30552 – Lecture 8.

Satellite radar altimetry – technology and theory

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Content

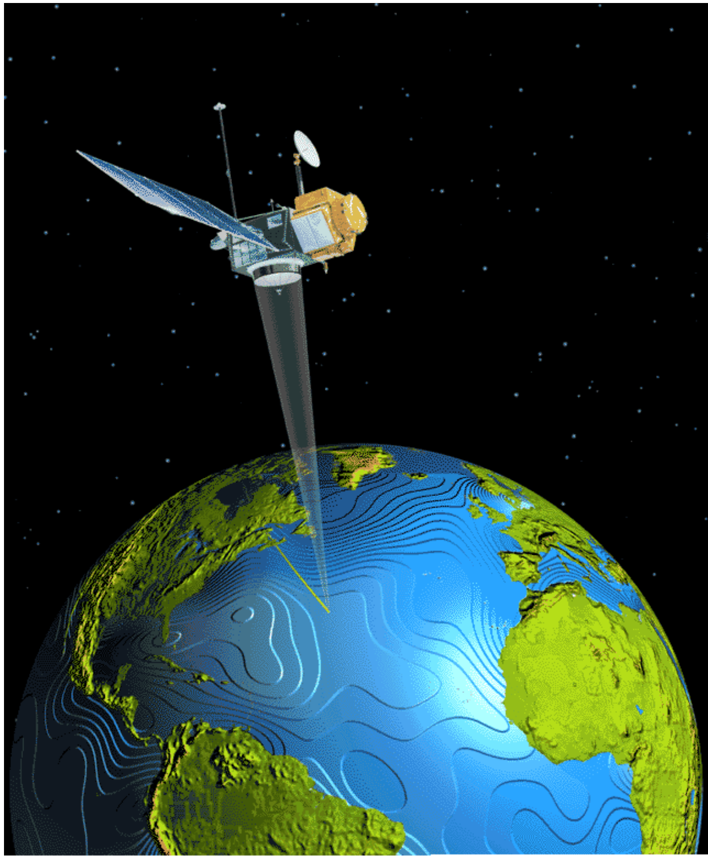
Rationale: Why and what's the benefits.

Principles: Orbits
How does it work
Waveform analysis.

Corrections: how do we make it accurate
range precision/accuracy

Geodetic: What parameters are extracted

Applications: Next time



Acknowledging Teaching material from R. Klees (TU Delft)

Requirement

- We want to measure the shape of the Earth.
- You need high density to resolve small features.
- Two thirds of the globe is covered with water and many regions are NOT covered with observations from ship.
- A significant fraction is covered with Ice and hardly accessible. You don't want to go there if you can avoid it.
- Example average waveheight in the ACC is > 7 meters. Freakwaves up to 50 meters.

Content

Rationale: Why and whats the benefits.

Principles: Satellite Altimetry

Orbits

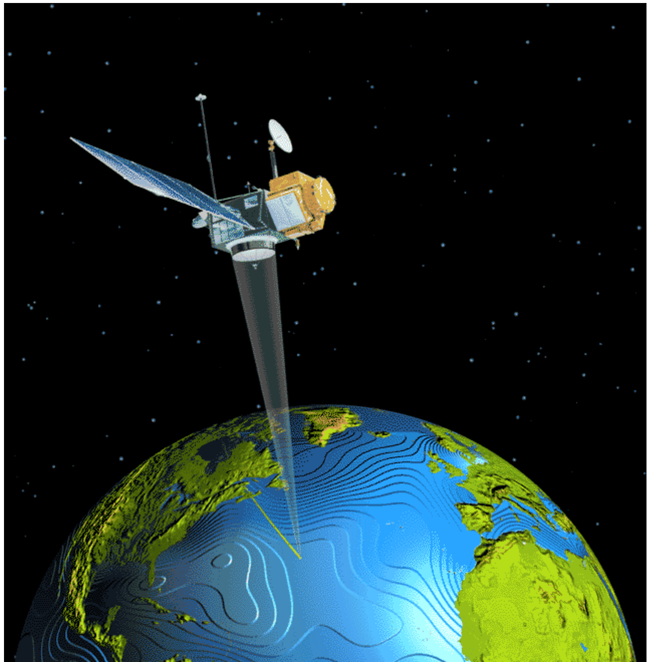
How does it work

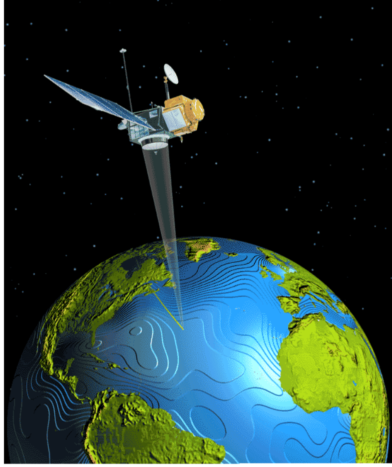
Turning power into height (Waveform analysis).

Corrections: how do we make it accurate

Geodetic: What parameters are extracted

Applications: Next time





What is a satellite radar altimeter ?

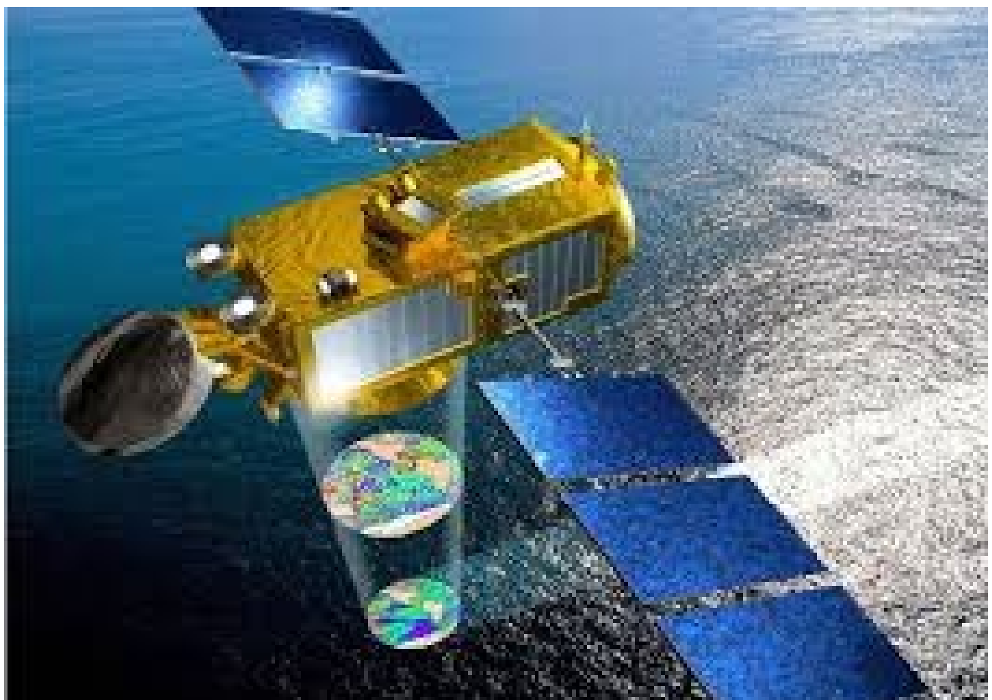
- **Altimeter** (altus (latin) = height; metron (greek) = to measure) An instrument that determines heights above a reference level, commonly by measuring the change of atmospheric pressure, or by measuring vertical distance directly with a radar (radar altimeter) or laser (laser altimeter).
- **Radar altimeter** – radar at vertical incidence; submits short pulses of microwave radiation; each pulse interacts with the surface and part of the incident radiation reflects back to the altimeter. Travel time is inferred from the received echo and scaled to the speed of light providing the range (shortest distance) between altimeter and surface.

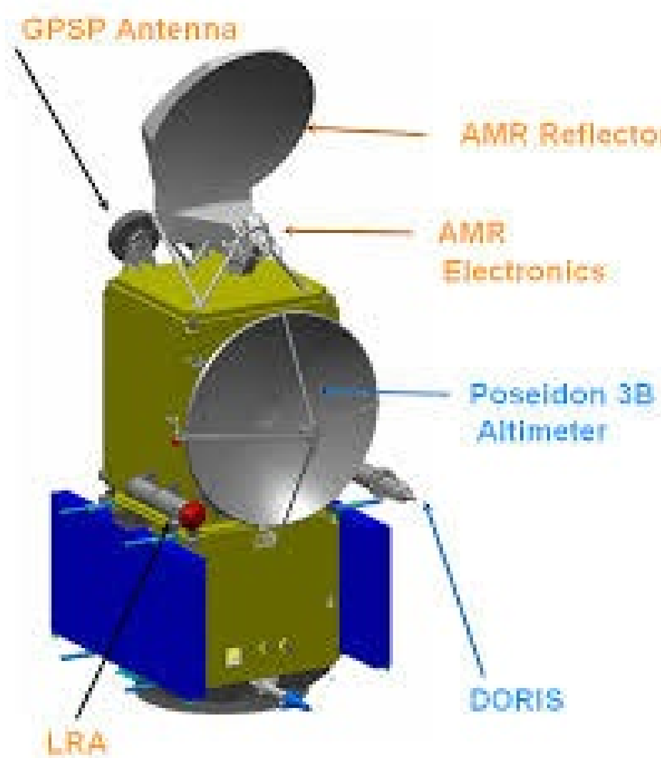
RADAR ALTIMERY IS THE MOST ACCURATE WAY TO DETERMINE THE SHAPE AND CHANGES OF THE OCEANS (70 % OF THE EARTH)

Satellite radar altimeter.

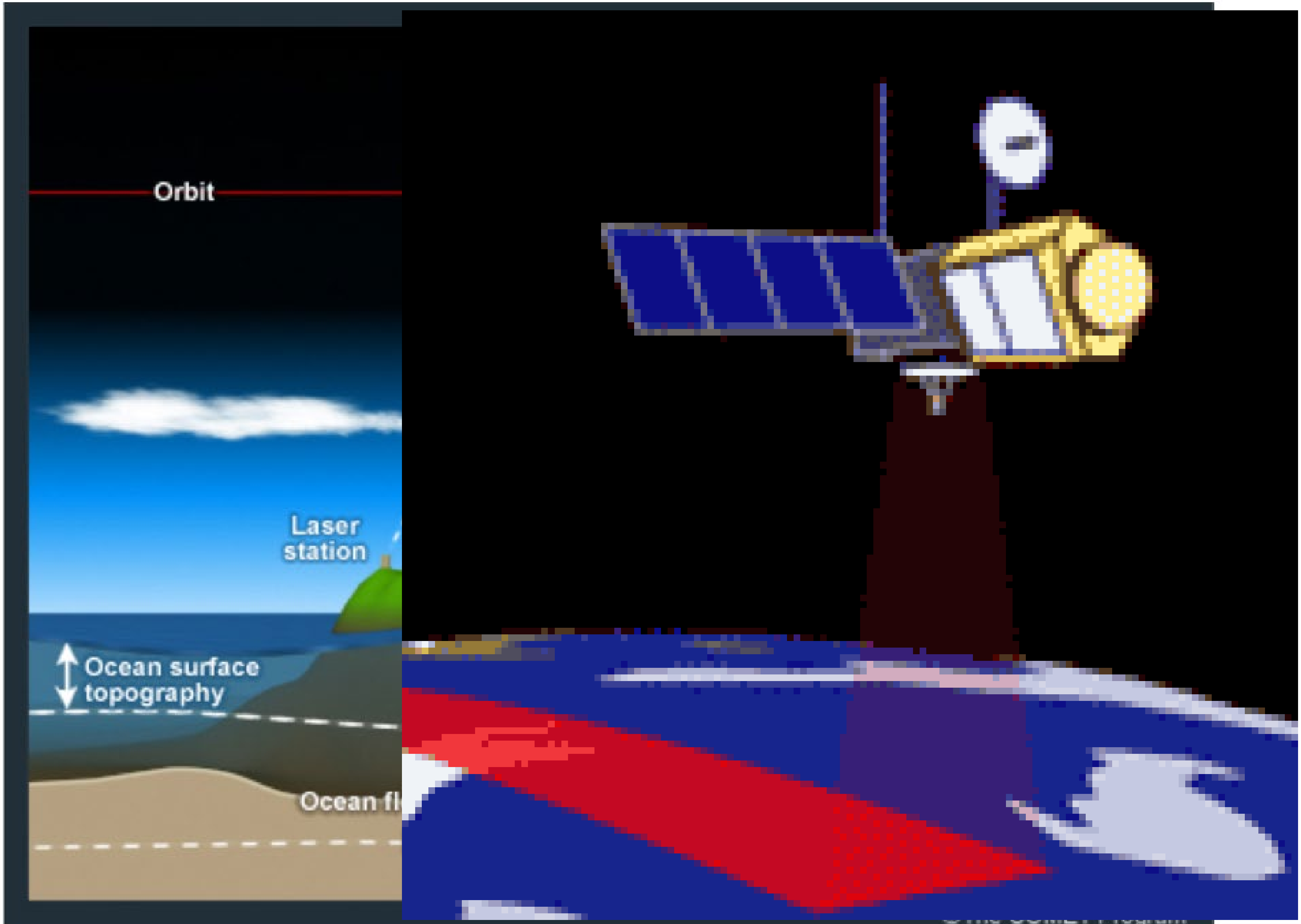
- **Satellite radar altimeter** – the platform which carries the radar altimeter is a satellite; also airborne altimeters are in use.

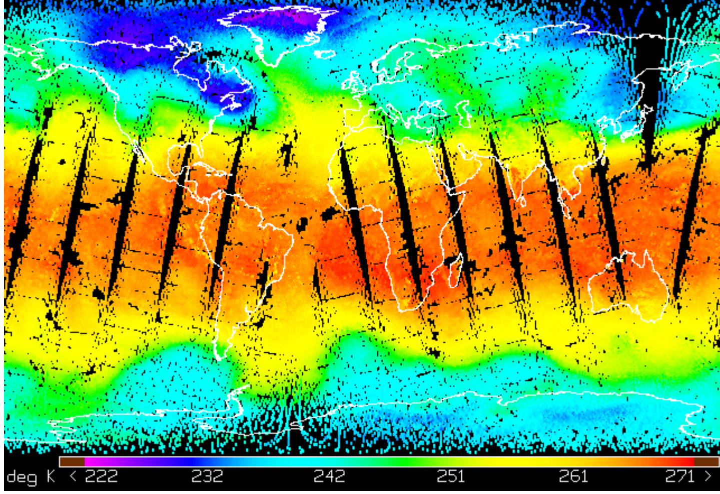
- **Technique -** is called 'satellite radar altimetry'





Components of a satellite radar altimeter system





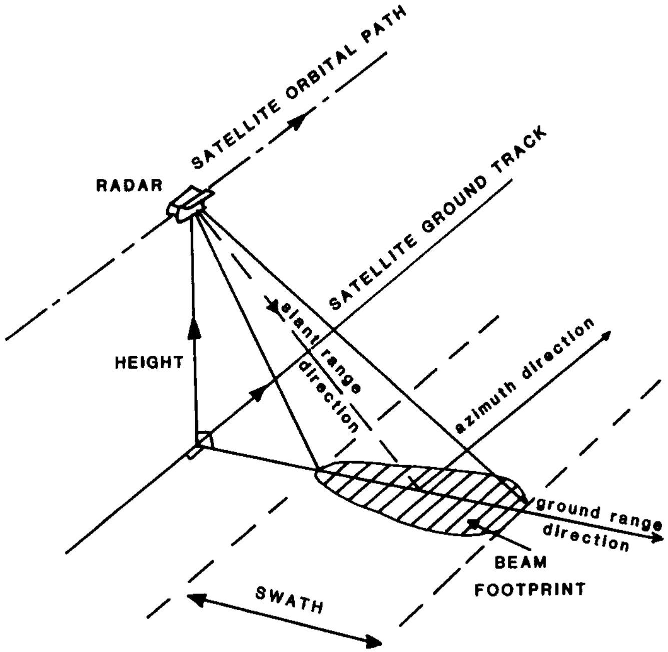
Why VERTICAL/Nadir Looking

- Only way to accurate measure range
- With ADEQUATE precision.

- Hence only way to measure the shape of the Earth.
- Disadvantage. Only **one point** below the satellite.

- Many Slant looking satellites (Sentinel-1,2)
  - Advantage: You get high spatial resolution
  - You get **an image** close to orbit
  - You can determine height changes
- But you can NOT determine accurate HEIGHT.

- Nadir looking satellite are frequently termed:
  - GEODETIC SATELLITES.
- Slant looking satellites are frequently termed:
  - EARTH OBSERVATION SATELLITES



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Rationale: Why and whats the benefits.

Principles: orbits

how does it work

Waveform analysis.

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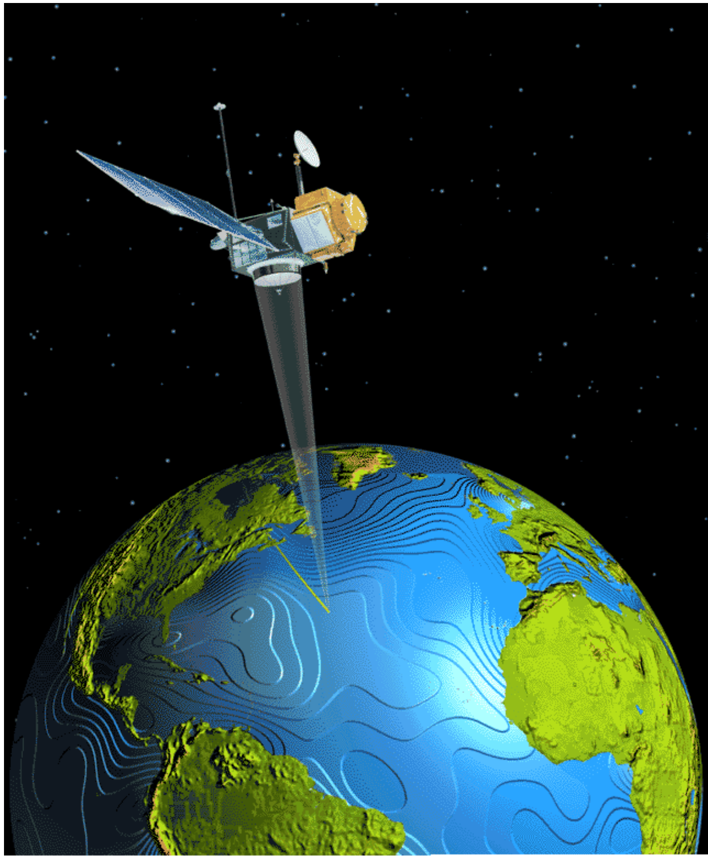
Applications: Next time

Defining the shape

Mean sea surface

Global gravity field

And then…..(next time – sea level change)



Launching a satellite


DSCOVR
SOHO
ACE
COMS
FY-2
FY-2
HIMAWARI-8
140.7° E
128.2° E
105° E
90° E
86.5° E
82° E
INSAT-3D
NOAA-15/18/19
ELECTRO-L
GPM
78° E
74° E
KALPANA
180° W
SENTINEL-1
SENTINEL-2
JASON -2/3
57° E
GCOM
METEOSAT-7
SENTINEL-3
FY-3
METEOR
135° W
METOP
0°
DMSP-F14-18
COSMIC
A-TRAIN CONSTELLATION
105° W
90° W
SUOMI NPP
METEOSAT-10
75° W
GEOSTATIONARY ORBIT
NEAR-POLAR ORBIT
GOES - EAST

Design the orbit to maximize the value of the satellite.

LEO = Low Earth Orbiting Satellites (700 and -1500 km height)

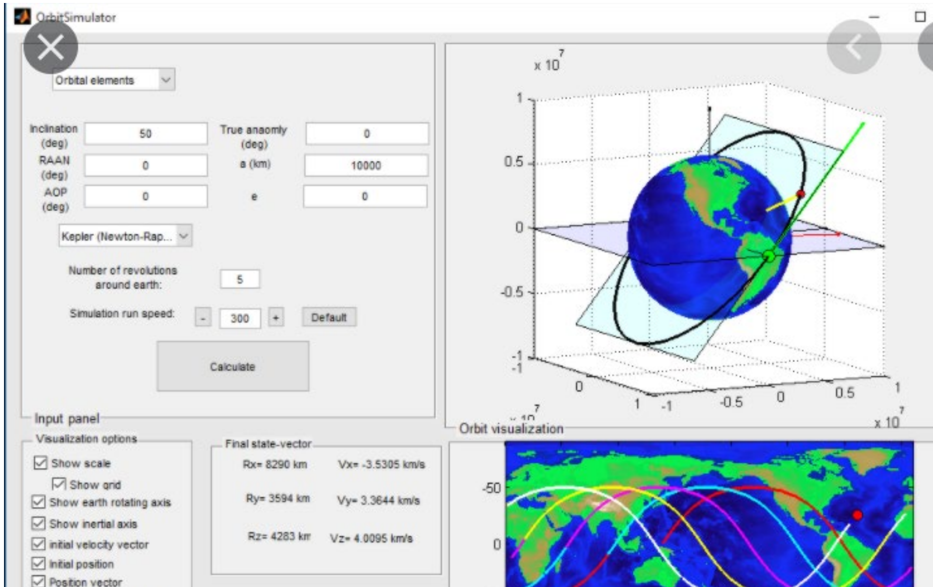
We need low orbit for detailed monitoring of the planet.
The lower the better, but drag increases.
Heigher more stable, but more radiation (shorter life)

Orbits are ellipsoidal

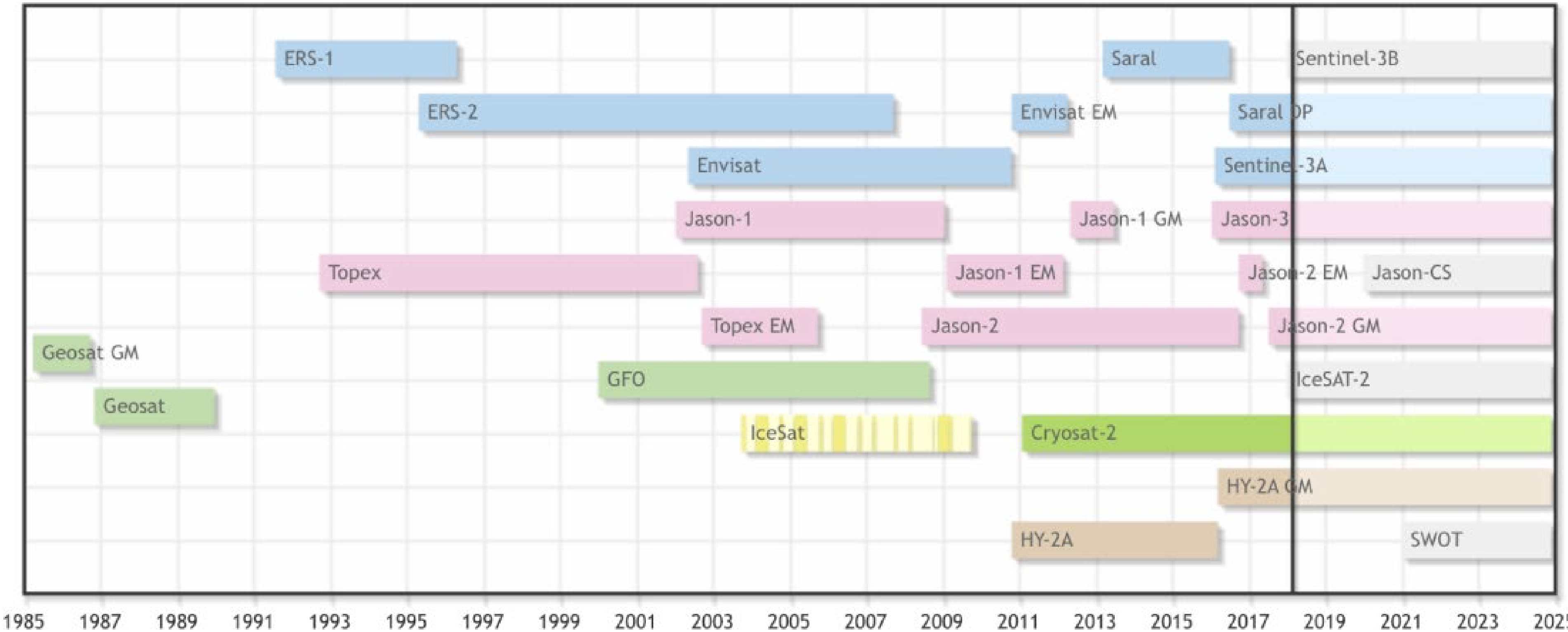
Orbital plane is inclined (wrt pole) to create mesh of observations.

