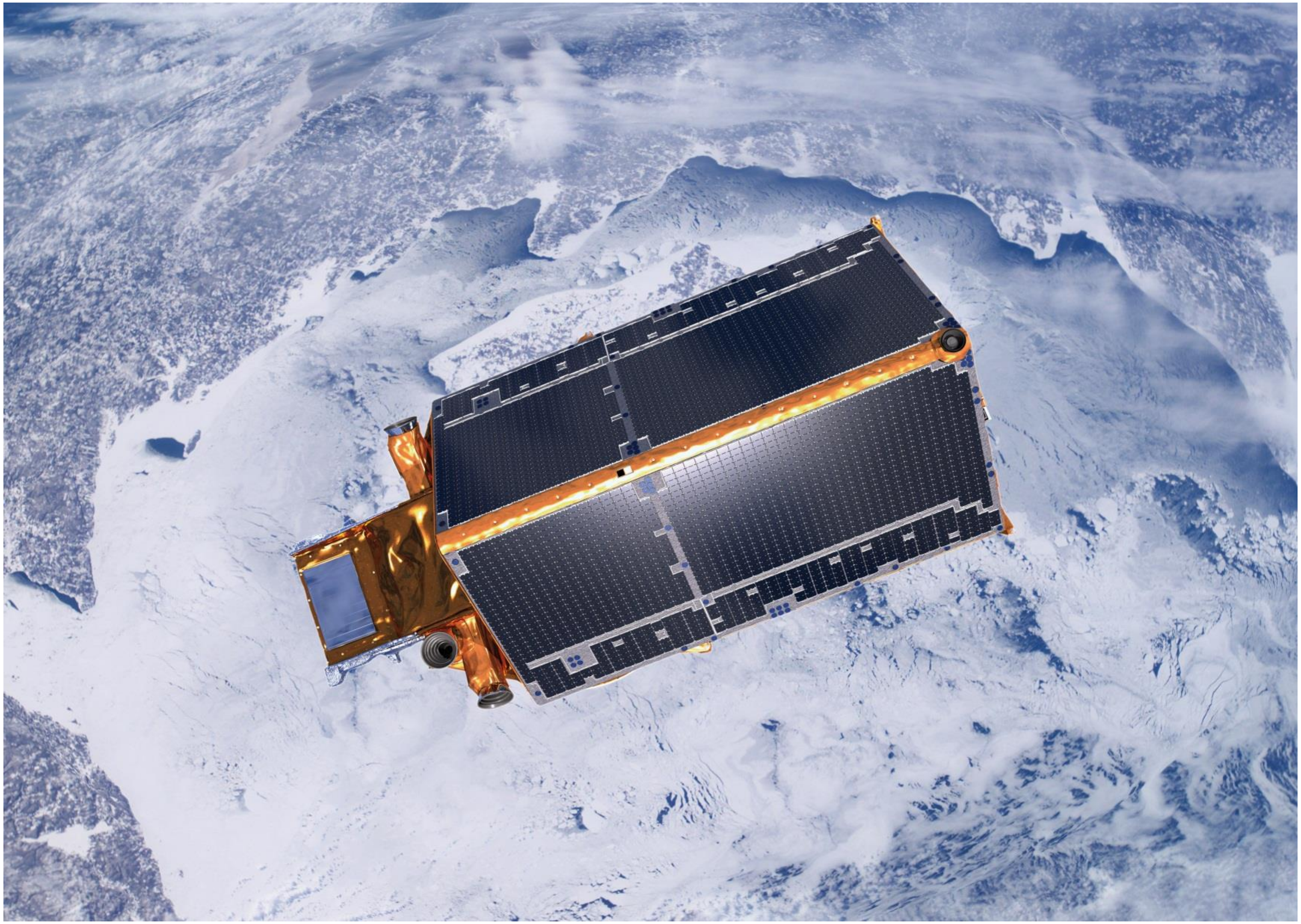
Courtesy: http://esamultimedia.esa.int/docs/arcgice_venice.pdf#search=%22%20freeboard%20height%22

ICESat Arctic Sea ice thickness



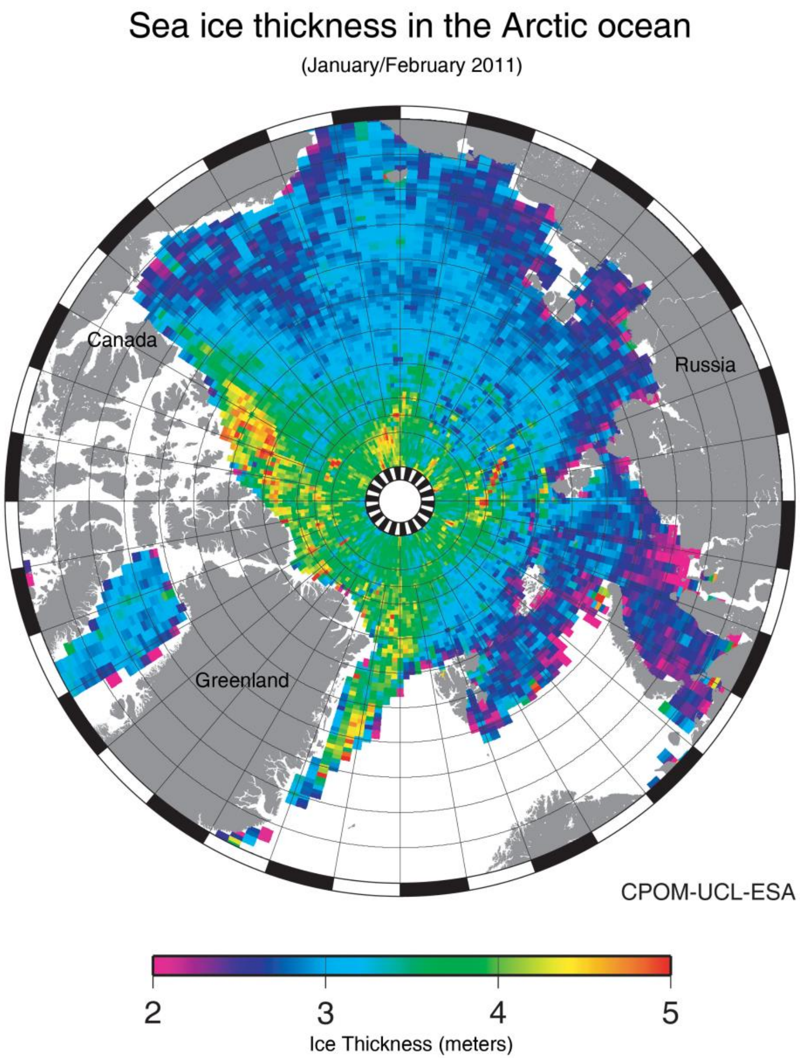
http://www.jpl.nasa.gov/news/news.php?release=2009-107

ESA Satellite Cryosat-2



http://www.esa.int/SPECIALS/Cryosat/index.html

Sea-ice thickness map of the Arctic
Cryosat-2



Courtesy: ESA, http://www.esa.int/esaLP/SEMAAW0T1PG_LPcryosat_0.html

3- Satellite Gravimetry
(Gravity and Mass changes)

- Old Generation gravimetry satellites were equipped with reflectors and high-precision laser ranging instruments

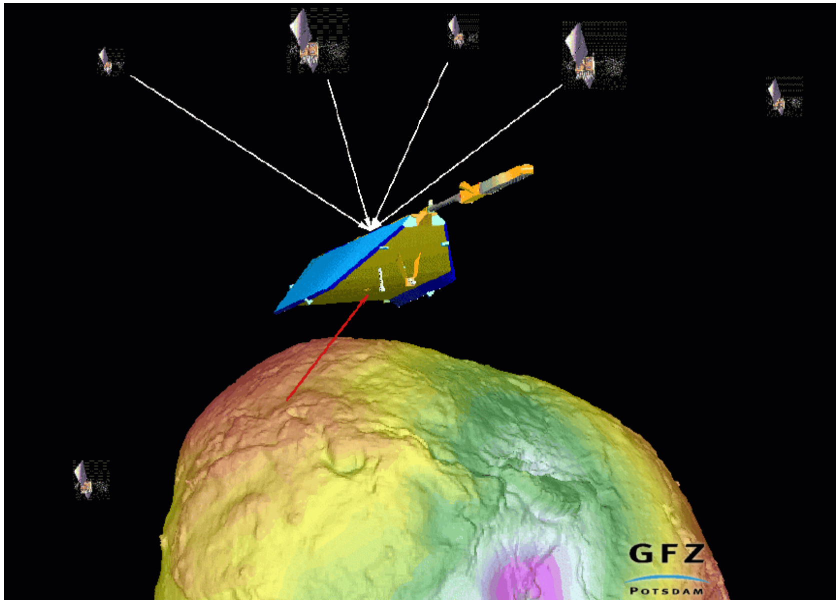
LAGEOS-1 launched 1976 covered with 426 reflectors with the mass 411 kg and the configuration of 60 cm sphere

http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/lag1_general.html

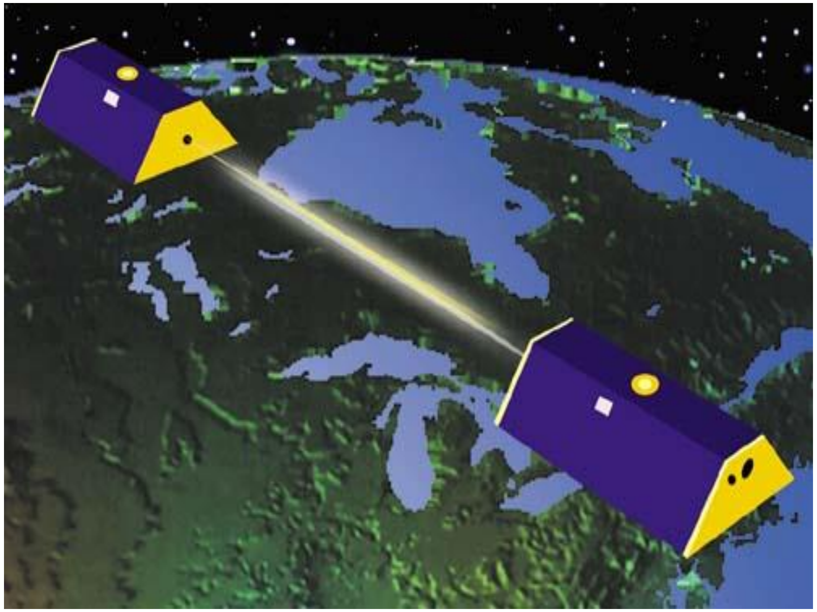
Monitoring Gravity field of the Earth

- New Generation of low-orbiting satellites are equipped with
  - Precise inter-satellites instruments
  - Accelerometer instruments
  - GPS receivers

CHAMP Mission



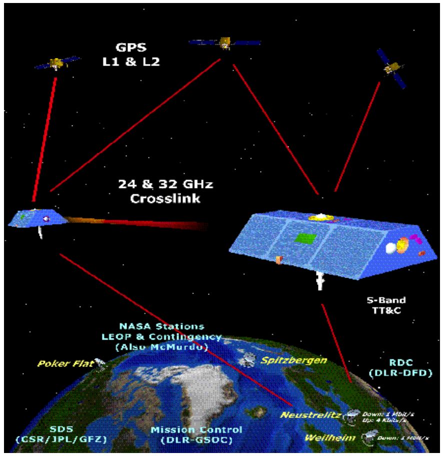
GRACE Mission



Satellite gravity missions: CHAMP, GRACE, GOCE

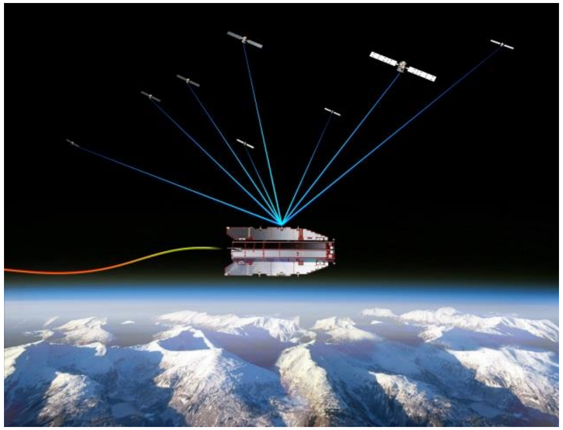
• CHAMP – CHAllenging Microsatellite Payload
- *German satellite, launched 2000. Accelerometer, GPS, magnetometer ..*
http://op.gfz-potsdam.de/champ/

• GRACE – Geopotential Research And Climate Experiment
- *NASA/GFZ satellite, launched 2002. Precision tracking between two spacecraft … looking for gravity change (monthly solutions)*
http://www.gfz-potsdam.de/portal/gfz/Struktur/Departments/Department+1/sec12/projects/grace
http://www.csr.utexas.edu/grace/

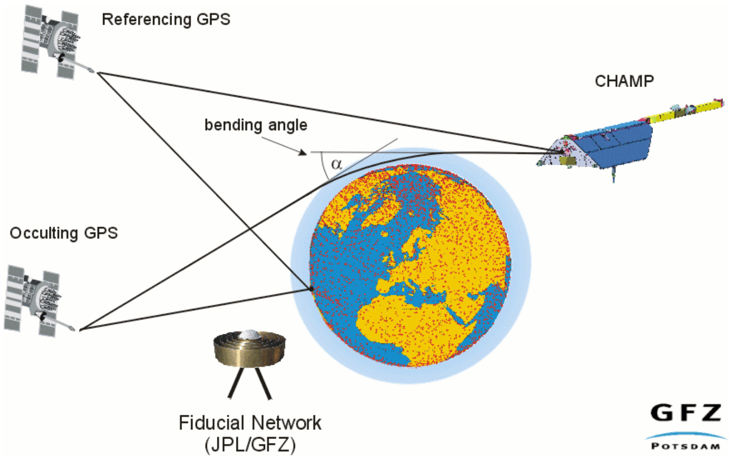


GRACE (NASA)

• GOCE – Global Ocean Circulation Explorer
- *ESA mission, launch 2009. Gravity gradiometer.*
http://www.esa.int/SPECIALS/GOCE/index.html



