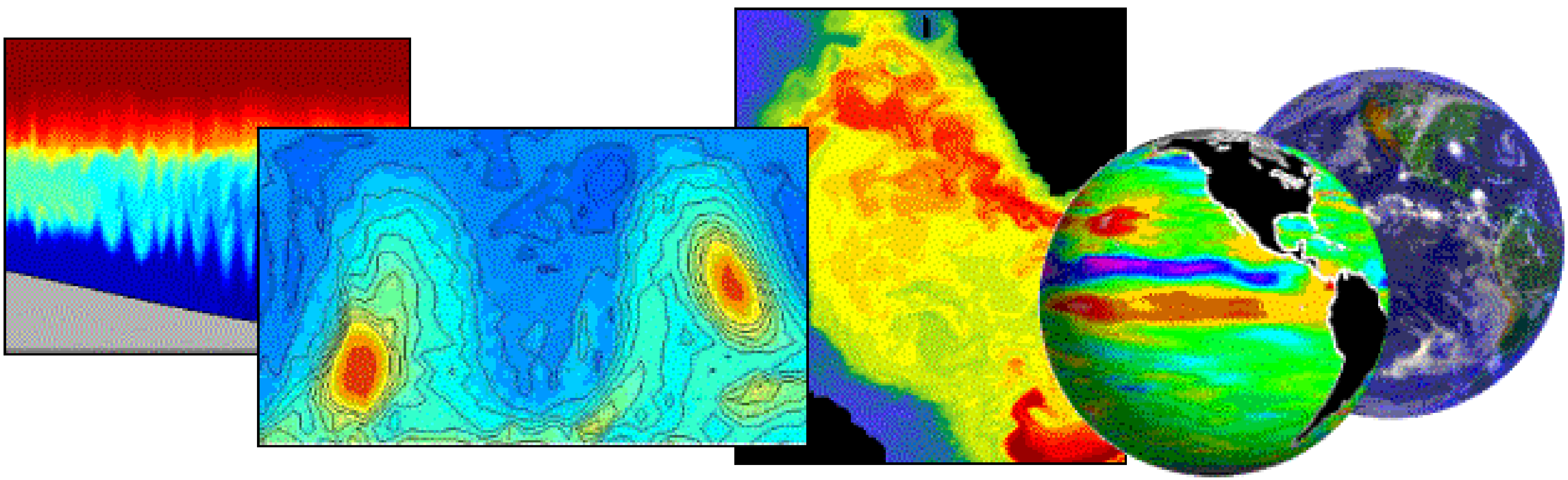
Satellite Oceanography and Applications 2: Altimetry, scatterometry, SAR, GRACE



RMU Summer Program (AUGUST 24-28, 2015)

Altimetry

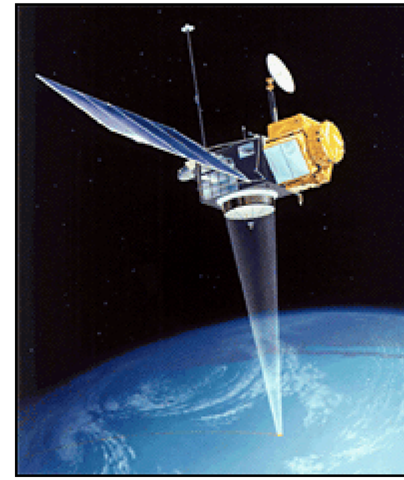
Basic principles of satellite altimetry

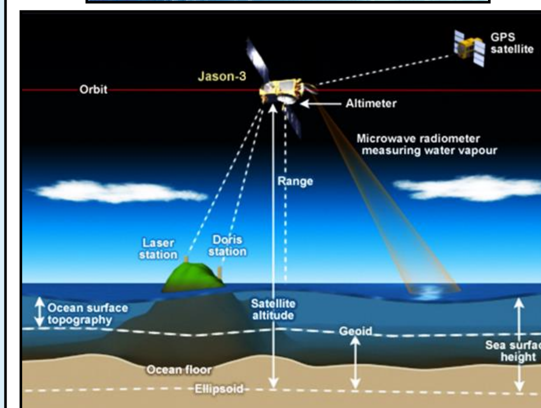
✓ Altimetry: the measurements of altitude/height/elevation above a fixed reference level

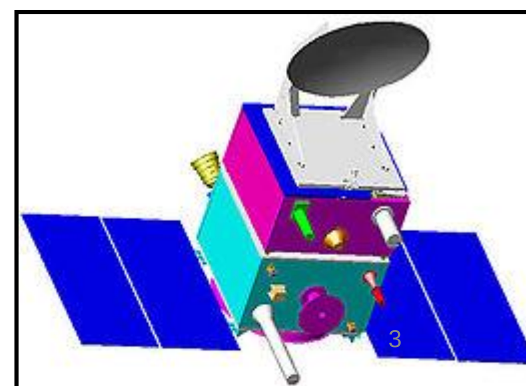
-- *altus (Latin) - height*

-- *metron (Greek) - to measure*

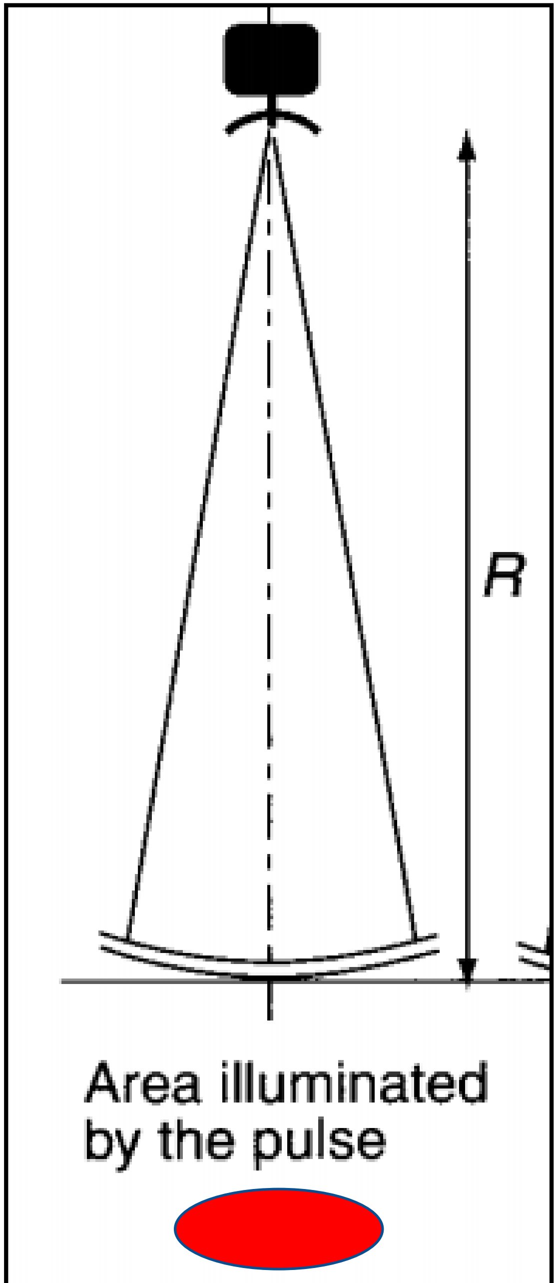
- Skylab, GEOS-3, Seasat: 1975-1980
- TOPEX/Poseidon: US & France.
  August 10, 1992 – December, 2005
- Jason-1: a follow on to TOPEX/Poseidon.
  December 7, 2001- July 3, 2013
- Jason-2: June 20, 2008-present
- Jason-3: to launch 2015
- SARAL/Altika: India & France. Feb 25, 2013 - present







Basic principles of satellite altimetry



• Altimetry satellites basically determine the distance from the satellite to a target surface by measuring the satellite-to-surface round-trip time of a radar pulse.

• Radar altimeters on board the satellite transmit signals at high frequency (e.g. Topex/Poseidon - over 1700 pulses per sec) to Earth

• The altimeter receives back echo from the sea surface

Time after pulse emission:

$$t = 2R/c$$

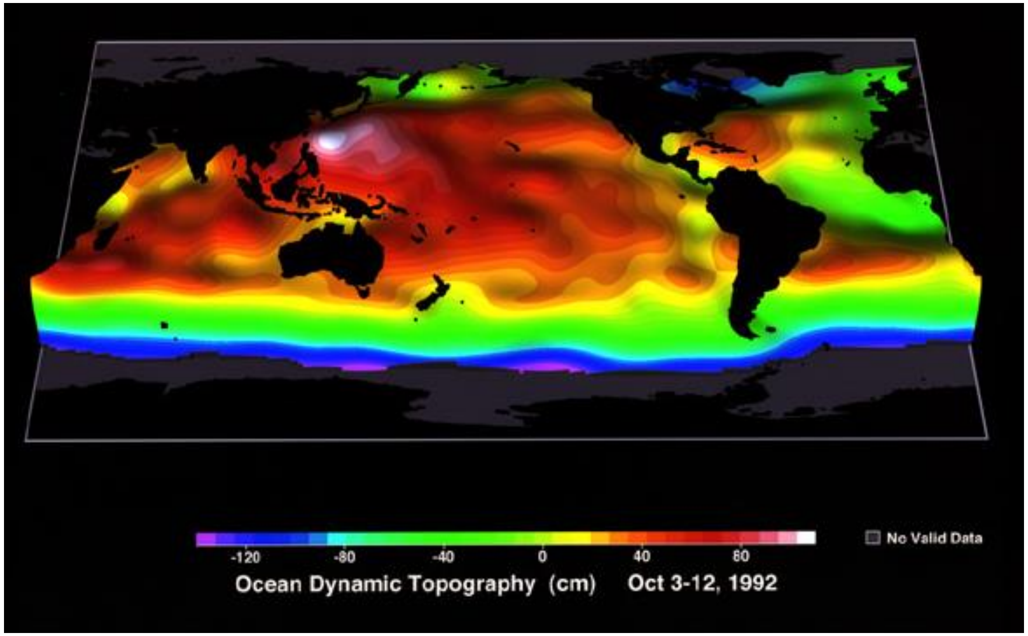
Main parameters measured by an altimeter

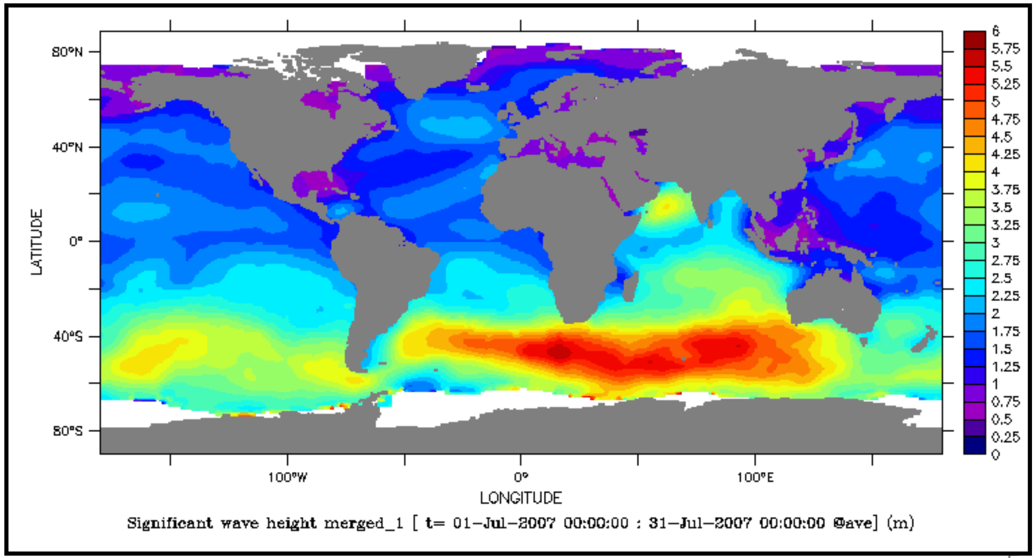
1. Sea Surface Height (SSH)

2. Significant Wave Height (SWH)

3. Wind speed

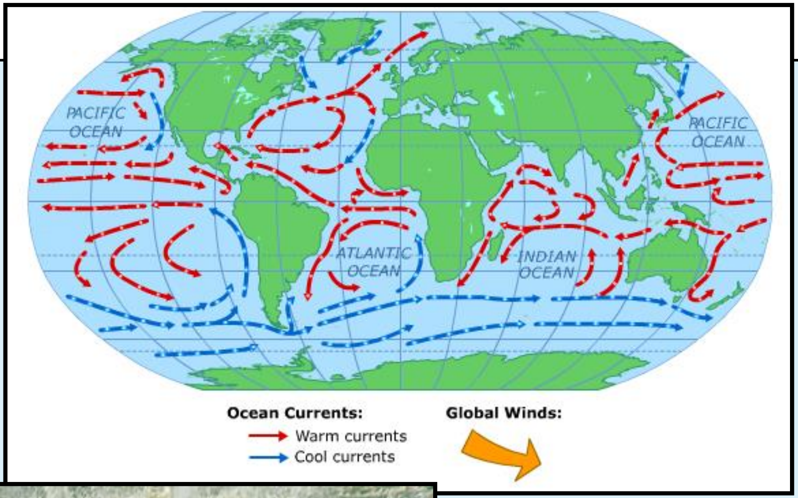
4. Ice/land/lakes characteristics





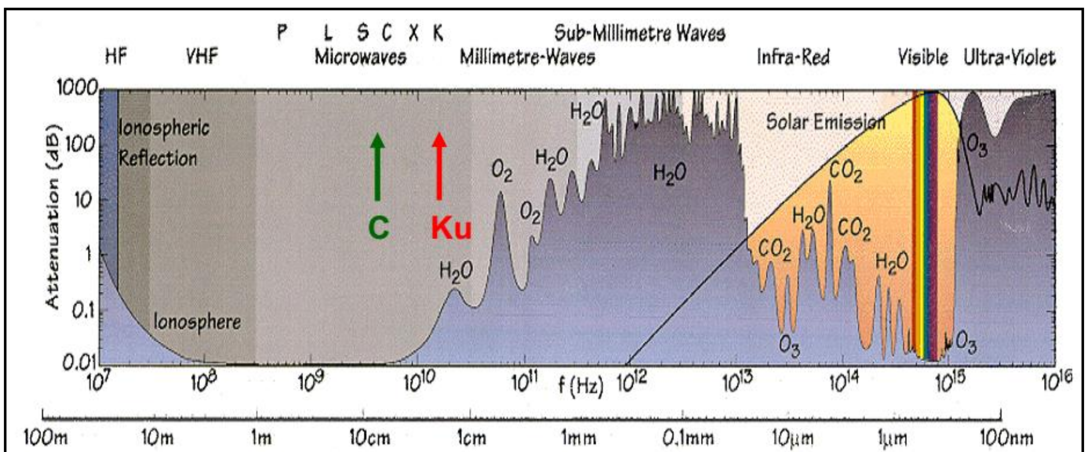
Importance of satellite altimetry data

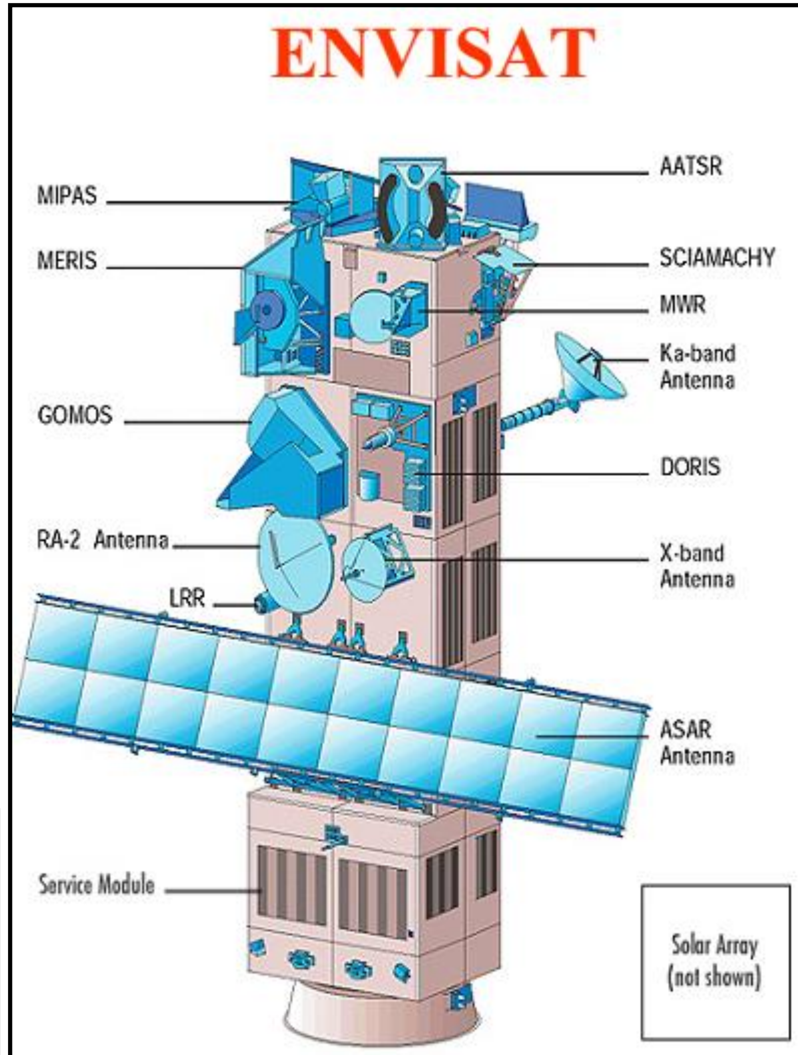
- Ocean variability
- Ocean circulation
- Sea level change
- Planetary waves
- Ocean tides
- Ocean models
- Hydrography
- Ship navigation