What does the satellites
Measure today:

Check out: altimetry.dk



Altimetric systems.

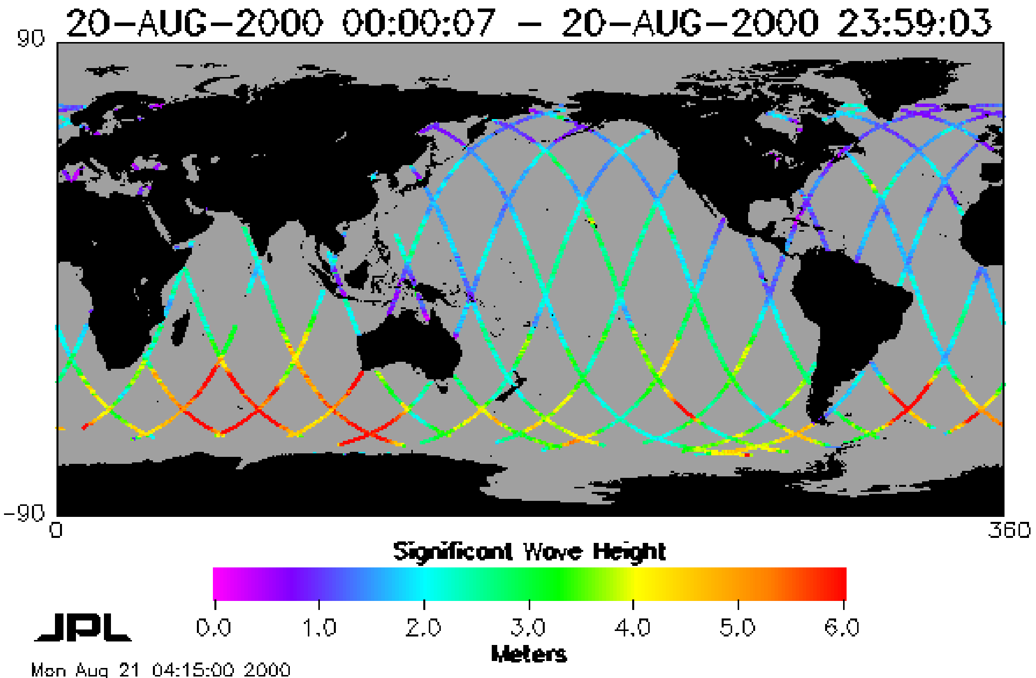


4 systems:
American: TOPEX /Jason 1 / 2 / 3 (1300 km orbit) – Reference missions
Europe / ESA: ERS-1/Envisat/Cryosat-2/S3A/S3B (800 km orbit)
French/Indian: Saral
Chinese : HY-2A + HY 2B.

Orbits

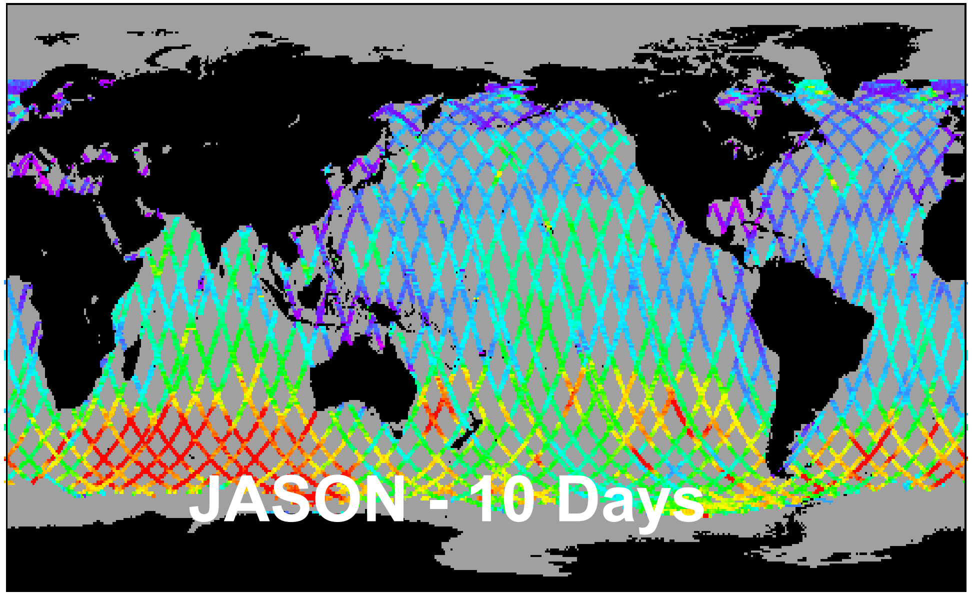
Typically 12-14 revolutions /day
Ascending and descending

Notice Track crossing



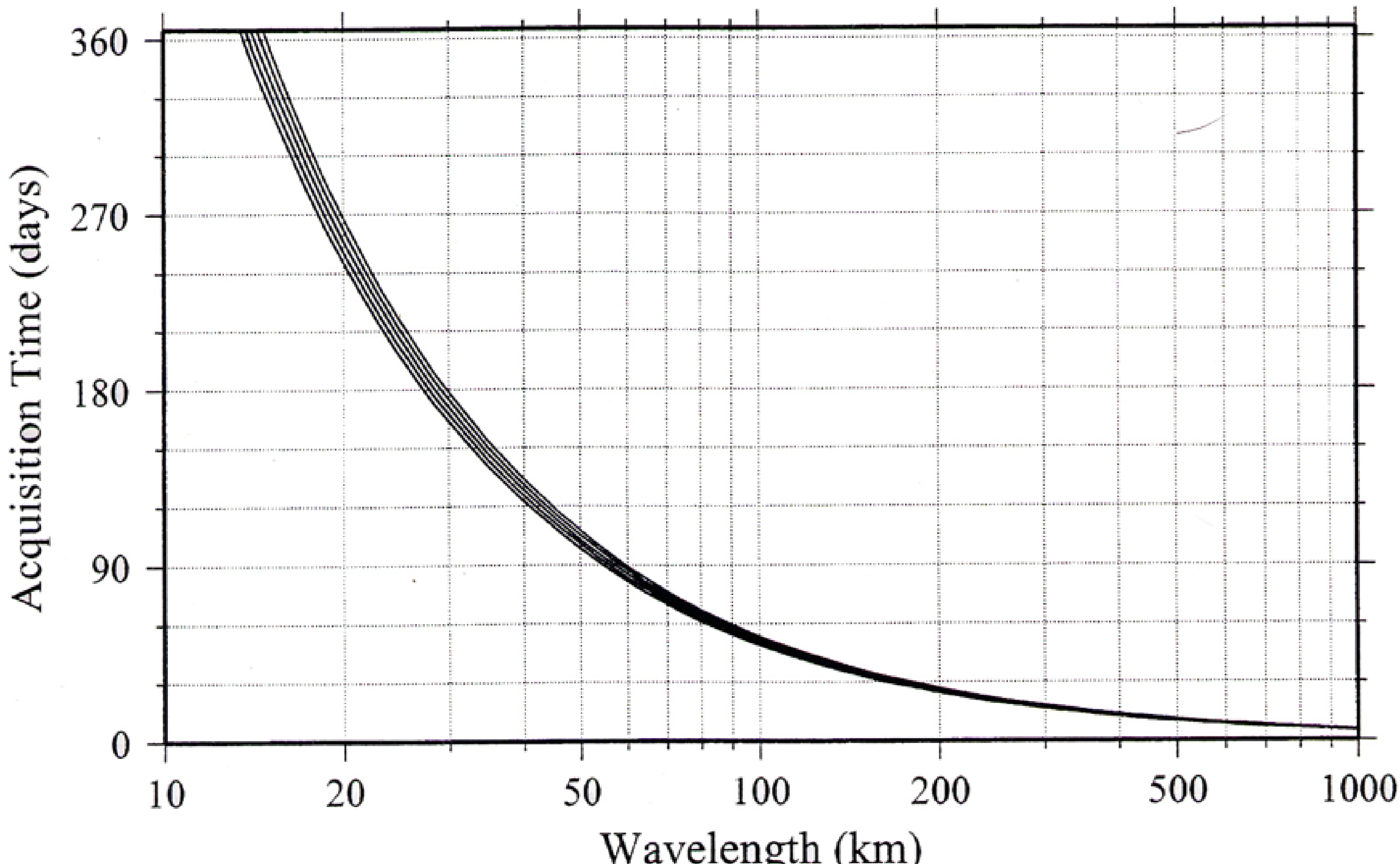
	Satellite	Height	Rev time	Tracks Per Day	Ground spd
Repeating (ERM)	ERS/ENVISAT/SARAL	780 km	1 h 40	~14	7 km/sec
	Sentinel 3A+B	800 km	1 h 43	~14	7 km/sec
	T/P+JASON 1-2-3	1300 km	1 h 59	~12	6.8 km/sec
Geodetic	Cryosat-2	750 km	1 h 43	~13	6.9 km/sec

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

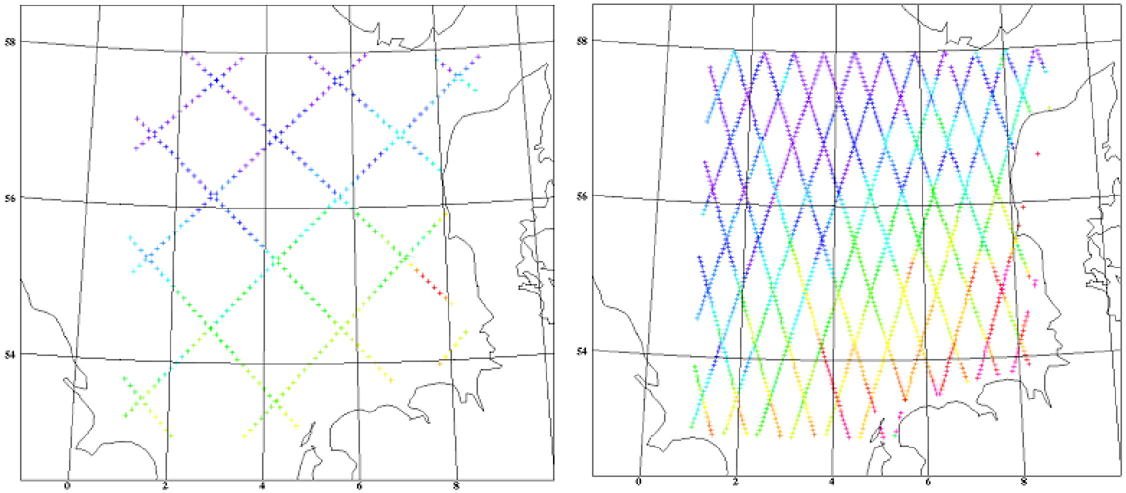


	Satellite	Repeat Period	Track spacing	Inclination Coverage
Repeating (ERM)	ERS/ENVISAT/SARAL	35 days	95 km	98° (+/-82)
	Sentinel 3A+B	27 days	70/35 km	98° (+/-82)
	T/P+JASON 1-2-3	9.915days	315 km	66.5°
Geodetic	Cryosat-2	369 days	7 km	92°

Spatial vs Temporal Resolution



ERM – GM data.



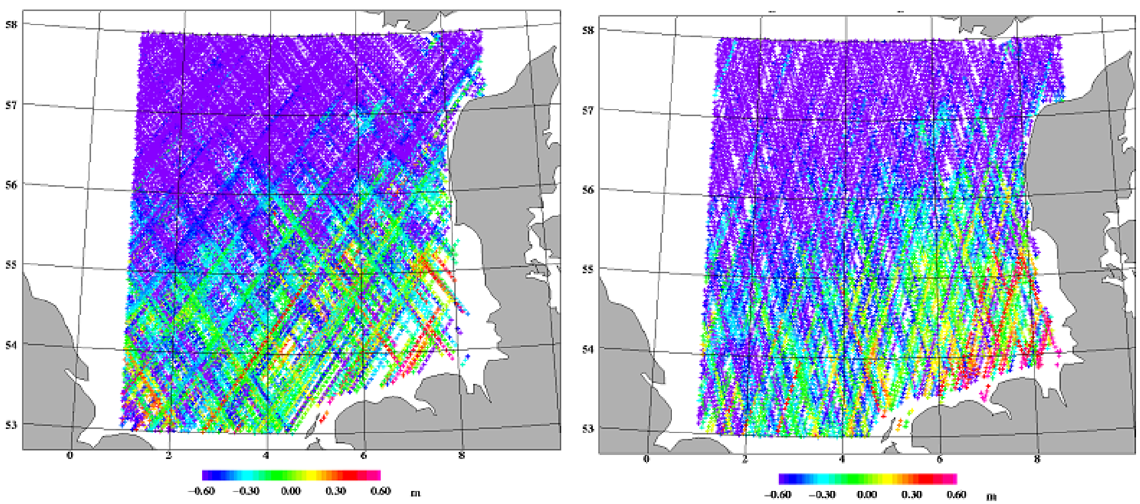
ERM Data

TOPEX/JASON –

(280 km)

ERS/ENVISAT

(80 km)



Geodetic Missions

I.e. ERS-1 Cryosat

(5 km track spacing)

Geodetic Missions are ESSENTIAL for high resolution (Detailed modelling)

ERM missions are ESSENTIAL for monitoring (variations in sea level change

Orbit Requirement / Design.

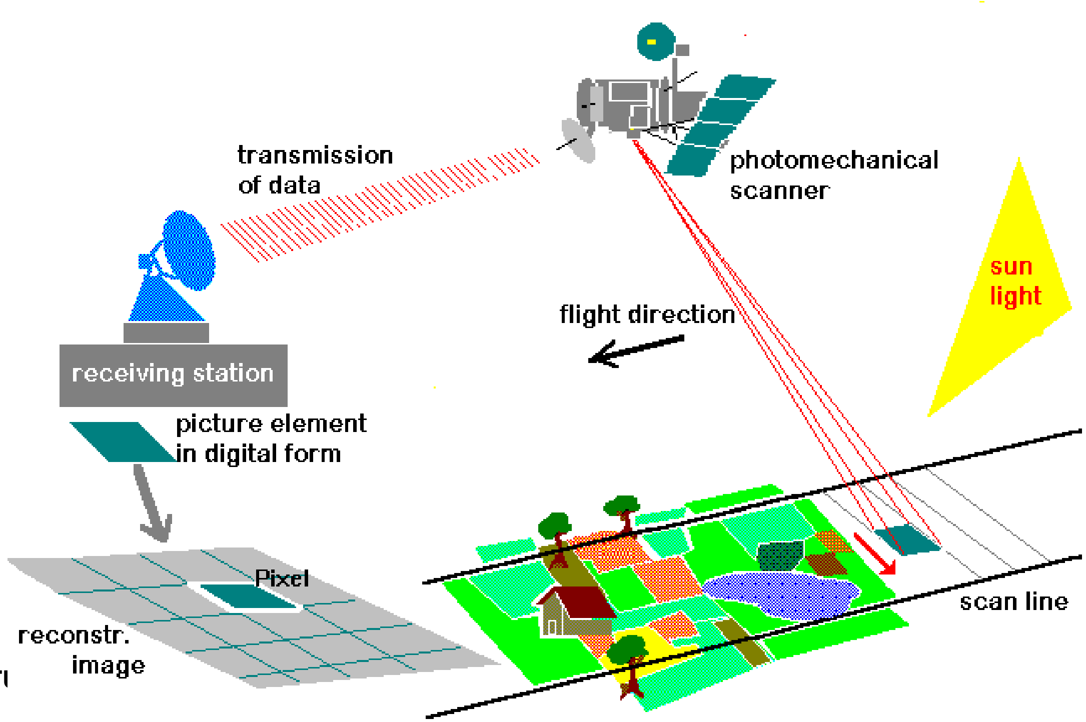
Geophysical	Oceanography
Signal constant in time • Needs to be measured once	Signal varies in time • Needs repeated measurements
Short (10-160 km) scales • Densely spaced (5 km) tracks • Non-repeat for ~ 1 year	Broad to global scales • Widely spaced (300 km) tracks • Short repeat orbit (e.g., ~10 days); trade off space and time resolution
Geodetic orbits • Geosat GM (US Navy, 1985-1986) • ERS-1 GM (ESA, 1994-1995) • CryoSat-2 (ESA, 2010-) • Jason-1 (NASA/CNES, 2012-2013)	Exact repeat orbits • T/P, Jason 1&2 (NASA/CNES) • ERS 1&2, Envisat (ESA) • Geosat, GFO (US Navy) • SARAL (CNES/ISRO) • Sentinel-3 (ESA/EUM/NOAA/CNES) • Jason-3 (ESA/EUM/NOAA/CNES)

Sun synchronous or not.

American is NOT Sun-synchronous
ESA satellites have sun-synchronous orbits.

This is dictated by other instruments
ESA satellites ALSO carry optical instruments):

Same location at same time of day some days later.



Orbital Accuracy

Technology paved with Skylab + Geos-3 + Seasat and Geosat (1970's and 1980).

During 1990 it became "good enough" LARGELY due to GPS.

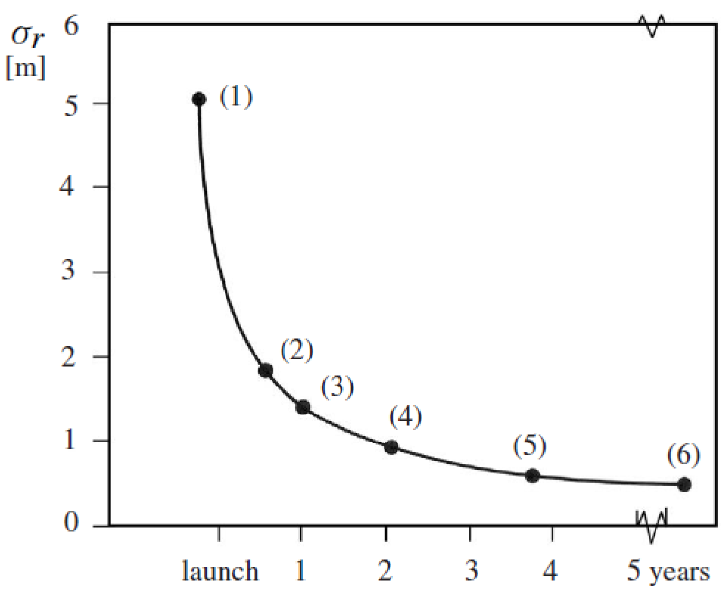
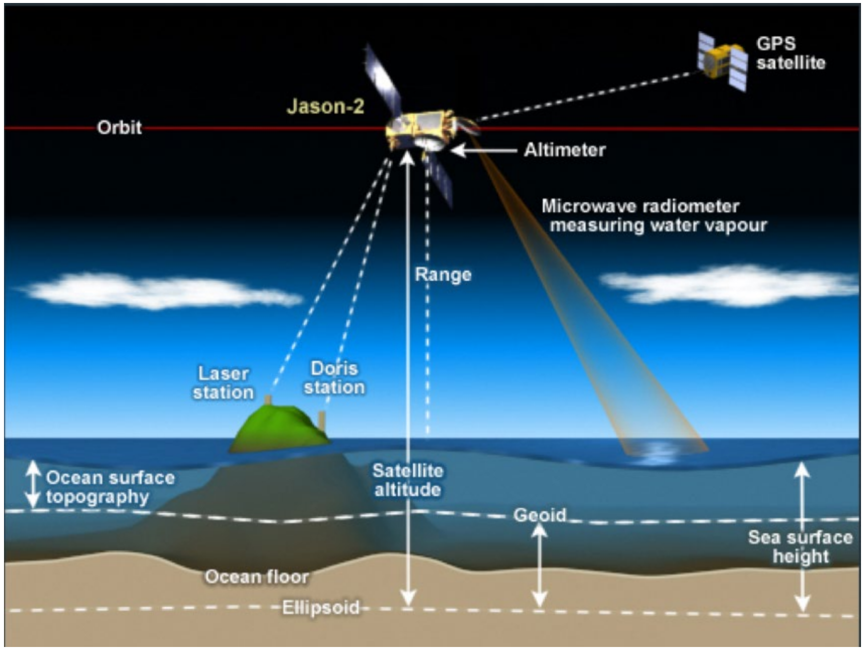


Figure 9.9. Improvement of the radial orbit accuracy for SEASAT ((1) before launch; (2), . . . , (5) additional data from SEASAT laser, GEOS-3 altimetry, SEASAT altimetry, TRANET Doppler; (6) final accuracy)



Orbit determination – post processing

- Orbit determination with post processing makes use of observations of the satellite
- Basically all current satellites in orbits lower than 20 000 km have GPS receivers onboard for orbit determination in (near) real-time or by post processing
- For precise orbit determination, GPS positioning may not be enough, therefore use other techniques:
  - For example: DORIS, satellite laser ranging (SLR) or inverse techniques based on observations collected by the satellites
  - Star cameras are used for orientation of satellites
- If only a short part of the orbit is needed, e.g. for remote sensing, a more simple representation of the orbit can be applied such as a polynomial approximation

Precise orbit determination (POD)

Many groups around the world specializes in **post** processing and orbit determination.