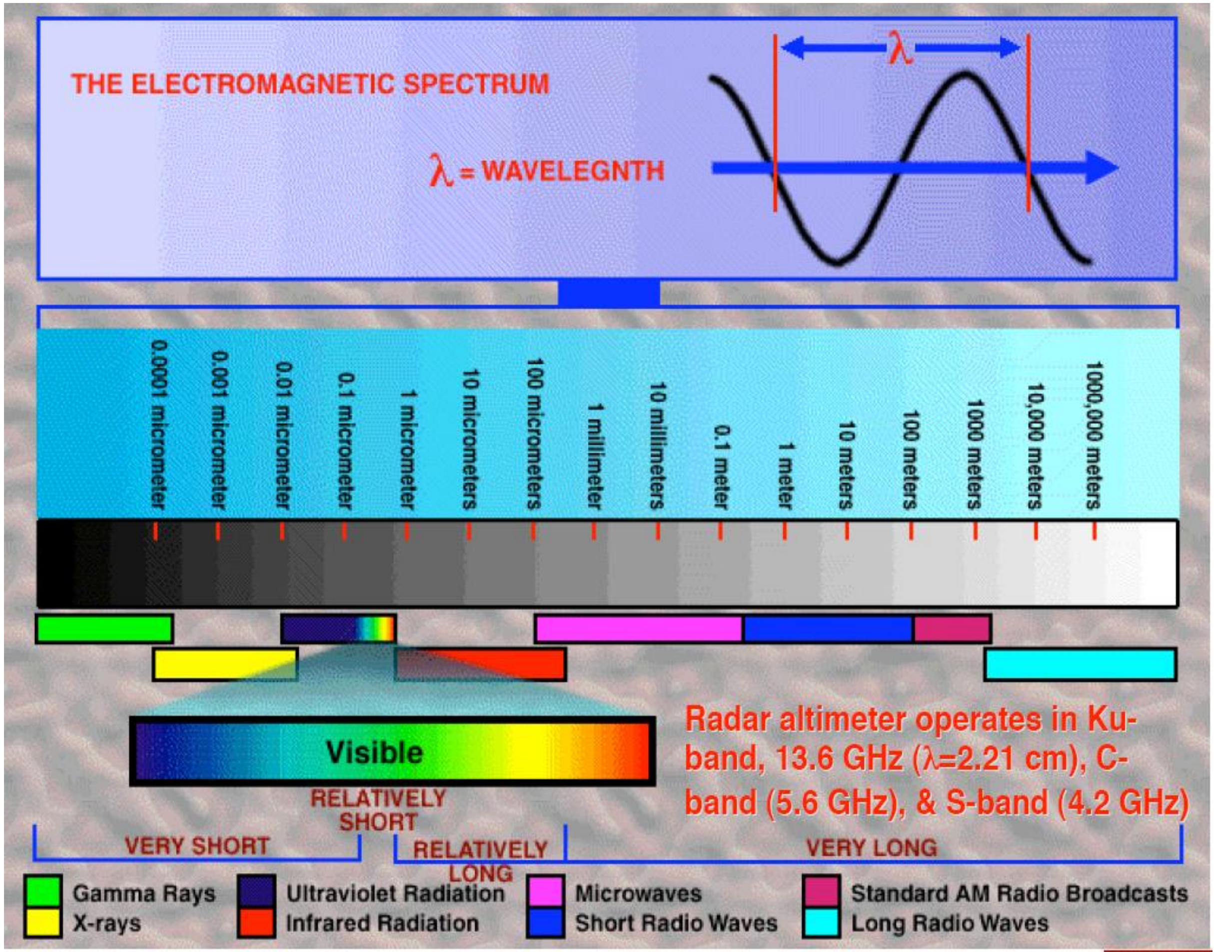
GOCE (ESA mission)



CHAMP (GFZ)

Electromagnetic wave spectrum

Courtesy:
NASA/JPL



L-band (1.0-1.5 GHz, S-band (1.5-4.2 GHz), C-band (4.2-5.4 GHz), X-band (5.7-10.9 GHz), **Ku-band (10.9-22.o GHz**)

CHAMP mission

CHAMP (**CHA**llenging **M**inisatellite **P**ayload) is a German small satellite mission for geo-scientific and atmospheric research and applications, managed by GFZ. With its highly precise, multifunctional and complementary payload elements (magnetometer, accelerometer, star sensor, GPS receiver, laser retro reflector, ion drift meter) and its orbit characteristics (near polar, low altitude, long duration) CHAMP generates for the first time simultaneously highly precise **gravity** and **magnetic** field measurements over a 8-9 years period. On July 15 2006 at 12:32 UTC CHAMP has finished its 6th year in orbit. This will allow to detect besides the spatial variations of both fields also their variability with time. The CHAMP mission opened a new era in geopotential research and will become a significant contributor to the **Decade of Geopotentials**.

GRACE mission

GRACE succeeded the CHAMP mission in the area of Earth gravity field measurements. It has been in orbit more than 9 years now. The anticipated increase in accuracy is achieved by utilizing two satellites following each other on the same orbital track. These satellites are interconnected by a K-band microwave link to measure the exact separation distance and its rate of change to an accuracy of better than 1 µm/s. To consider precise attitude and non-gravitational forces both satellites will be equipped with star cameras and accelerometers. The position and velocity of the satellites will be measured using onboard GPS antennae.

GOCE mission

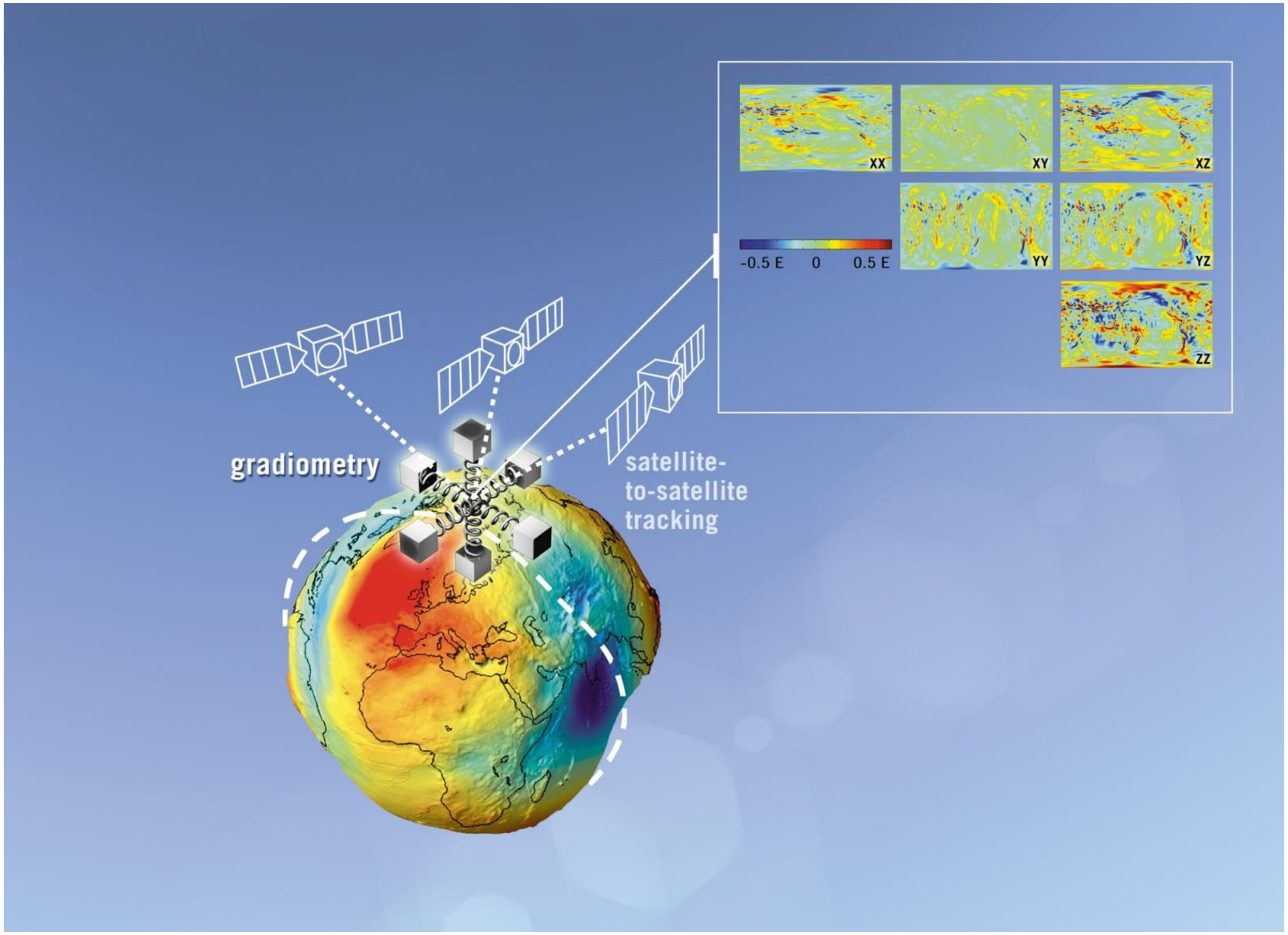
With its unique design, GOCE demonstrates Europe's excellence in both engineering and science through the realization of one of the most challenging space missions to date.

The GOCE payload includes:

- A gradiometer. With its three pairs of accelerometers (six accelerometers), this state-of-the-art instrument will measure gravity with unprecedented accuracy (some 100 times more sensitive than any previously flown in space). Within its measurement band, each accelerometer can detect accelerations to within 1 part in 10 000 000 000 000 of Earth's surface gravity.
- A Global Positioning System (GPS) receiver. To ensure such precise measurements, GOCE's own position must be precisely known at all times. The positions provided via GPS will also supply gravity information through analysis of the perturbations in GOCE's orbit.
- An advanced drag compensation and attitude-control.
- A Laser Retro Reflector. This will enable tracking by terrestrial lasers.

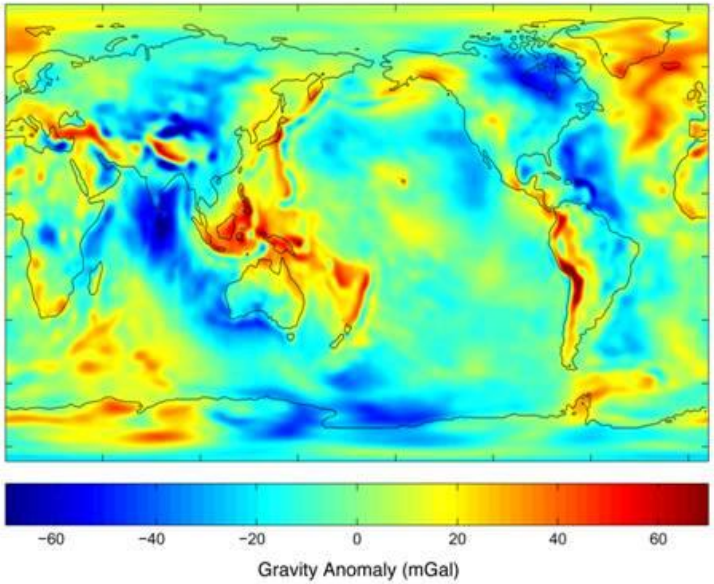
Launched in 17 March 2009 with Nominal life of 20 months and an Orbit of about 260 km altitude, polar, Sun-synchronous and Mass of 1100 kg, Sized 5.3 m long and about 1 m body diameter, GOCE provide an Geoid accuracy of 1 - 2 cm vertically with 100 km spatial resolution.

GOCE mission

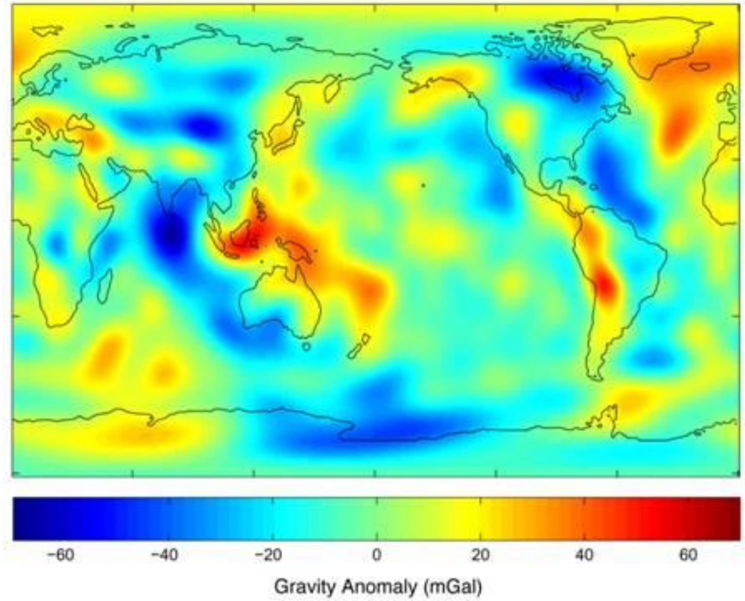


The GOCE gradiometer contains three pairs of proof masses positioned at the outer ends of three 50 cm long orthogonal arms. Because of their different position in the gravitational field they all experience the gravitational acceleration of Earth slightly differently. The three axes of the gradiometer allow the simultaneous measurement of six independent but complementary components of the gravity field.
Credits: ESA – AOES Medialab
https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/goce

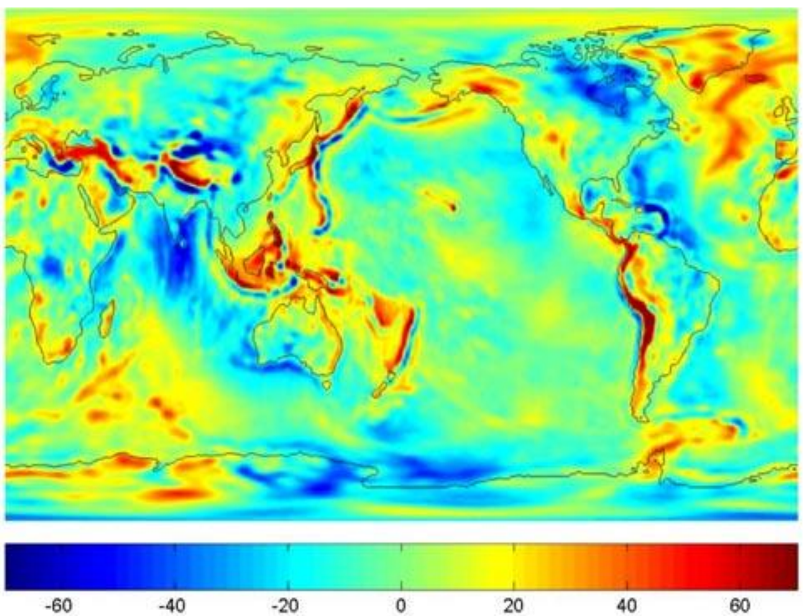
Progress in Measuring the Earth's Gravity field



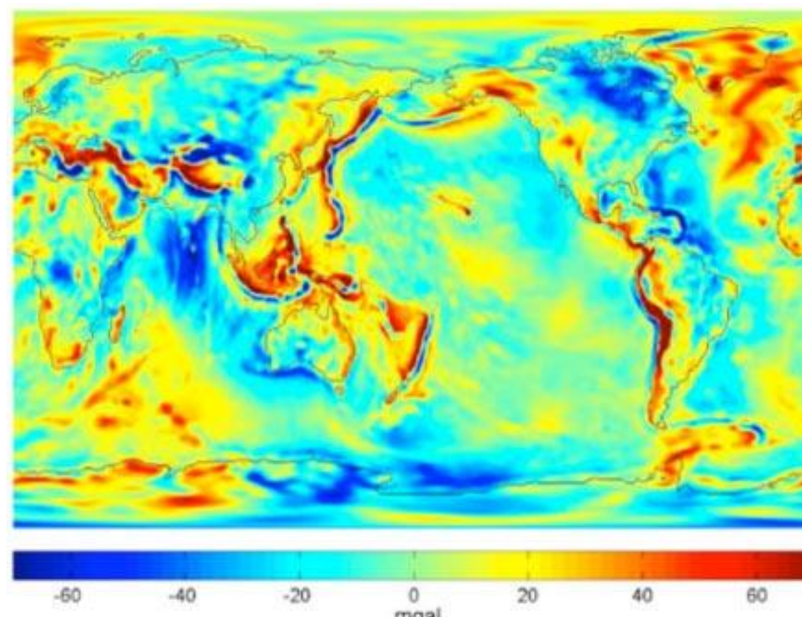
GRACE Gravity Model 01 based on 111 days of GRACE data