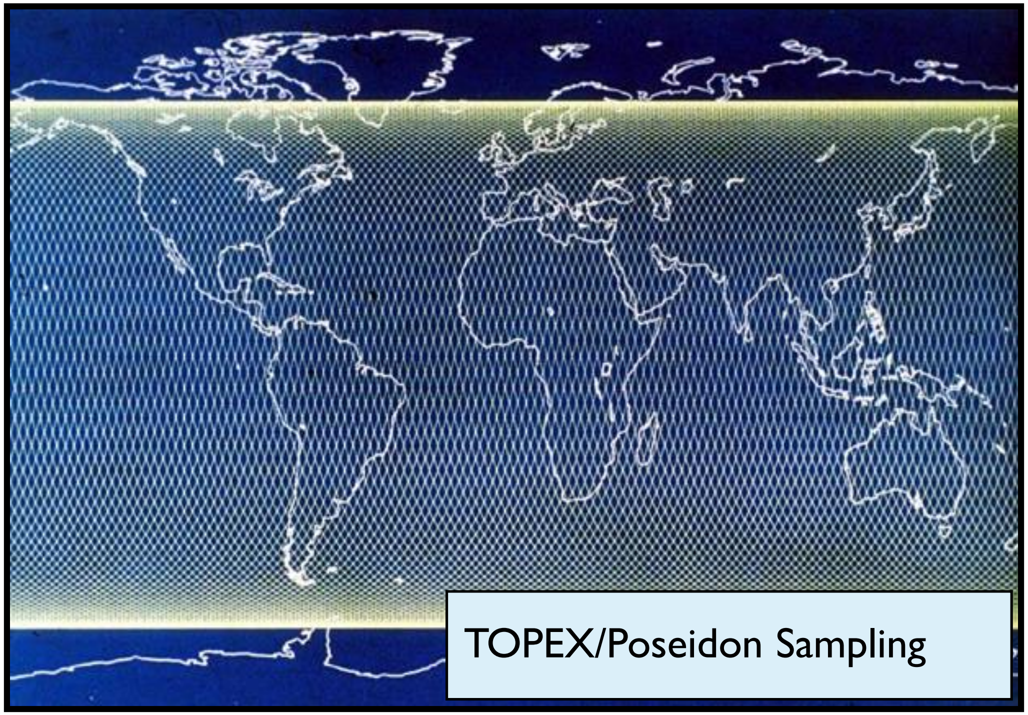
Anatomy of an Altimeter mission

1. Radar altimeter – Ku band (13.5 GHZ).
2. C or S band for ionospheric correction.
3. Microwave radiometer for atmospheric corrections.
4. Tracking system for precise orbit determination (DORIS, LRA, GPS)





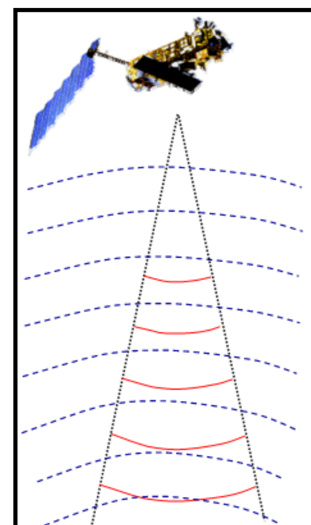
Satellite altimetry coverage



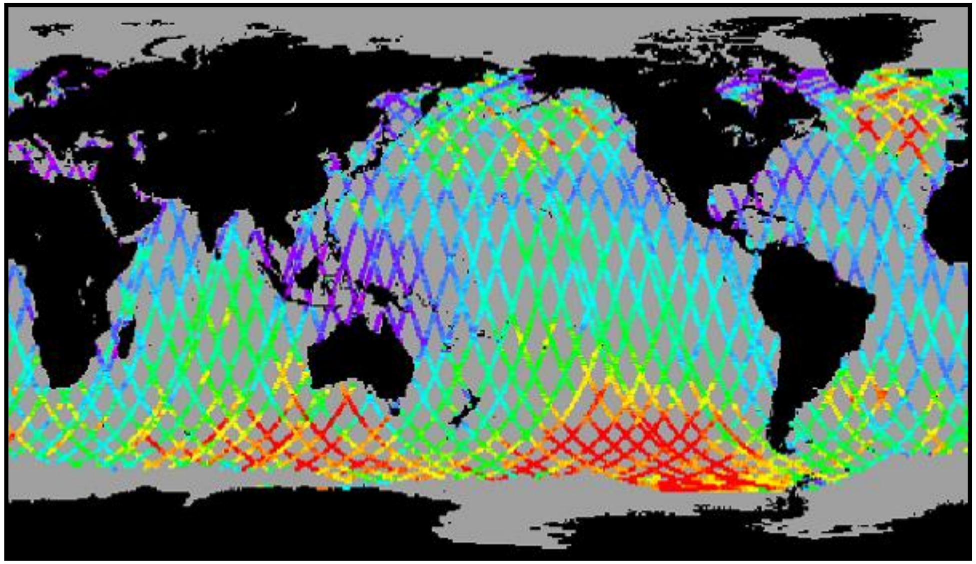
TOPEX/Poseidon Sampling

- Spatial coverage :
  - global
  - homogeneous
  - Nadir (not swath)
- Temporal coverage :
  - repeat period
  - 10 days, T/P-Jason-1
  - 35 days, ERS/ENVISAT

	Geosat	ERS	TOPEX	Poseidon-1	Poseidon-2	ENVISAT
Altitude	785 km	800 km	1336 km	1336 km	1347 km	800 km
Inclination	108 °	98.5 °	66 °	66 °	66 °	98.55°
Trajectory	Retrograde	Retrograde	Prograde	Prograde	Prograde	Retrograde
Repeat Period	17 days	35 days	10 days	10 days	10 days	35 days
Track Spacing Equator	163 km	77 km	315 km	315 km	315 km	77 km



Wave height and wind estimations



• SSH depends on:
-- Geoid
-- Ocean Tides
-- Atmospheric pressure
-- Geostrophic circulation
-- Ocean waves

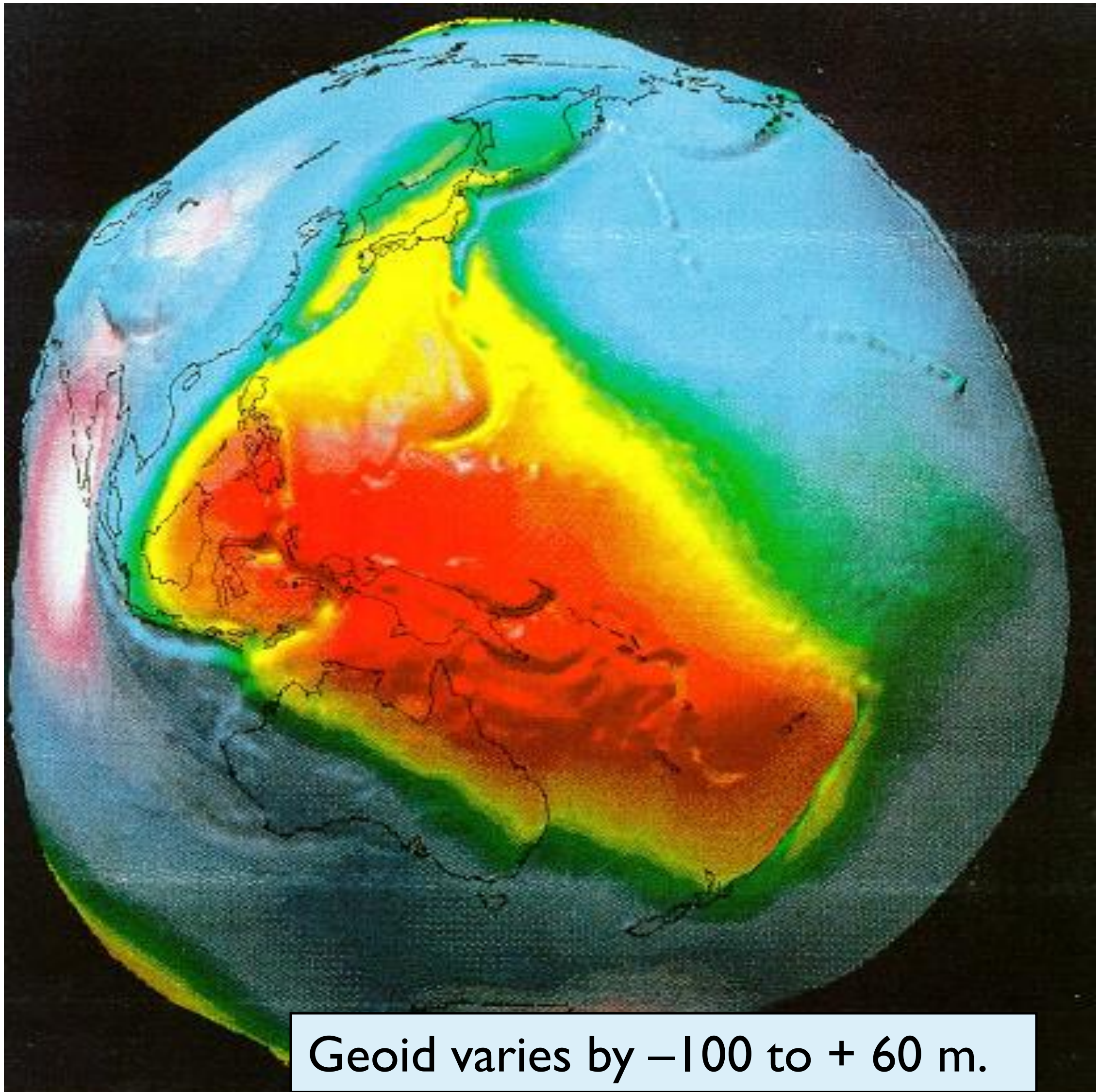
• Significant Wave Height is estimated from the change in slope of the wave form's leading edge.

• The power of the return signal is related to the wind-induced roughness of the sea-surface.

• Wind Speed is then estimated from empirical formulae. Wind direction cannot be resolved.

SSH measurement

SSH (relative to an earth ellipsoid) = Orbit height – Range – Σ Corr



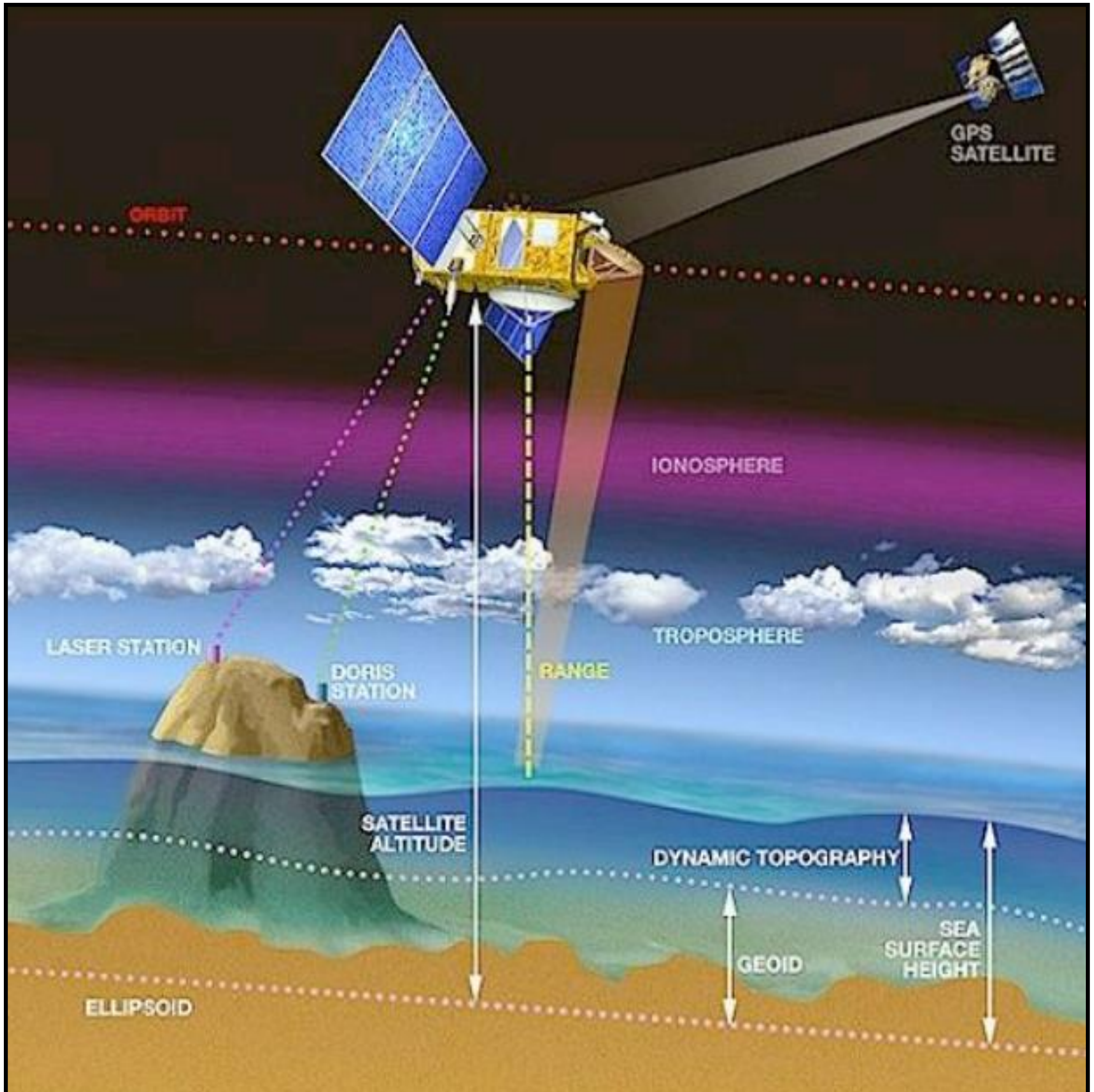
Geoid varies by –100 to + 60 m.

The earth has large bumps and troughs due to variations in the ocean bottom topography and inhomogeneous density distributions in the earth's interior.

These density variations create a **bumpy geoid**. If the ocean were at rest, the sea surface would exactly follow the geoid.