GPS standard

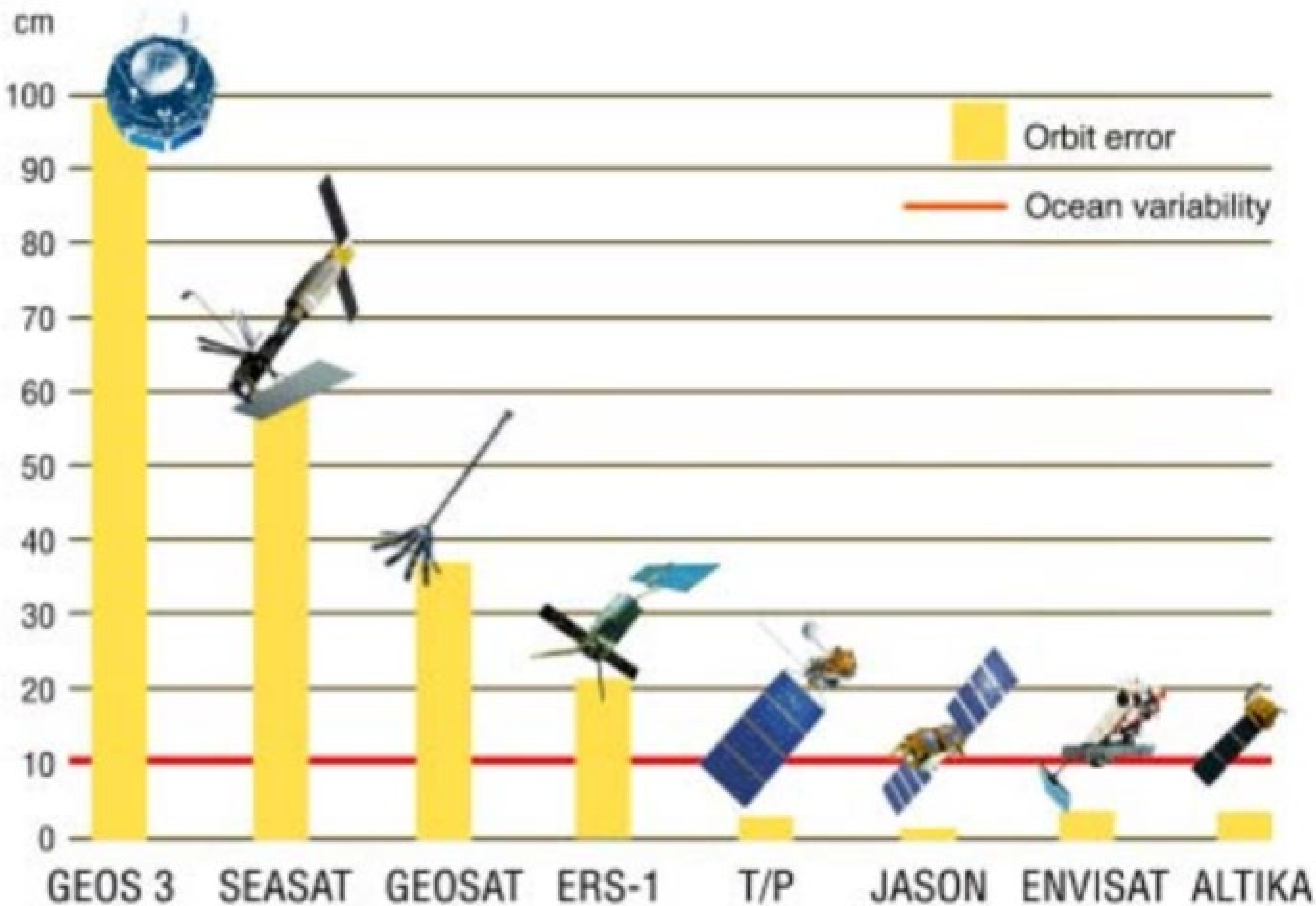
SLR (Satellite carries Laser Reflector

DORIS (Doppler Orbitography and
Radio-positioning Integrated by Satellite

Typical Near Real Time = 10 cm (GPS alone)
Post Processing (3 days) = 1 cm…

Since 2000 Orbit is precise to 1 cm

Why does it have to be accurate



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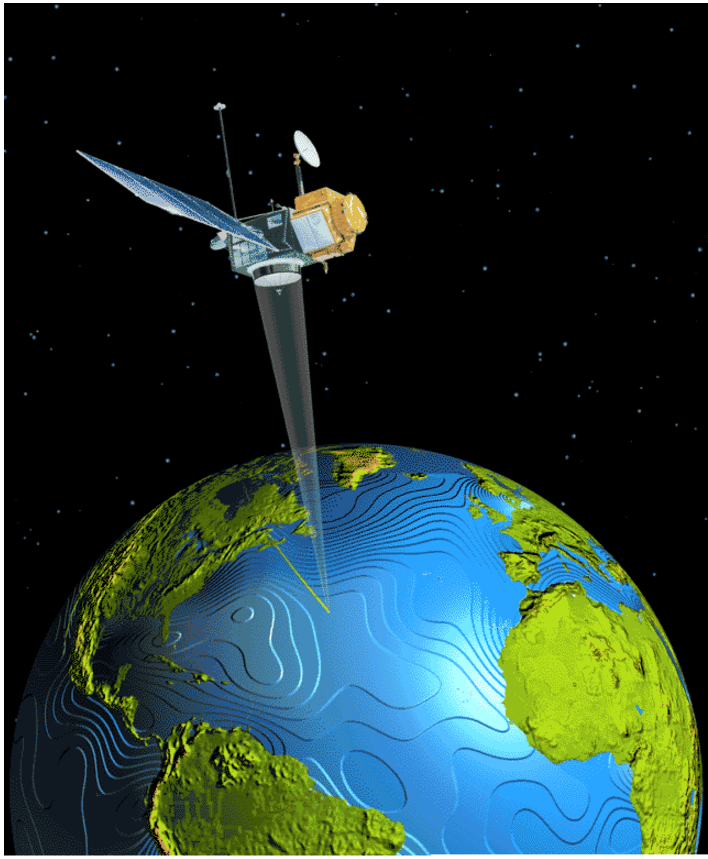
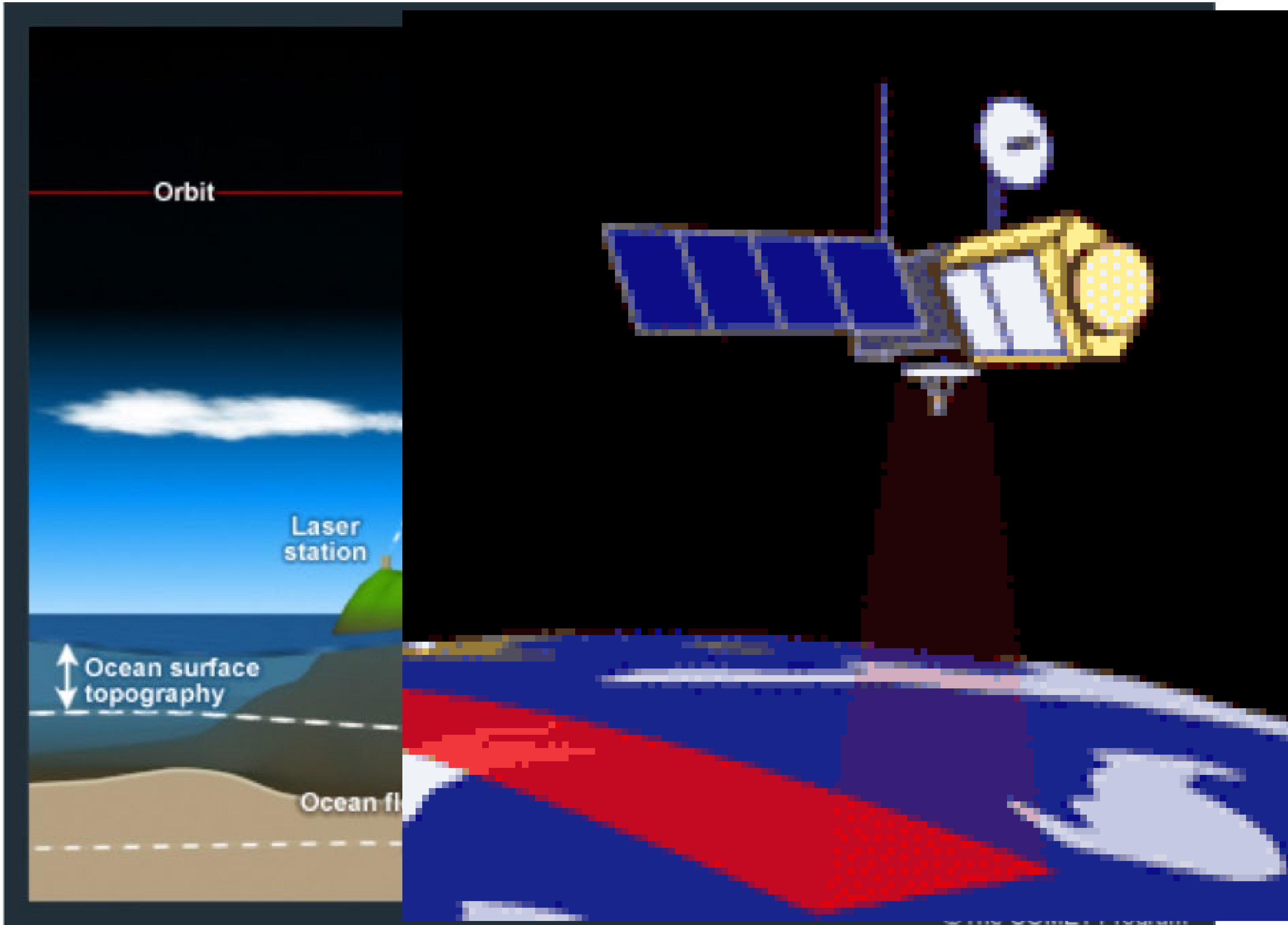
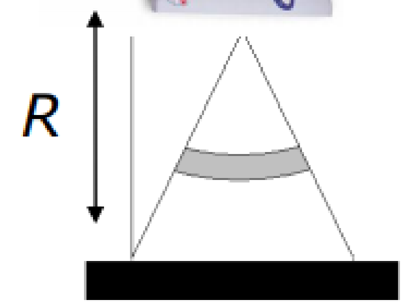


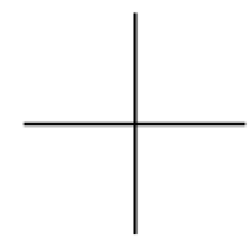
Components of a satellite radar altimeter system



Principle of satellite altimetry

Side view





Plan view

(1) Radars transmit pulses of electromagnetic radiation at radio frequencies

(2) The radar pulse is scattered or reflected by solid surfaces.

(3) The backscattered pulse (echo) is detected by the radar receiver

(4) The pulse travel time is recorded.

(5) The travel time is converted into the distance (range) separating the radar and the surface.

One big difference to Police radar.

We want to measure sea surface height

To an accuracy of say 1 cm from 800 km
Height.

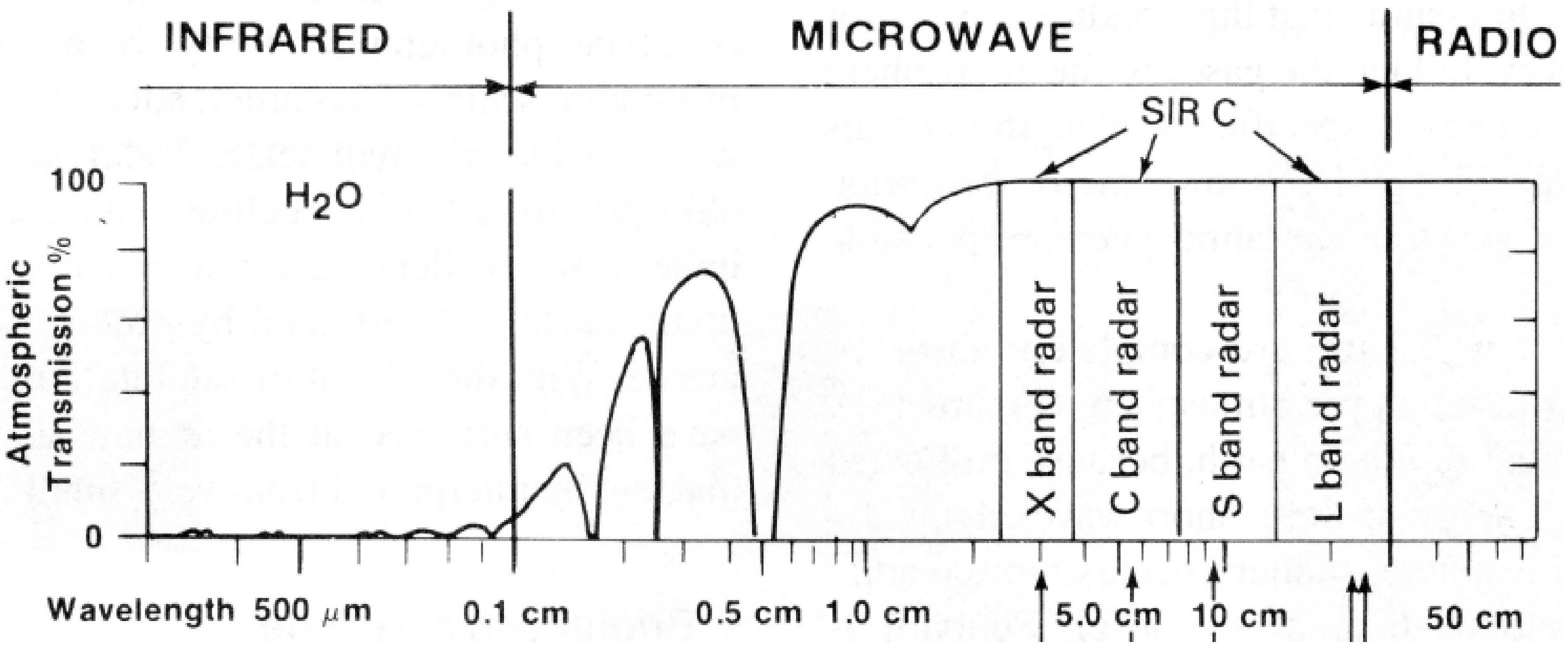
FOR REFERENCE

Great Belt Bridge in Denmak is 7 km.

It correspond to measuring its length
And changed in length to an accuracy
Of 0.09 mm = the diameter of a hair

Measuring Range using Radar

We use Radar to gain full **global** coverage.



There are also LASER altimeters.
These has an advantage in resolution
However they are limited by clouds (Lecture 11 will give you all the details).

Radar Frequencies

We use Radar to gain full global coverage.

Band	Frequency [GHz]	Wavelength [cm]
VHF	0.03-0.3	1000-100
UHF, P	0.3-1	100-30
L	1-2	30-15
S	2-4	15-7.5
C	4-8	7.5-3.75
X	8-12.5	3.75-2.4
Ku	12.5-18	2.4-1.7
Ka	18-40	1.7-0.75
V	50-75	0.60-0.40
W	75-111	0.40-0.27

1

Measuring range from satellite.

Distances or range is measured using time.

Clocks can measure time to 10-^{12}s accuracy
If you measure two-way traveltime you only
Need ONE CLOCK. This is important

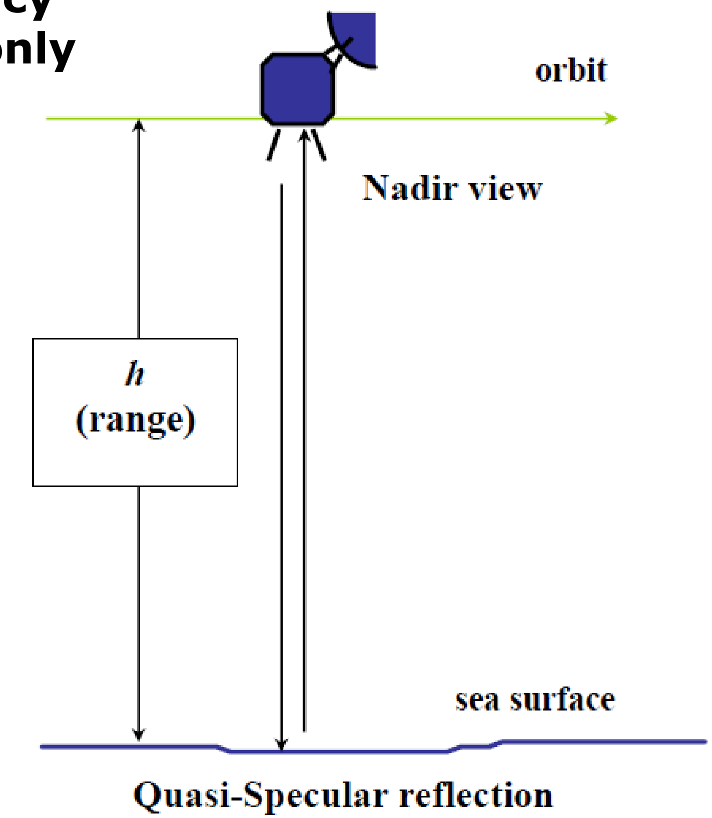
Traveltime is T

h = c*T / 2 (back and forth).

c = 3 x 10^8 m/s

Assume for a second.
Pulse width determines resolution.

If you wanted a resolution of 1 cm.
You would need a pulse lasting 3 x 10^{-10}
Or 0.3 nanoseconds.
This is instrumentally impossible

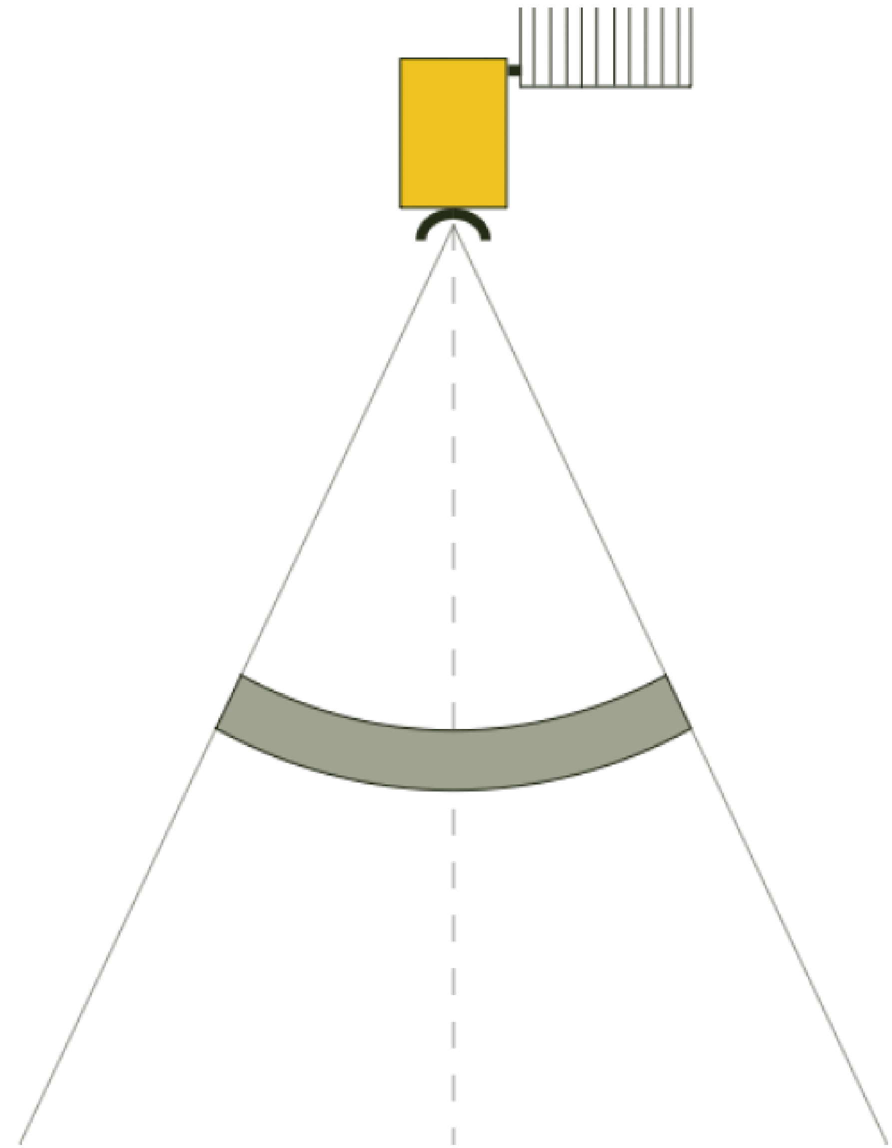


Pulse limited Radar.

- In a pulse-limited altimeter the shape of the return is dictated by the length (width) of the pulse

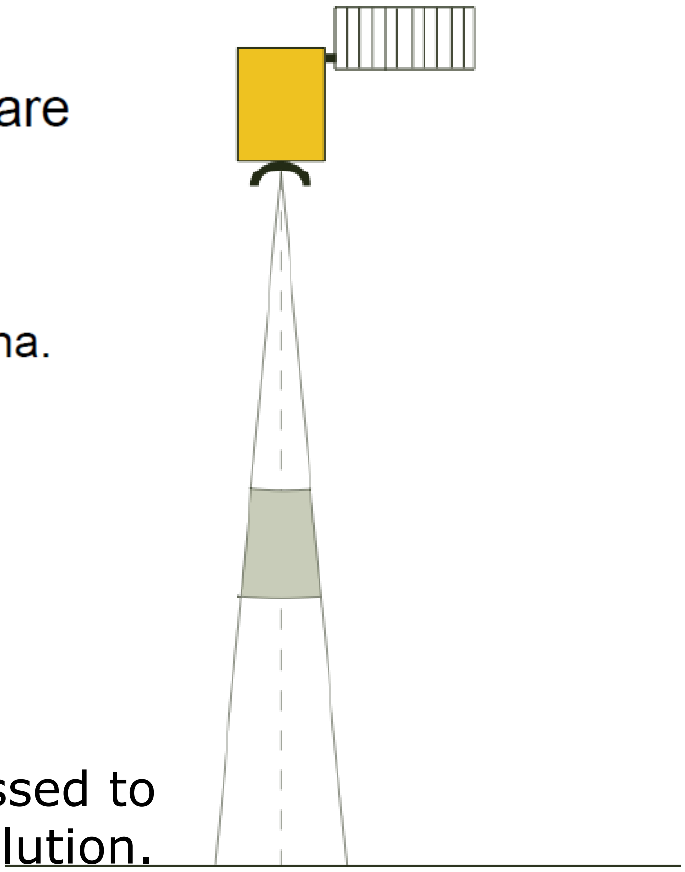
A typical Antenna has a beam width of 1°

So it will illuminate a disk of 14 km in diameter if satellite flies at 800 km altitude....



Beam limited ("constant/burst" beam).

- Narrow beams require very large antennae and are impractical in space
  - For a **5 km** footprint a beam width of about **0.3°** is required.
  - For a 13.6 GHz altimeter this would imply a **5 m** antenna.
- Even more important: highly sensitivity to mispointing, which affects both amplitude and measured range



Beam limited Radars are the fundament of SAR Syntetic Aperture Radars where data are processed to Increase "antenna" or aperture to increase resolution.

A small simple Class-excersize/discussion.

The satellite is 800 km away from the Earth.

It illuminate a disk of 14 km in diameter

1) How many ms does it take for the center point of the beam to return to the satellite.

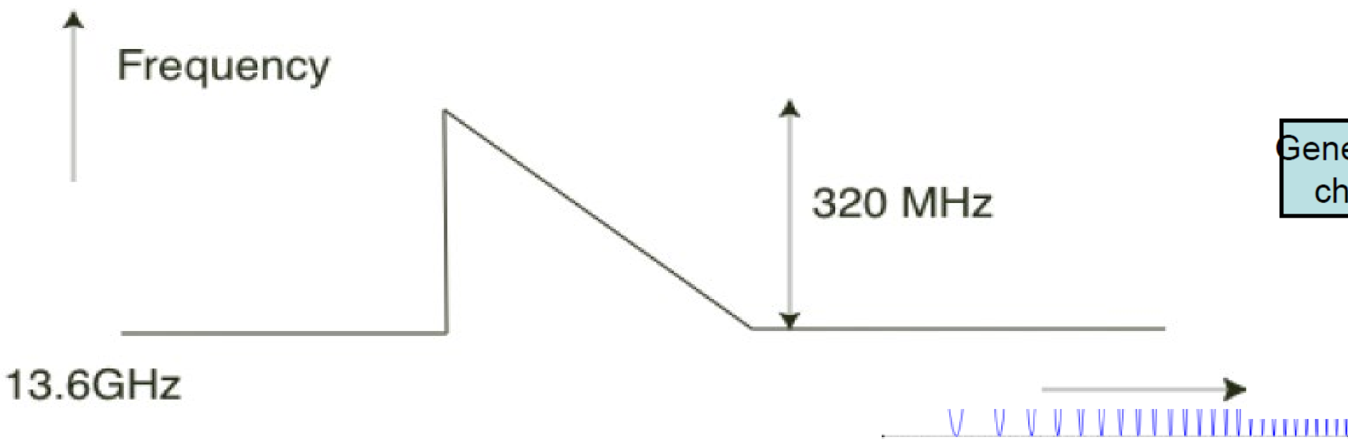
2) How many ms does it take for the outermost point to return to the satellite.