Gravity Model based on decades of tracking geodetic satellites



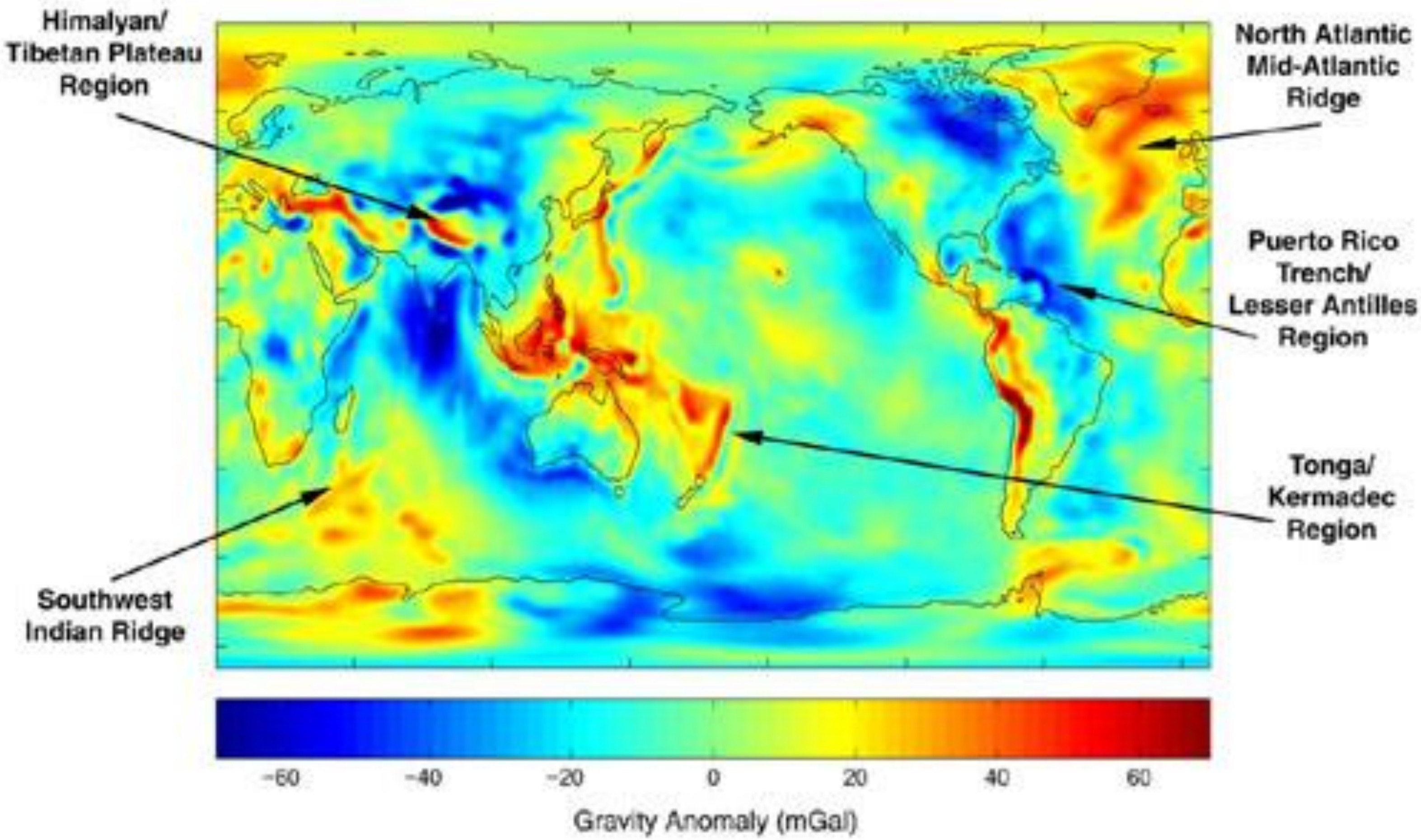
GRACE Gravity Model 02 based on 363 days of GRACE data



GRACE Gravity Model 03 from four years (2003-2006) of GRACE data

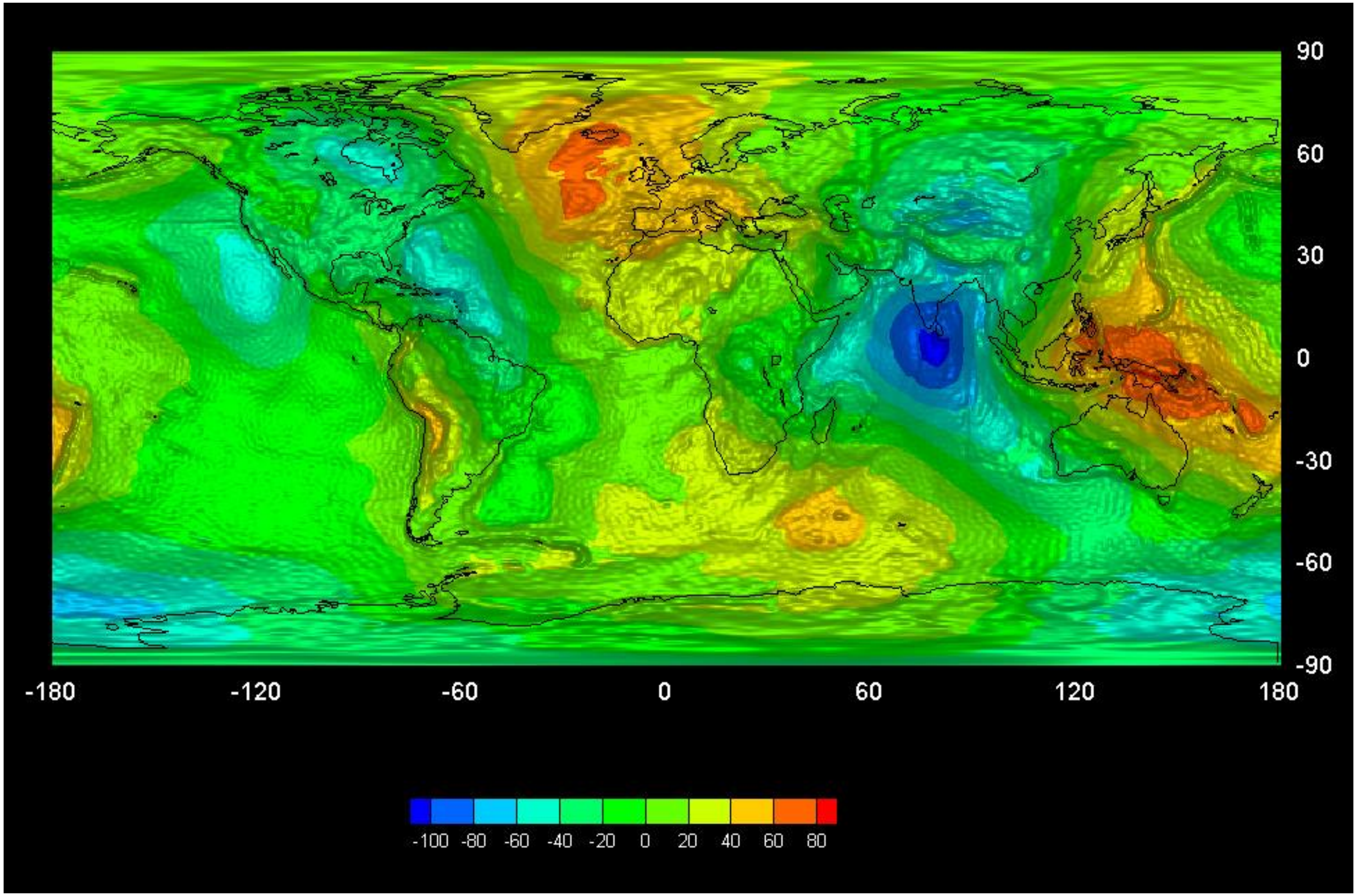
http://www.csr.utexas.edu/grace/

Detailed Geophysical Features



GOCE

First Global Gravity in mGal, Two month data



Courtesy: ESA http://www.esa.int/esaLP/ESAG4L1VMOC_LPgoce_0.html

Global Gravity Models

CHAMP mission:

Many gravity models have been released, for example, **EIGEN-CHAMP03S** derived from 33 months of CHAMP data http://op.gfz-potsdam.de/champ/

GRACE mission:

Many gravity models have been released, for example, **GGM02** (**http://www.csr.utexas.edu/grace/gravity/ggm02/**) model which is based on the analysis of 363 days of GRAC data, **GGM01** (**http://www.csr.utexas.edu/grace/gravity/ggm01/**) model which is based on the analysis of 111 days of GRACE data and the **GGM03** (http://www.csr.utexas.edu/grace/gravity/) model which is based on the analysis of four years of GRACE in-flight data.

There are combined gravity models of CHAMP and GRACE: EIGEN-CG01C (http://op.gfz-potsdam.de/champ/) using CHAMP (860 days) and GRACE (200 days) satellite gravity data

GOCE mission:

New GOCE gravity model (DIR3 and TIM3) (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/goce) is released up to may 2012.

Other models:

EGM96 and EGM08 models
http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html

What are these different Global Gravity Models?

The Global Gravity Models are the coefficients of the Earth's gravitational potential to some degree and order(n, m). These coefficients (J_{nm} and K_{nm}) are mathematically related to the coefficients (R_{nm} and q_{nm}) in the formula below:

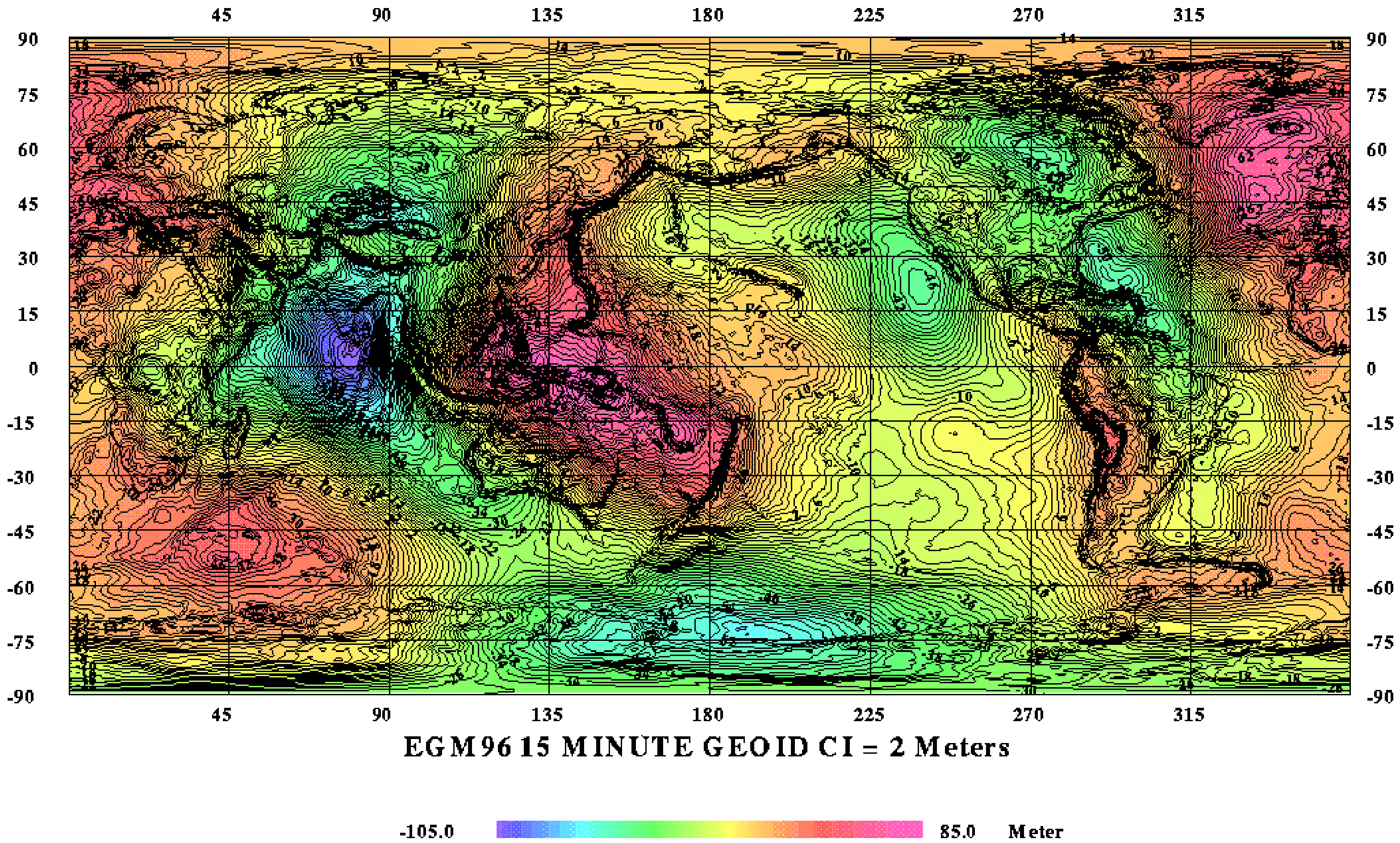
$$N(R,\phi,\lambda)=\frac{GM}{R\gamma}\sum_{n=2}^{n_{\max}}\left(\frac{a}{R}\right)^{n}\sum_{m=0}^{n}\left(\bar{R}_{nm}\cos m\lambda+\bar{q}_{nm}\sin m\lambda\right)\bar{P}_{nm}(\sin\phi)$$

- N is the Geoidal Height
- P_{nm} are associated Legendre functions of degree n and order m, and can be computed from mathematical formulas. Other constant values in the formula (for GRS80 reference ellipsoid) are:
- a= 6378137.0000 m
- R=6371000.7900 m
- GM= 3986005m ^{3} s $^{-2}$
- $\gamma = 981\ \text{Gal}$ an average normal gravity
- To compute gravity anomalies, the formula above should be multiplied by $\gamma(n-1)/R$.