SSH measurement

SSH (relative to an earth ellipsoid) = Orbit height – Range – Σ Corr



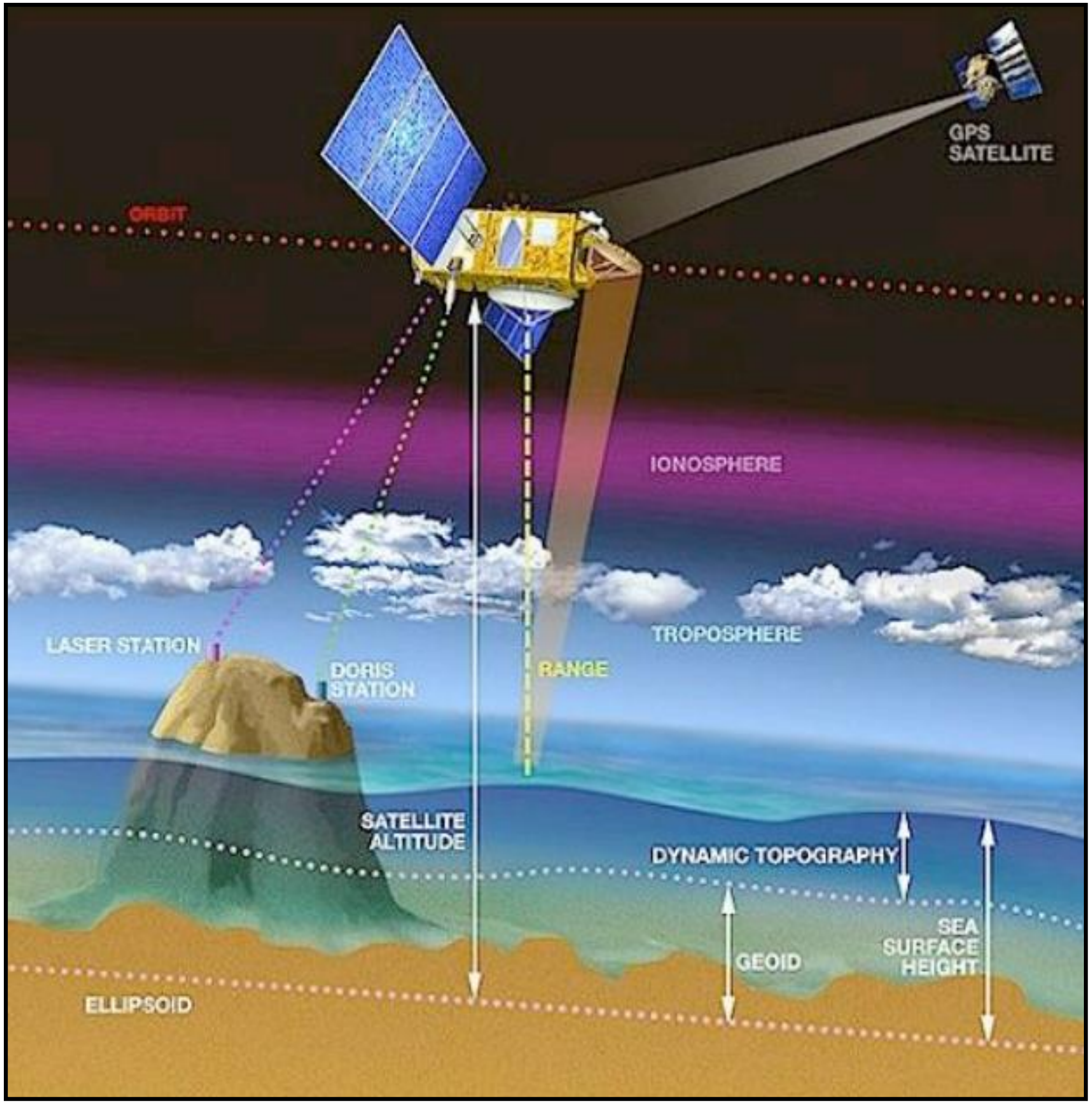
SSH = Geiod + Dynamic topography (η)

Geoid: is that equipotential surface of the Earth gravity field, that most closely approximates the mean sea surface height.

The earth is not a perfect ellipsoid due to uneven distribution of mass

SSH measurement

SSH (relative to an earth ellipsoid) = Orbit height – Range – Σ Corr



Precision of the SSH:

- Orbit error
- Errors on the range

 - - instrumental noise

 - - various instrument errors

 - - various geophysical errors (e.g., atmospheric attenuation, tides, inverse barometer effects, …)

Satellite Tracking Systems … Laser Tracking and GPS

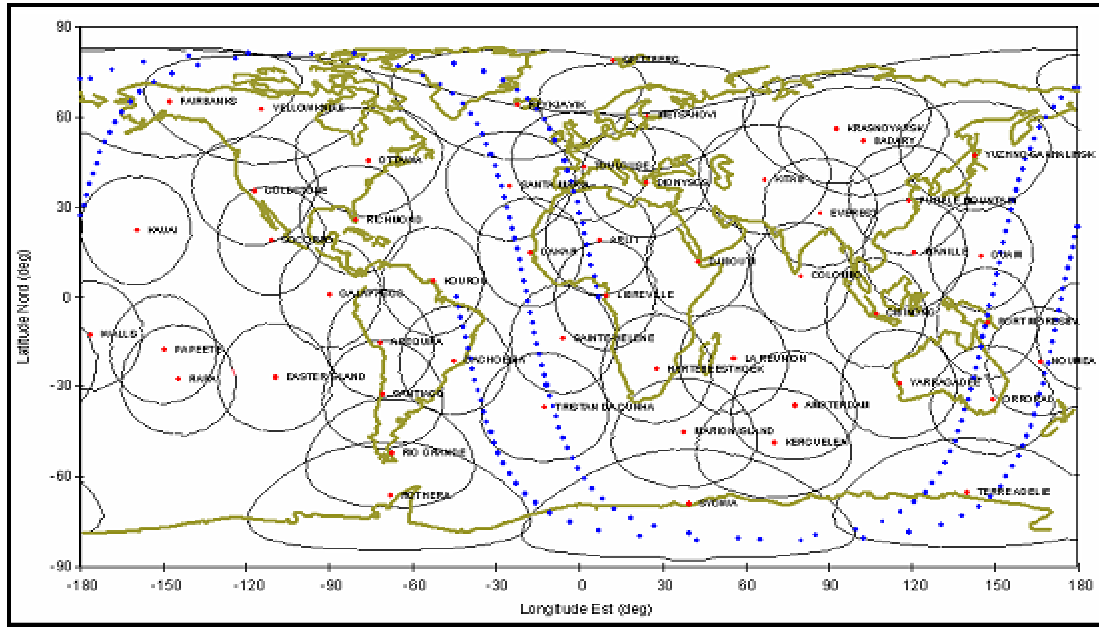
Satellite tracking is also made using complementary systems : Laser tracking, DORIS and GPS

Global Positioning System (GPS):

- An onboard GPS receiver provides precise, continuous tracking of the satellite by monitoring range and timing signals from up to 6 GPS satellites at the same time.

Satellite Tracking Systems … Laser Tracking and GPS

Satellite tracking is also made using complementary systems : Laser tracking, DORIS and GPS



DORIS: Doppler Orbitography and Radiopositioning Integrated by Satellite

DORIS: a Doppler tracking system. A network of DORIS beacons emit 2 signals at different frequencies. An onboard captor measures the Doppler shift between the signals to determine the distance between the satellite and the ground beacon.

Limitations of Satellite Altimetry

- Measures SSHA to an accuracy of 2-3 cm

☐ Measures only along the precise orbit repeat track

- Detects only the variable signal

☐ Long term mean SSH lost in the geoid
☐ Mean ocean currents cannot be detected
☐ Needs longer time series to measure lower frequencies
☐ An independent measure of gravity is needed

- SSH unreliable in shelf seas

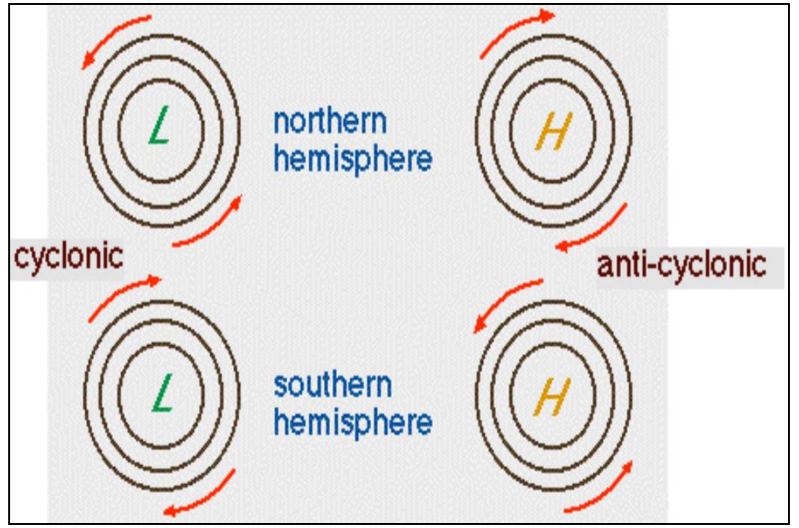
☐ The tidal signal cannot be accurately predicted
☐ Other ageostrophic motions are likely

- Currents cannot be recovered in equatorial waters

☐ Geostrophy not valid

Observing ocean currents using satellite altimetry

- Geostrophic currents: current in which the horizontal pressure gradient is balanced by Coriolis force.
- May occur when conditions are barotrophic (homogeneous) or baroclinic (variations in density)



Geostrophy

u,v zonal and meridional currents

P pressure, f = Coriolis parameter

$$\begin{cases} fv = \dfrac{1}{\rho_0}\dfrac{\partial P}{\partial x} & (1) \\ -fu = \dfrac{1}{\rho_0}\dfrac{\partial P}{\partial y} & (2) \end{cases}$$

$$f = 2\Omega \sin\theta$$

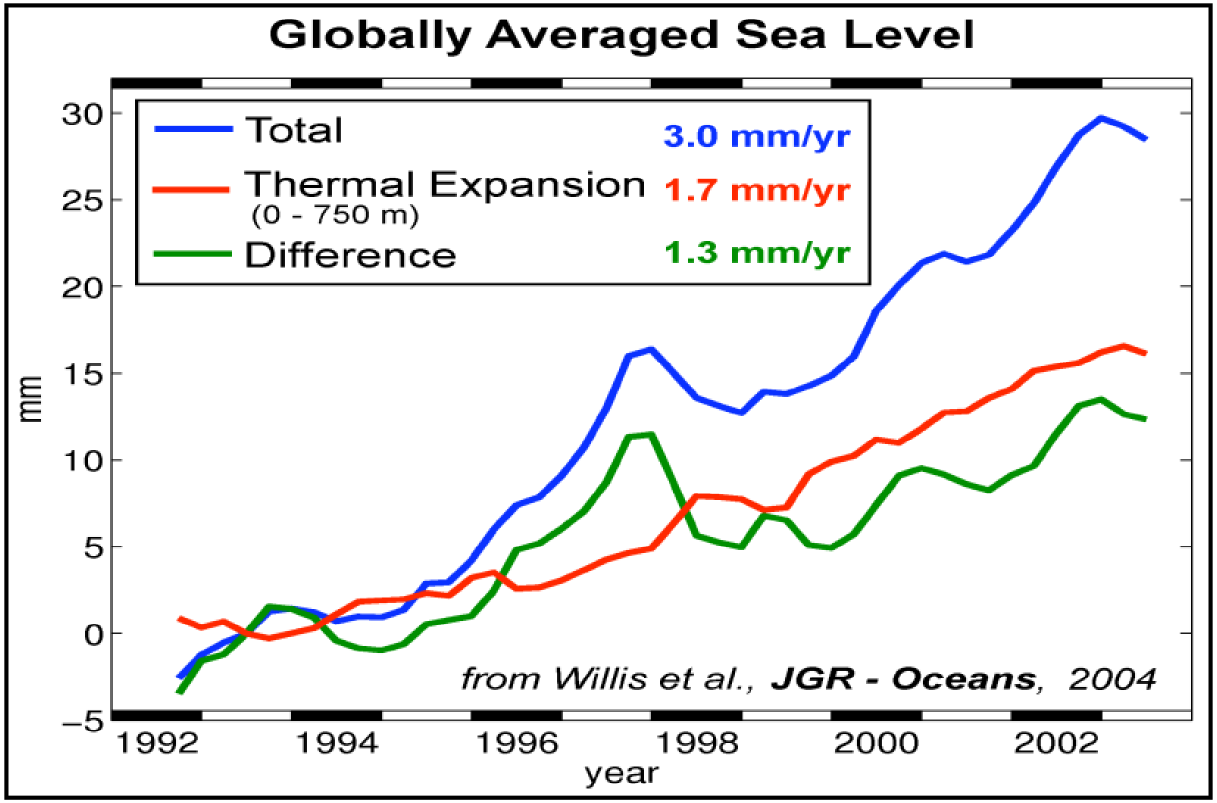
Hydrostatic balance

$$\left\{ \frac{\partial p}{\partial z} = -\rho g \right. \qquad (3)$$

- At the surface P = ρg η(η= sea surface topography relative to the geoid - z local vertical) =>

$$\begin{cases} fv = g\dfrac{\partial \eta}{\partial x} \\ -fu = g\dfrac{\partial \eta}{\partial y} \end{cases} \qquad (4)$$

Global Mean Sea Level Trends



- Recent rate of ice discharge from Greenland ~ 0.5 mm/year
- Over 10 years, the heat absorbed by the ocean is enough to do

--- heat the entire atmosphere by 5 degrees,

--- melt all of the world's sea ice (3 times over),

--- melt enough land-bound ice to raise sea level by 24 cm

- Current global sea level rise apx **2.6-2.9** mm per yr since 1993

Consequences of sea level rise

• Over 10 years, the heat absorbed by the ocean is enough to do
--- heat the entire atmosphere by 5 degrees,
--- melt all of the world's sea ice (3 times over),
--- melt enough land-bound ice to raise sea level by 24 cm

Scatterometry

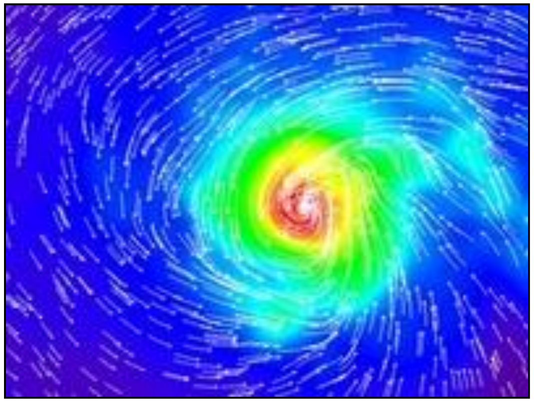
Scatterometry - Observing ocean winds

- Scatterometers measure the power of backscattering reflected from the surface of objects.

- The sensor is an active microwave radar sensor that measures the two dimensional velocity vectors of the sea wind

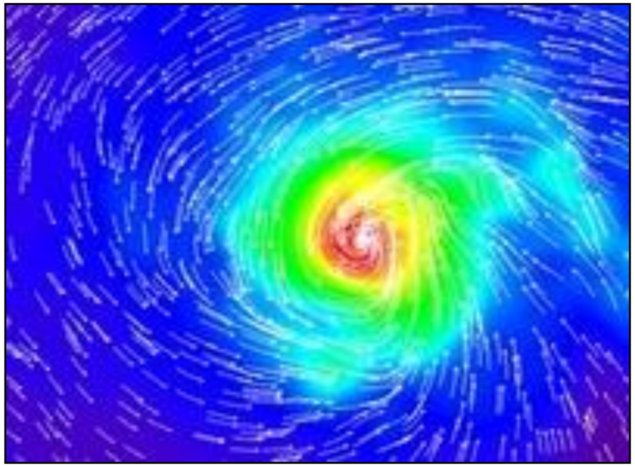
- The **wind speed** can be determined from the strength of the backscatter signal.

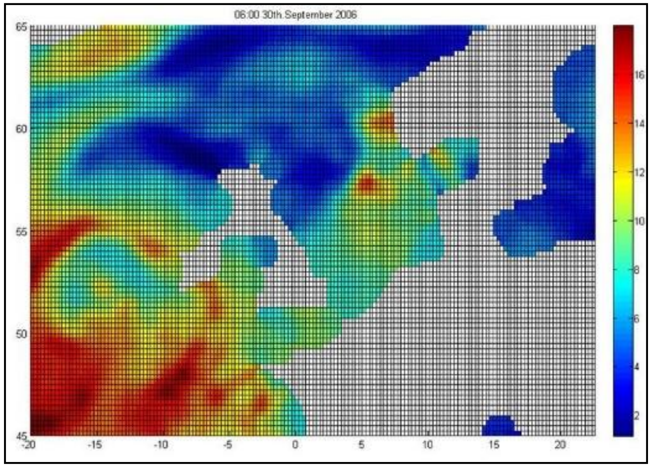
- The **wind direction** is found by determining the angle that is most likely to be consistent with the backscatter observed from multiple angles.