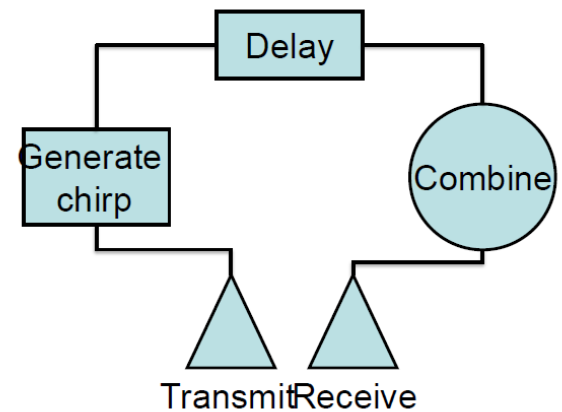
During this we want to measure 100 times.

Whats the required sampling rate (bin size) for the receiver in the satellite.

Pulse limited radars

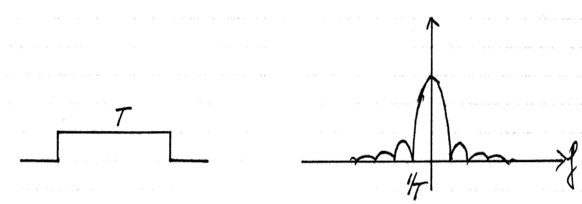
- The shorter the pulse, the higher the range resolution, but the more power is needed to guarantee a minimum SNR. Therefore, the pulse is frequency modulated („chirp“), and a special processing of the received chirp (matched filter), provides a result which is equivalent to a pulse length equal to the reciprocal bandwidth of the chirp („effective pulse length“). Typical chirp bandwidth B = 320 MHz -> effective pulse length = 3.1 ns, which provides a range resolution of 46 cm.





- Typical beam-width of the antenna is about 1º , which for a satellite altitude of 800 km implies that the pulse irradiates a disk of about 14 km diameter.

Range resolution of 46 cm is far from good enough. So to increase range resolution we need to average many pulses.Fortunately the altimeter Pulse Repetition Frequency (PRF)is 2-2000 times per second……



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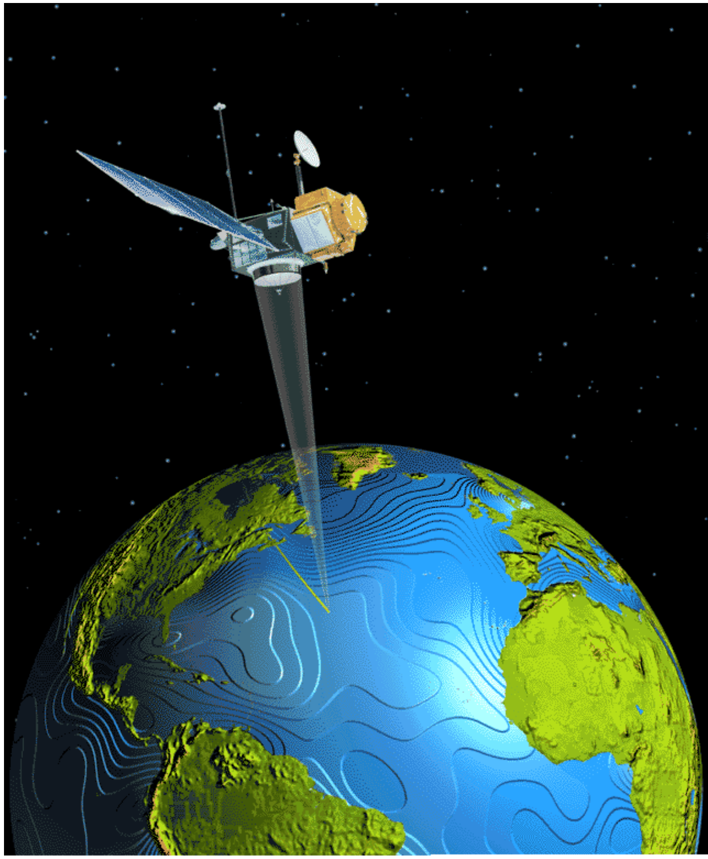
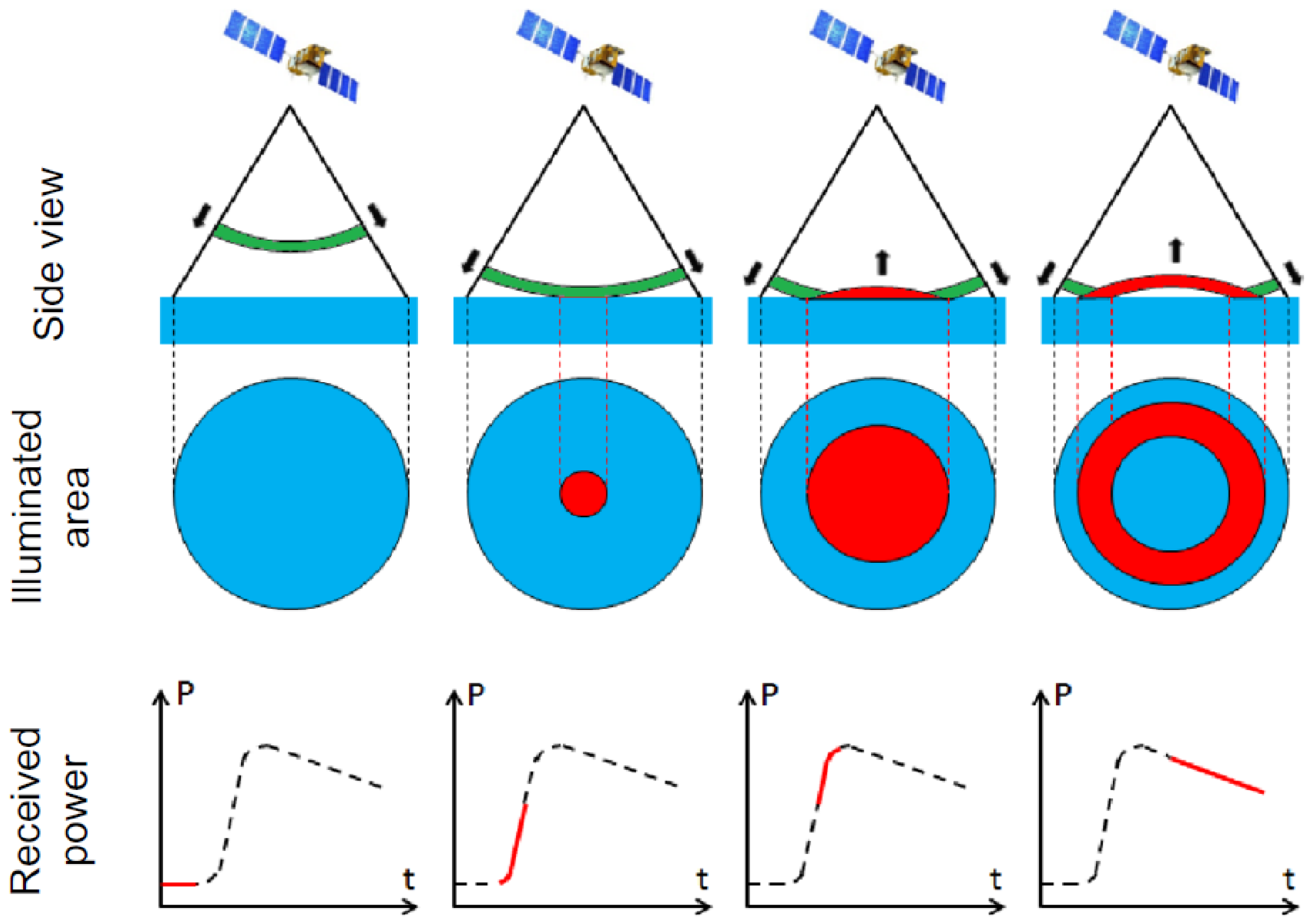


What does the Altimeter se..........

We transmit a thin shell of Radar energy out and look at the power returned

Ideal waveform

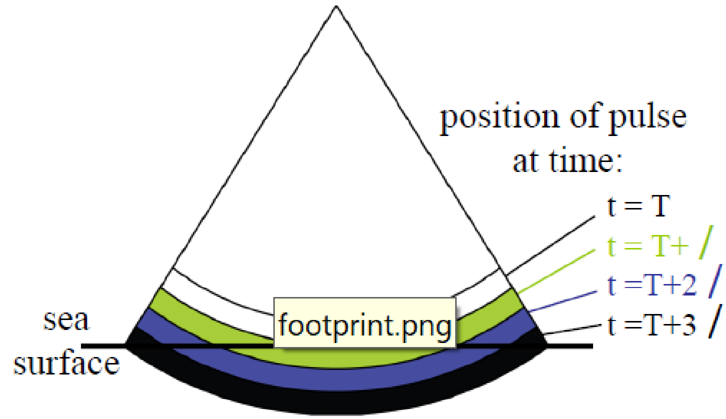


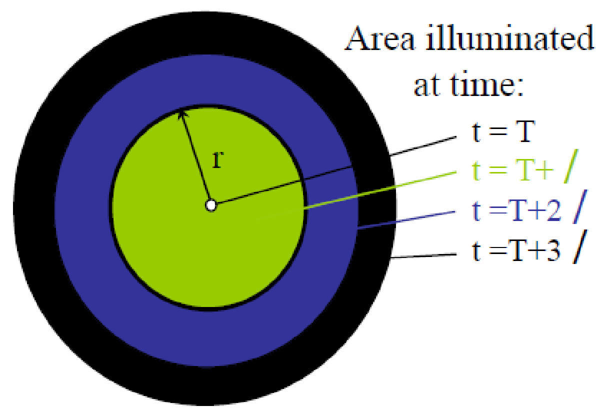
Received waveform = Received power as function of time delay

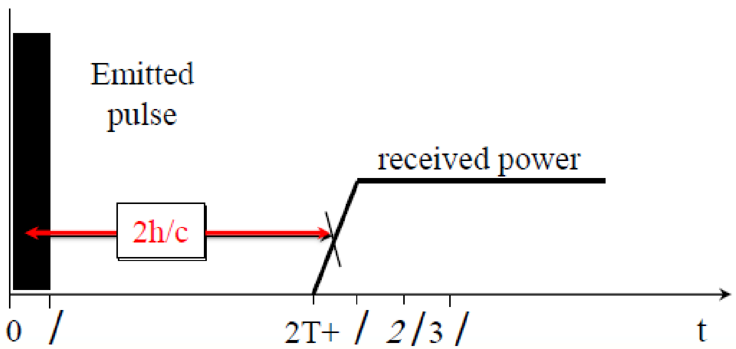
Illuminated / Efficient footprint

- Full illumination when rear of pulse reaches the sea – then area illuminated stays constant

$$A_p = \pi r_p^2 = \frac{\pi c \tau h}{\alpha}$$

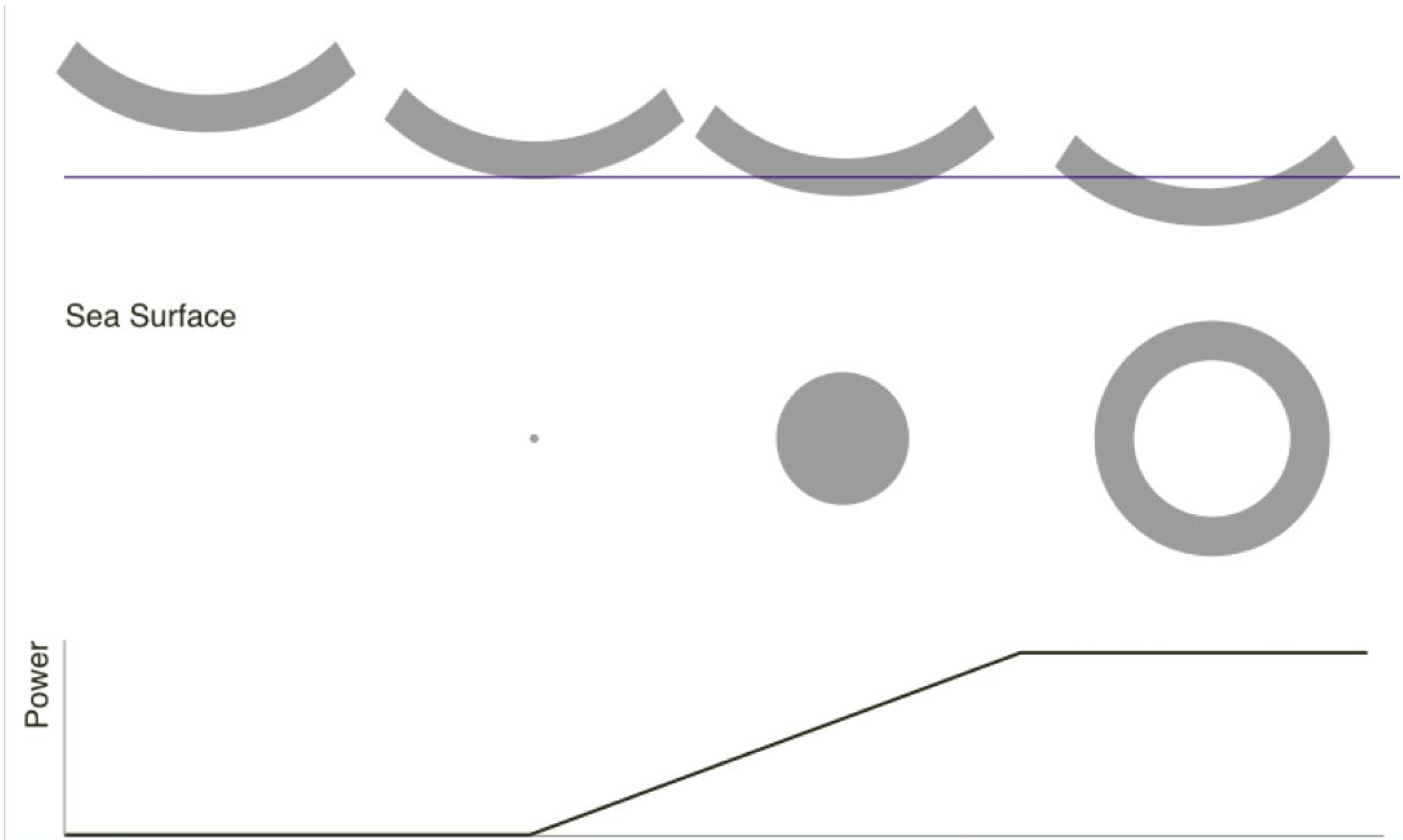




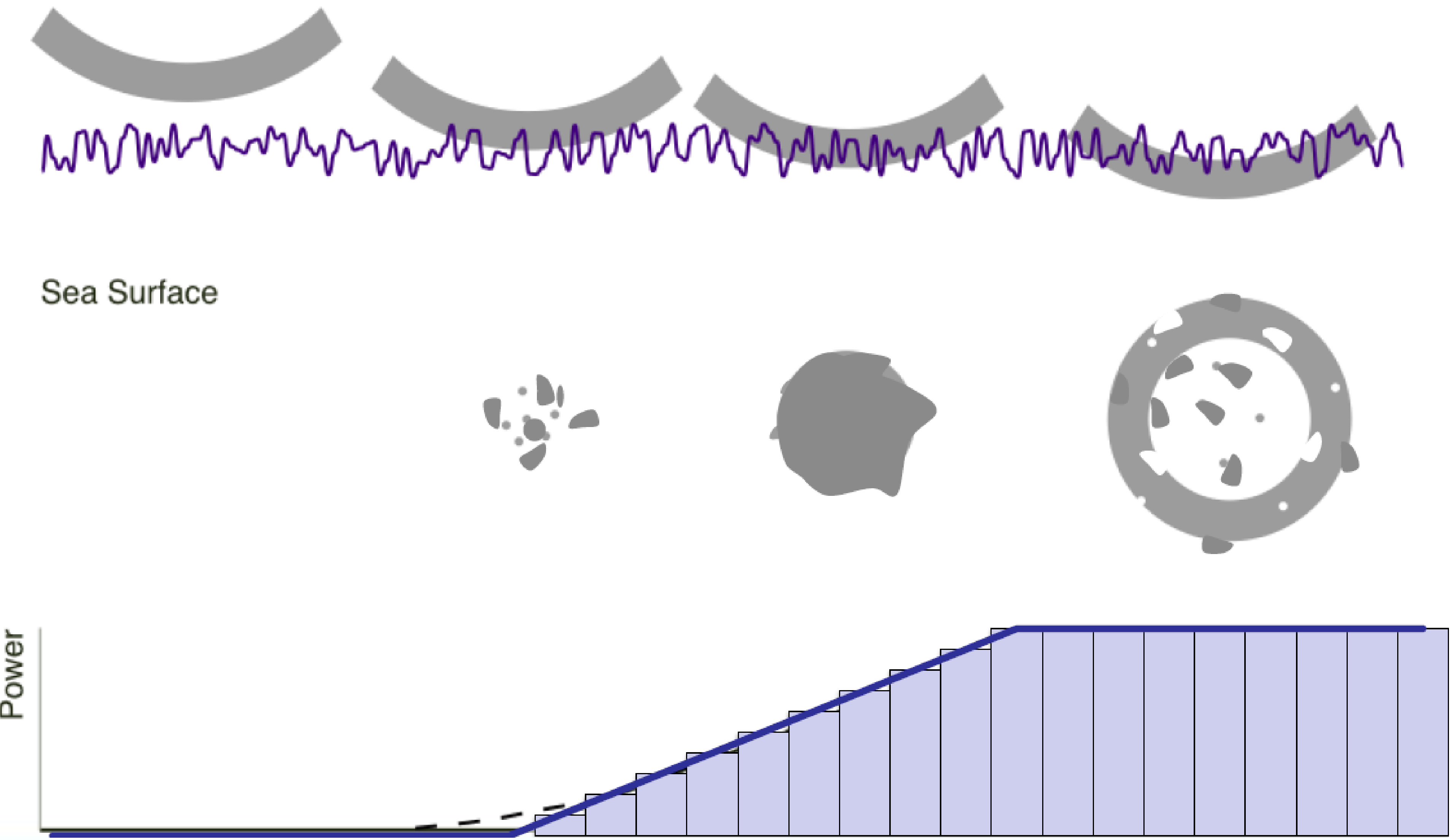


τ = compressed pulslength in [s], h = satellite altitude, α = correction factor for spherical geometry, R_E = mean earth radius. <u>Example:</u> h=800 km, B=320 MHz, r_p=0.8 km, A_p=2.0 km^2.

Real word is not perfect



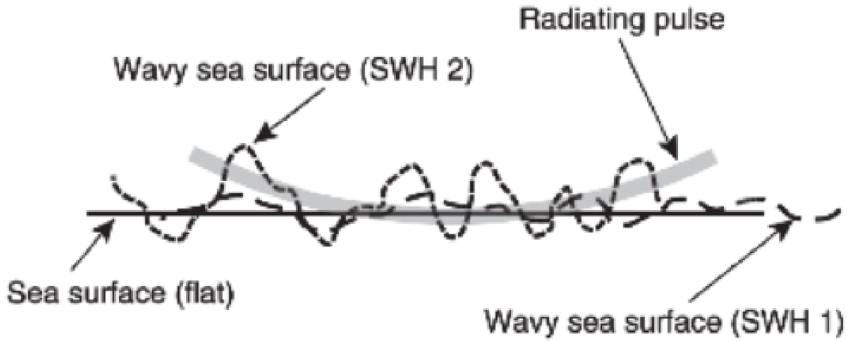
Waves on the ocean



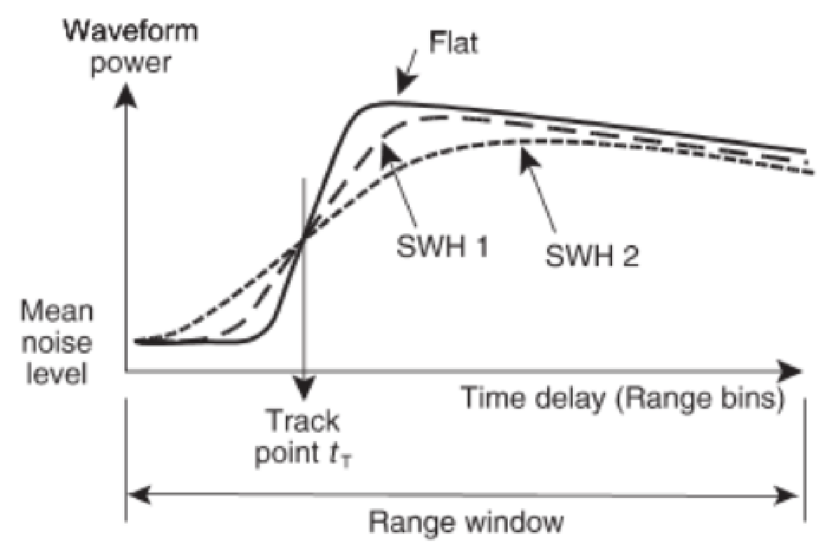
Returned waveform

The part of the waveform where the power rises is the "leading edge"; the part of the waveform where the power decreases is the „trailing edge". The latter is mainly due to the non-isotropic antenna gain.

The width of the region over which the power rises to its maximum level depends on the range resolution Δr of the altimeter and on the large-scale roughness of the scattering surface (the latter is expressed as significant wave height, SWH). A SWH>0 reduces the slope of the leading edge, i.e., smoothes the shape of the waveform.