<u>Examples</u>:

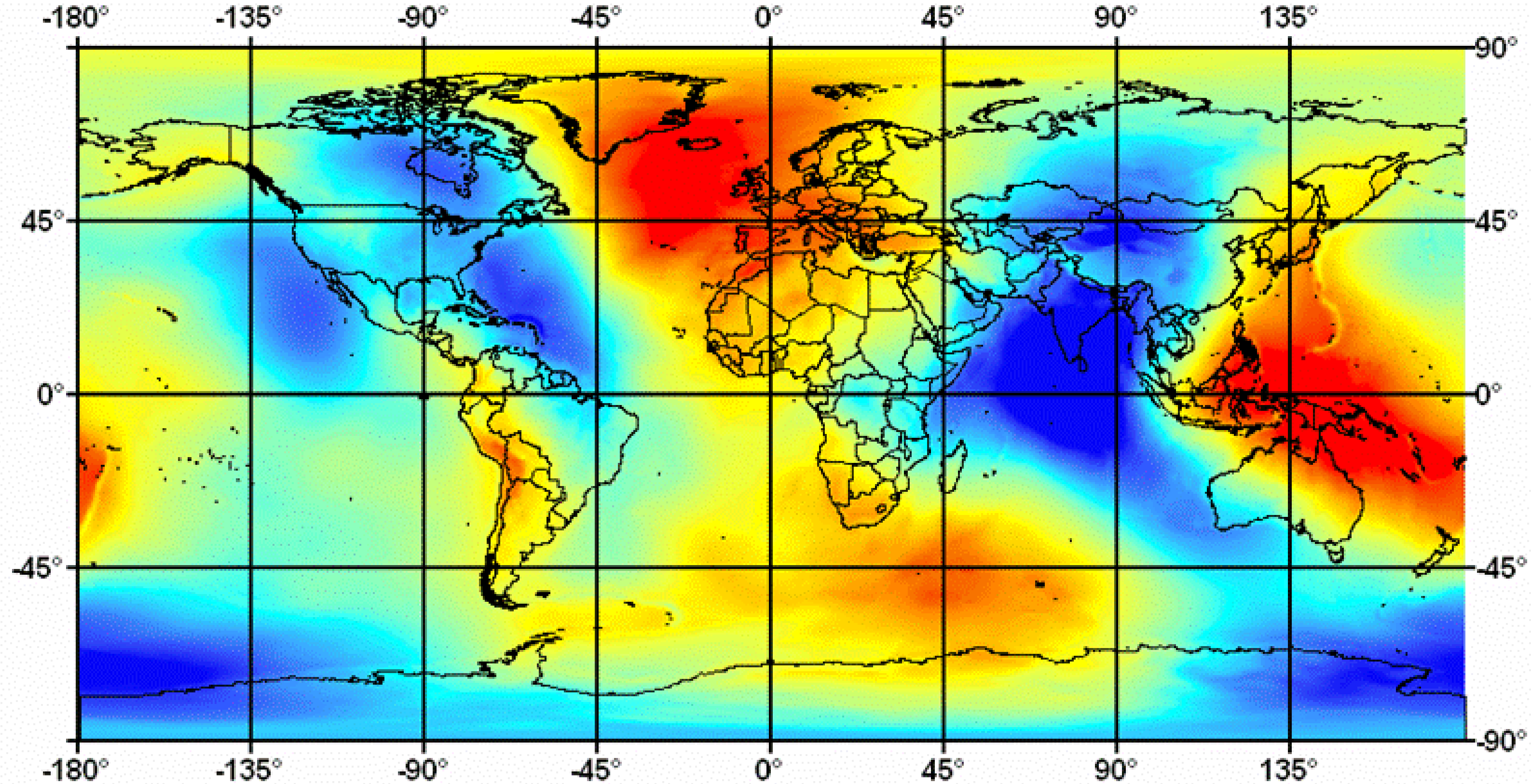
- GRACE: GGM02S, n_{max} = 160; GGM03, n_{max} = 180
- GOCE gravity model (DIR3 and TIM3), n_{max} = 240/250
- EGM96, n_{max} = 360
- EGM08, n_{max} = 2160

EGM96 global geoid



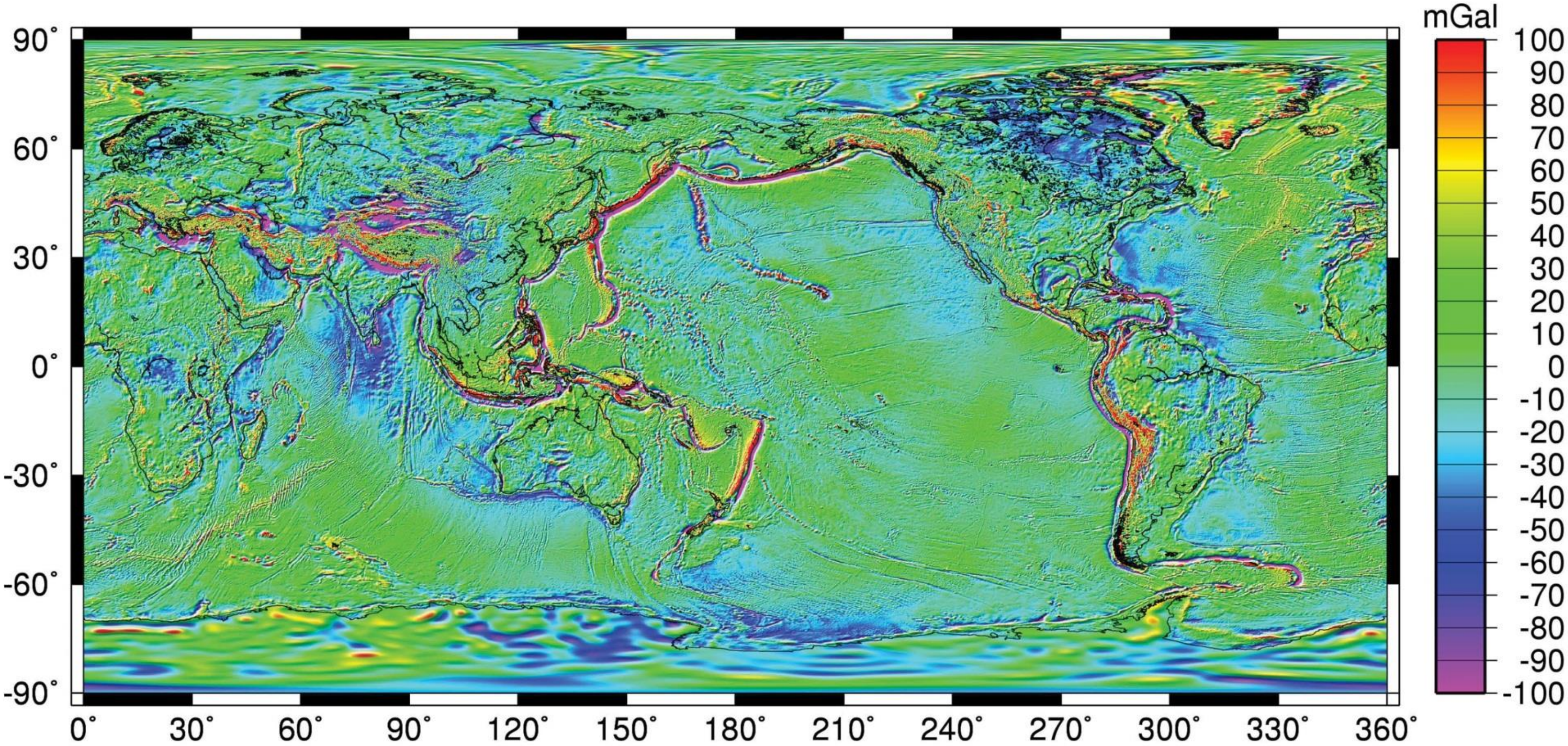
Courtesy: http://cddis.nasa.gov/926/egm96/egm96.html

EGM2008 global geoid



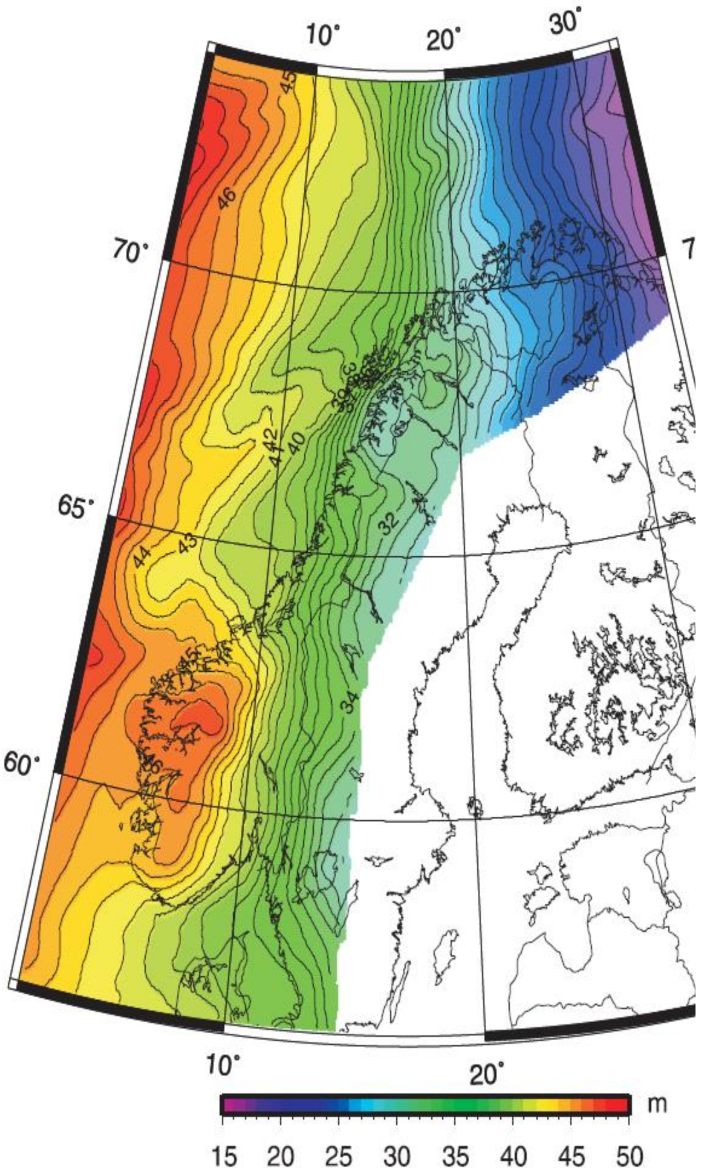
http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_wgs84.html

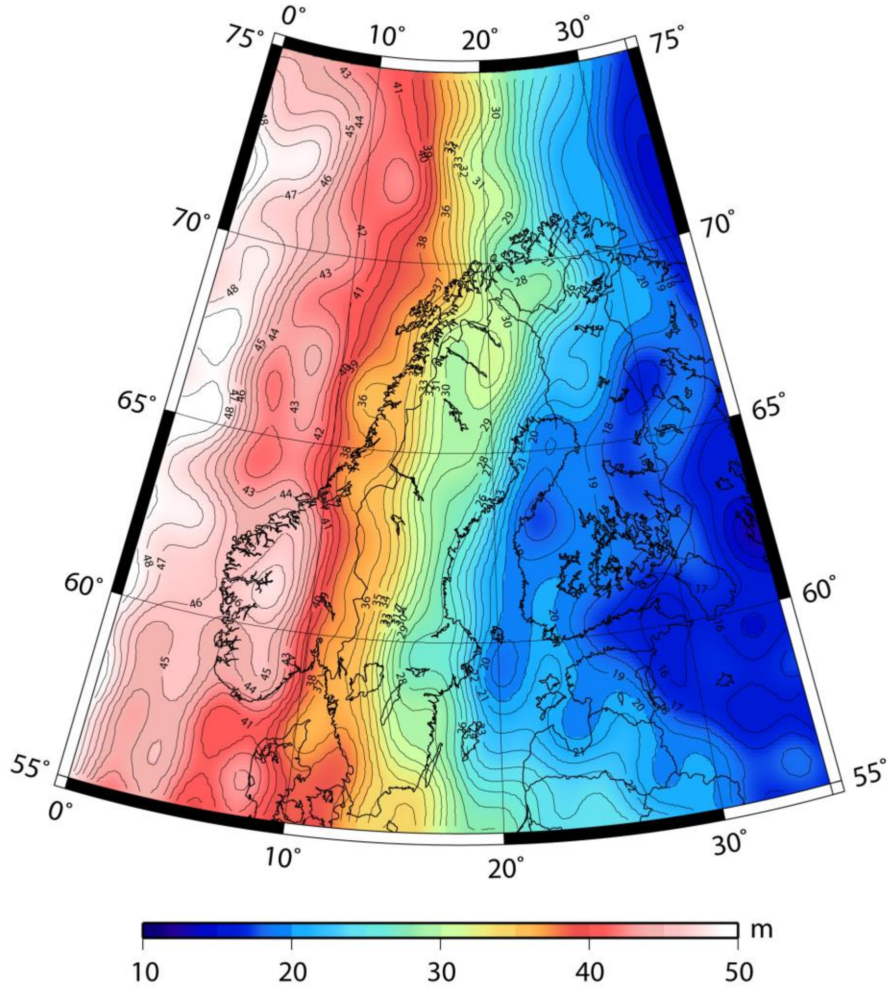
EGM2008 global gravity anomaly



Courtesy: http://earth-info.nima.mil/GandG/wgs84/gravitymod/egm2008/index.html

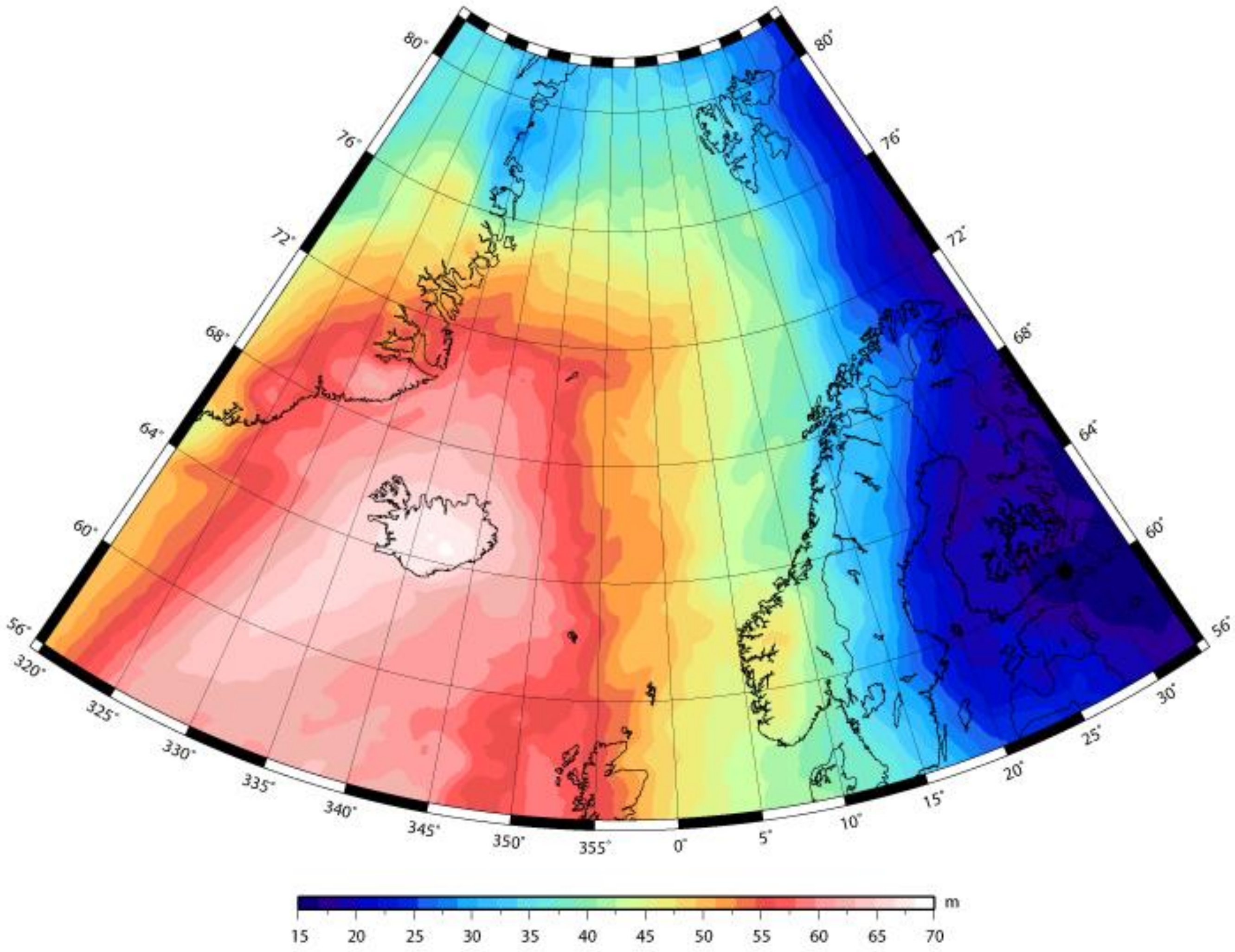
Geoid model of Norway





Courtesy: Soltanpour and Nahavandchi, NTNU.