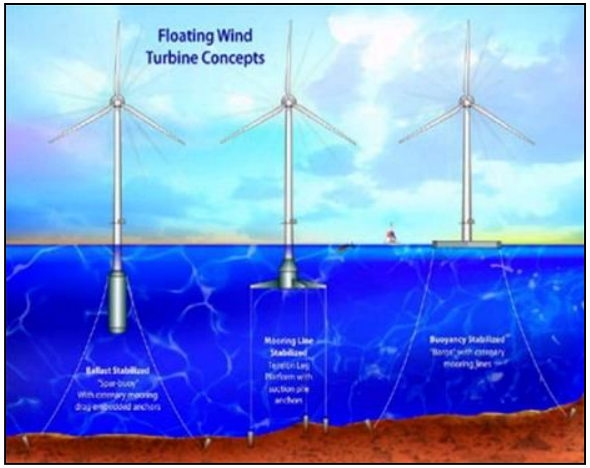


Applications/importance of Scatterometry

- **Weather Forecasting**: provides an all-weather, high-resolution measurements of near- surface winds over global oceans.
- **Oceanography:** helps understand atmospheric forcing, ocean response, and air-sea interaction on various spatio-temporal scales.
- **Climate Variability**: helps us better understand the mechanisms of global climate change and weather patterns. Tropical Cyclones





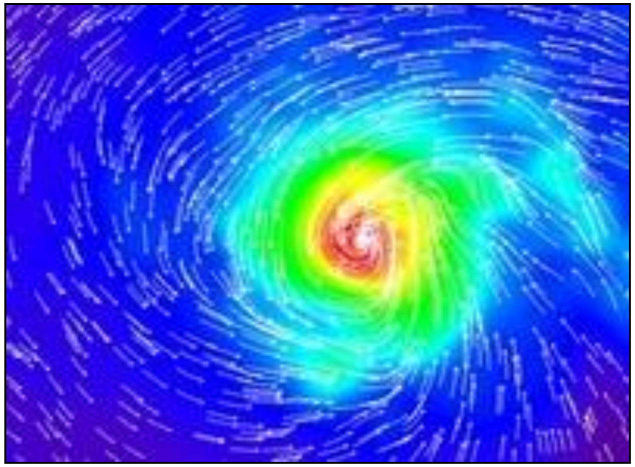


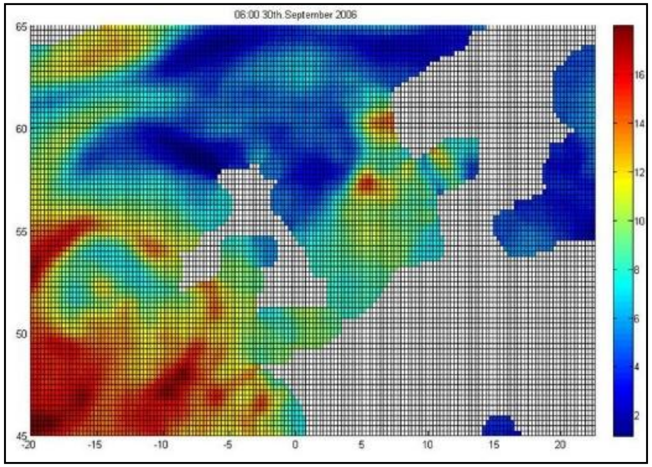
Applications/importance of Scatterometry

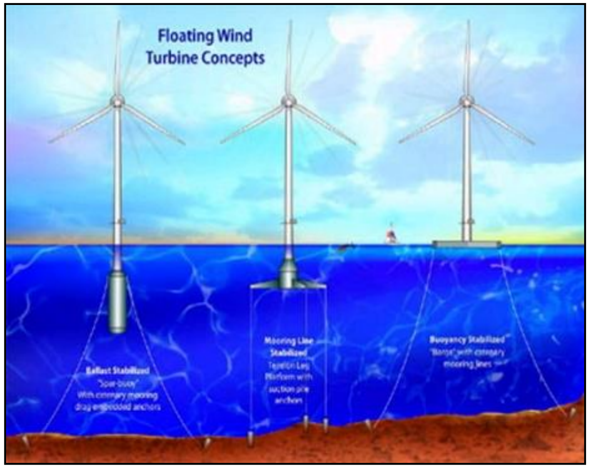
- **Land and Sea Ice**: study daily/seasonal sea ice edge movement and Arctic/Antarctic ice pack changes.

- **Wind Energy**: emerging offshore wind energy industry.

- **Marine Safety** (NRT): monitor severe weather, fronts, storms

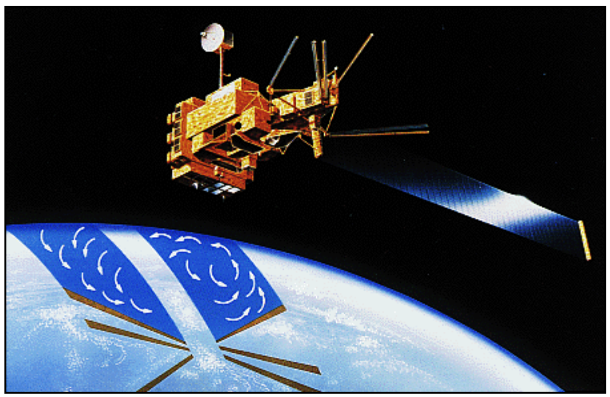




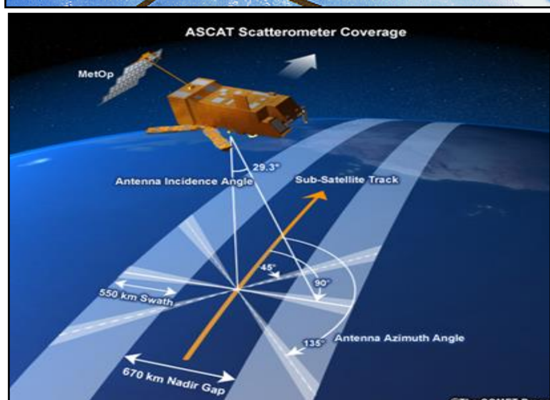


History of Scatterometry

- **SeaSat**: first Earth-orbiting satellite designed for remote sensing of the Earth's oceans
- Carried on board the first spaceborne SAR
- Operated by NASA/JPL. Lasted 105 days (1978/7/7 -1978/10/10)



- **NSCAT**: aboard the Advanced Earth Observing Satellite (ADEOS)- Japan Space Agency
- Lasted 9 months, due to a solar panel failure

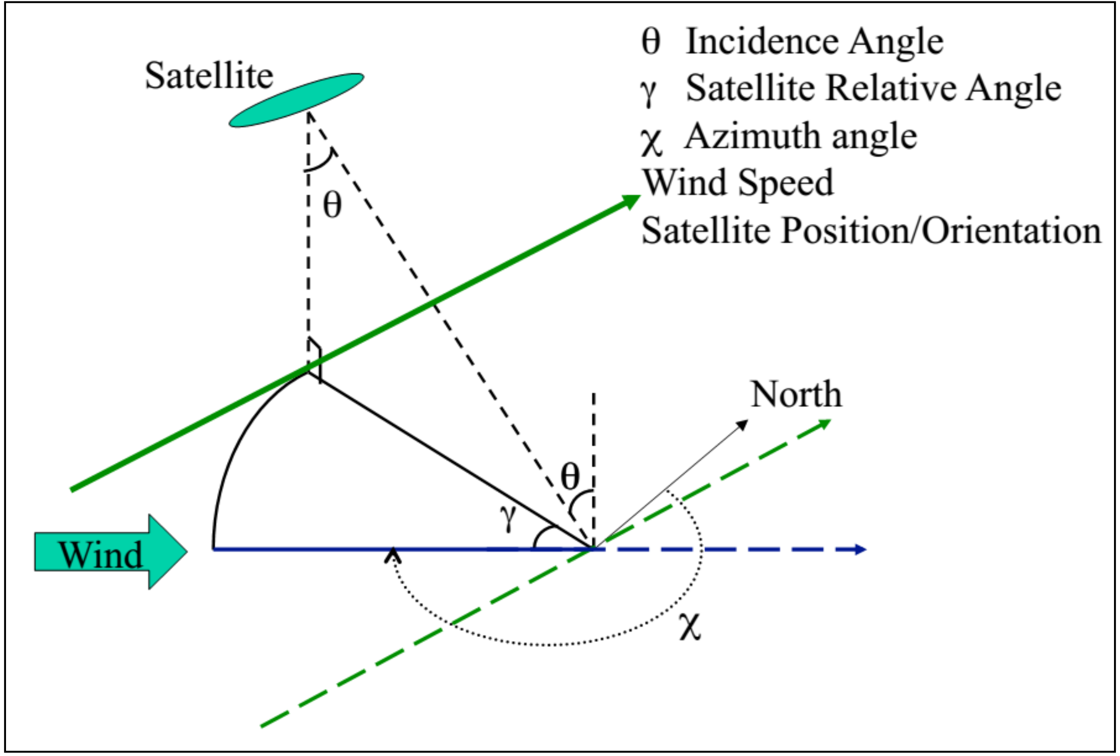


- **ASCAT**: Advanced SCATterometer (ASCAT) is a real aperture radar operating at 5.255 GHz (C-band)
- Operated by the European Space Agency (ESA)

History of Scatterometry: QuikSCAT

- a "*quick recovery*" mission after the loss of NSCAT in 1997.
- Expected to last 3 years; did 10 years! –1999 - 2009
- ***Satellite:***
  -- The QuikSCAT satellite
  -- Polar orbiting satellite
  -- Orbital height ~ 803 km
  -- One orbit in ~ 100 minutes
- ***Sensor:***
  -- SeaWinds scatterometer
  -- Active microwave sensor
  -- Responds to short water waves which respond very rapidly to changes in vector wind

Basic principles of Scatterometry



- ***Sensor:*** Active microwave sensor
- ***What is being sensed:***
  -- Microwaves Bragg scatter off of short water waves.

  -- 1 to 100 cm wavelengths, depending on microwave frequency

- Bragg scattering is a function of the
  -- incident angle

  -- azimuth angle (relative to the mean wind/wave direction)

  -- and wave characteristics such as amplitude and wavelength, over a band of wavelengths.

Outstanding Problems

- Lack of angular diversity near nadir and near swath edges

-- Near nadir the directions are parallel to the satellite track
-- Near the edge they are perpendicular to the track
-- Results in poor ambiguity selection in these regions

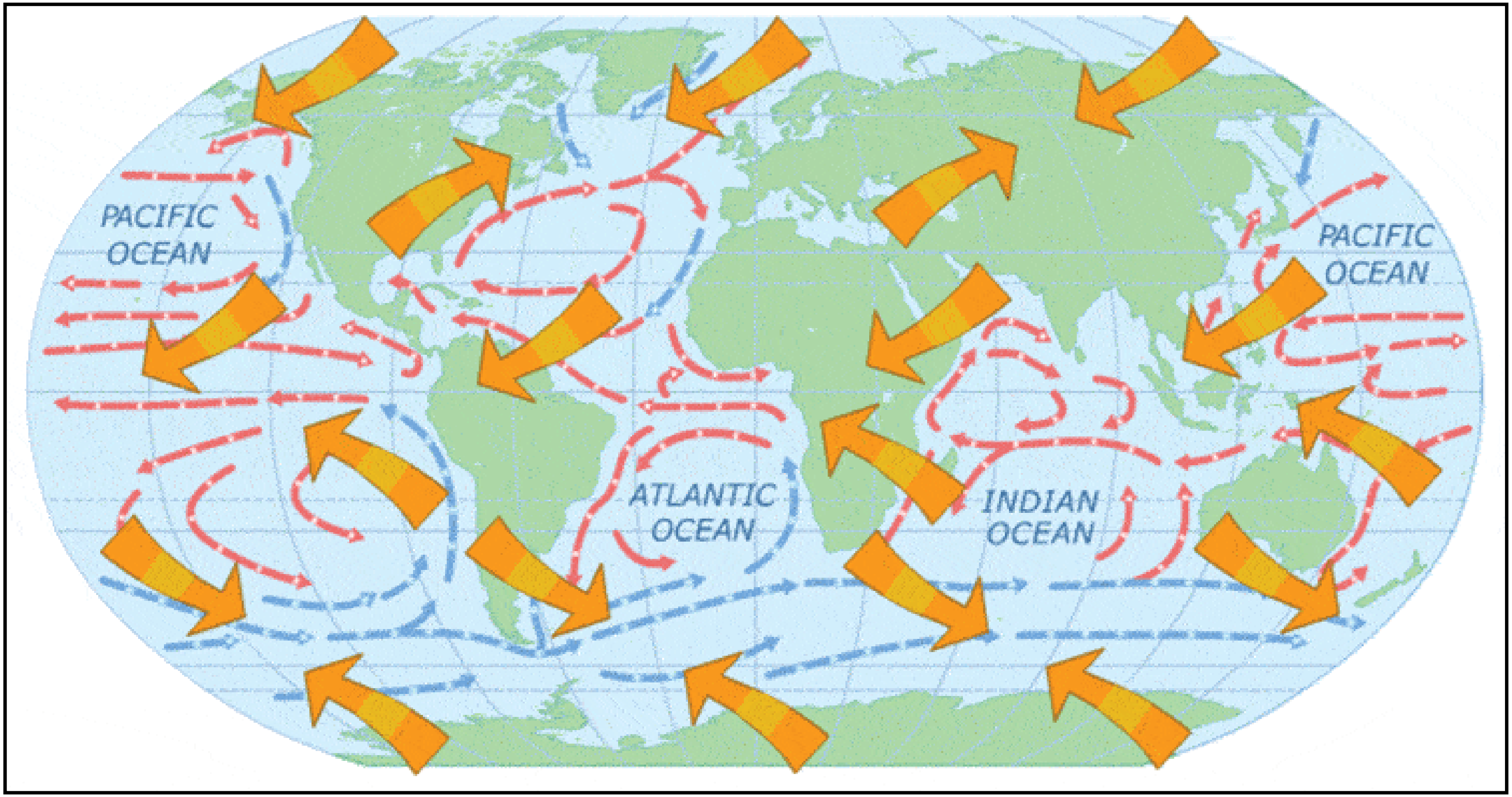
- Rain Contamination

-- Rain influences the retrieved signal through thee mechanisms
-- -- Attenuation of signal
-- -- Backscatter from rain
-- -- Modification of the water surface
-- Flags for rain are inadequate