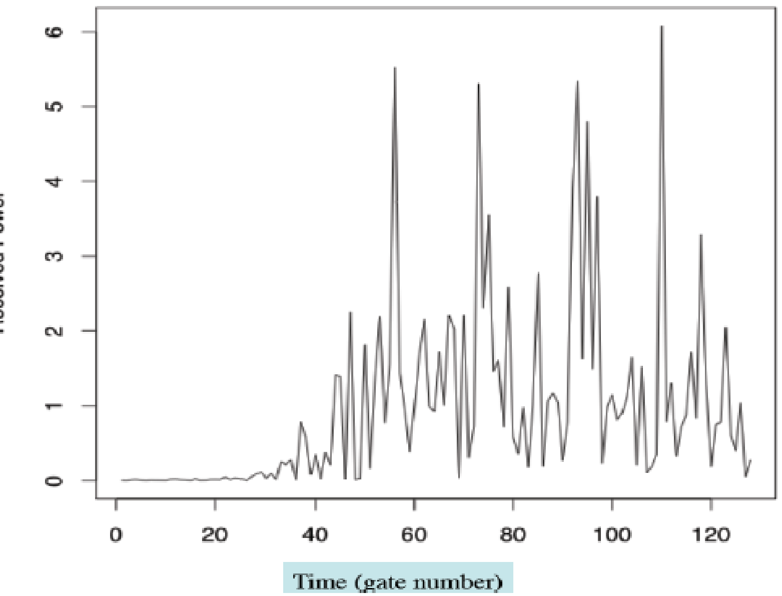


(a)



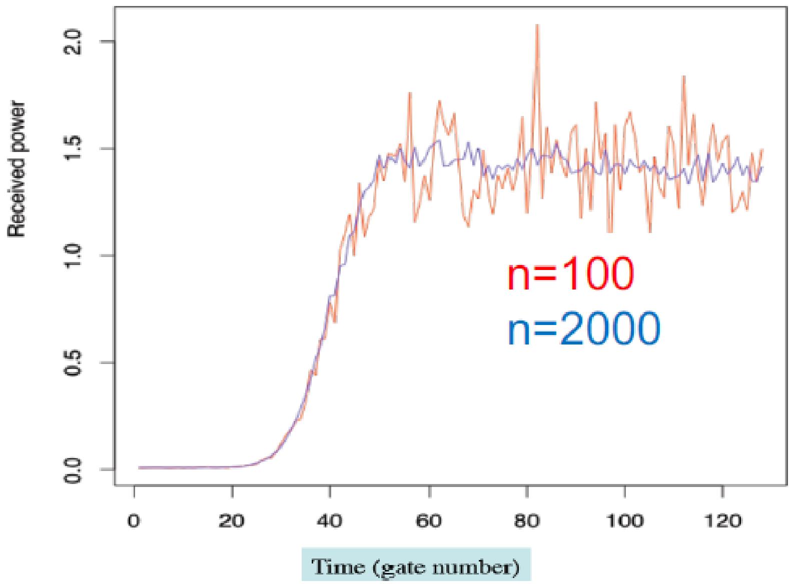
Pulse-limited radar altimeter averaged waveform

The PRF of a pulse-limited altimeter is about 2000 Hz. Hence, the echos of successive pulses are statistically independent, and the random fluctuations in power of a single waveform can be reduced by averaging over many waveforms.



Single waveform with random fluctuations in power

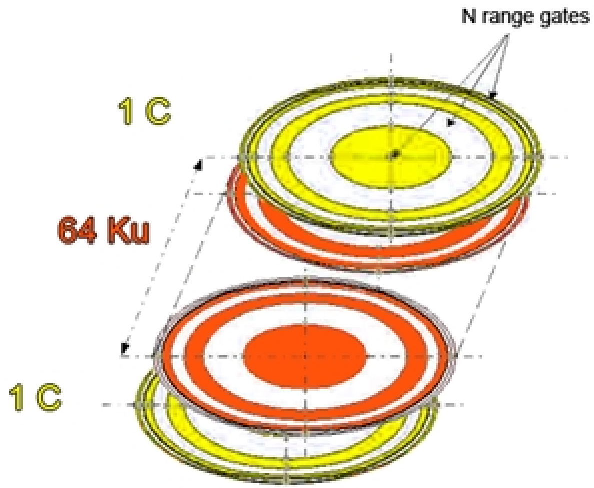
Pulse repetition frequency ~ 2000 Hz (i.e., 2000 echoes per second)



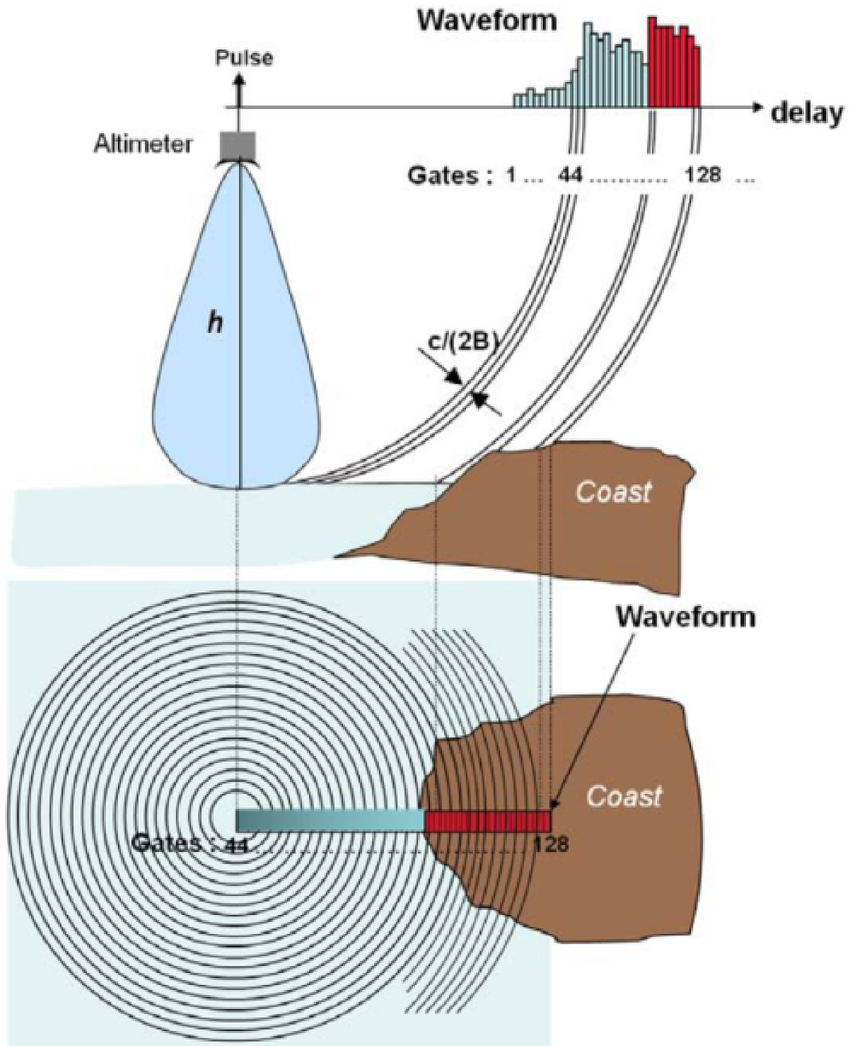
Averaged waveform. 20 Hz waveform = average over 100 echoes; 1 Hz waveform = average over 2000 echoes. The more waveforms are averaged the more the random fluctuations average out.

Elephant in the room

- Statistically independent
- Uncertainty of mean
- Improves with 1/sqrt(N)
- Average out speckle noise
- Radar pulses overlap….



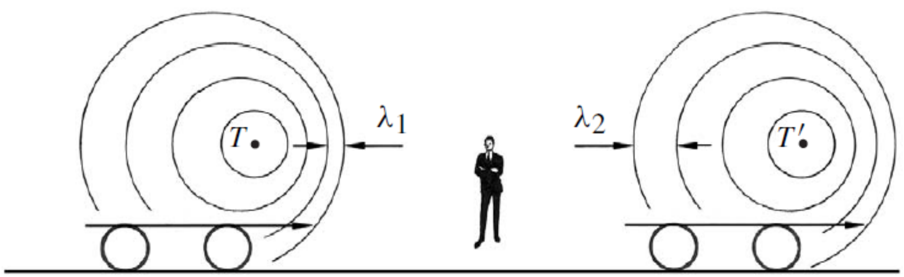
Limitations of a pulse-limited radar altimeter

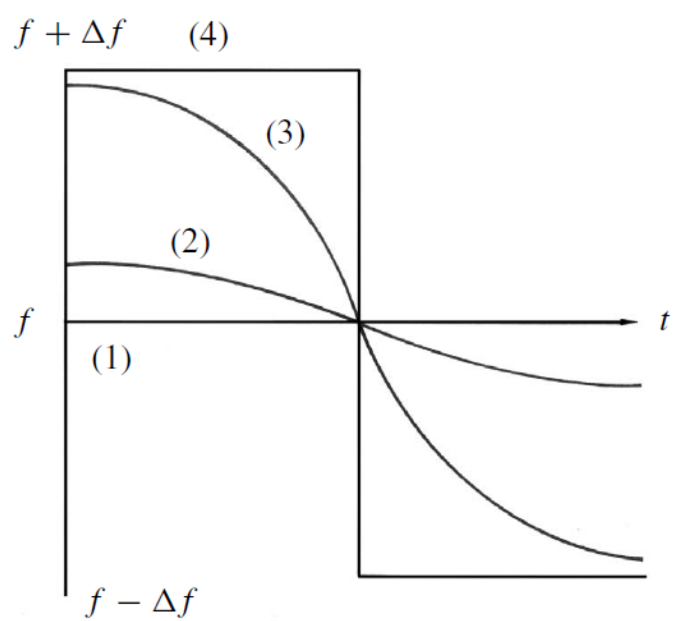


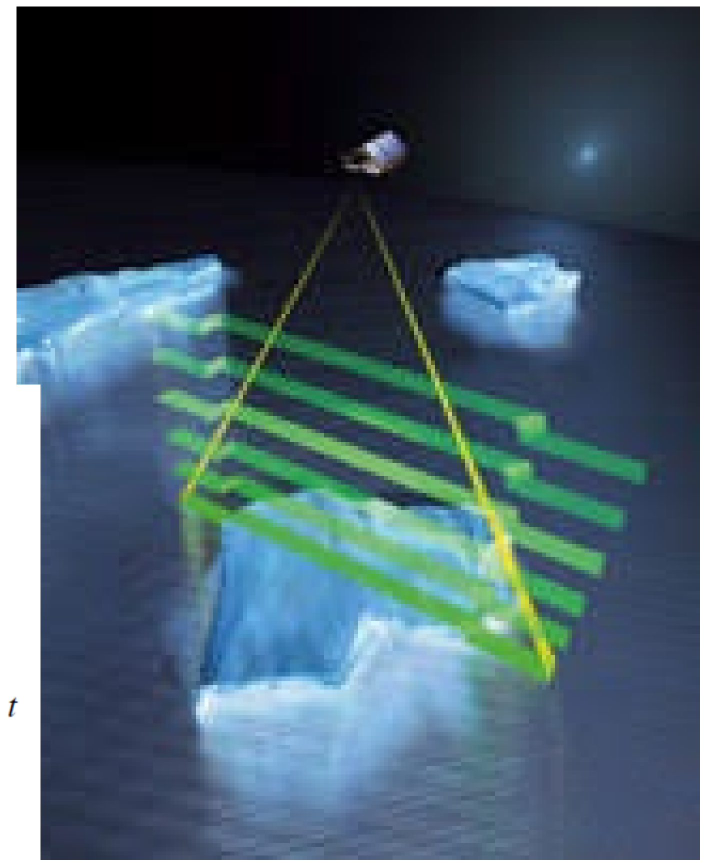
- Large footprint (depends on effective pulse length, altitude, and wave heights) -> limited spatial resolution
- Range accuracy for single pulse ~ 0.46 m -> increasing range accuracy requires averaging over many pulses, which reduces spatial resolution further. SD=2 cm only possible for 1Hz data -> 1 data point per ~7 km along-track.
- Closer to the coast (< 10-15 km), waveform is corrupted by land returns

Delay Doppler Altimetry

- Since Cryosat-2 in 2010
- Now with Sentinel-3A/B
- Sentinel 6 (both).







GS
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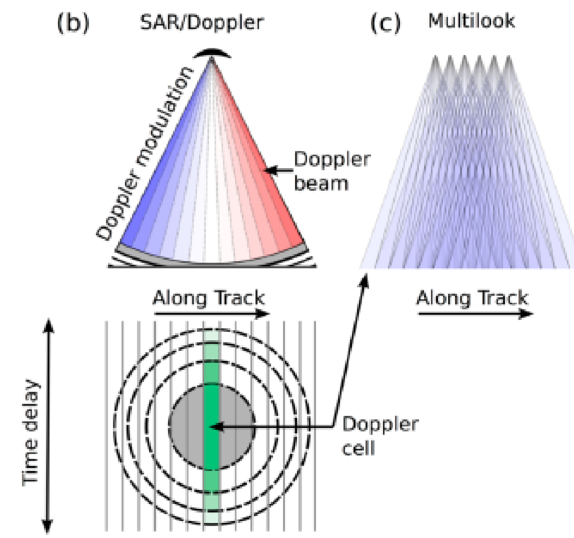
Delay-Doppler radar altimeter

The area illuminated by today's pulse-limited satellite altimeters is about 2 km^2 (for an ideal flat ocean surface). An improvement in along-track resolution is achieved by a delay-Doppler altimeter. It submits bursts of N pulses each with a high PRF (Cryosat-2: N=64, PRF ~18kHz). This high PRF ensures pulse-to-pulse coherence (see next slide).

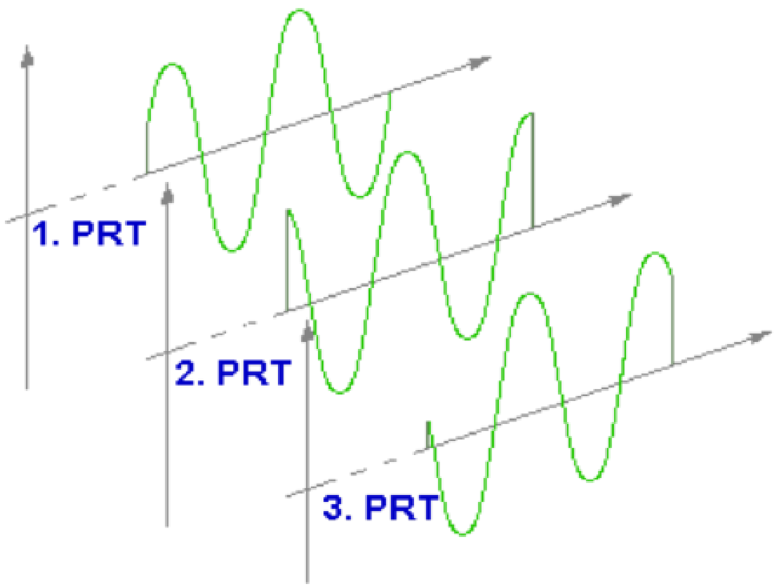
Due to satellite motion, each of the N echos of a burst is frequency shifted (Doppler effect). This information is used to separate each echo into strips arranged cross track. Each strip is about 250 m wide along-track.

The result of the data processing is equivalent to decomposing the main antenna beam into a set of N narrower synthetic beams along track. Each beam has a rectangular footprint („delay-Doppler footprint"), which over a flat surface is about 250 m wide along track.

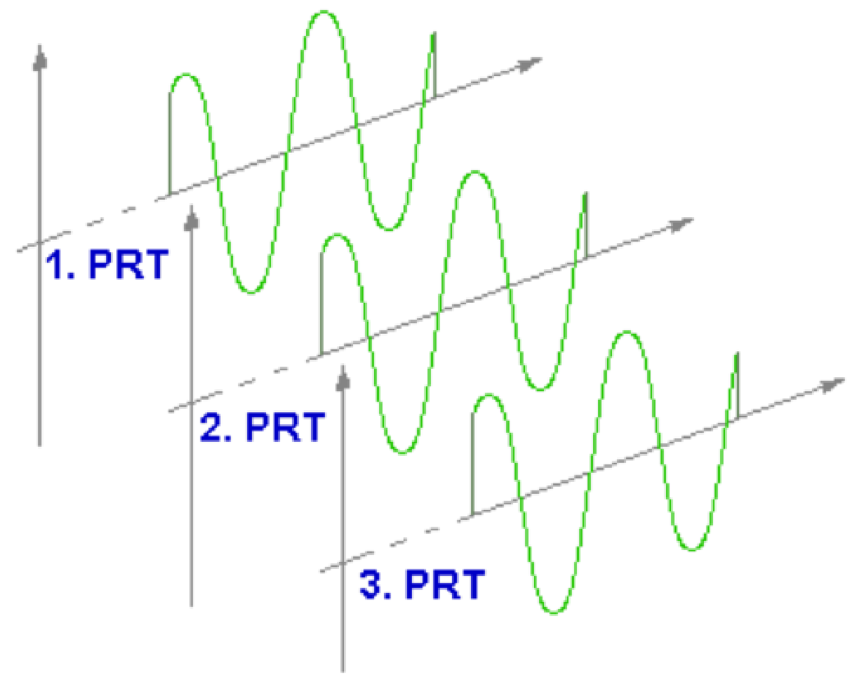


After the Doppler beams were formed, all beams that have illuminated the same delay-Doppler footprint are collected to form a stack. The whole stack is averaged („multi-looking") providing the delay-Doppler waveform.

Coherent and non-coherent pulses

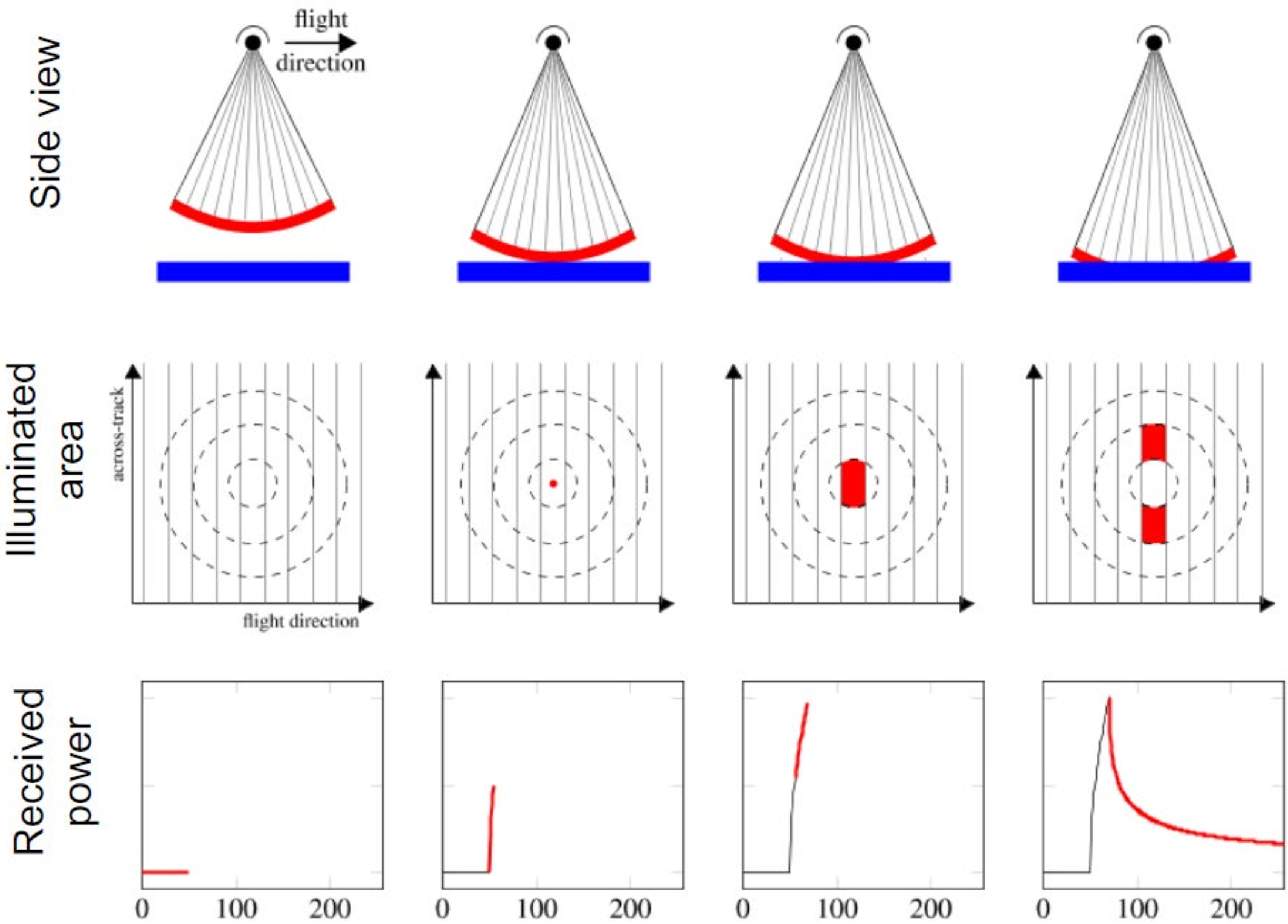


Non-coherent pulses with random phase from pulse to pulse.