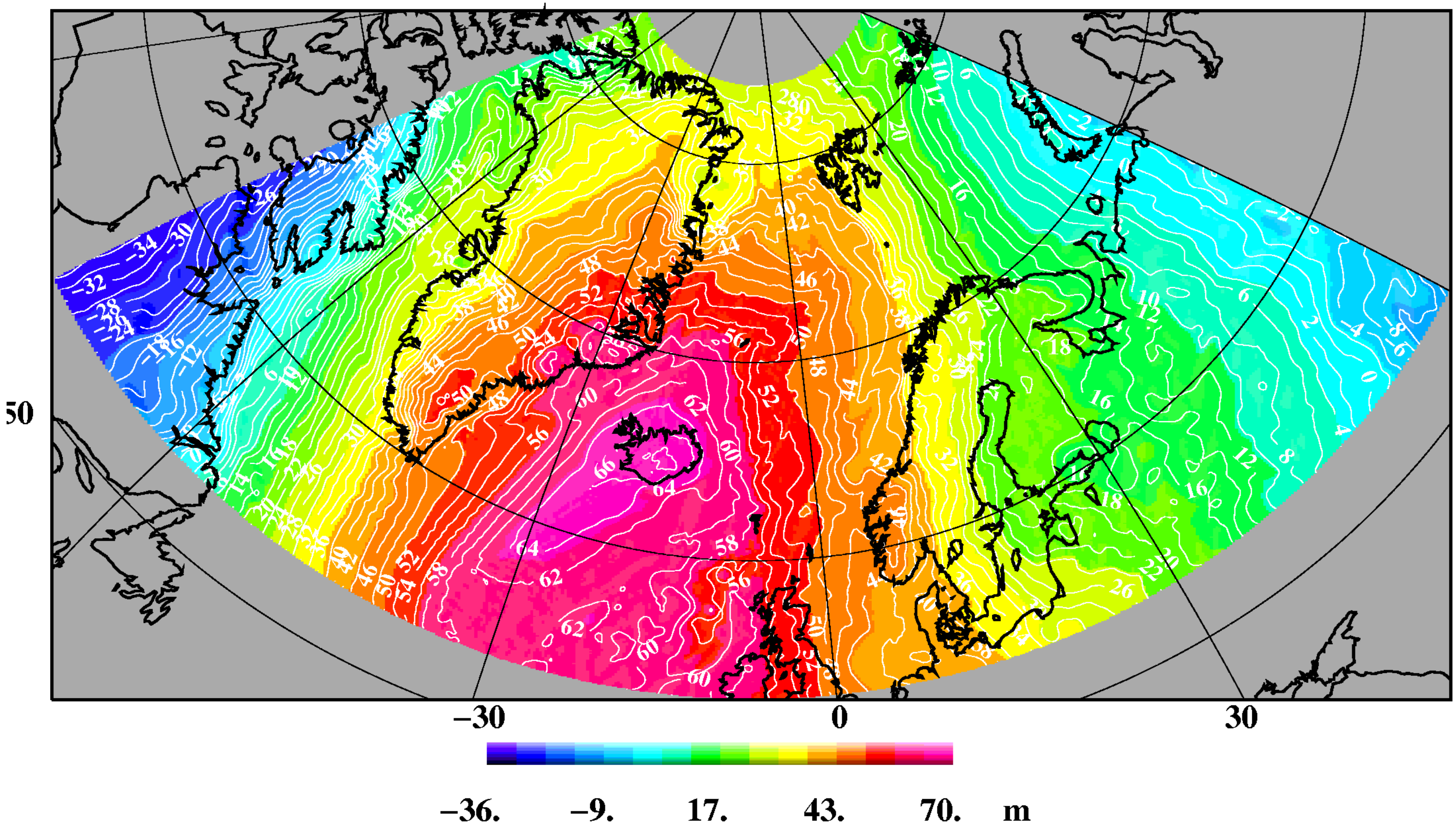
OCTAS Project Geoid Model



Courtesy: Omang et al. OCTAS project

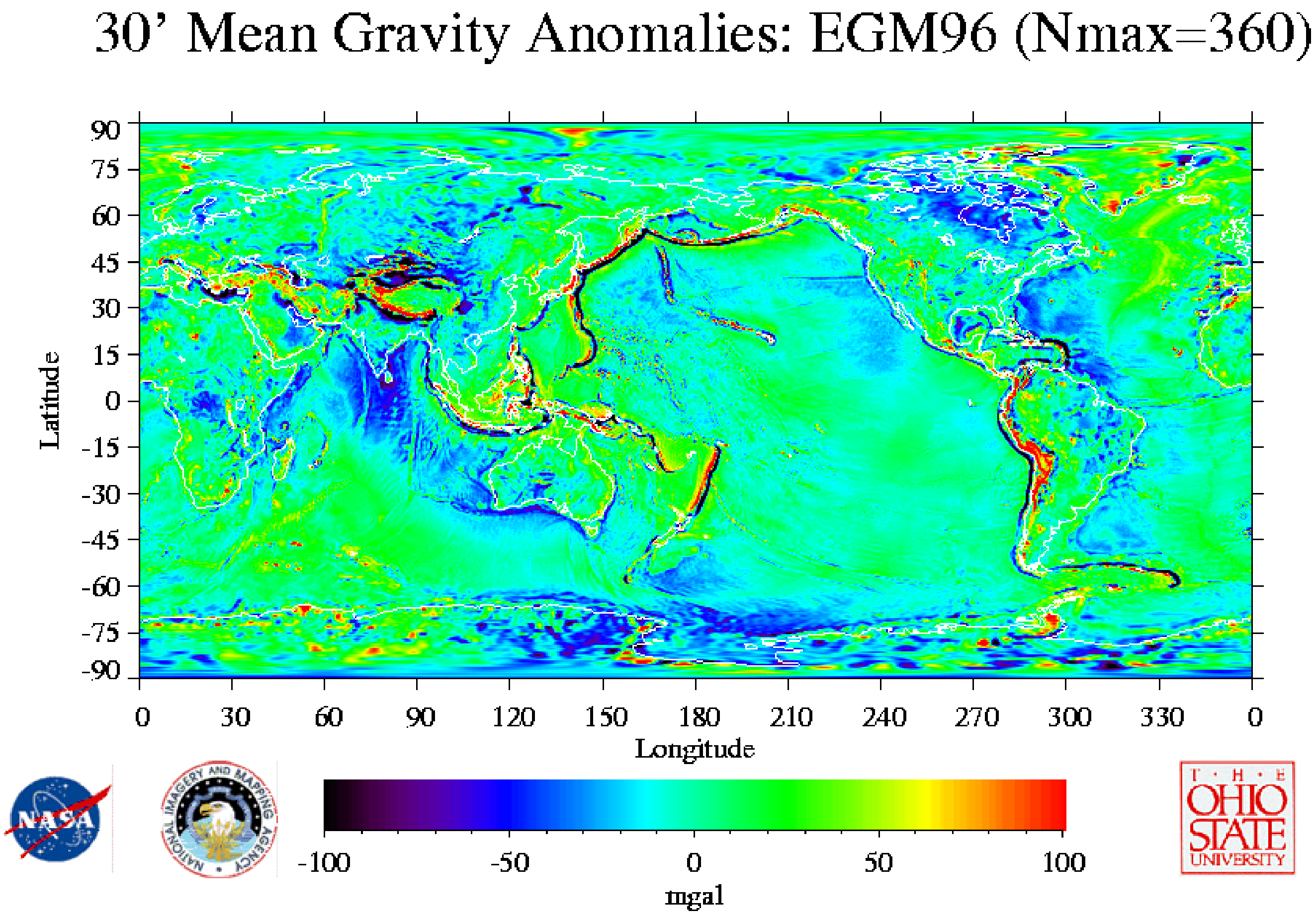
http://earth.esa.int/goce06/participants/169/pres_solheim_169.pdf

Another geoid Model



Courtesy: GOCINA Project (http://gocinascience.spacecenter.dk/)

Gravity Anomaly



Courtesy: http://cddis.nasa.gov/926/egm96/egm96.html

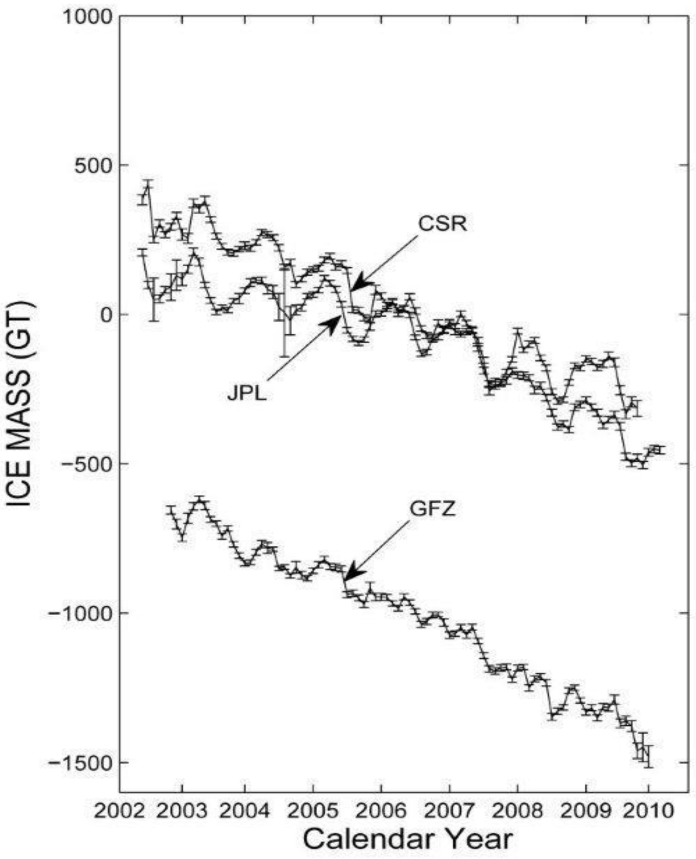
Other Applications

The Earth’s gravity field is a product of its mass distribution. The mass distribution is constantly changing. GRACE tracks changes in Earth's gravity field due to changes in Earth's mass distribution. This includes:

- changes in the ice mass,
- changes in the snow and water storage,
- changes in the groundwater,
- changes in the soil moisture, and
- changes in the surface water.

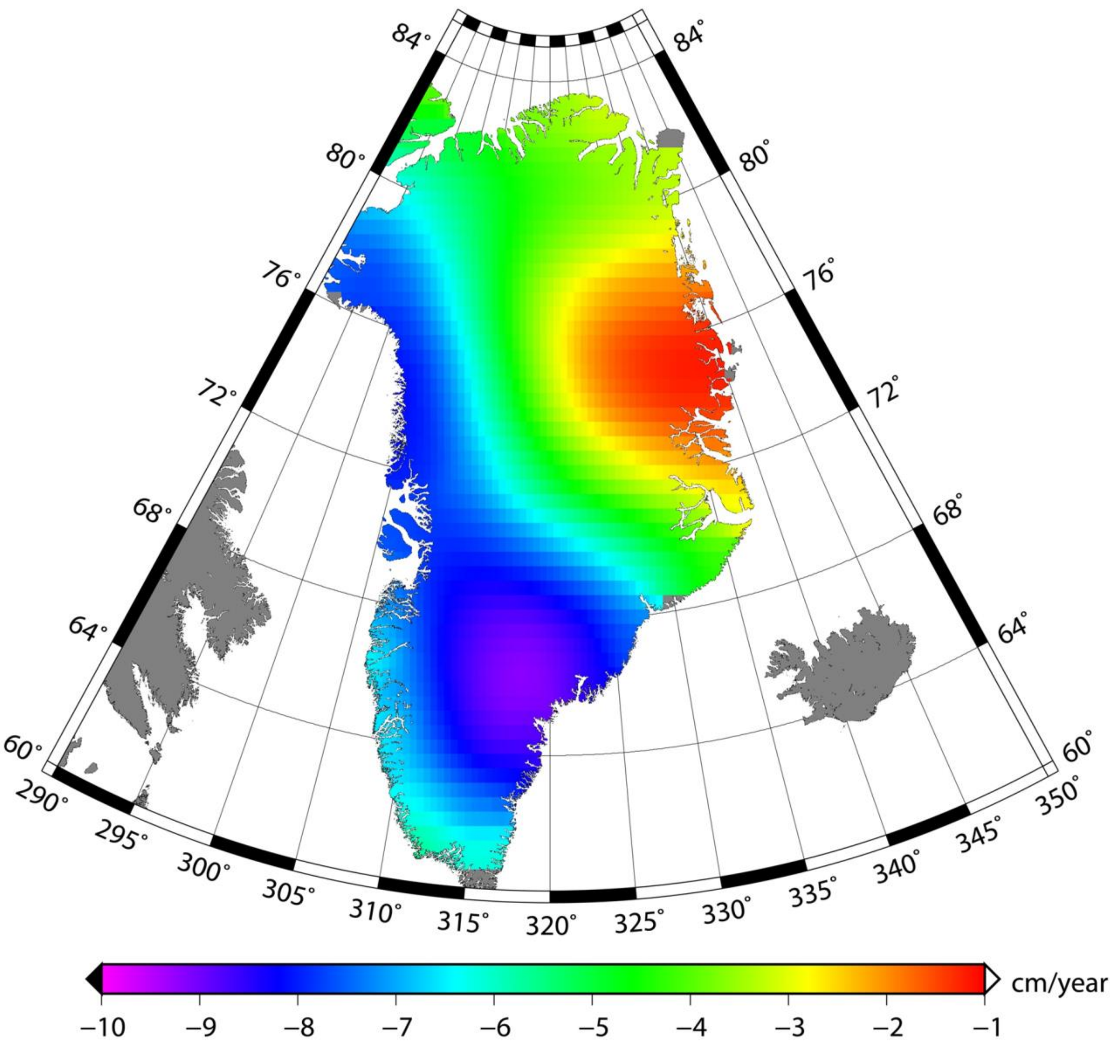
Greenland Ice mass Loss

The Figure shows monthly ice mass changes summed over the entire Greenland ice sheet, between April 2002 and February 2010, estimated in Gigatone from three GRACE data sets released by GFZ (Potsdam), JPL(California) and CSR (Texas). Note that this plot shows deviation from the average ice mass over the 2002 to 2010 period. It does not mean that the ice sheet was gaining ice before 2006 but that ice mass was above the 2002 to 2010 average. The ice mass was below the 2002 to 2010 average after 2006. The trend of the best fitting straight line for CSR data is ice loss of -163±20 Gigatone per year.