- Coverage

-- Need one more satellite to resolve diurnal cycle

Global wind & current patterns

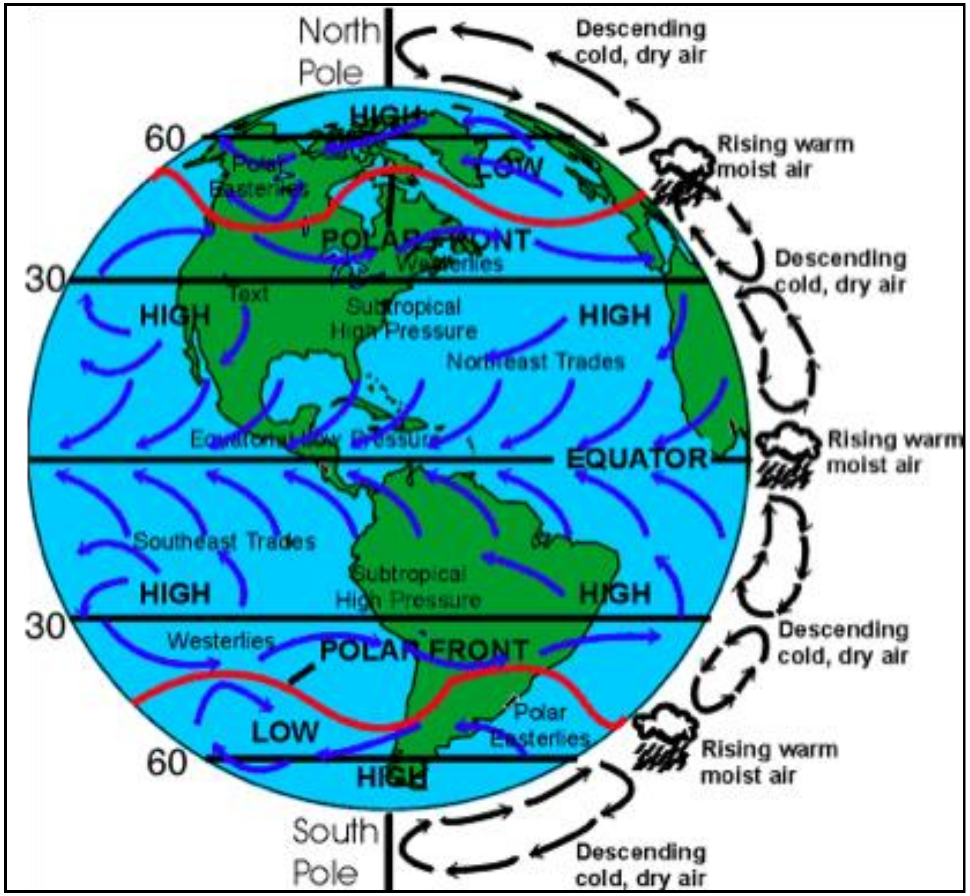


- Winds drive the ocean surface circulation

-- winds are described in terms of where they are ***blowing from***

-- currents are described in terms of where they are ***flowing towards***

Global wind patterns



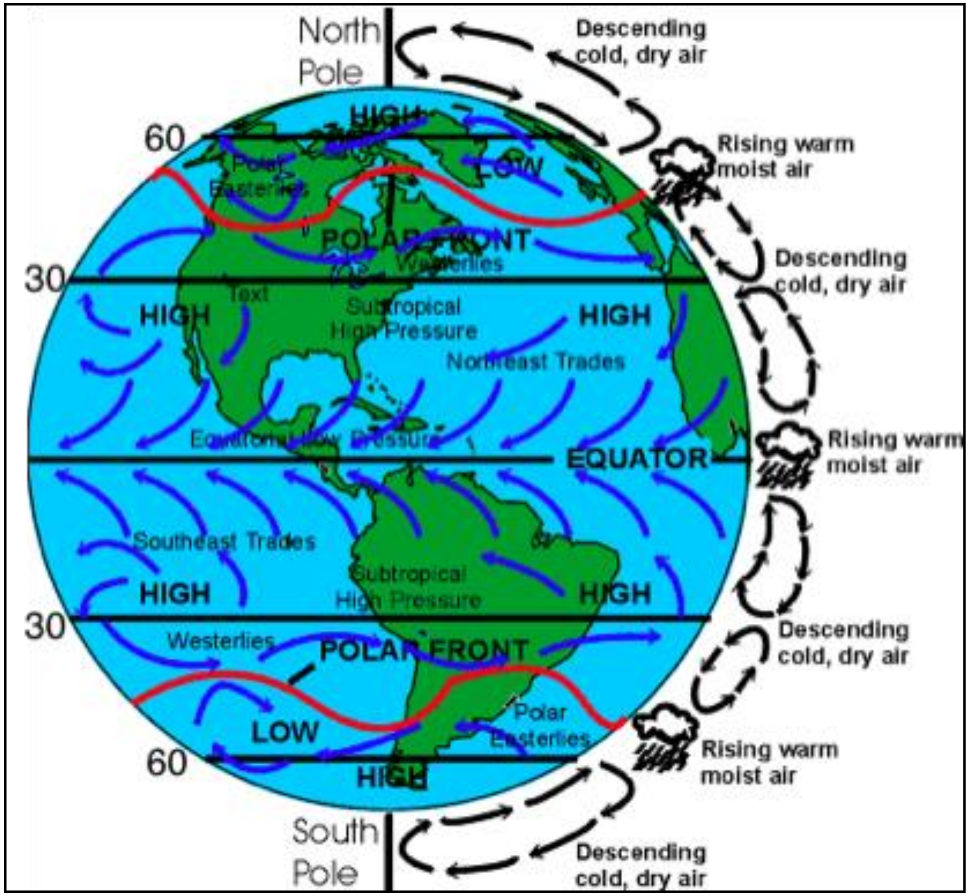
- Each hemisphere has 3 main zonal winds bands
- These are driven by the vertical circulation of the atmosphere:

-- ***easterlies*** close to the poles

-- ***westerlies*** at subpolar latitudes

-- ***trade winds*** at subtropical latitudes

Global wind patterns



- The trades are NE in the NH and SE in the SH.
- At the equator (just north) is the ITCZ where winds are light
- Seasonality: winds are stronger during winter than summer.
- In the NIO and NWP winds change direction due to the Asian monsoon.

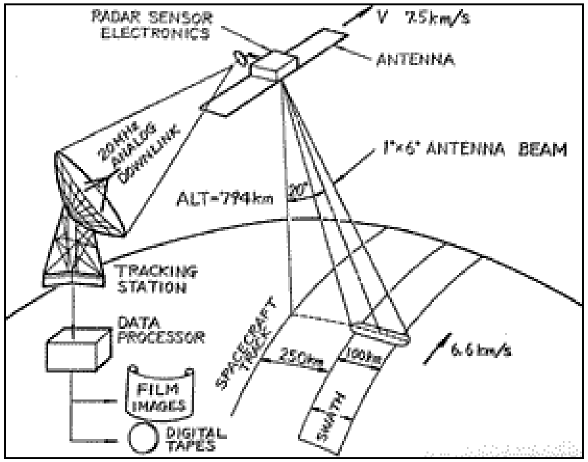
Synthetic Aperture Radar (SAR)

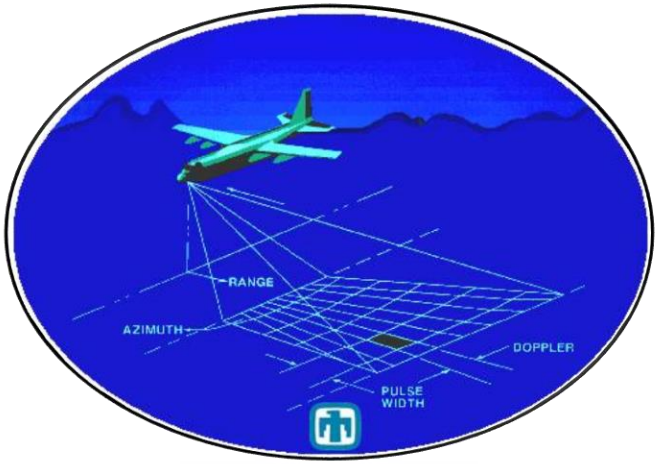
Synthetic Aperture Radars

- SAR provides broad-area imaging at very high resolutions.
- SAR images are typically of finer spatial resolution than is possible with conventional beam-scanning radars.
- SAR range measurement and resolution are achieved in the same manner as most other radars:

  -- range is determined by measuring the time from transmission of a pulse to receiving the echo from a target and,

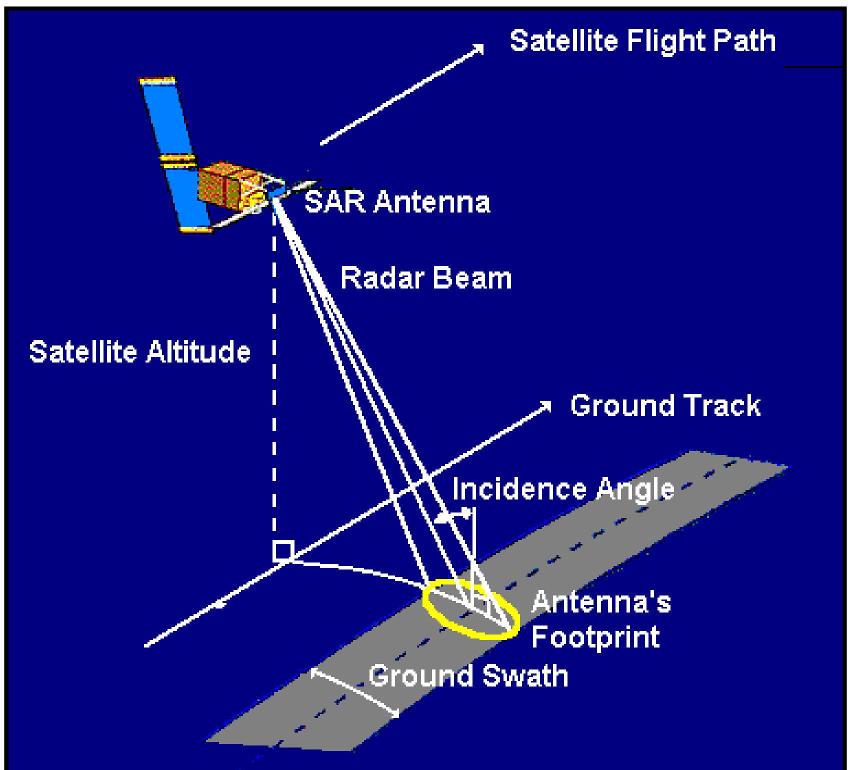
  -- range resolution is determined by the transmitted pulse width, i.e. narrow pulses yield fine range resolution.





Synthetic Aperture Radars

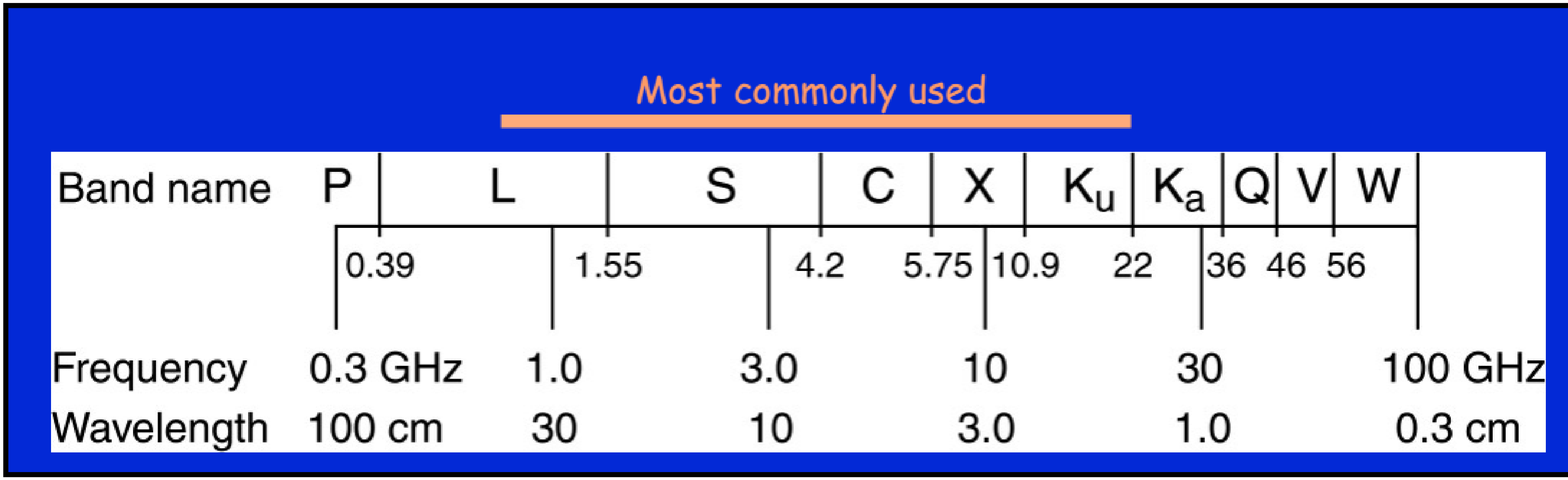
- *Aperture:* a hole or an opening through which light travels.
- the aperture and focal length determine the cone angle of a bundle of rays that come to a focus in the image plane.



- SAR uses a ***side looking radar*** system which utilizes the flight path of the platform to simulate an ***extremely large antenna*** *or* ***aperture*** electronically
- this generates high-resolution remote sensing imagery.

Microwave Bands

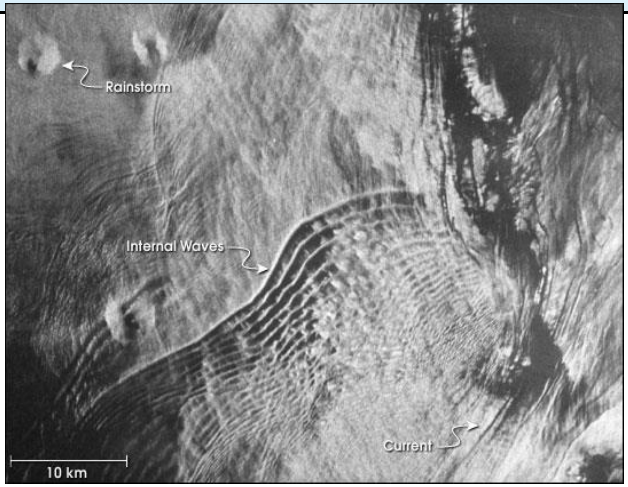
- Microwave sensors are generally defined by frequency and referred to by band names

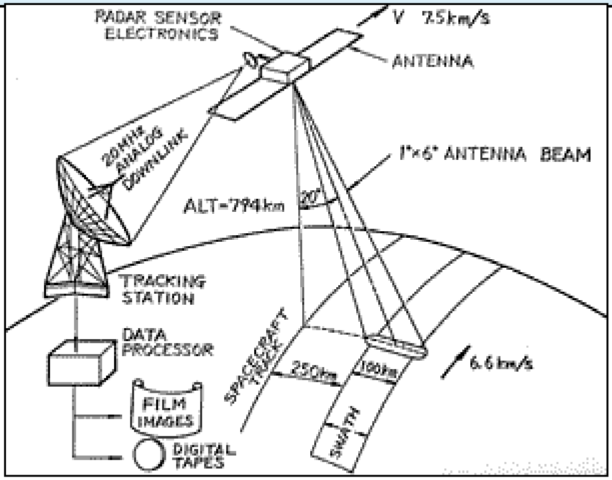


Synthetic Aperture Radars

- Seasat SAR (1978)
  - -- L-Band: 1.275 GHz; 23.5 cm wavelength.
  - -- 20° incidence: Bragg wavelength is 30 cm.
  - -- 100 km swath; Resolution 25 m (4 - looks).

- ERS Advanced Microwave Instrument (SAR-mode)
  - -- ERS-1 (1991-1996) ; ERS-2 (1995 - 2011)
  - -- C-Band: 5.3 GHz; 5.6cm.
  - -- 23° incidence: Bragg wavelength is about 8cm.
  - -- 100 km swath; Resolution about 30 m depending on processing.