Pulse-to-pulse phase coherence (each pulse starts with the same phase)

Delay-Doppler radar altimeter footprint and waveform

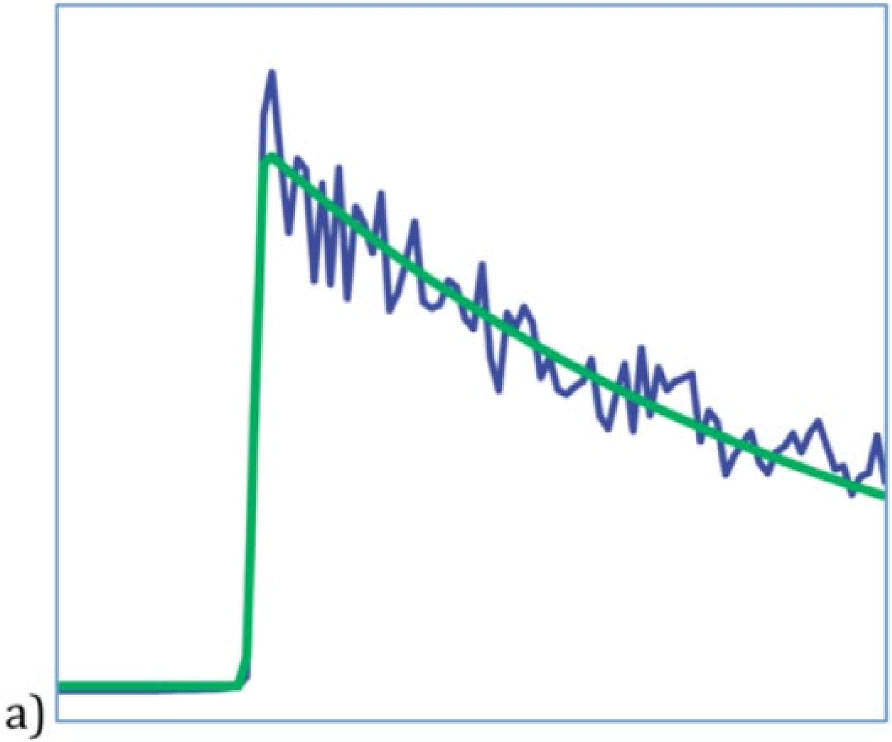


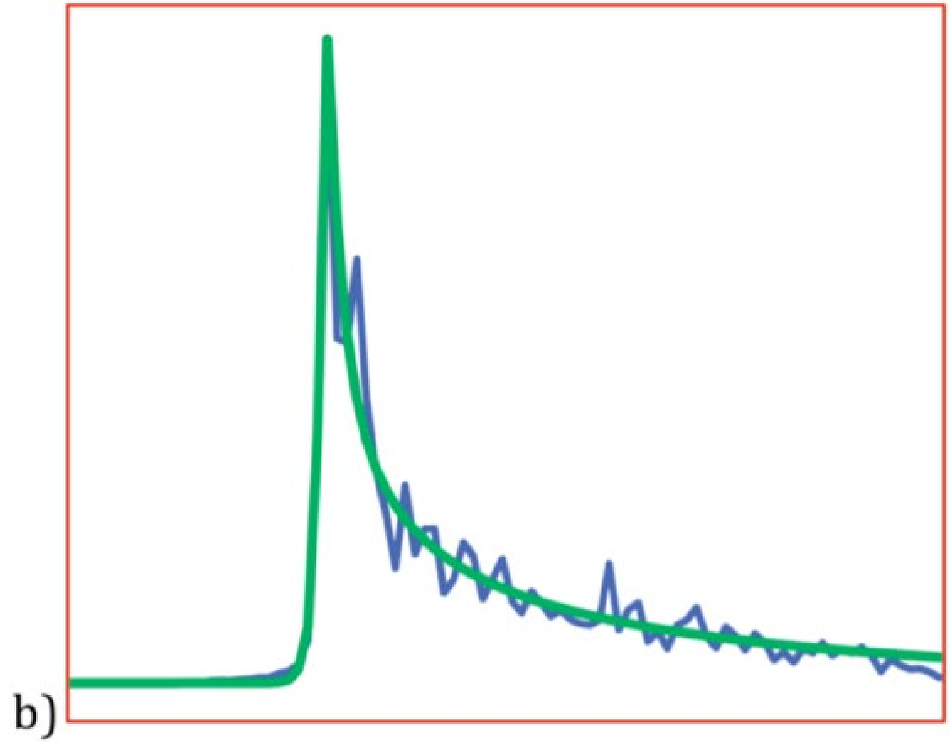
Ideal waveforms

Pulse limited altimetry

Delay-Doppler altimetry

LRM (Low Resolution Mode)



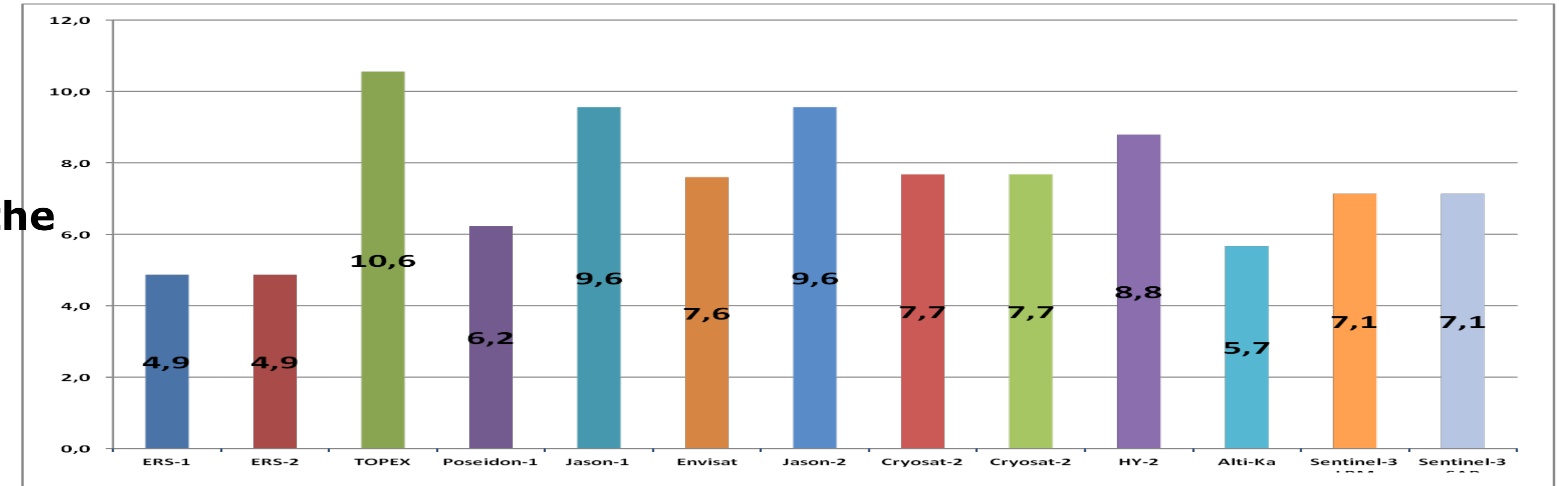


Brown waveform model

Samosa waveform model

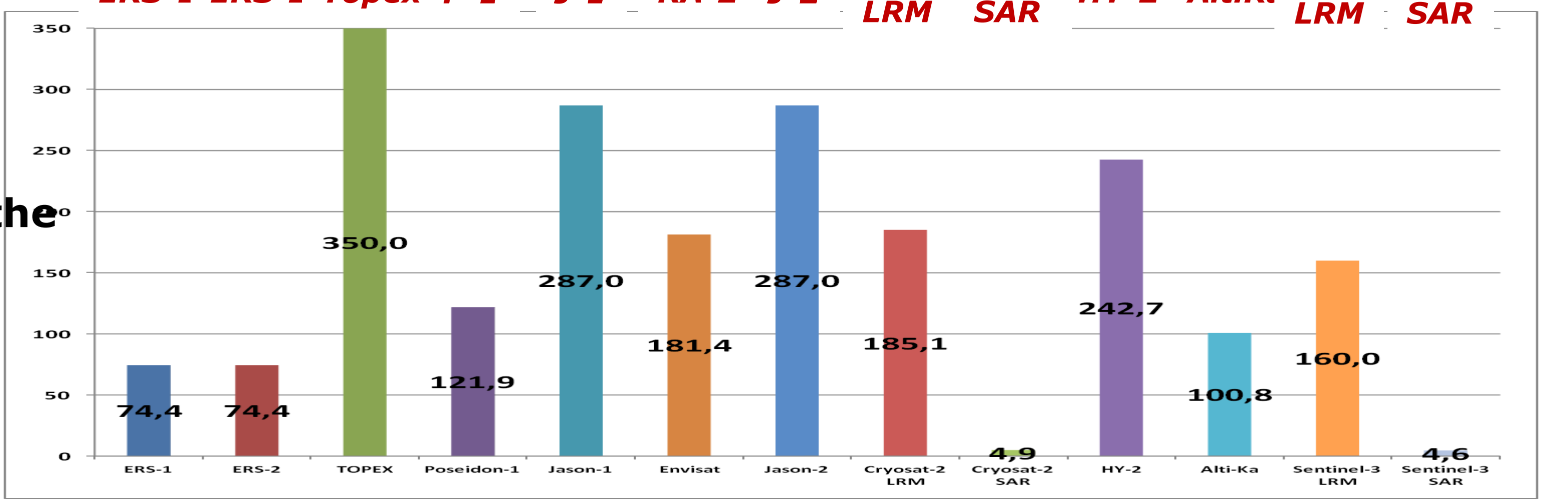
Surface of the waveform footprint

Radius of the waveform footprint (km)



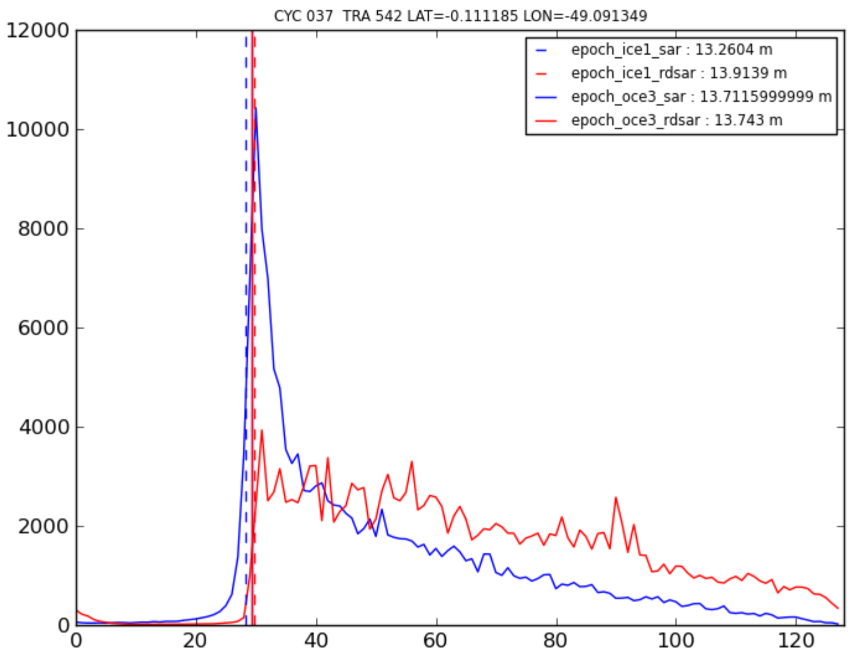
ERS-1 ERS-2 Topex P-1 J-1 RA-2 J-2 CS-2 LRM CS-2 SAR HY-2 AltiKa S3 LRM S3 SAR

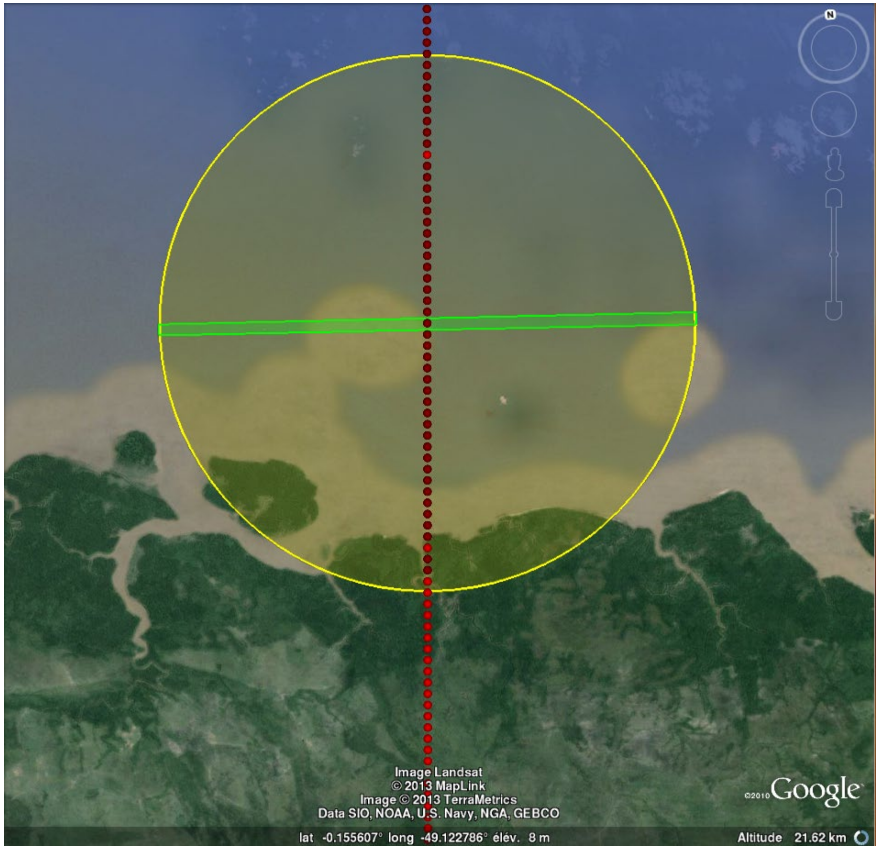
Surface of the waveform footprint (km²)



Impacts of coasts on altimeter measurements

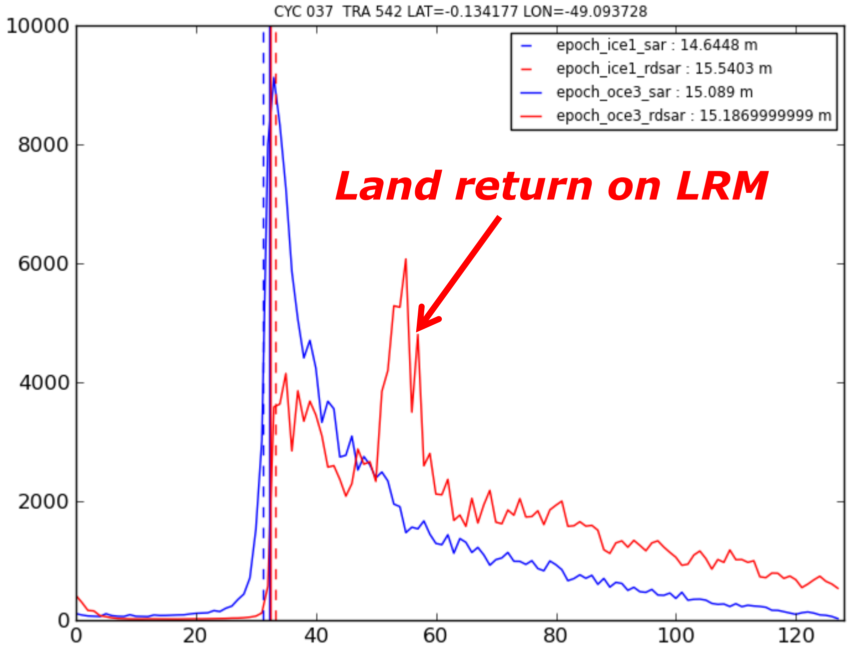
CASE #1: illustration

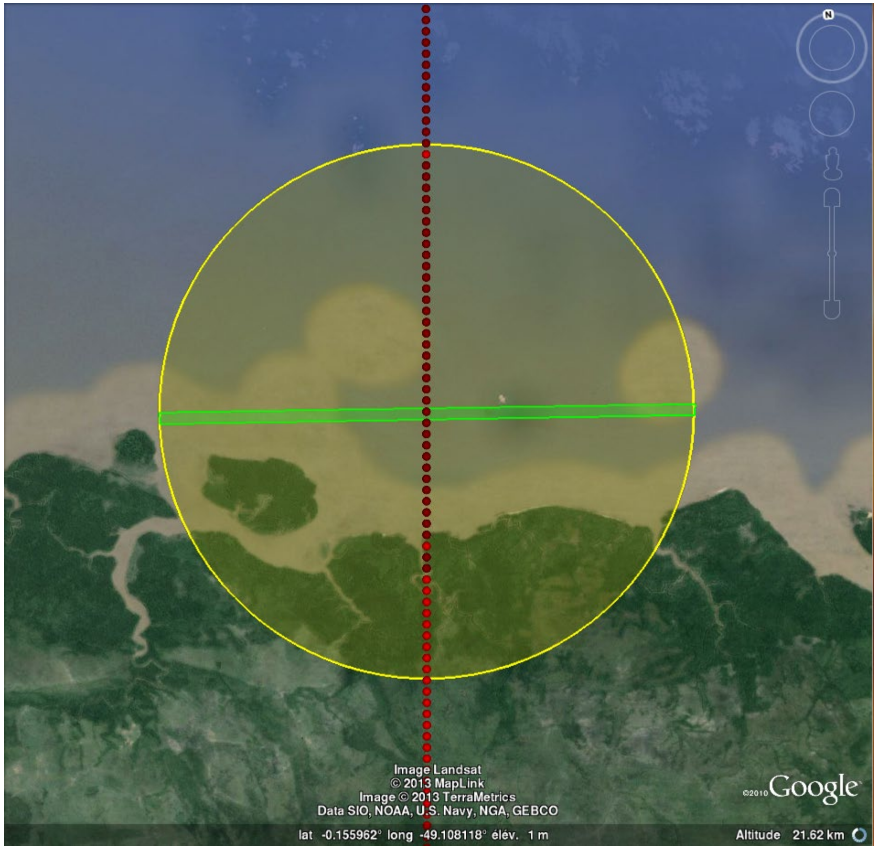




Impacts of coasts on altimeter measurements

CASE #1: illustration

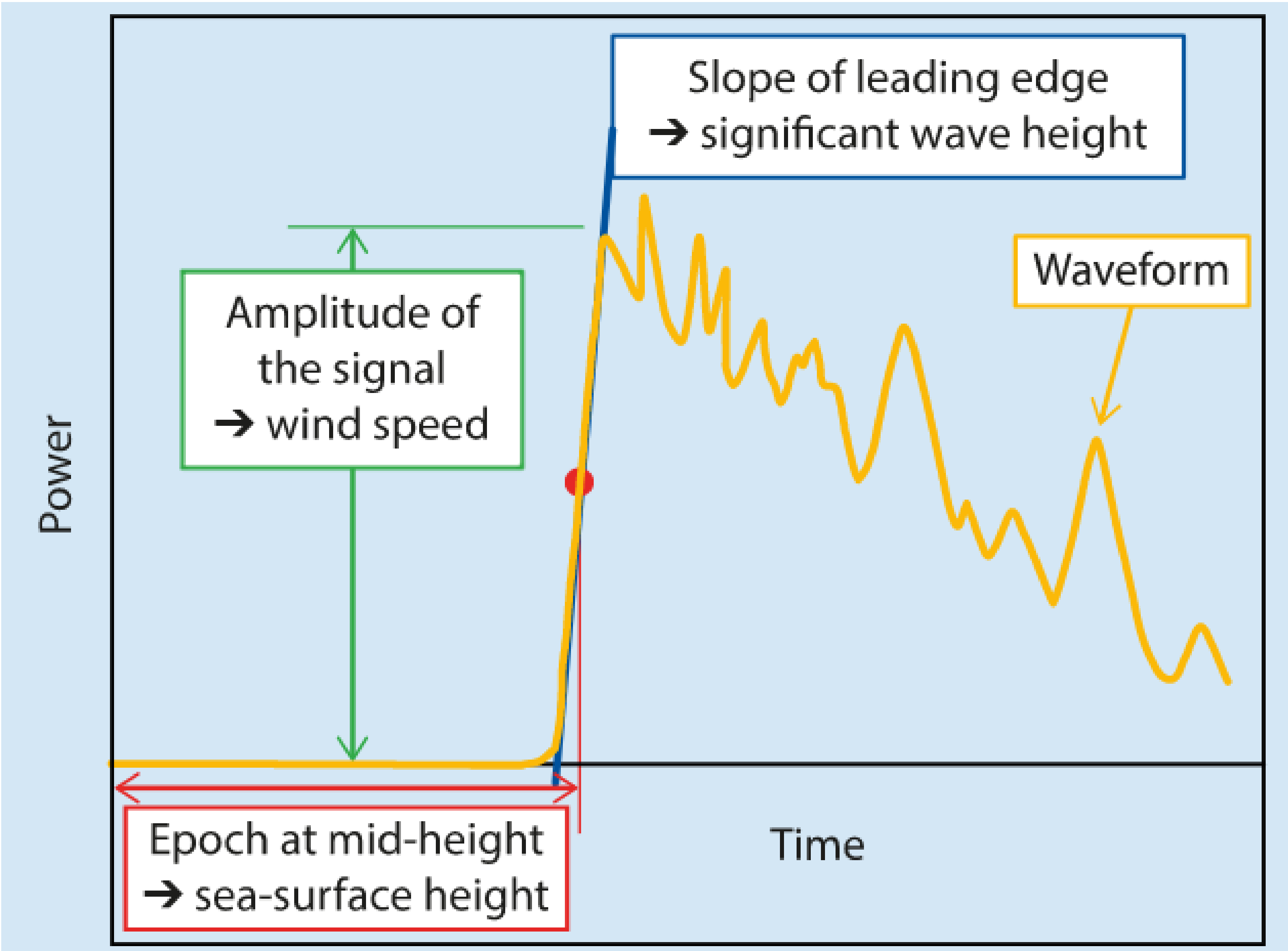




http://Youtu.be/V7_43bsybYk

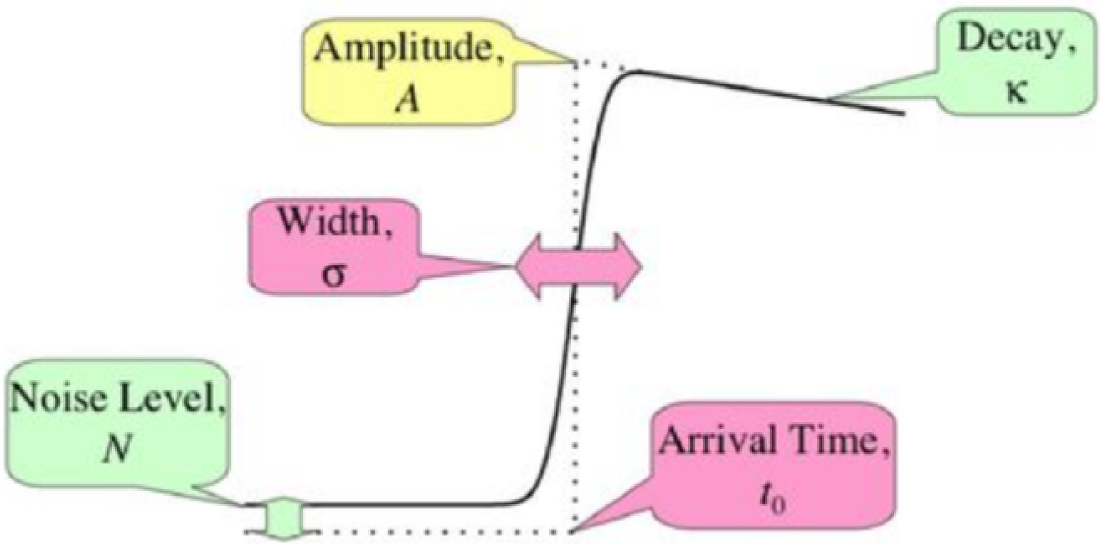
Very nice illustration prepare by ESA in preparation of the launch of the Sentinel-6 (November 6^{th}).
The satellite will simultaneous fly a conventional (LRM) and SAR altimeter due to an extremely high Pulse Repetition Frequency.

From waveform (power(t)) to sea surface height (waveform fitting)



Waveform retracking

= fit a model waveform through the <u>averaged</u> (e.g., 1 Hz) waveform (e.g, using least-squares); the fitted model is used to extract all relevant information. Classical waveform model for conventional altimetry: 5-parameter Brown model



$$P(t) = N + \frac{A}{2}\left[1 + \operatorname{erf}\left(\frac{t - t_0}{\sigma\sqrt{2}}\right)\right]\begin{cases} 1, & t < t_0 \\ \exp[-\kappa(t - t_0)], & t > t_0 \end{cases}$$

Smith, NASA OSTST 4/30/2004

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp[-t^2]\, dt$$

GS Brown, The average impulse response of a rough surface and its applications. IEEE Transactions on Antennas and Propagation, 25 (1), 1977, 67-74.