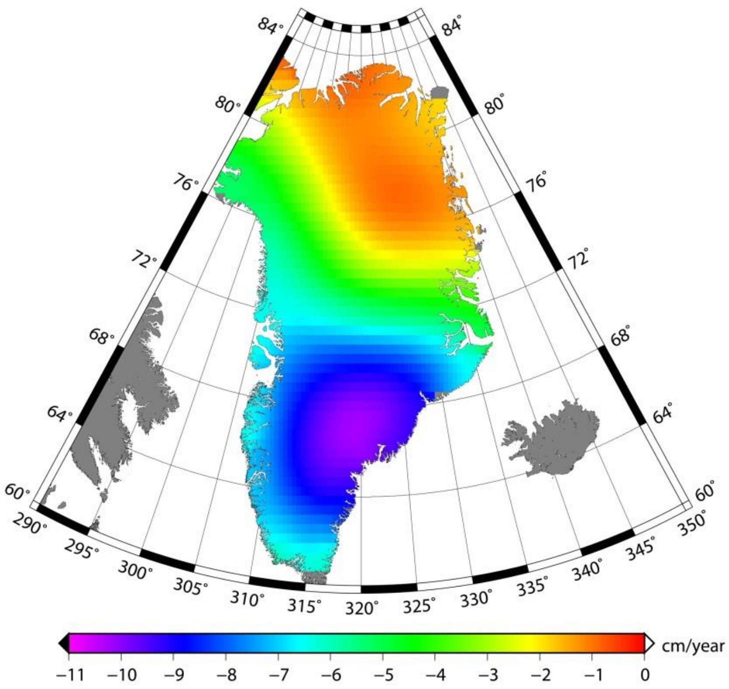
Courtesy: Nahavandchi and Joodaki.
http://versita.metapress.com/content/llm6v452v33k7622/fulltext.pdf

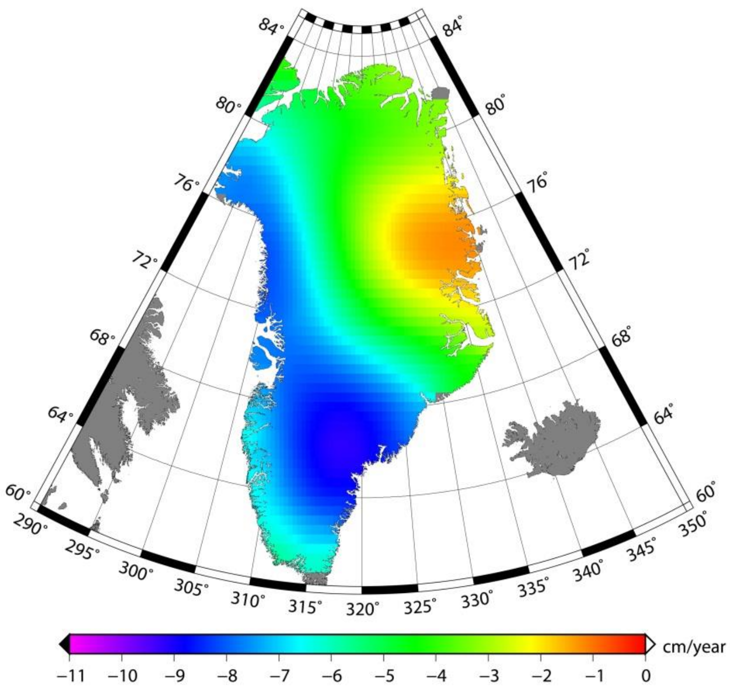
Greenland Secular changes



Courtesy: Nahavandchi and Joodaki.
http://versita.metapress.com/content/llm6v452v33k7622/fulltext.pdf

Greenland melting faster

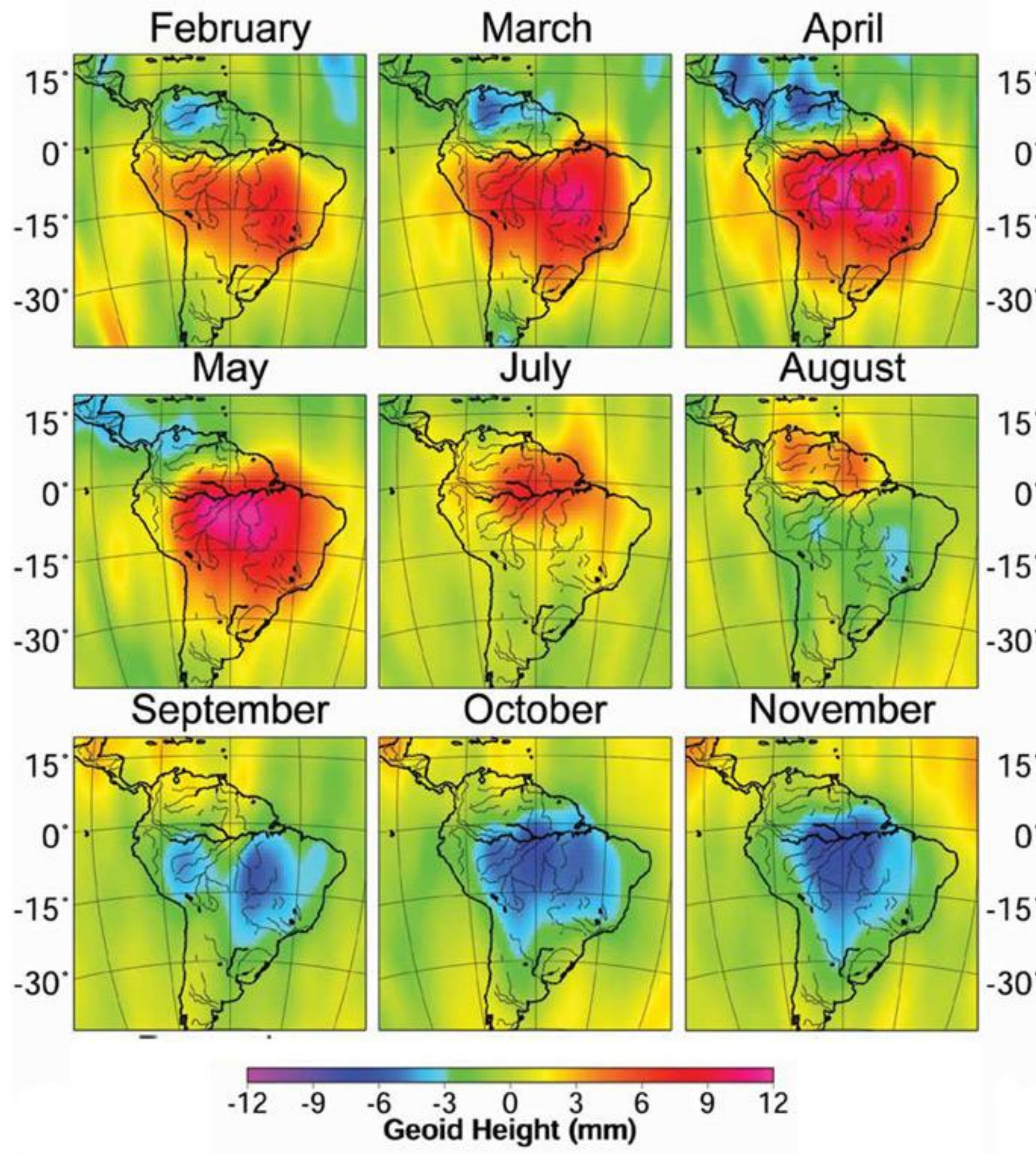




Courtesy: Nahavandchi and Joodaki.

GRACE
Amazon water variations

Maps of South America, created from GRACE readings
taken in 2003, show how water storage in the Amazon basin increases and decreases with seasonal changes in rainfall. Red indicates greater gravitational force, and hence higher water storage; blue reveals that less water is present.

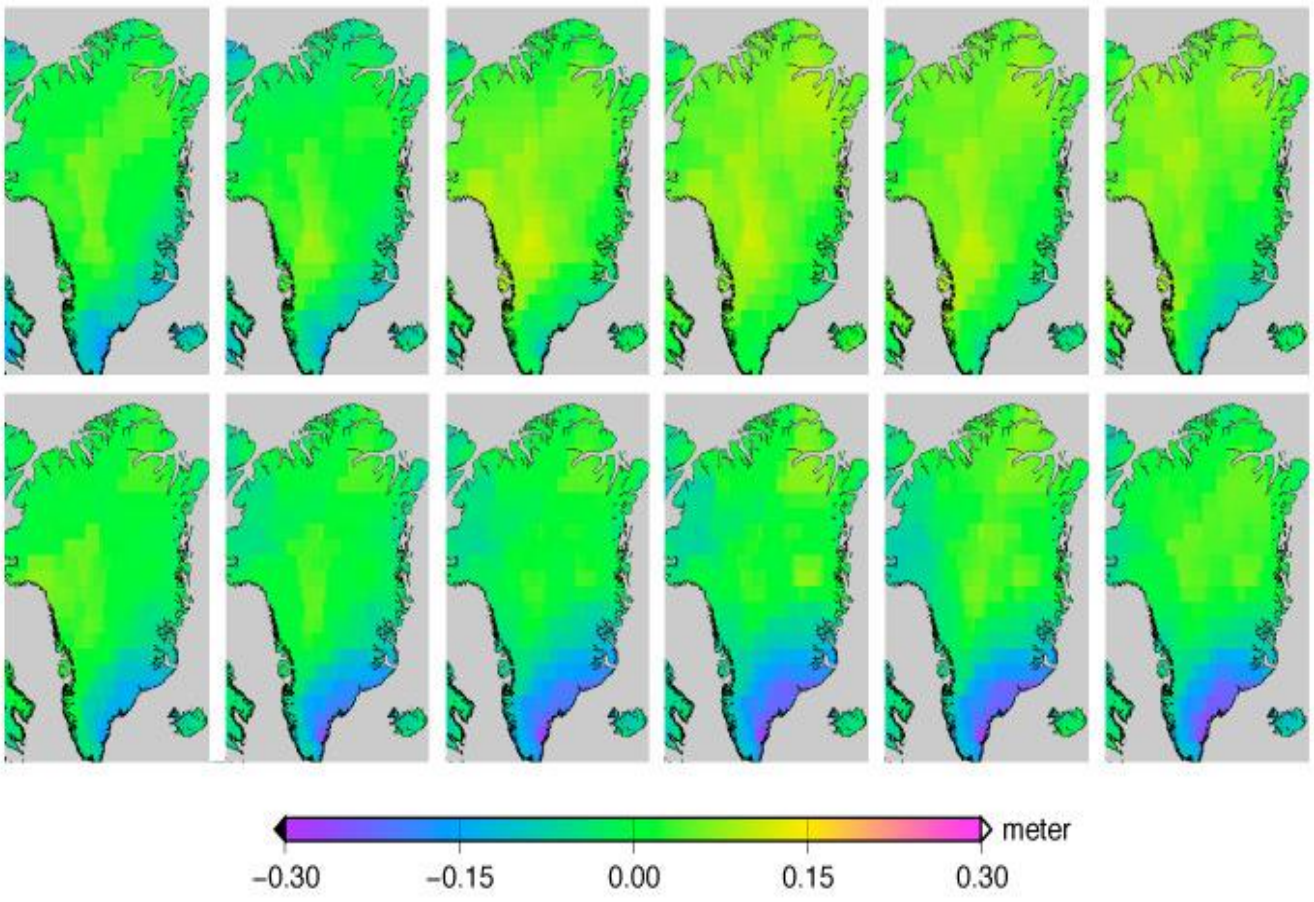


Courtesy: NASA, JPL
http://www.jpl.nasa.gov/news/news.php?release=2012-077#6

GRACE

Monthly Greenland ice mass changes

Monthly changes in the mass of Greenland's ice sheet observed by the GRACE satellites during 2005. Purple and dark blue areas indicate areas of largest mass loss.



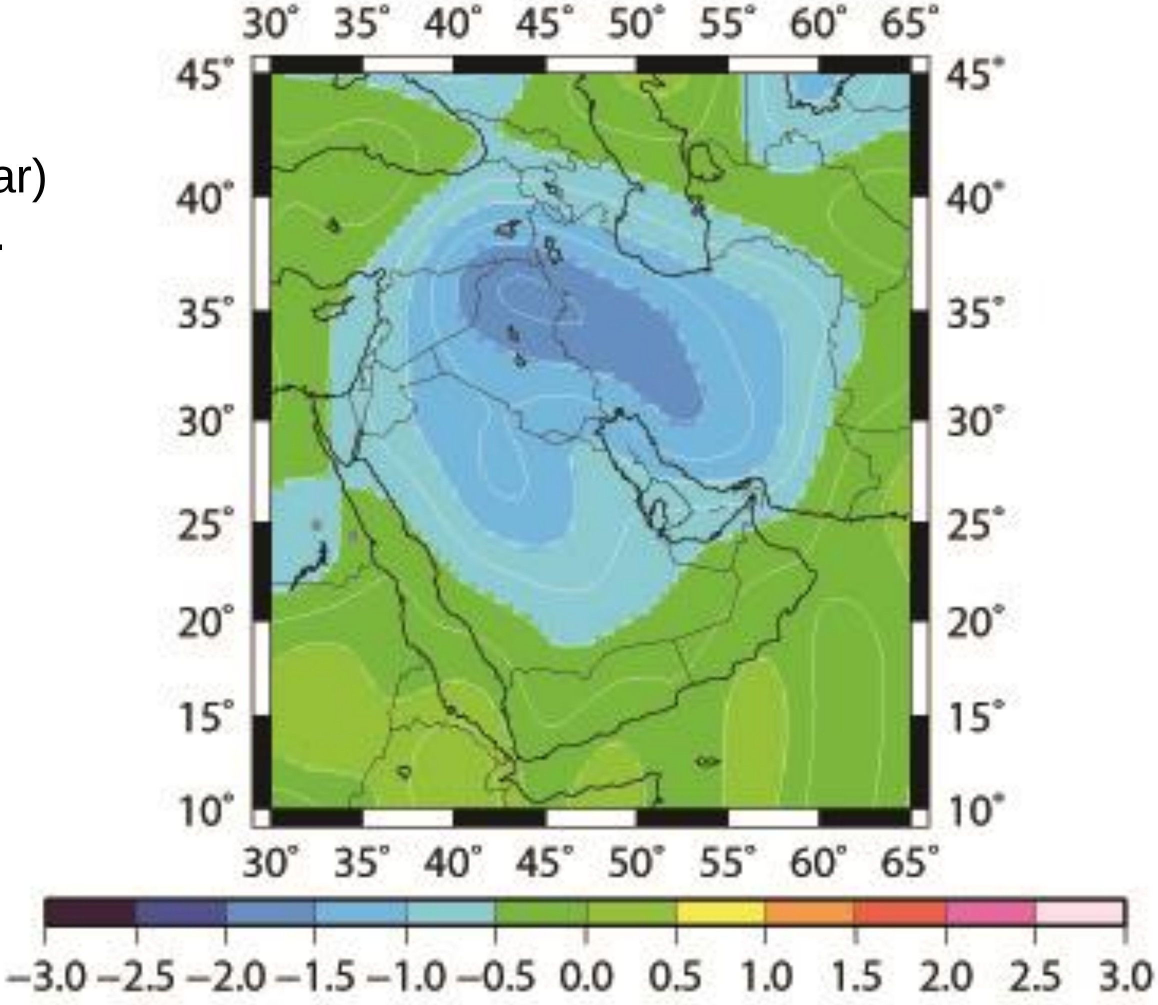
Courtesy: Alan Buis, NASA, JPL

http://www.jpl.nasa.gov/news/news.php?feature=1315

GRACE

Changes in continental water storage (ground water + soil moisture)