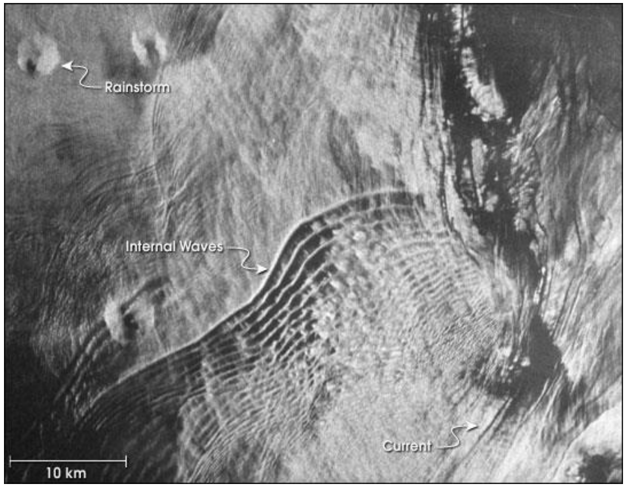


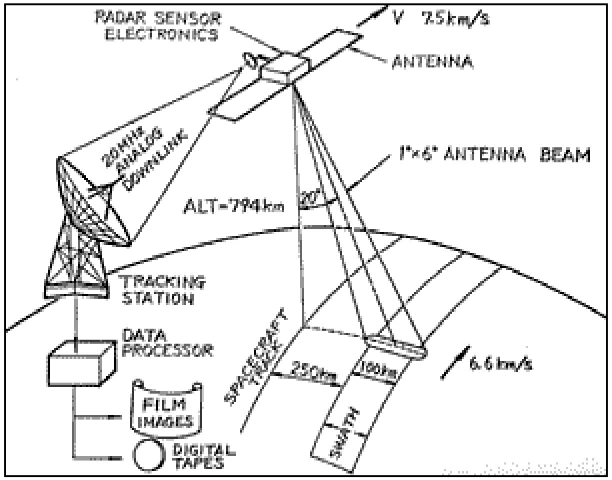


Synthetic Aperture Radars

- Radarsat
  - -- Canadian C-band SAR, 1995 - present
  - -- Similar to ERS (but poor calibration)
  - -- Also has ScanSAR mode producing wide (400 km +) swath at reduced resolution

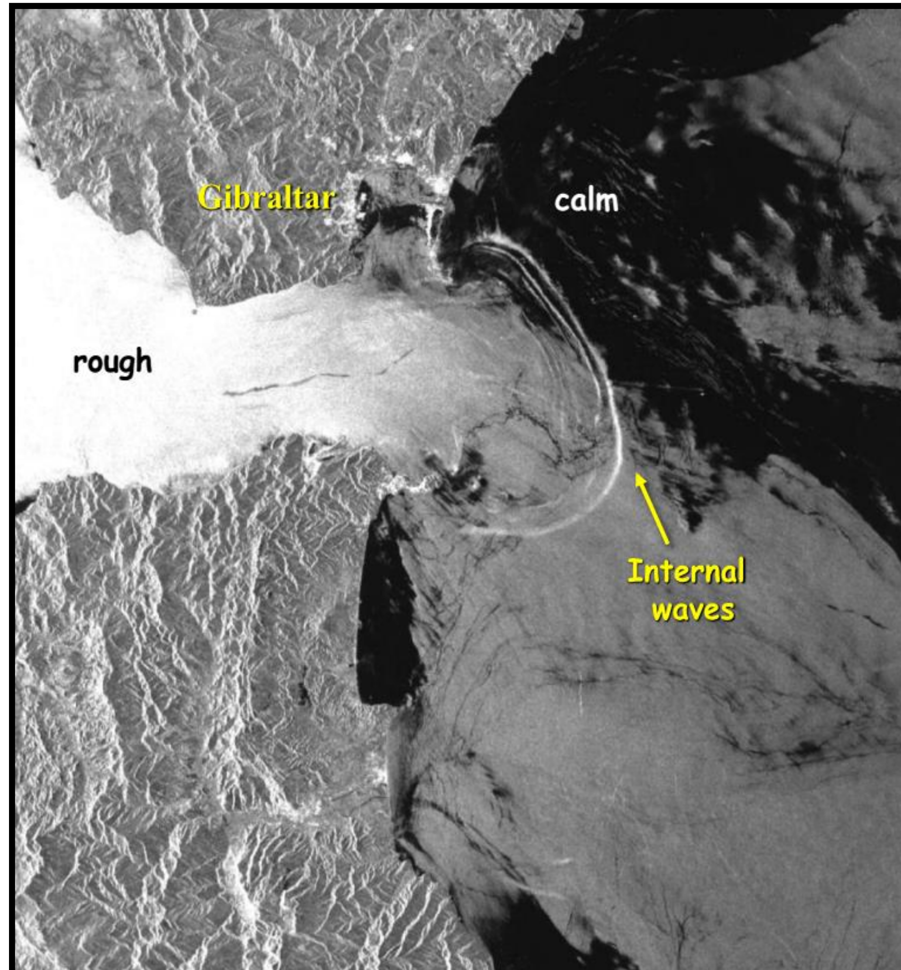
- Envisat Advanced SAR (ASAR)
  - -- C-band , HH and VV polarization, Various imaging modes





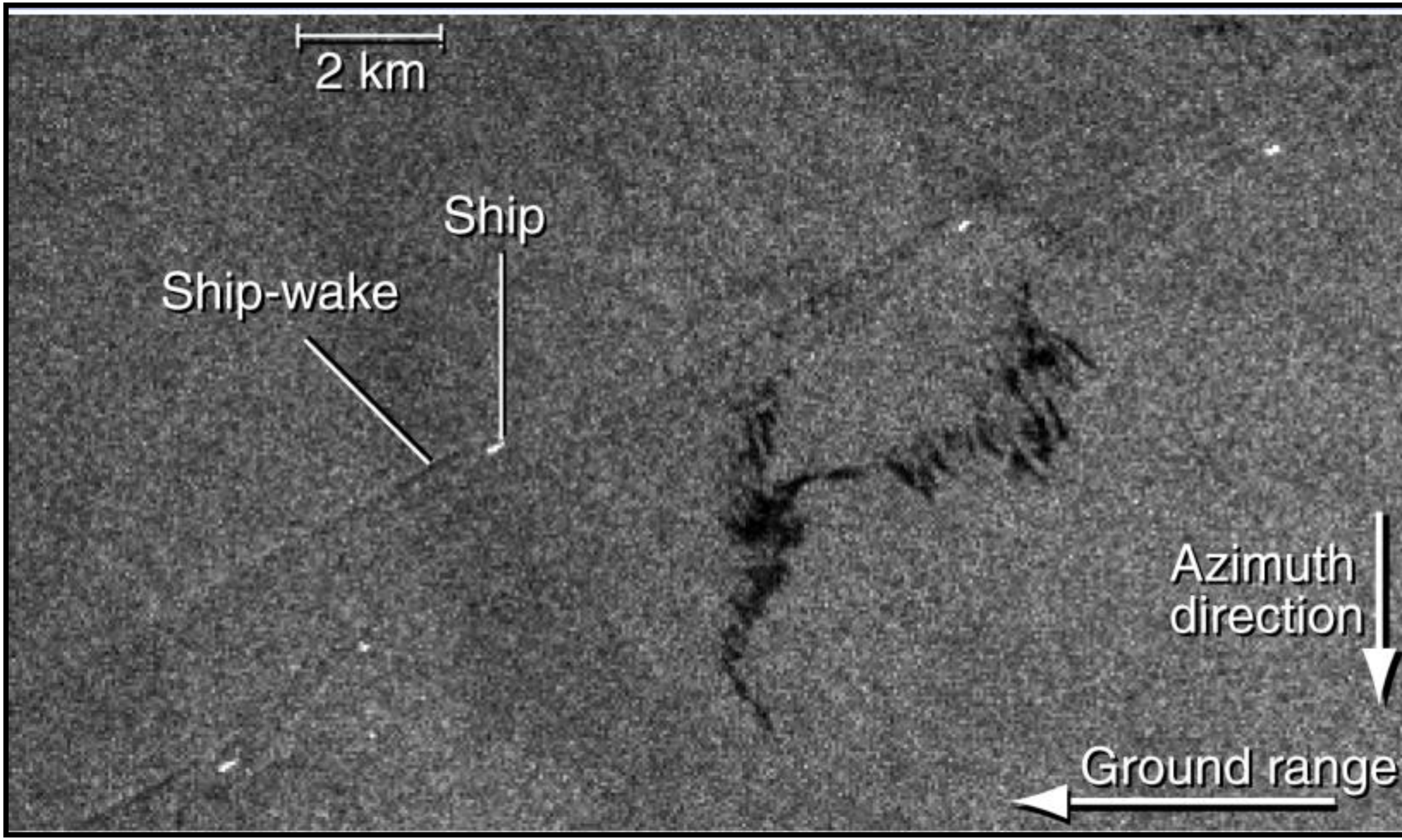
SAR Images

Eddies in the Caspian Sea



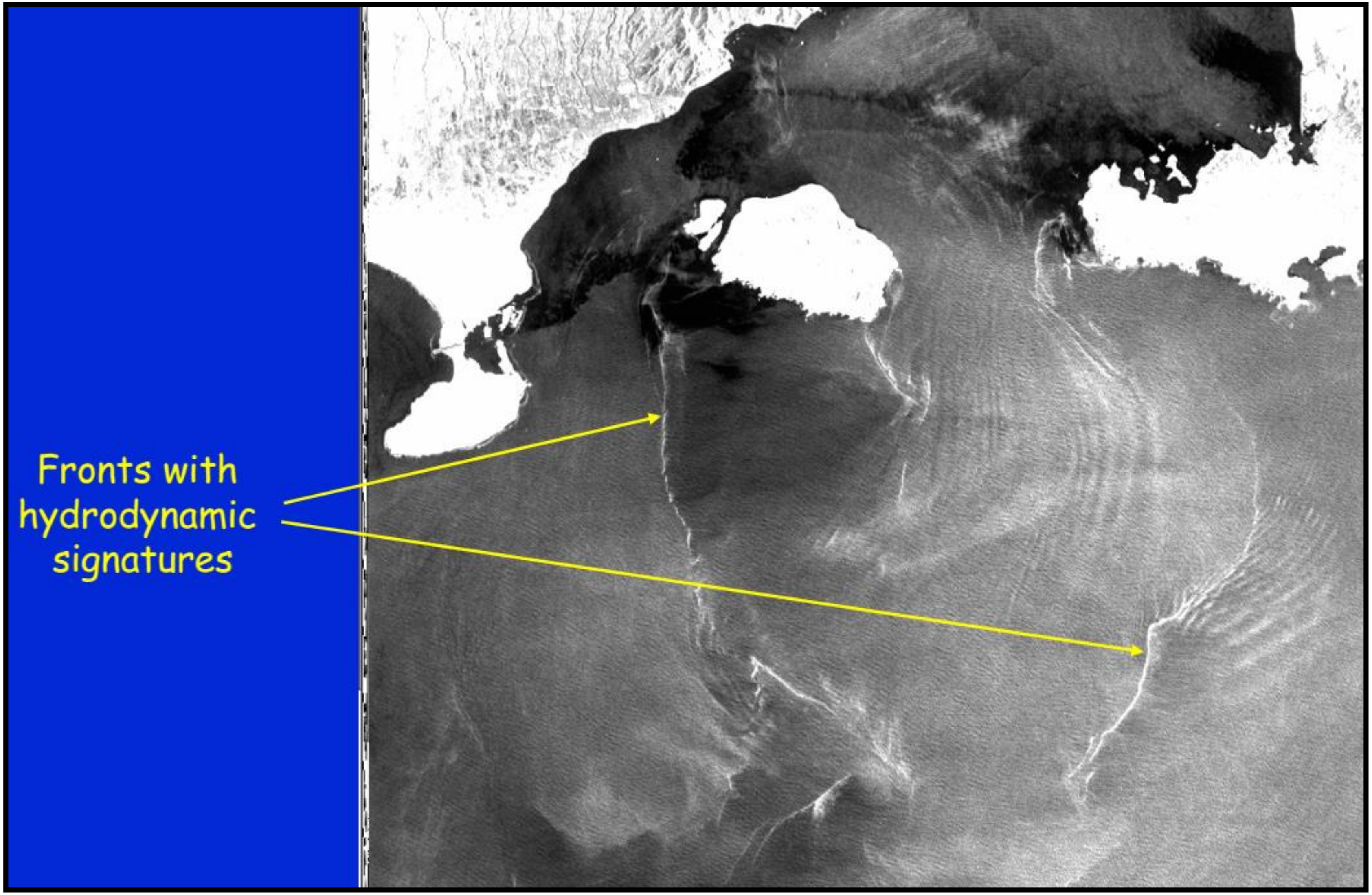
Internal waves

SAR Images



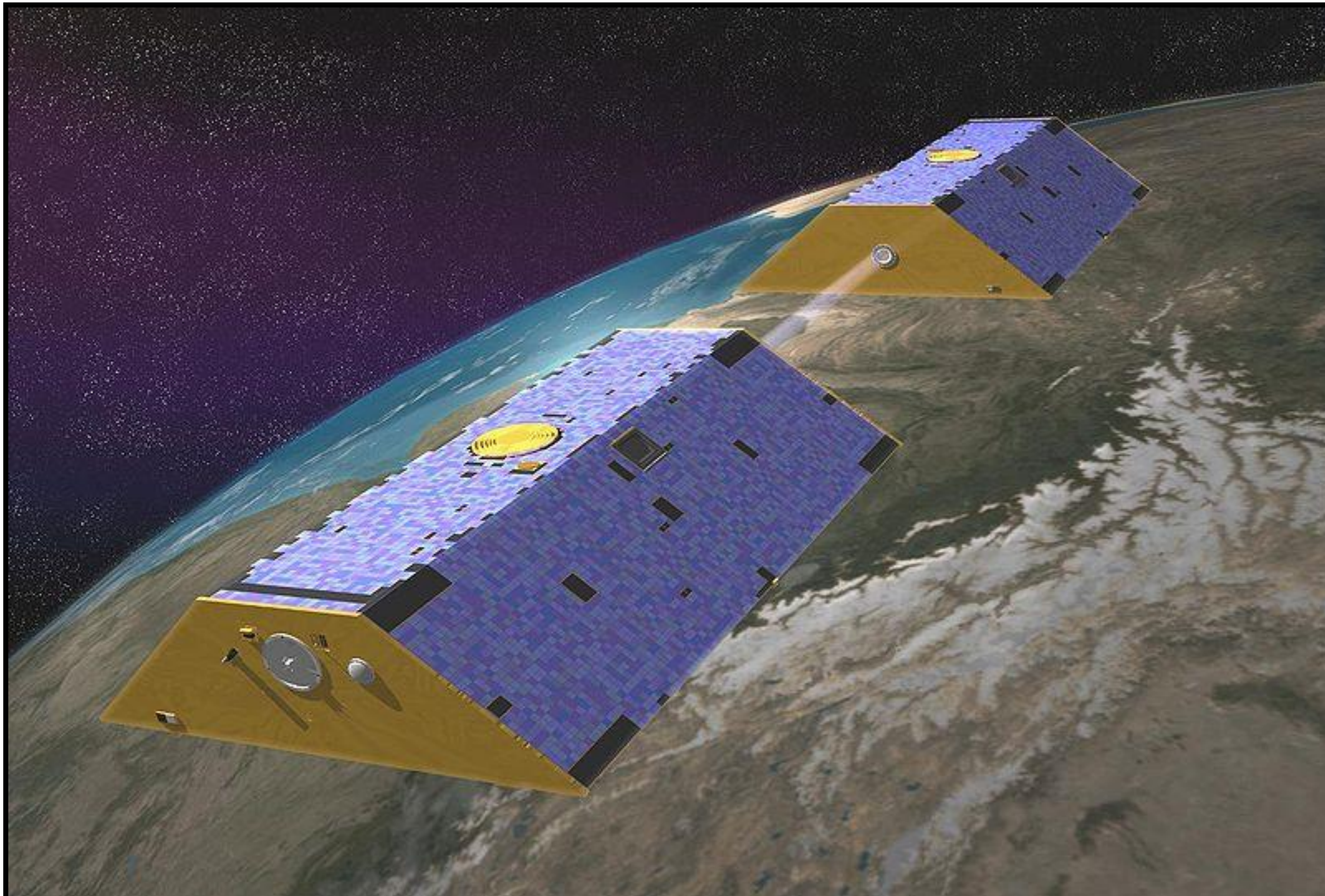
Ship wake

SAR Images



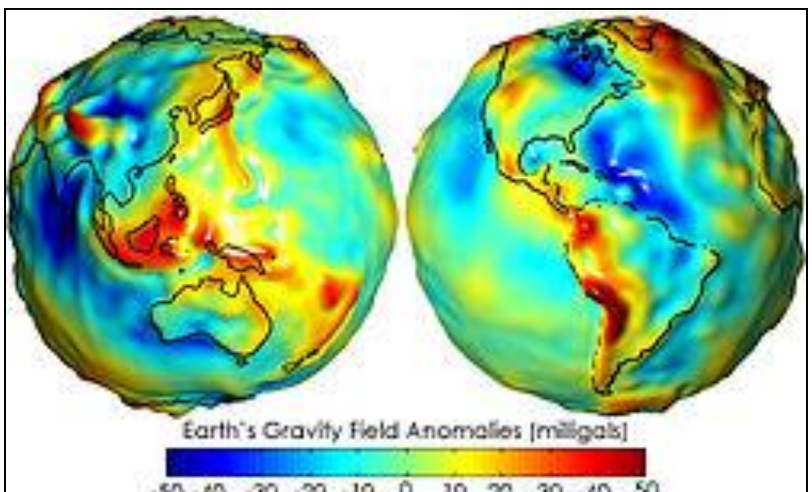
Ocean fronts

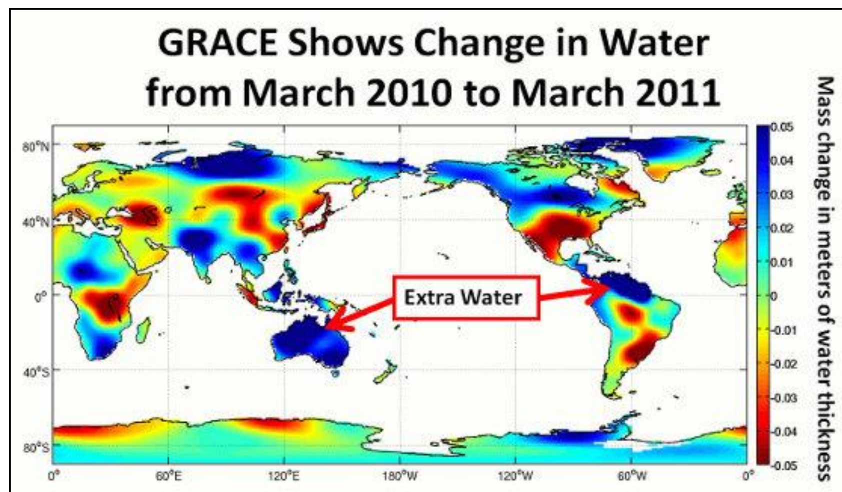
GRACE



GRACE

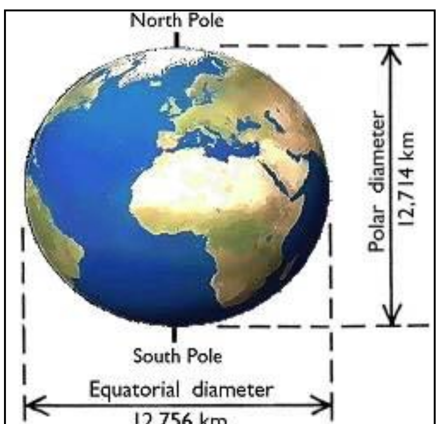
- **GRACE:** Gravity Recovery And Climate Experiment
- NASA & German Aerospace Center. Launched March 17, 2002
- GRACE makes detailed measurements of Earth's gravity field anomalies
- Measure time variable gravity field to detect changes in the water storage and movement from reservoir to another (e.g., from ice sheets to ocean)