Physical retracker - Brown model

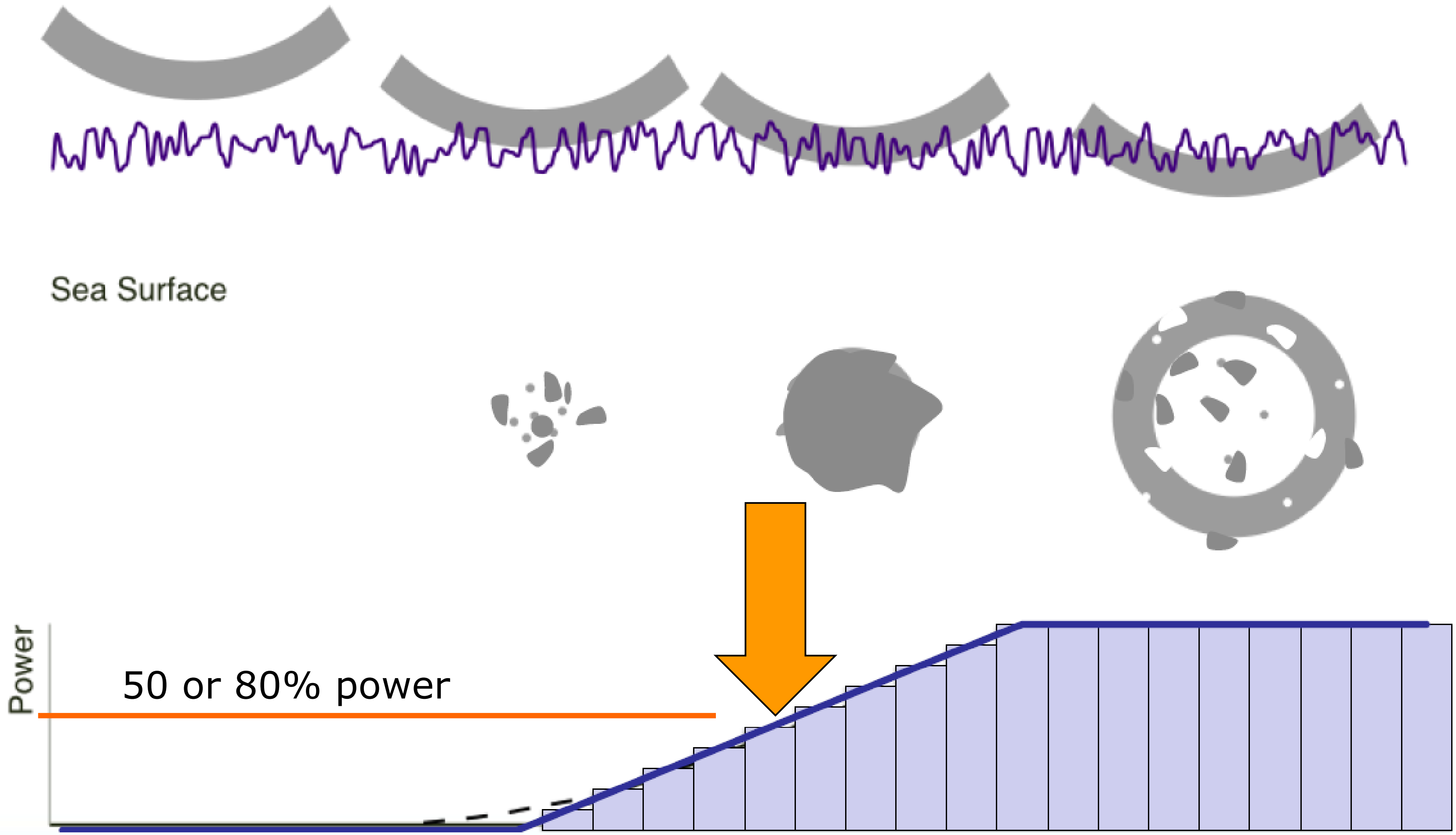
- A model to retrack ocean waveform. From this various parameters such as range and significant wave height can be derived.
- The Brown model is given by a three fold convolution

$$W(t) = P_{FS}(t) * q_s(t) * P_{TR}(t) \tag{1}$$

where

- $W(t)$ is the return power
- $P_{FS}(t)$ is the flat surface response
- $q_s(t)$ is the ocean surface elevation probability function of specular points.
- $P_{TR}(t)$ is the point target response

A simpler way to retracking if you are only interested in height



- **Want to find the Gate/Cell where the power exceeds a certain threshold (Threshold retracking)**

Threshold retracker

$$P_N = \frac{1}{5}\sum_{1}^{5} p_i \qquad (6)$$

$$T_h = P_N + q(A - P_N) \qquad (7)$$

$$G_r = G_{k-1} + \frac{T_h - P_{k-1}}{P_k - P_{k-1}} \qquad (8)$$

- p_i power if the i'th gate
- P_N Thermal noise
- T_h Threshold level
- q Threshold value e.g 50% (LRM) or 80% (SAR)
- A The MAX amplitude
- p_k is the power at the k'th gate, where k is the location of the first gate that exceeds T_h
- G_{k-1} The gate before the power exceeds T_h
- G_r The retracking gate

Measuring range from satellite.

Distances or range is measured using time.

Clocks can measure time to 10-^{12}s accuracy
If you measure two-way traveltime you only
Need ONE CLOCK. This is important

Have estimated Traveltime T via estimating the Δg decimal gate (1 gate = 3.12 ns).

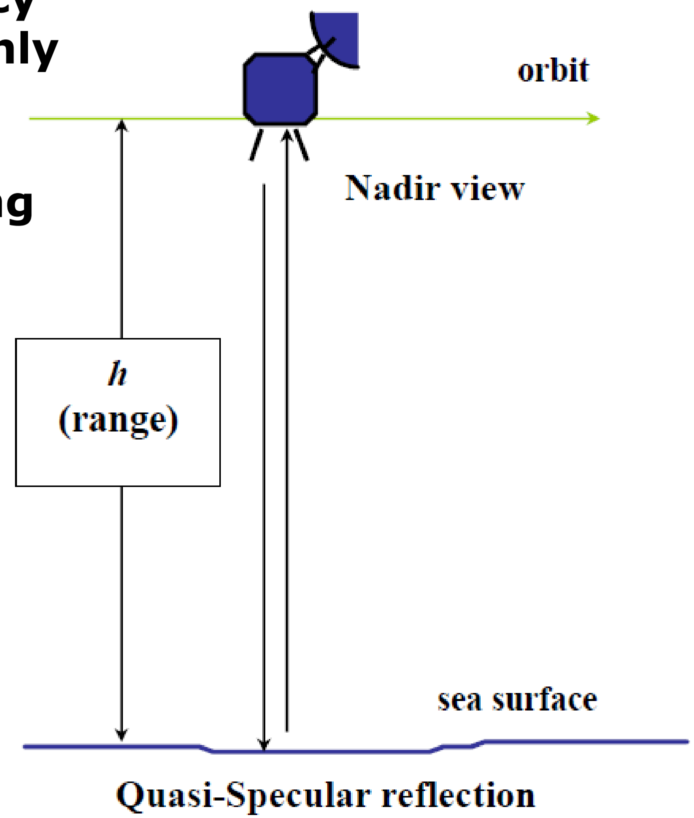
$T = \Delta g + T_{tracker}$

$T_{tracker}$ is time since emission of pulse

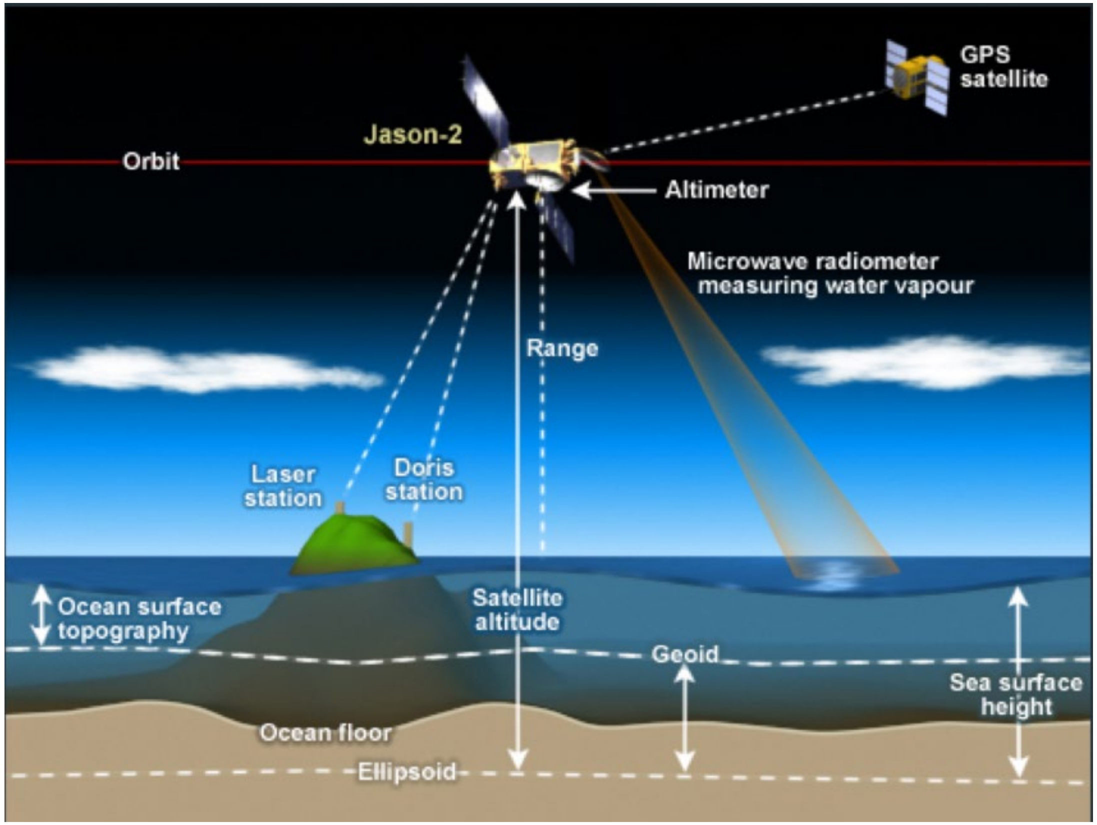
This is

h = c*T / 2 (back and forth).

$c = 3 \times 10^8$ m/s



Turning Range into Height



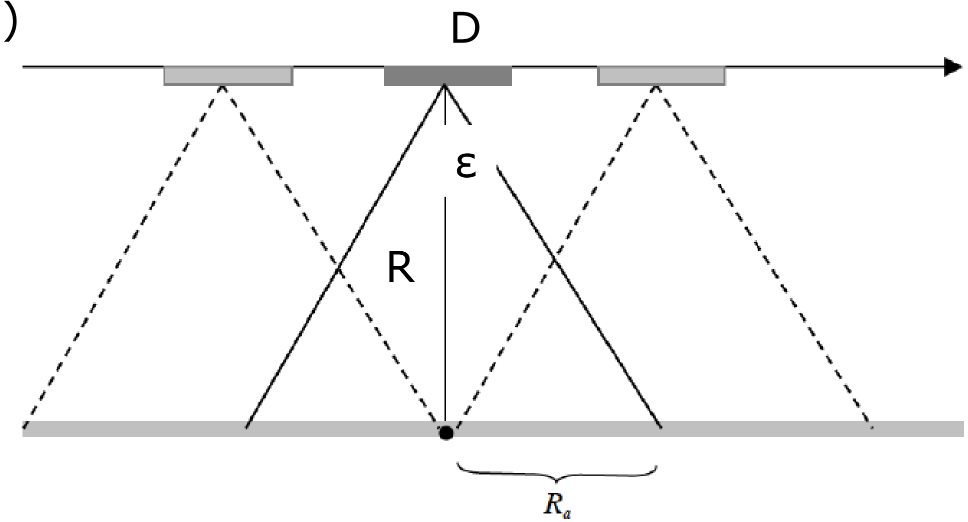
SSH = H – Range = H – c T /2

SSH will be relative to Reference Ellipsoid
as orbit height is relative to reference ellipsoid.

In principle RANGE precision is accurate to around 1 cm (SAR) 1-2 cm else.

Synthetic Aperture.

Azimutal resolution (Seeber 11.3)



$\varepsilon = \lambda/D$

$R_a = R \tan(\varepsilon) = R\,\varepsilon$

$R_a = R\,\lambda / D$

Length of illumination is $2\,R_a$

Assuming that scattere remains stationary while satellite passage.

"Syntetic Aperture" becomes equal to $2\,R_a$.
Hence $R_a^* = D / 2$

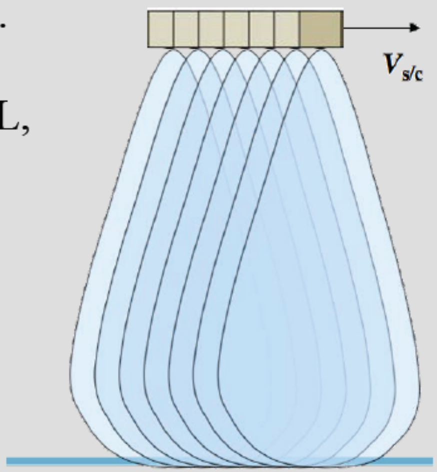
Observations from different "bursts" are separated using Delay Doppler.

Taking SAR to the limit. Fully Focused SAR-

- The main beam is 8 km in Radius, but if you use information from the side lobes the "total beam" can be considered to be much longer.

Conventional Altimeter

Image K. Raney, JHU/APL, TGARS, 1998

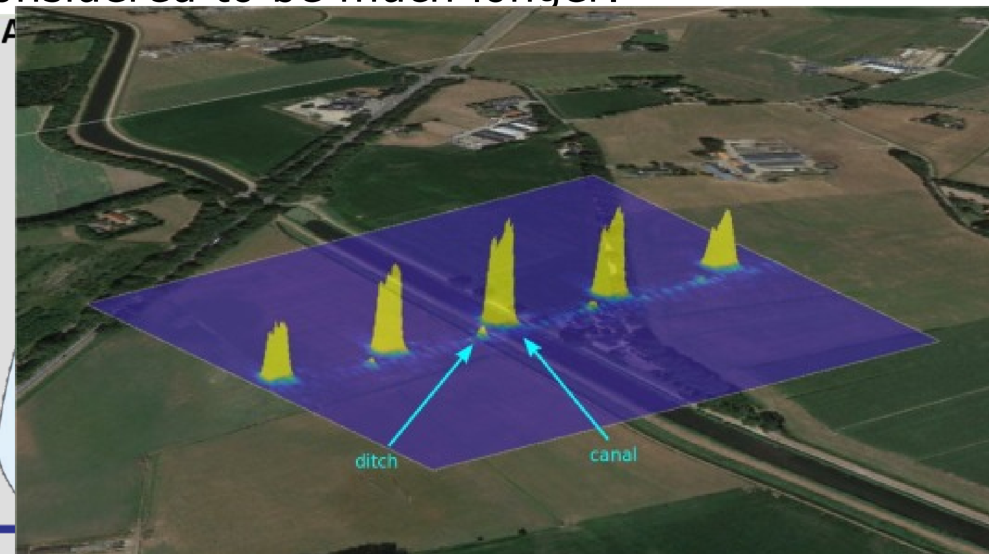


Low Resolution Mode
Pulse limited footprint (circular)
1.5 / 5 km res. depending on SWH
Open burst operation
PRF ~ 2 kHz

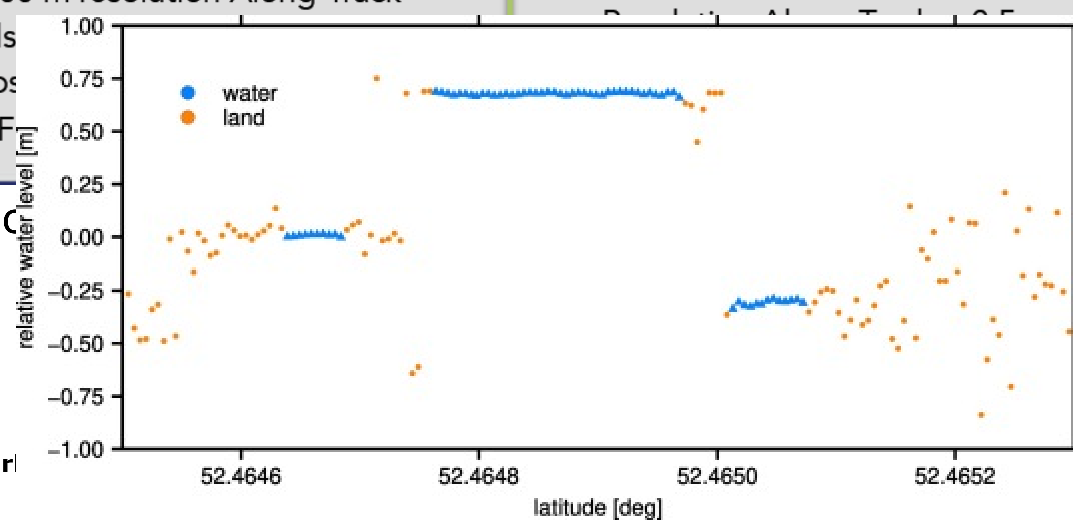
Delay-Doppler A

Image K. Raney, JHU/APL, TGARS, 1998

- Unfocused SAR processing
- ~300 m resolution Along-Track
- Puls
- Clos
- PRF



- Fully Focused SAR processing
  Coherent processing for ~2 seconds



- Target must be stable over 2 sec
- Ocean is NOT……..
- Inland water is…..

Content

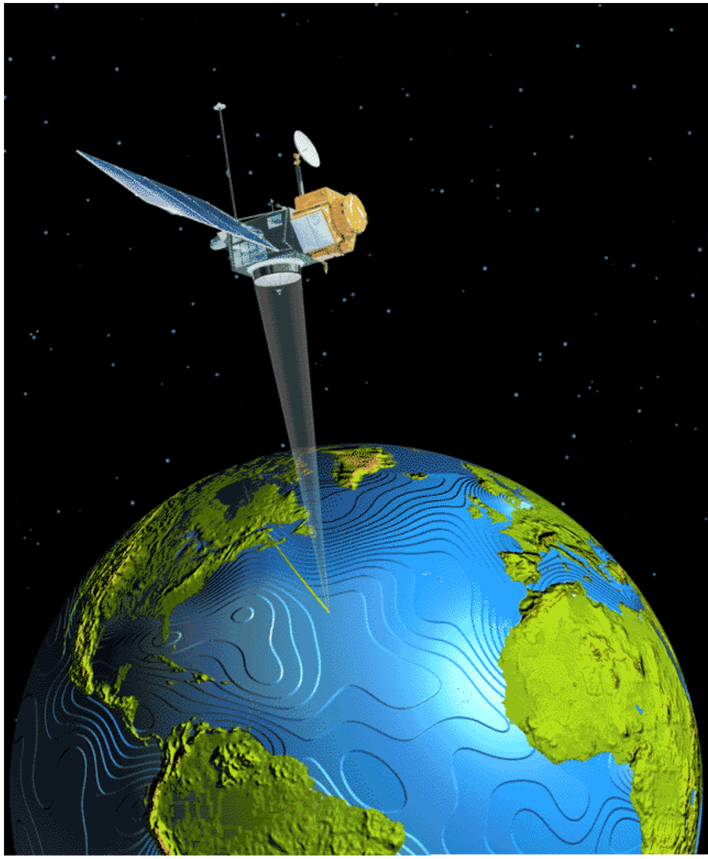
Rationale: Why and whats the benefits.

Principles: orbits
how does it work
Waveform analysis.

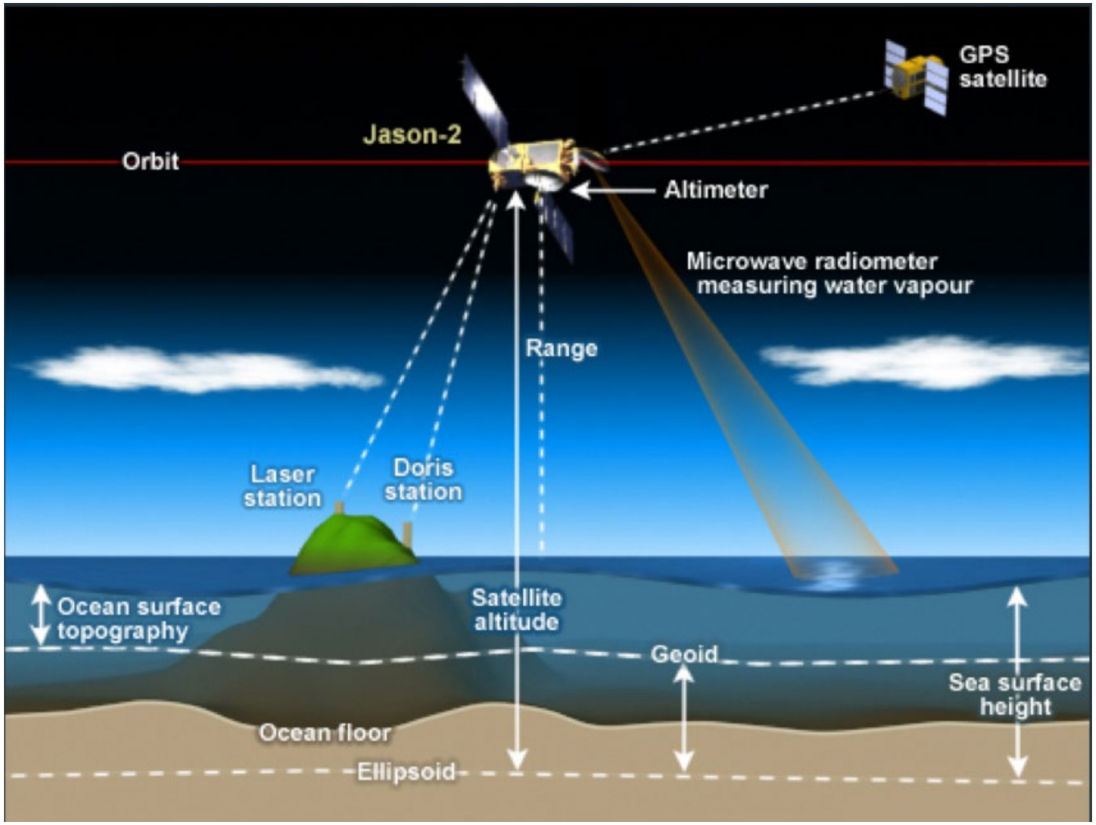
Corrections: how do we make it accurate

Geodetic: What parameters are extracted

Applications: Next time



Making it accurate



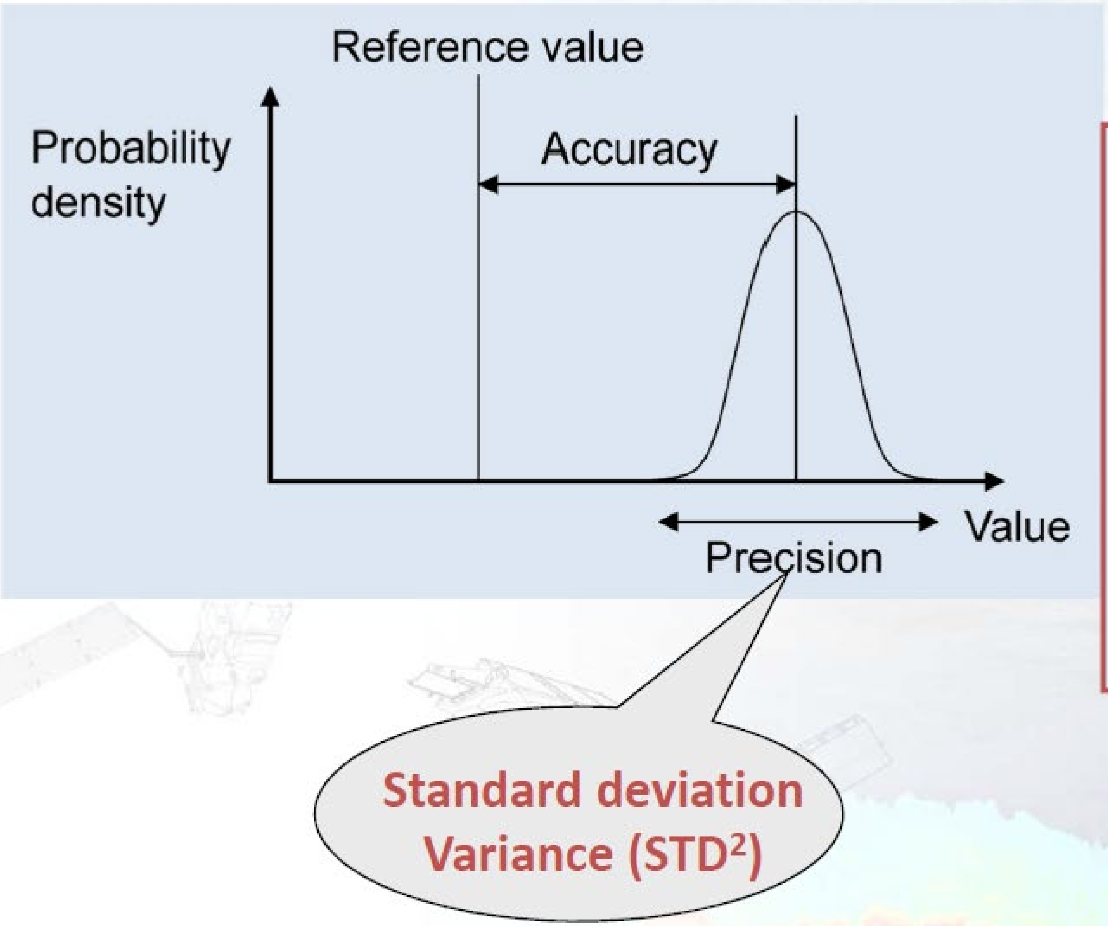
In principle RANGE precision is accurate to around 1-2 cm.