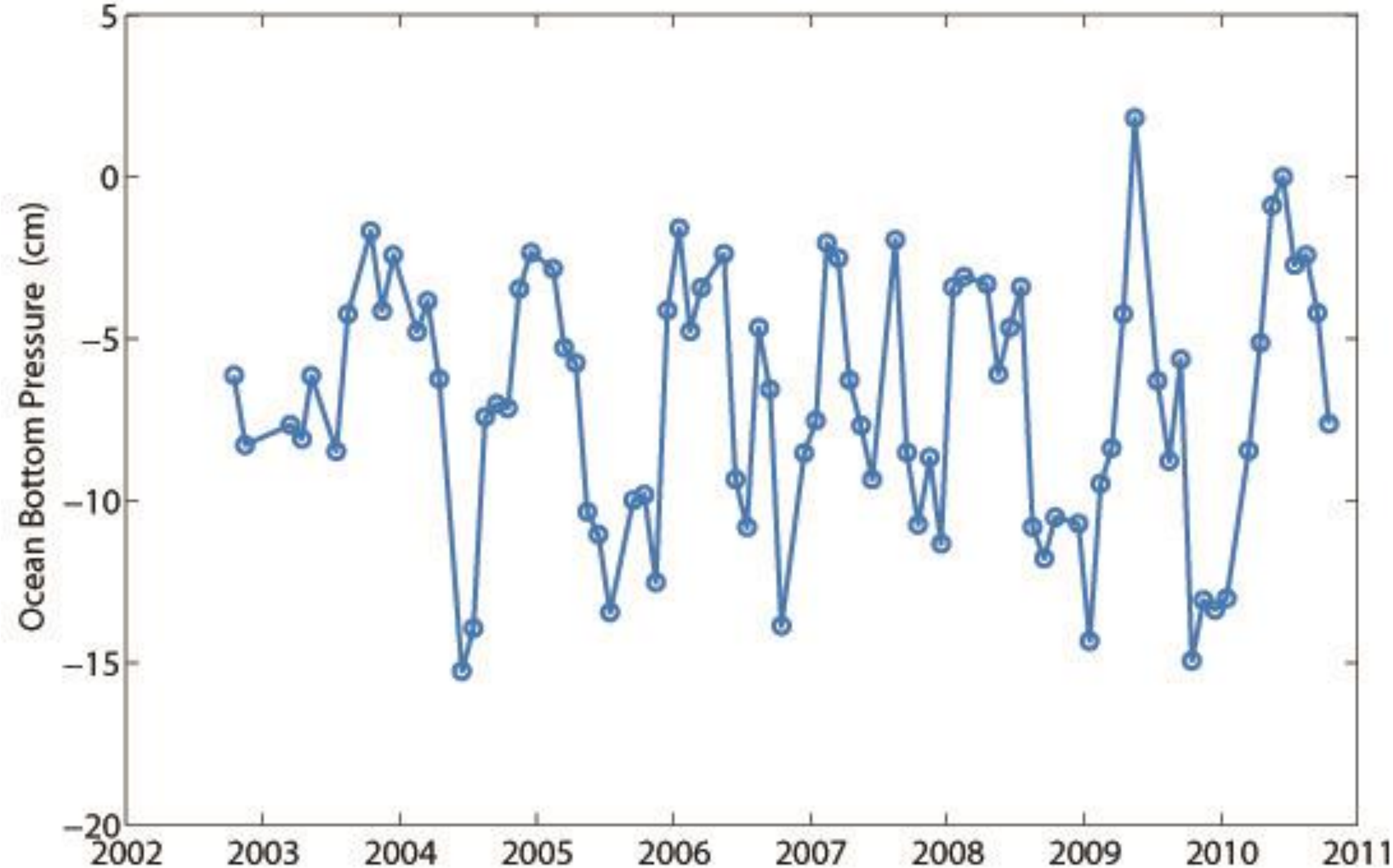
The 2003-2012 secular trend (cm/year) over the Middle East.



Courtesy: Joodaki and Nahavandchi, NTNU

GRACE

Ocean Mass change in Nordic Seas



Courtesy: Joodaki and Nahavandchi, NTNU

4-1 Other type of Earth Monitoring Satellite

ESA Sentinel-1

Courtesy: ESA
http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-1/Introducing_Sentinel-1

Observing the Earth

ESA Copernicus program

- Copernicus is the most ambitious Earth observation program to date. It will provide accurate, timely and easily accessible information to improve the management of the environment, understand and mitigate the effects of climate change and ensure civil security.

- This initiative is headed by the European Commission (EC) in partnership with the European Space Agency (ESA).

- ESA is developing a new family of missions called Sentinels specifically for the operational needs of the Copernicus program.
-
- Each Sentinel mission is based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for Copernicus Services.

- These missions carry a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring:

- **Sentinel-1** is a polar-orbiting, all-weather, day-and-night radar imaging mission for land and ocean services. Sentinel-1A was launched on 3 April 2014 and Sentinel-1B on 25 April 2016. Both were taken into orbit on a Soyuz rocket from Europe's Spaceport in French Guiana.

Courtesy: ESA
http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus

Observing the Earth

ESA Copernicus program

- **Sentinel-2** is a polar-orbiting, multispectral high-resolution imaging mission for land monitoring to provide, for example, imagery of vegetation, soil and water cover, inland waterways and coastal areas. Sentinel-2 can also deliver information for emergency services. Sentinel-2A was launched on 23 June 2015 and Sentinel-2B will follow in the second half of 2016.

- **Sentinel-3** is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean color and land color with high-end accuracy and reliability. The mission will support ocean forecasting systems, as well as environmental and climate monitoring. Sentinel-3A was launched on 16 February 2016. Sentinel-3B is scheduled for launch in 2017.

- **Sentinel-4** is a payload devoted to atmospheric monitoring that will be embarked upon a Meteosat Third Generation-Sounder (MTG-S) satellite in geostationary orbit.

- **Sentinel-5** is a payload that will monitor the atmosphere from polar orbit aboard a MetOp Second Generation satellite.

- **Sentinel-5 Precursor** satellite mission is being developed to reduce data gaps between Envisat, in particular the Sciamachy instrument, and the launch of Sentinel-5. This mission will be dedicated to atmospheric monitoring.

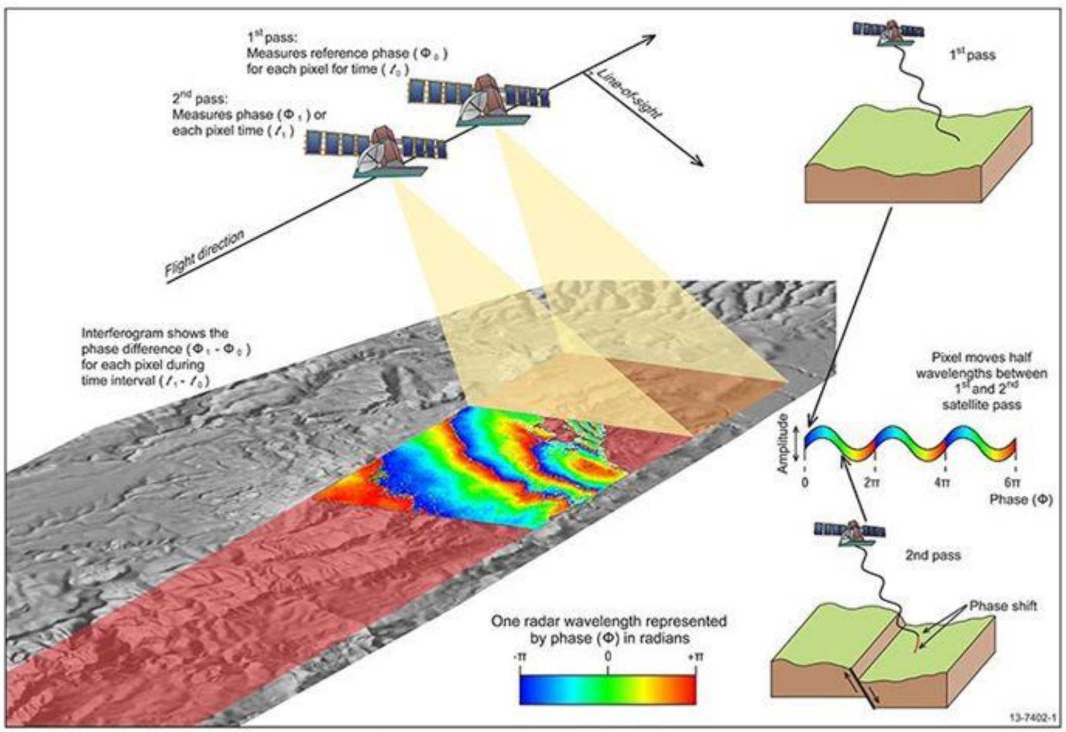
- **Sentinel-6** carries a radar altimeter to measure global sea-surface height, primarily for operational oceanography and for climate studies.

Courtesy: ESA
http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus

Radar Interferometry
Sentinel 1

InSAR - Theory

- Differential InSAR uses two SAR images of the same area acquired at different times. If the distance between the ground and satellite changes between the two acquisitions due to surface movement, a phase shift will occur

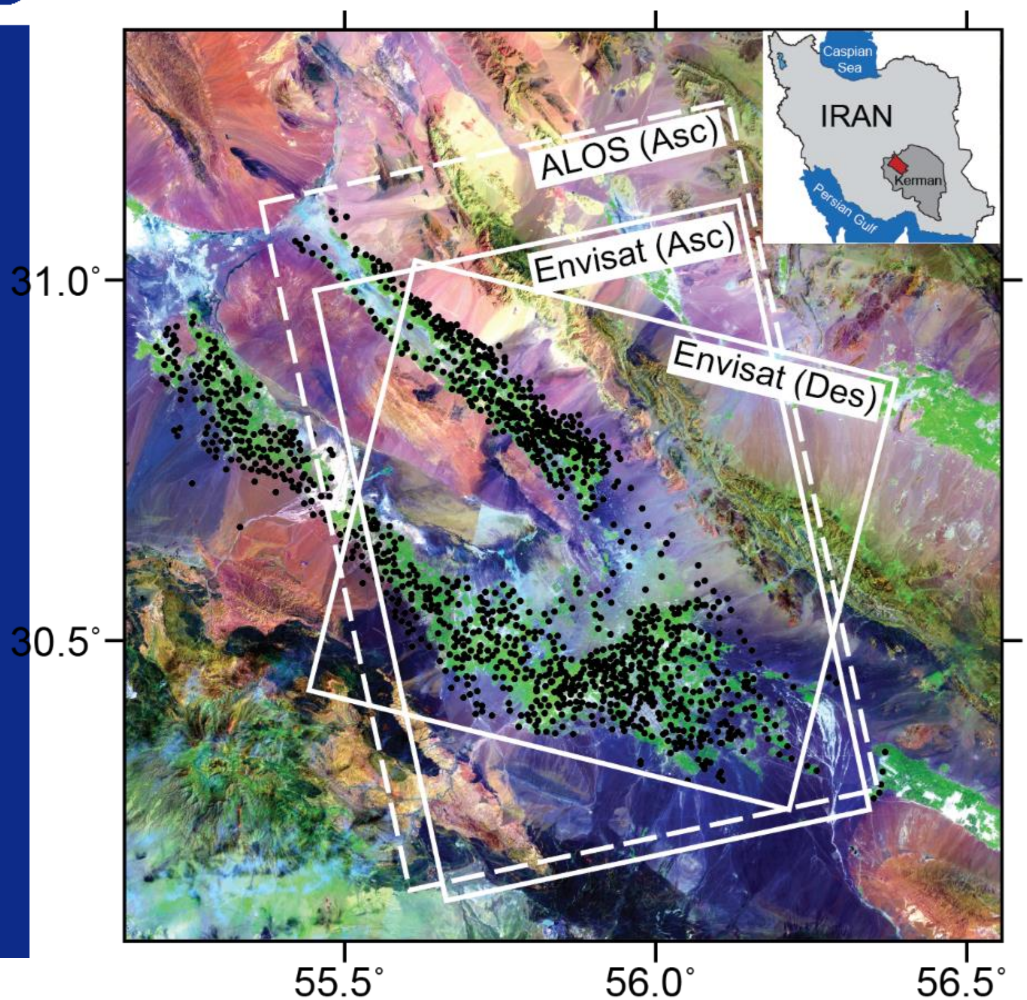


SOURCE: http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/geodetic-techniques/interferometric-synthetic-aperture-radar