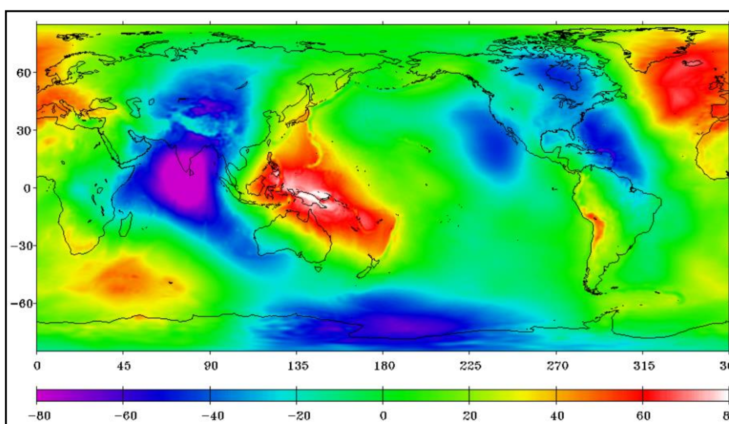




Shape of the Earth

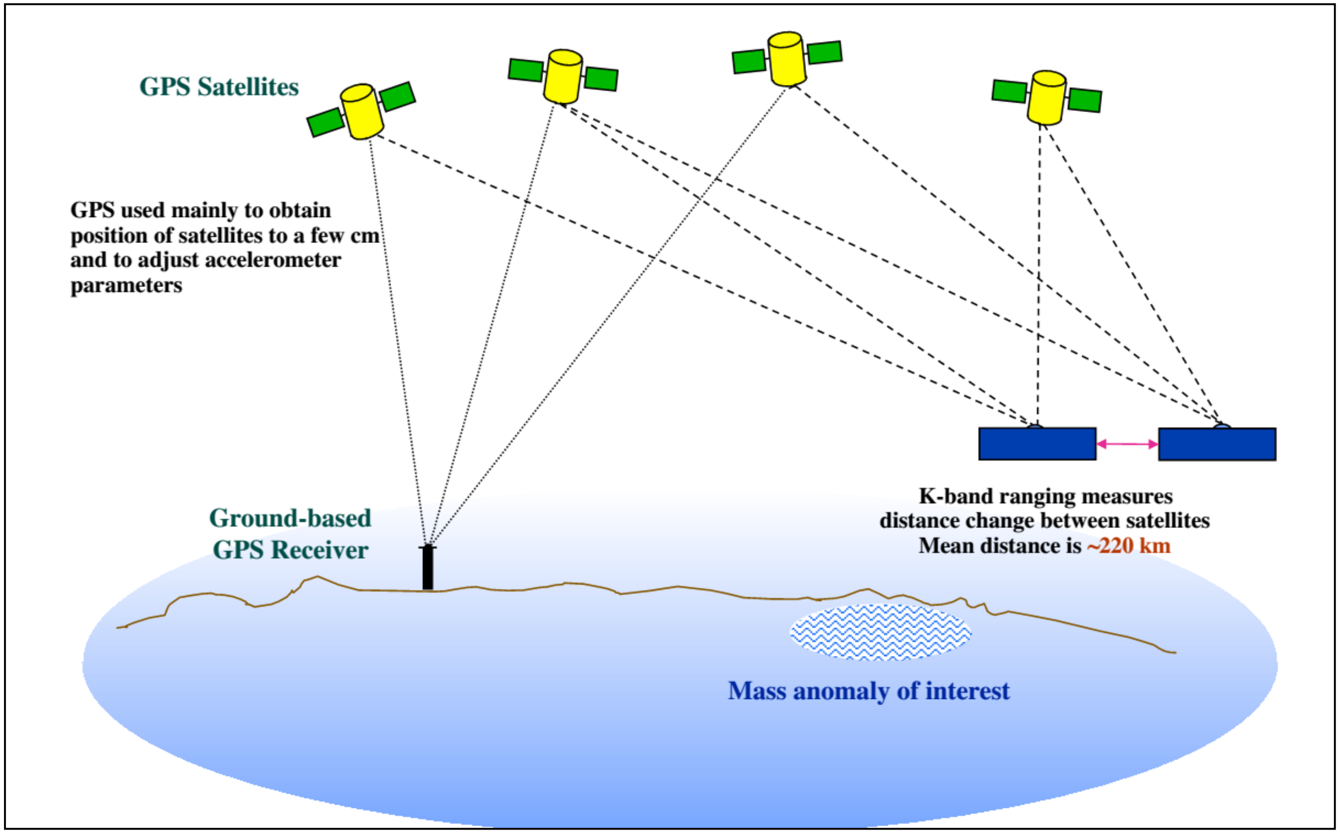
- Earth is not a perfect sphere
- Poles are ~ 21 km (13 mi) closer to the center of the Earth than the Equator (shape of an ellipsoid)
  -- Only a 0.3% difference
- 99.99% of the sea surface height measured by an altimeter is due to this gravitational shape of the Earth (or geoid)
- If we remove the ellipsoid shape, there are still ± 100 m deviations in the SSH or geoid





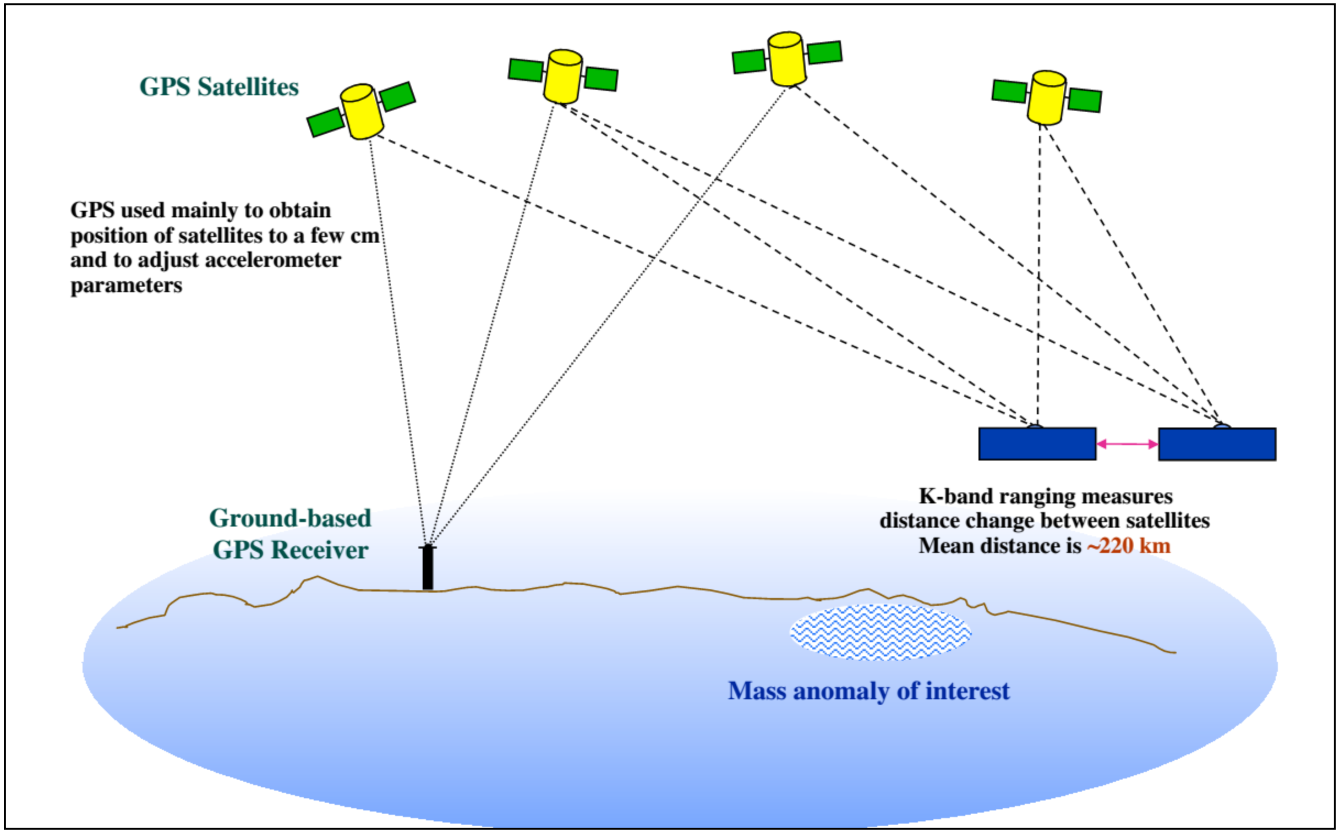
Earth mean sea surface/geiod

GRACE: Measurement principle



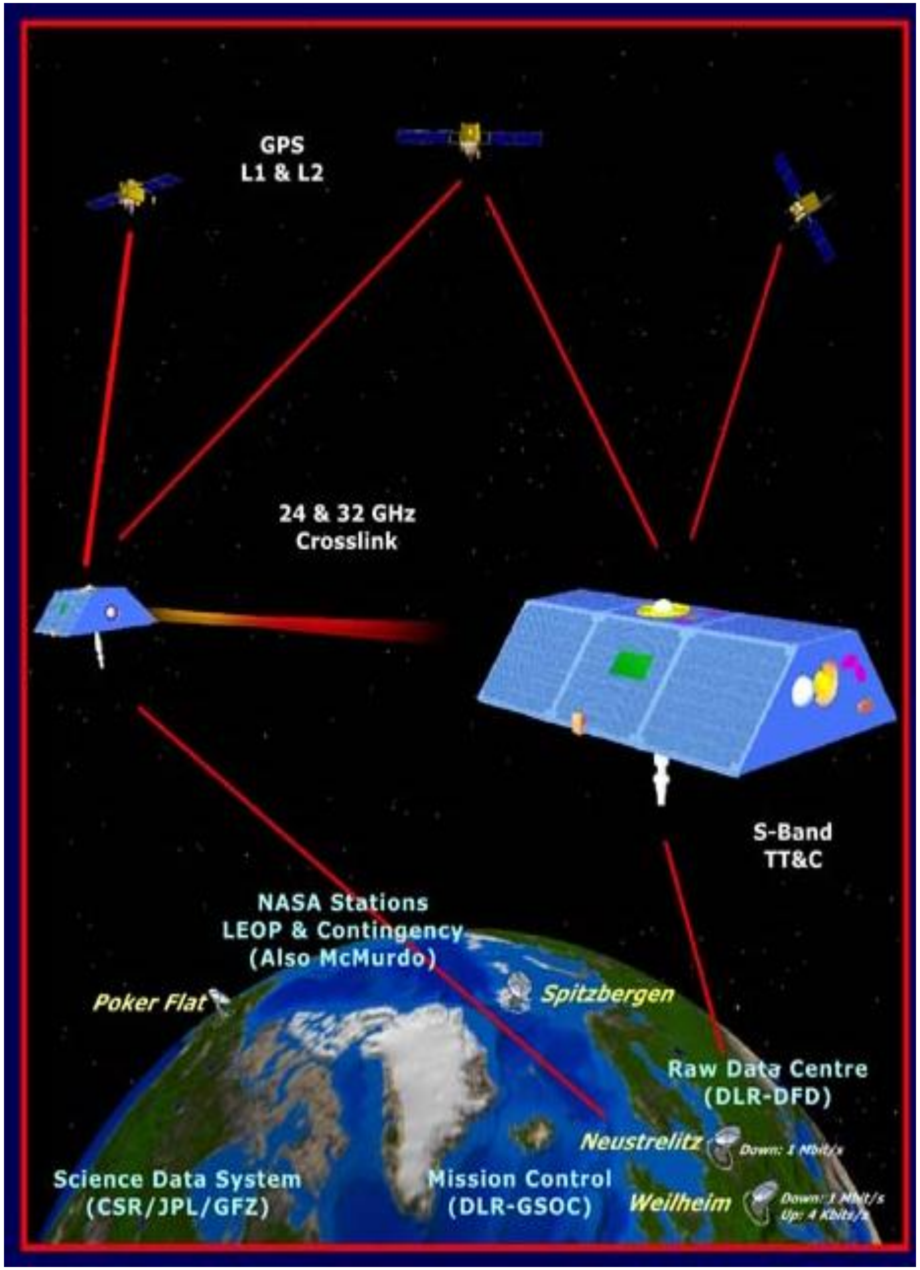
• uses a microwave ranging system to accurately measure changes in the speed and distance between ***two identical spacecraft*** flying in a polar orbit about 220 kilometers (140 mi) apart, 500 kilometers (310 mi) above Earth.

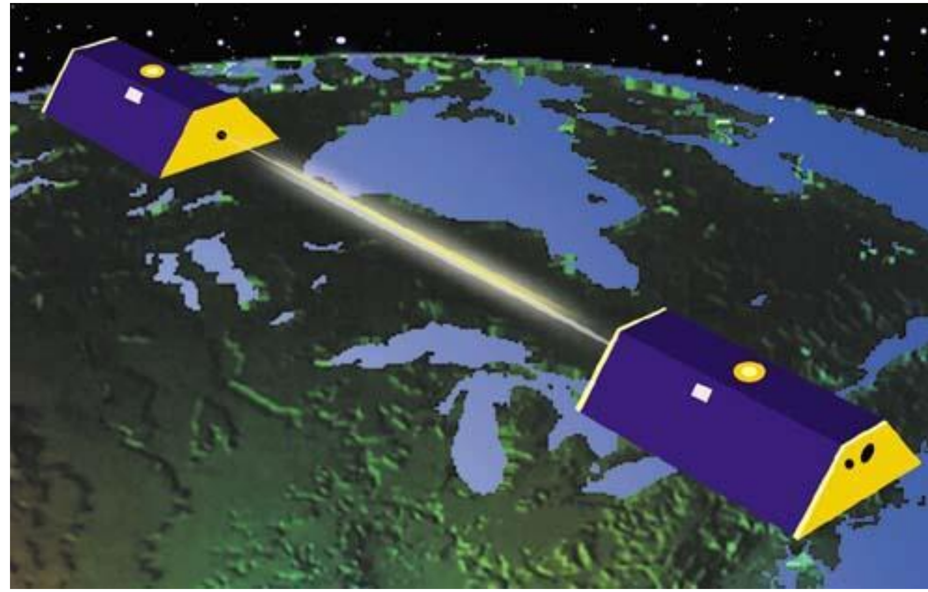
GRACE: Measurement principle



• uses a microwave ranging system to accurately measure changes in the speed and distance between ***two identical spacecraft*** flying in a polar orbit about 220 kilometers (140 mi) apart, 500 kilometers (310 mi) above Earth.

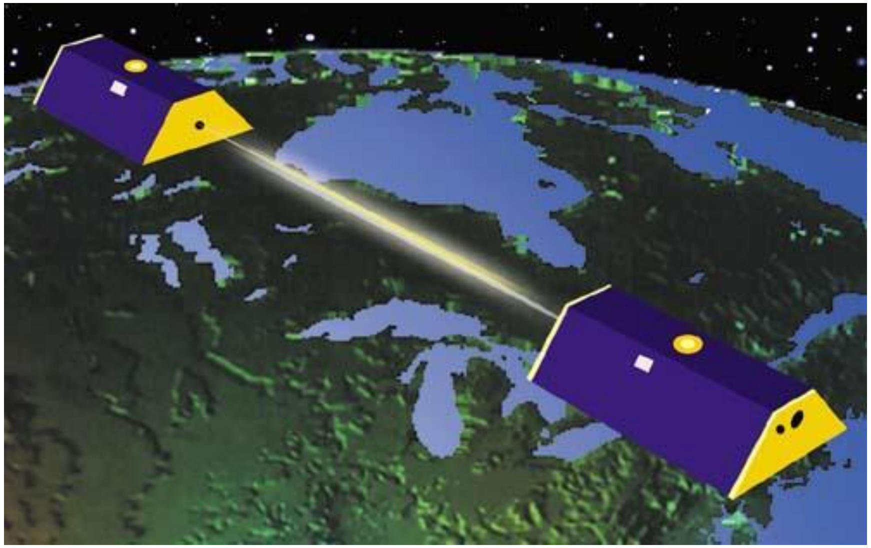
GRACE: Measurement principle





- The ranging system is sensitive enough to detect separation changes as small as 10 micrometers
- (approximately one-tenth the width of a human hair) over a distance of 220 kilometers

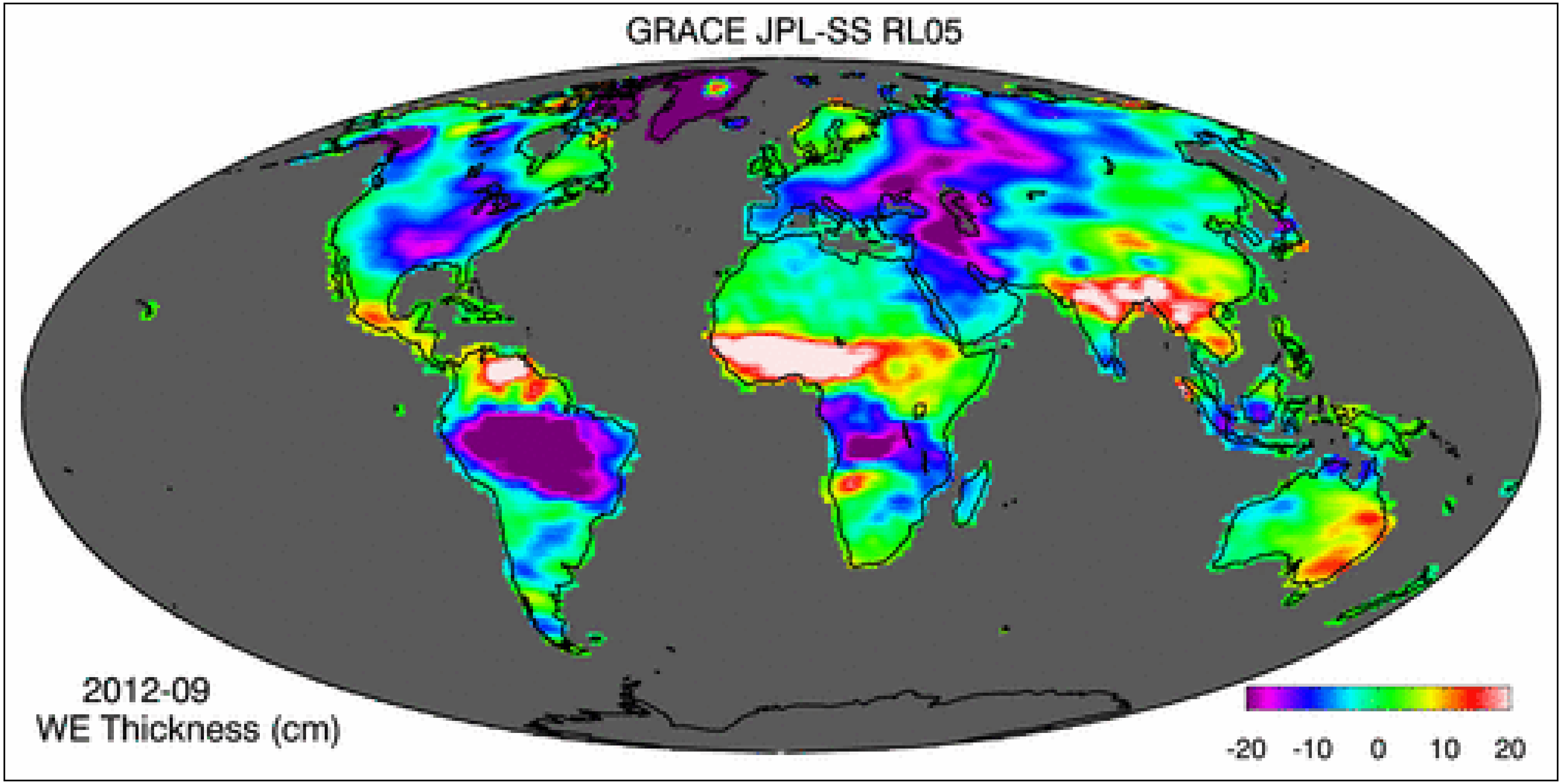
GRACE: Measurement principle



- As the twin GRACE satellites circle the globe 15 times a day, they sense minute variations in Earth's gravitational pull
- When the first satellite passes over a region of slightly stronger gravity, a gravity anomaly, it is pulled slightly ahead of the trailing satellite.

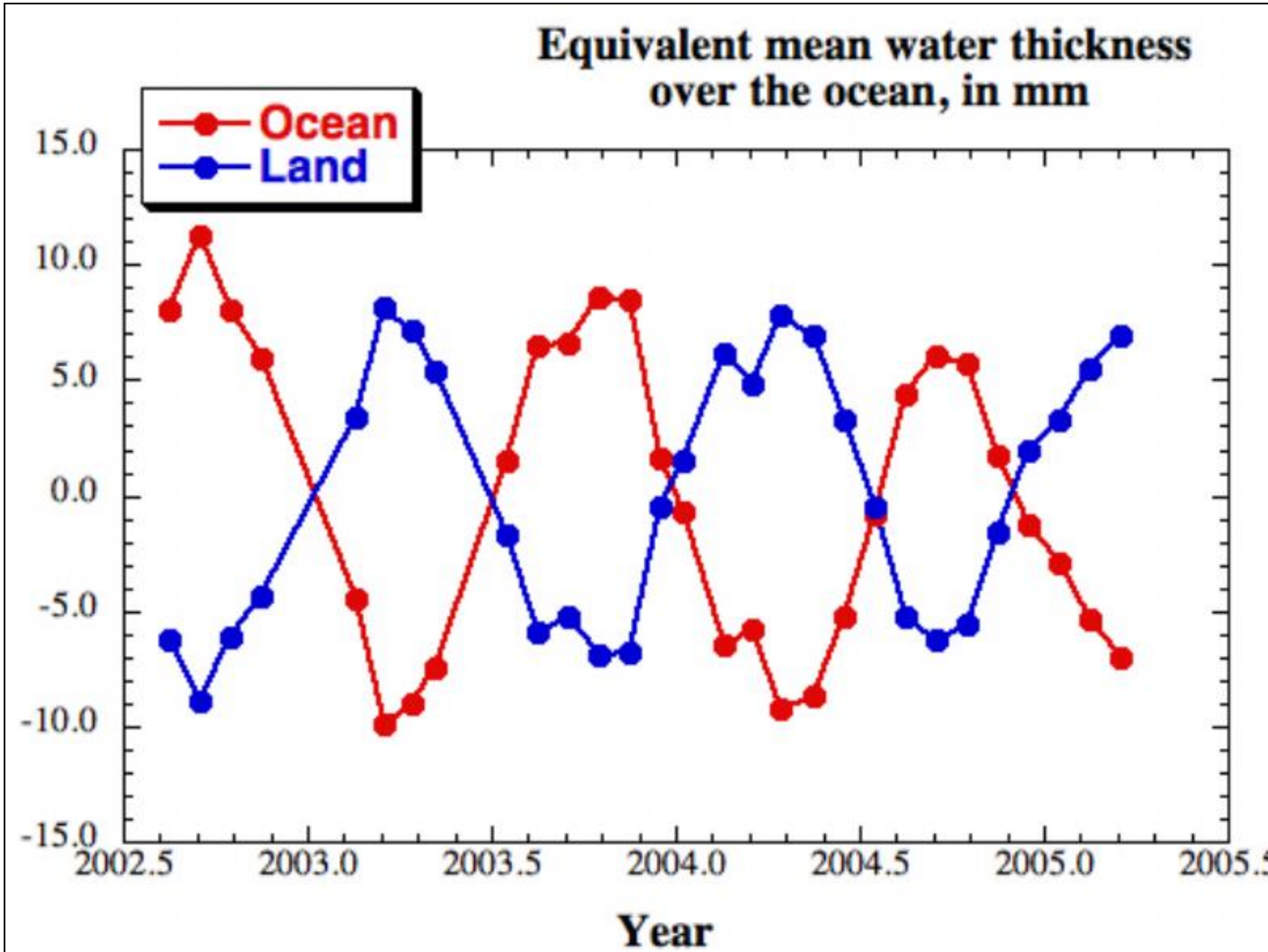
- This causes the distance between the satellites to increase.
- The first spacecraft then passes the anomaly, and slows down again; meanwhile the following spacecraft accelerates, then decelerates over the same point.

GRACE: Water Thickness



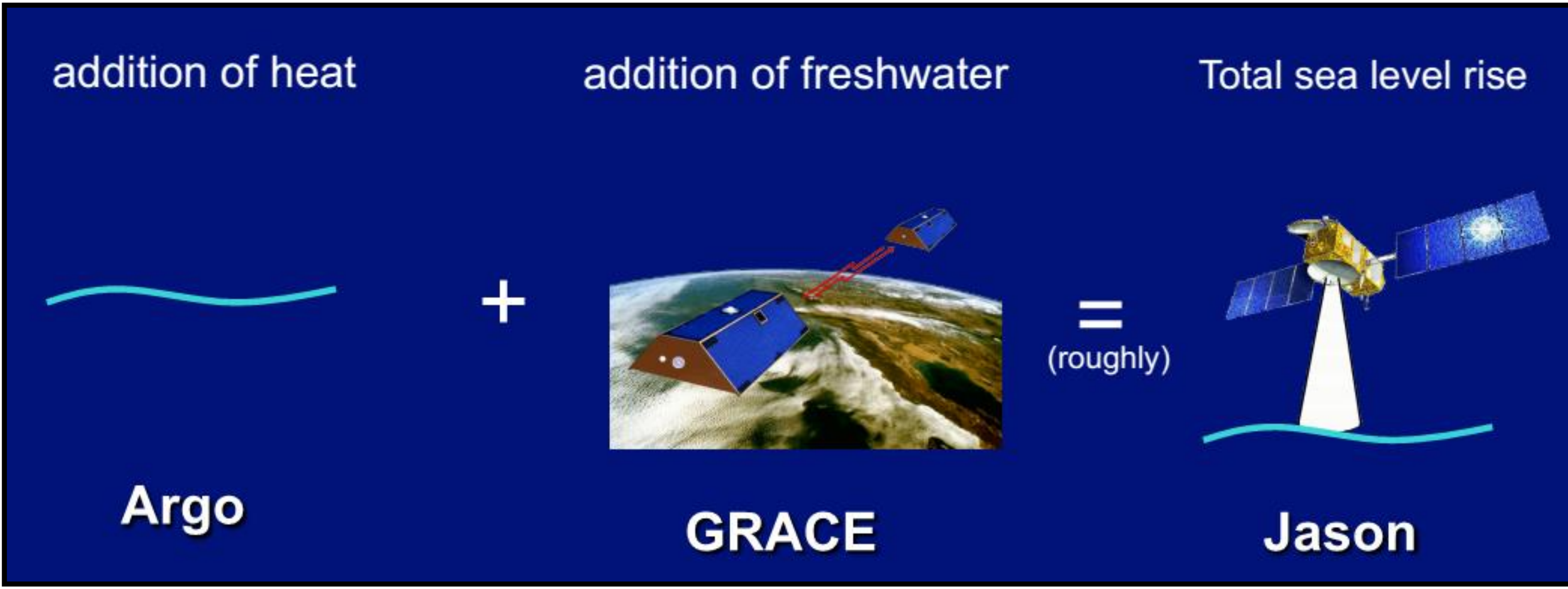
• GRACE measures the mass flux over both the ocean and land; these are out of phase

GRACE: Water Thickness



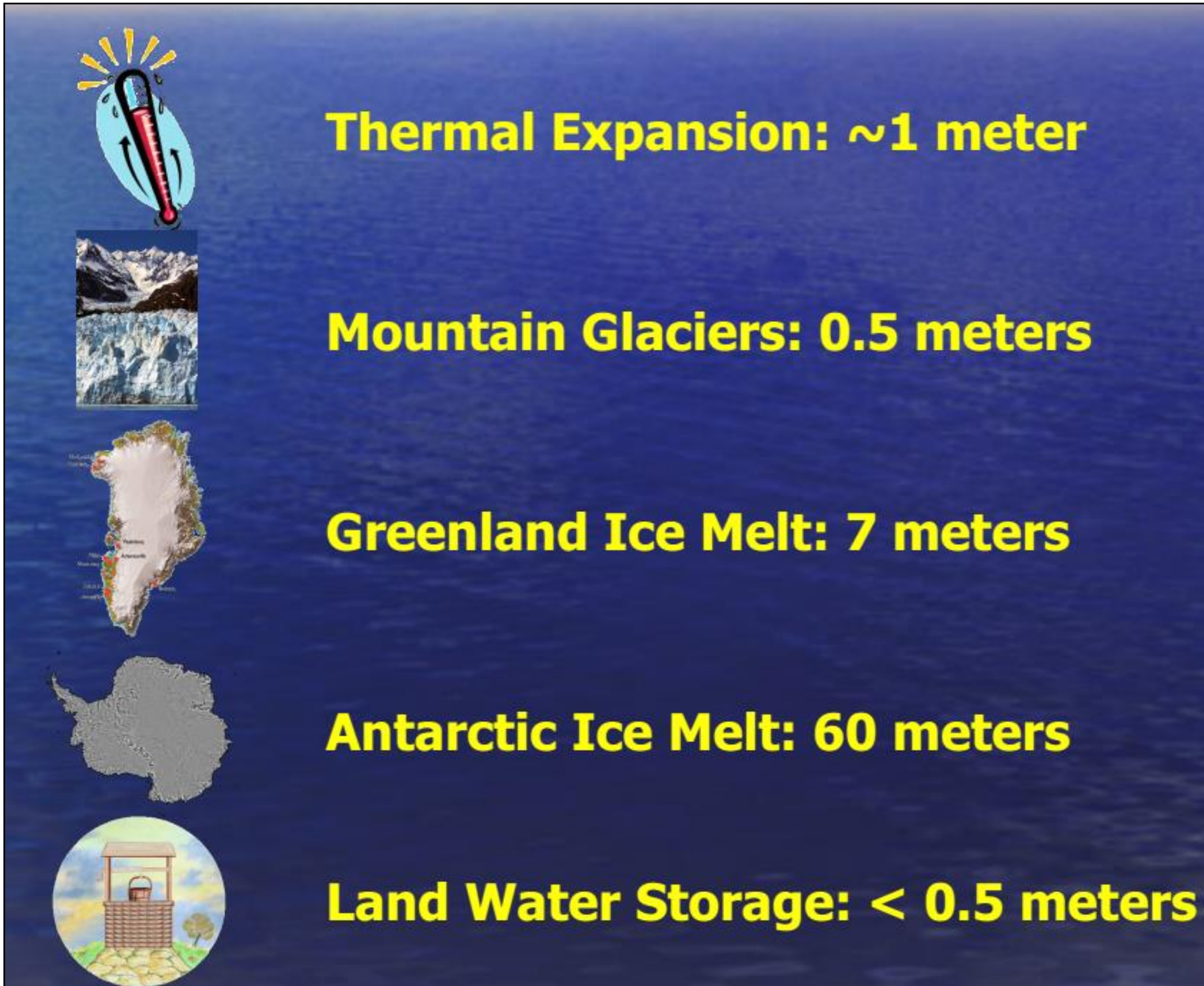
- GRACE measures the mass flux over both the ocean and land; these are out of phase

GRACE: Sea level changes



- Globally averaged sea level rise

GRACE: Sea level changes- potential contributions



GRACE: Sea level changes- potential contributions