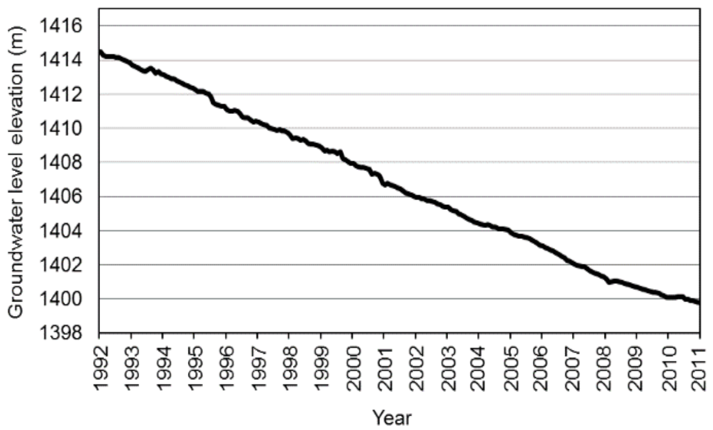
Radar Interferometry

Rafsanjan plain

Radar Interferometry can be used to monitor deformations in time

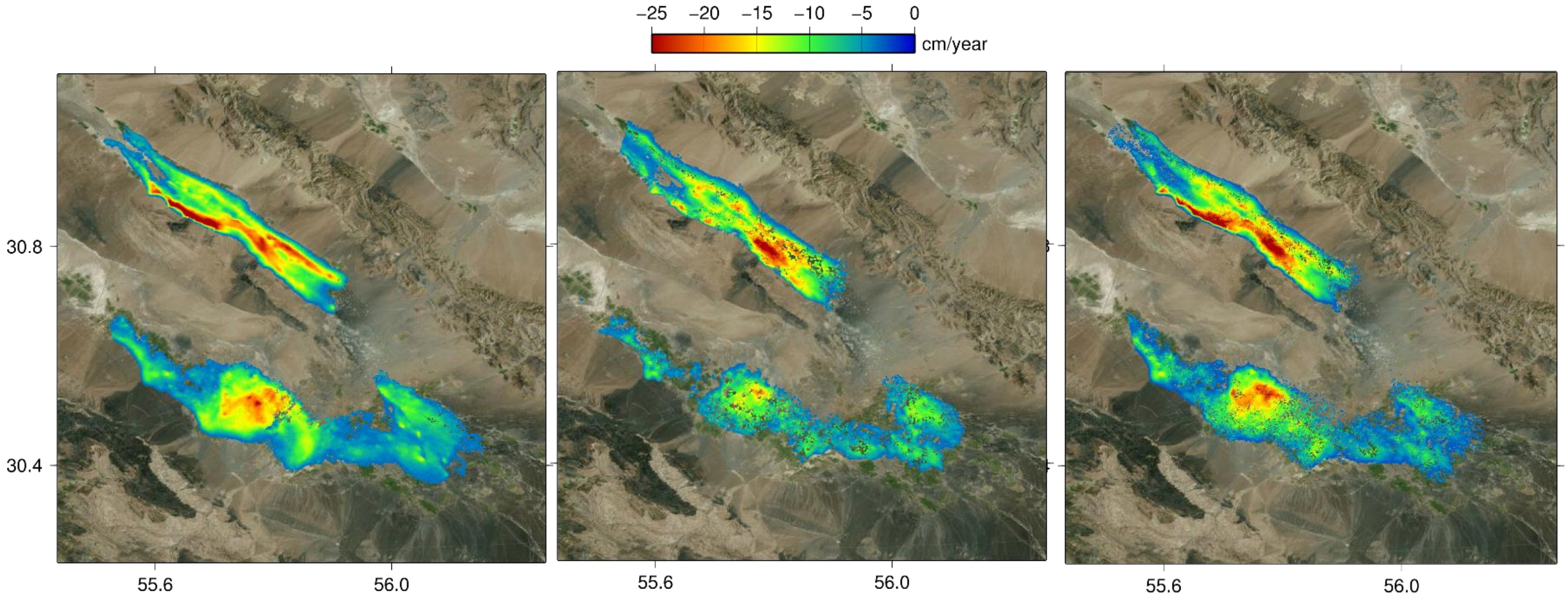


Courtesy:
Motagh et al. 2016



Radar Interferometry

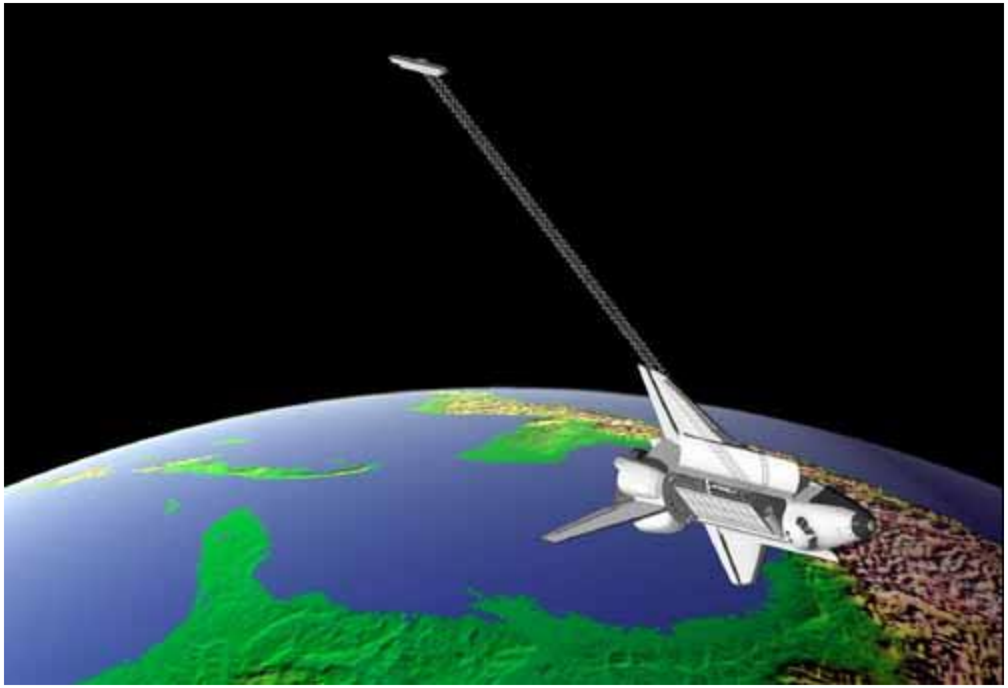
Deformation in Rafsanjan plain



Courtesy:
Motagh et al. 2016

4-2 Other type of Earth Monitoring Satellite

Shuttle Radar Topography Mission (SRTM)



Courtesy: NASA/JPL-Caltech
http://www2.jpl.nasa.gov/srtm/

Shuttle Radar Topography Mission (SRTM)

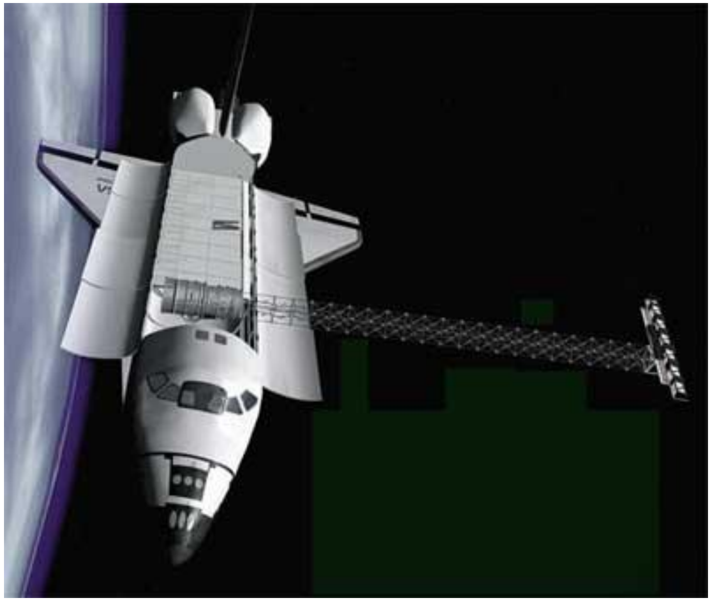
The Shuttle Radar Topography Mission (SRTM) is a joint project between the National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA), and German Aerospace Center (DLR) and Italian Space Agency (ASI). The objective of this project is to produce digital topographic data for 80% of the Earth's land surface (all land areas between 60º north and 56° south latitude), with data points located every 1-arc-second (approximately 30 meters) on a latitude/longitude grid. The absolute vertical accuracy of the elevation data will be 16 meters (at 90% confidence). This radar system gathered data that resulted in the most accurate and complete topographic map of the Earth's surface that has ever been assembled.

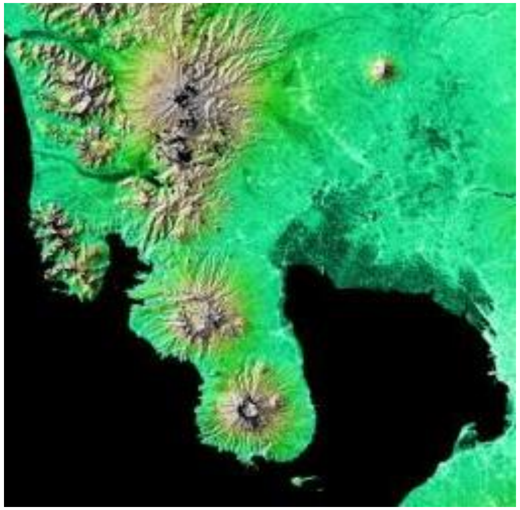
Courtesy: http://srtm.usgs.gov/index.html

Global source of DEM data
SRTM 1''and 3'' data

The SRTM radar contained two types of antenna panels, C-band and X-band. The near-global topographic maps of Earth called Digital Elevation Models (DEMs) are made from the C-band radar data. These data were processed at the Jet Propulsion Laboratory and are being distributed through the United States Earth Resources Observation and Science EROS Center.

Data from the X-band radar are used to create slightly higher resolution DEMs but without the global coverage of the C-band radar. The SRTM X-band radar data are being processed and distributed by the German Aerospace Center, DLR.





Manila Bay SRTM sample data

Courtesy: NASA/JPL-Caltech
http://www2.jpl.nasa.gov/srtm/

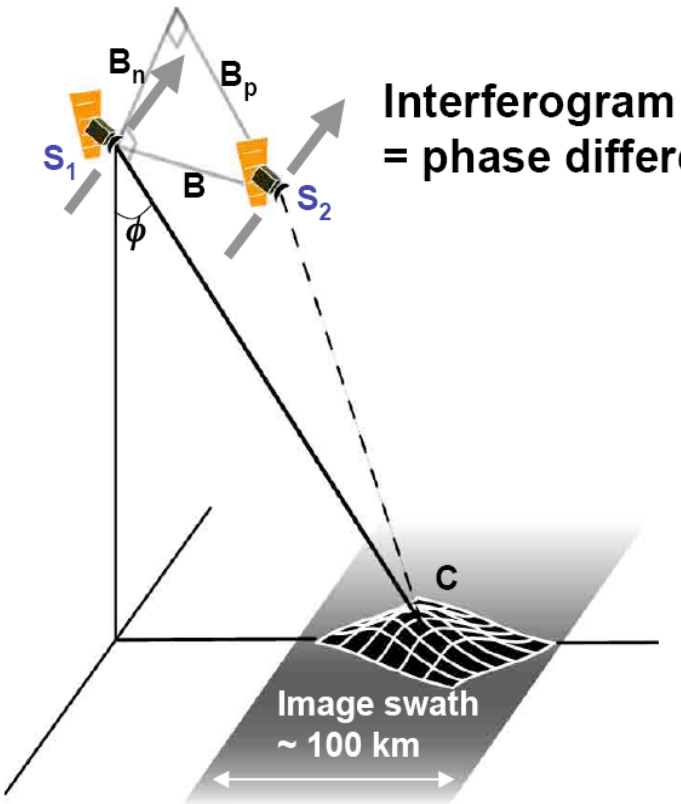
Shuttle Radar Topography Mission (SRTM)

- SRTM made use of a technique called **radar interferometry**. In radar interferometry, two radar images are taken from slightly different locations. Differences between these images allow for the calculation of surface elevation, or change.

- To get two radar images taken from different locations the SRTM hardware consisted of one radar antenna in the shuttle payload bay and a second radar antenna attached to the end of a mast extended 60 meters out from the shuttle.

Courtesy: http://srtm.usgs.gov/index.html#

Shuttle Radar Topography Mission (SRTM)



Interferogram
= phase difference between S_1-C and S_2-C.

B : Baseline
B_n : Perpendicular baseline
B_p : Parallel baseline
ϕ : Incidence angle

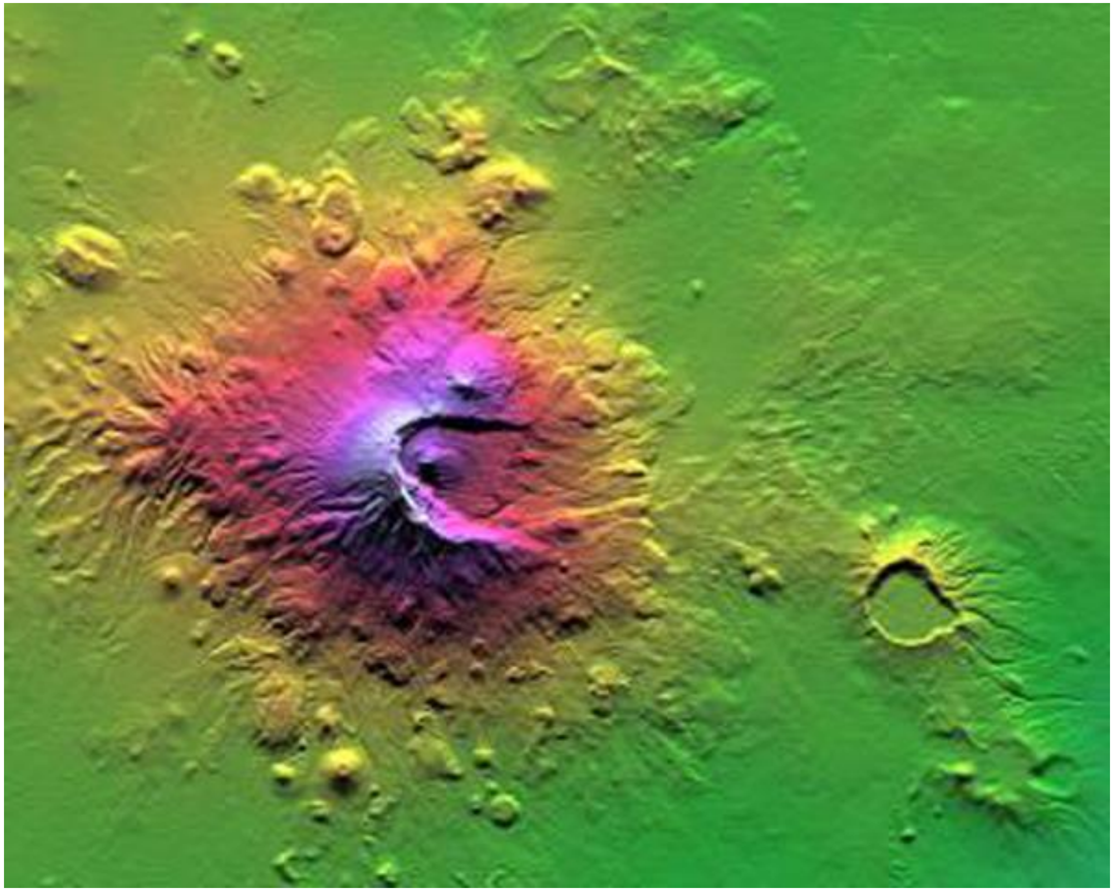
Any phase difference will contain information about the angle from which the radar echo returned. Combining this with the distance information, one can determine the position in three dimensions of the image pixel. In other words, one can extract terrain altitude as well as radar reflectivity, producing a digital elevation model (DEM) with a single airplane pass.

http://www2.jpl.nasa.gov/srtm/instrumentinterfmore.html

Shuttle Radar Topography Mission (SRTM)

- Launch: February 11, 2000, 12:44 pm EST.
- Landing: February 22, 2000, 6:22 pm EST at Kennedy Space Center.
- Mission Duration: 11 days, 5 hours, 38 minutes.
- Project Start: August 1996.
- Project End: March 2001

SRTM
Mount Meru, Tanzania



Courtesy: SRTM, US Geological Survey
http://srtm.usgs.gov/srtmimagegallery/Mount%20Meru,%20Tanzaniasmall.php