Orbit is precise to around 1 cm (using GPS etc).

So system determines SSH to a precision of sqrt(1+1) = 1.5 cm

But is this the "REAL ACCURACY"

Accuracy *vs* Precision

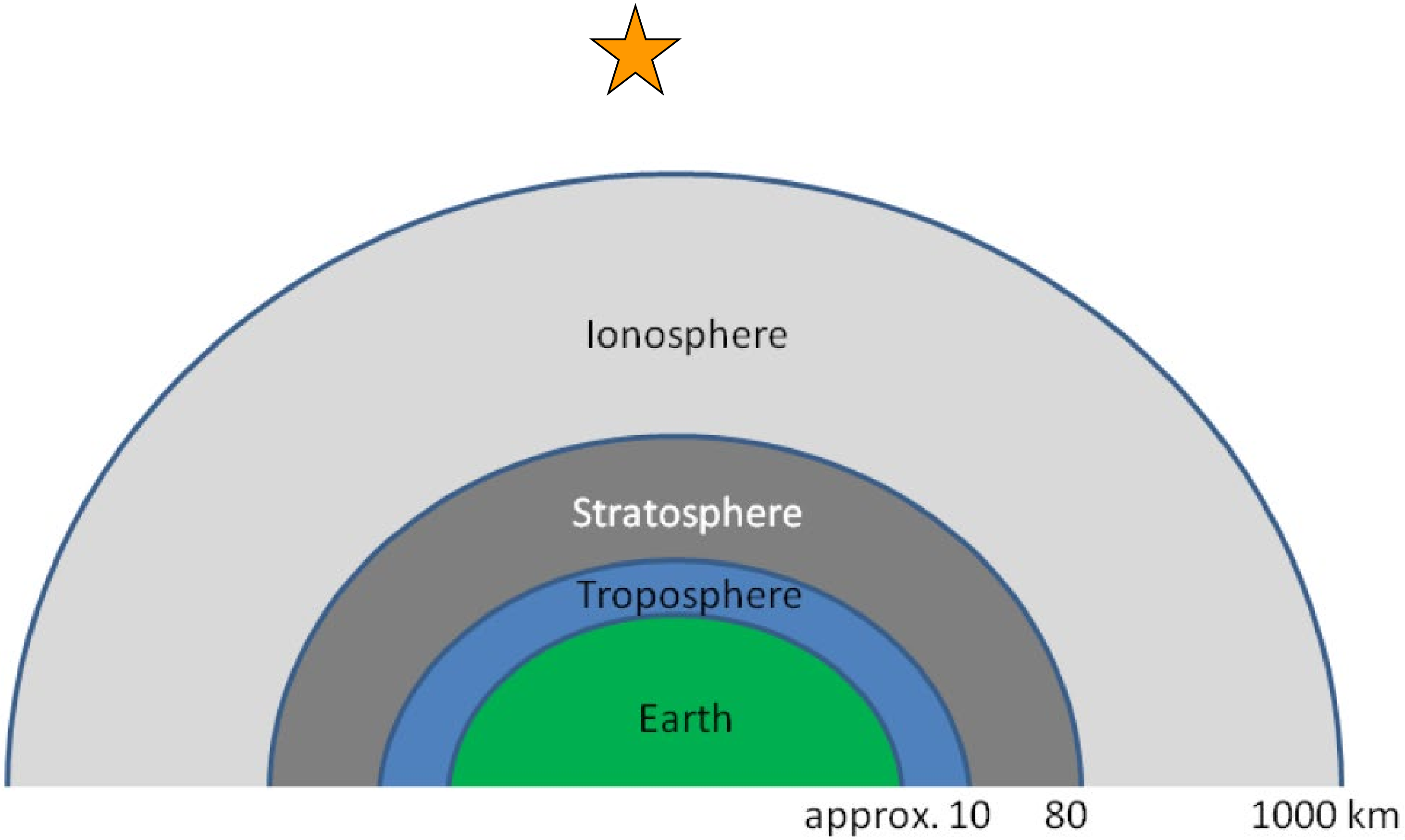


PRECISION
is determined primarily by radar design,
in contrast to Accuracy which depends on orbit knowledge and many delay corrections

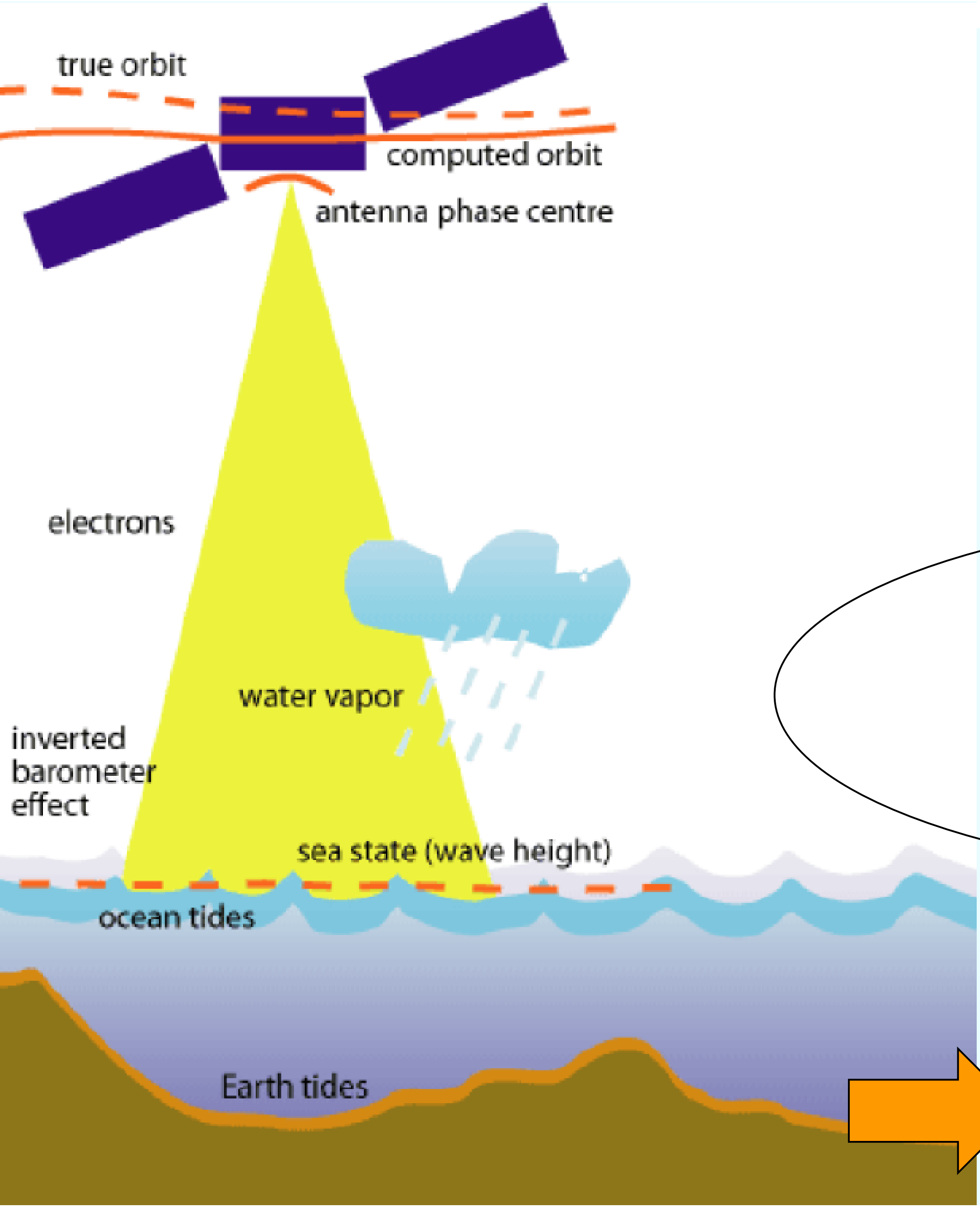
Atmosphere propagation

- is a problem for all Earth observing satellites and GPS.
- When we later determines distances between satellites in space this is not an issue. Hence this can be done much more accurate

Earth's atmosphere



Overview of range corrections



instrumental effects

- electronic time delay
- clock (oscillator) drift
- offset antenna phase centre
- centre of gravity
- time tagging of observations
- doppler shift error

atmospheric refraction due to

- ionosphere
- troposphere, dry component
- troposphere, wet component

target (ocean surface)

- ocean tides , loading effects,
- Earth tides, pole tide
- electromagnetic bias (sea state)
- inverted barometer effect

Modelling accuracy

- At sea level approximate size of zenith delay is:
  - 2.3 meter for dry delay
  - 0.05 - 0.2 meter for wet delay
- Generally the dry part is about 90% and the wet part is about 10% of the total zenith delay
- The dry part is modelled well; std. dev. < 5 mm for most models
- The wet part is more difficult to model; std. dev. 3-4 cm for the best models (e.g. Saastamoinen)

Range corrections

Measured range *R* needs to be corrected:

$$R_{cor} = R + \Delta R_{dry} + \Delta R_{wet} + \Delta R_{ion} + \Delta R_{ssb} + \Delta R_{instr}$$

ΔR_{dry} : delay of the pulse in the tropophere, dry component.
ΔR_{wet}: delay of the pulse in the troposphere, wet component
ΔR_{ion}: delay of the pulse in the ionopshere
ΔR_{ssb}: correction due to the presence of waves (sea state bias)
ΔR_{instr}: various instrumental corrections (electronic time delay, oscillator drift, ...)

The first 4 types of corrections are discussed in more detail.

The Corrections generally all have the effect of making the Range shorter (negative)
Hence the Sea surface SSH = H-Range will be higher.

Dry tropospheric range correction

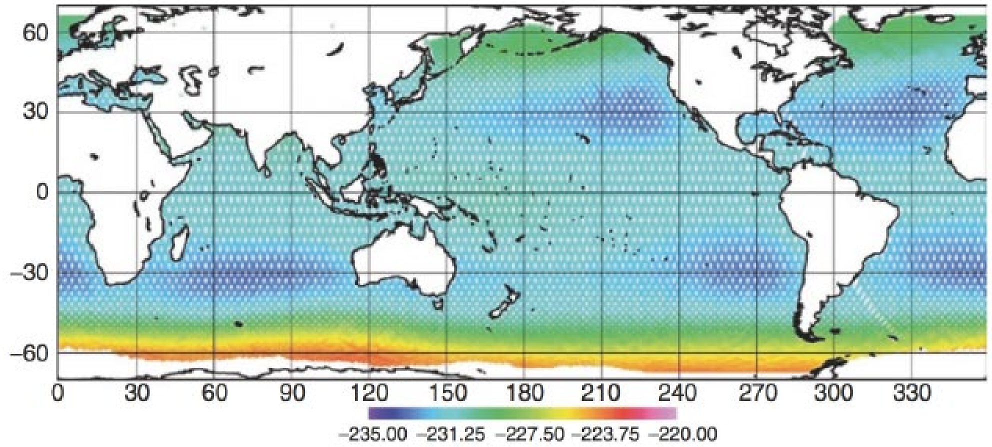
$$\Delta R_{\text{dry}} \approx -2.2768 P_0 (1 + 0.0026 \cos 2\varphi)$$

[mm] [mbar] geographic latitude

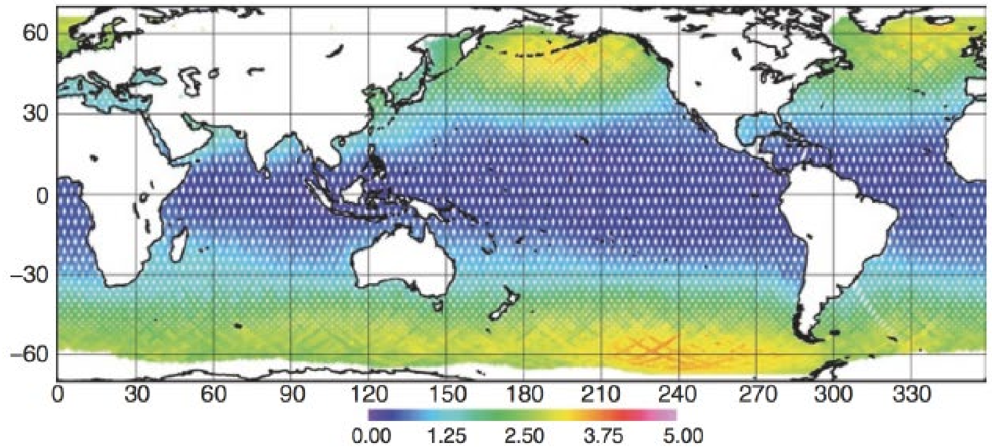
Dry air gasses in the troposphere (not water vapor) cause a path delay

- Path delay is proportional to the surface atmospheric pressure P_0 (980 ... 1035 mbar), does slightly depend on latitude, but does not depend on the frequency of the electromagnetic wave (non-dispersive).
- Order of magnitude ~ 2.3 m, SD = 0.03 m (little spatial-temporal variation).
- Error of 1 mbar in surface pressure causes 2 mm error in range correction
- Path delay is computed using global meteorological models
  - Operational: ECMWF (~16 km x 6 hours) (changes regularly)
  - Operational: NOAA/NCEP (2.5º x 1.25º x 6 hours) (stable for many yrs)
  - Reanalysis: ERA Interim (~76 km x 6 hours)

Dry tropospheric range correction



6-year mean (cm)



SD (cm)

After Andersen and Scharroo, 2011

Wet tropospheric range correction

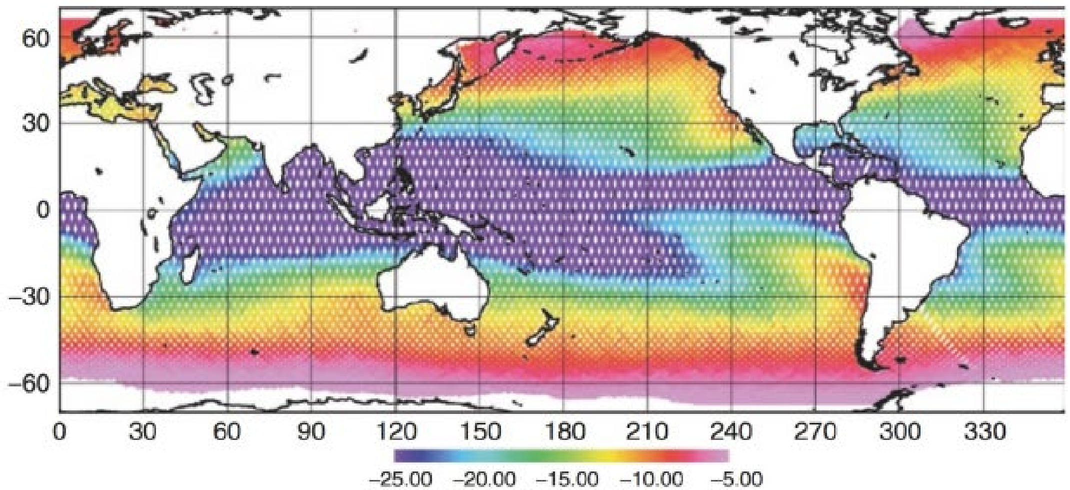
$$\Delta R_{\text{wet}} \approx -6.36 \text{ IWV}$$

[mm] [kg/m²]

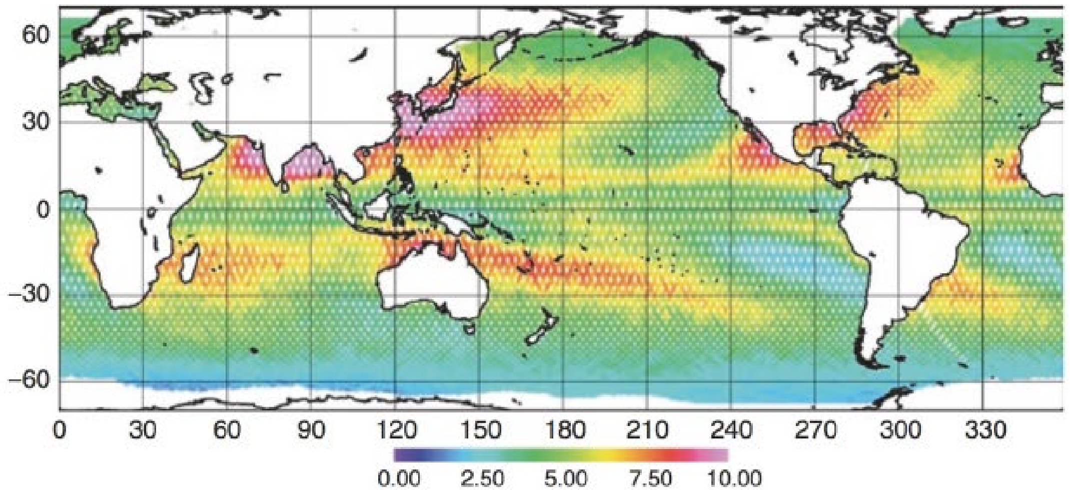
Water vapor in the troposphere causes a path delay

- The path delay is proportional to the vertically integrated water vapor (IWV) measured in kg/m^2; there is also a slight dependency on temperature, but no dependency on the radio frequency.
- Order of magnitude: 5-35 cm; average value ~ 0.15 m, SD ~ 0.05 m; accuracy of correction ~ 0.01-0.02 m
- Based on measurements or global meteorological models
  - On-board Microwave Radiometer (MWR)
  - Operational model: ECMWF (~16 km x 6 hours) (changes regularly)
  - Operational model: NOAA/NCEP (2.5º x 1.25º x 6 hours) (stable for many yrs)
  - Reanalysis model: ERA Interim (~76 km x 6 hours)
- Accuracy of the computed path delay is limited due to the high spatial-temporal variability of water vapor

Wet tropospheric correction



6-year mean (cm)



std.dev. (cm)

After Andersen and Scharroo, 2011

Ionospheric range correction

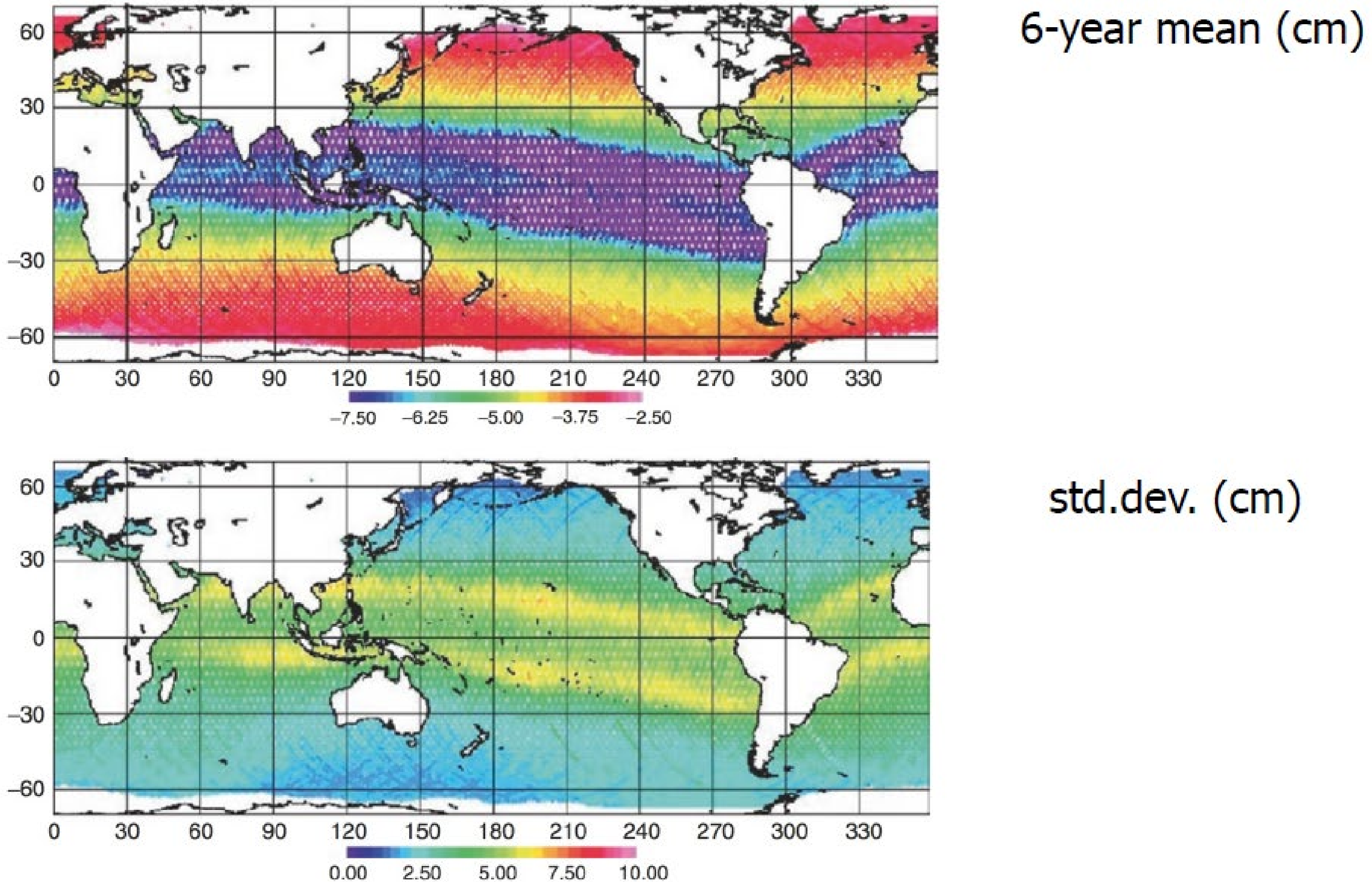
$$\Delta R_{ion} = -40250 \frac{\mathrm{TEC}}{f^2}$$

[mm]

Charged particles in the ionosphere (50-2000 km altitude) cause a path delay

- The delay is proportional to total number of free electrons in a column of unit cross section (1 m^2) = TEC (unit 1 TECU = 10^{16} electrons/m^2) and inverse proportional to the square of the radio frequency (in Hz)
- The delay also depends on solar cycle (diurnal, seasonal, sunspot cycle) and geographic location; it is largest at the electromagnetic equator, at ~14:00 local time; there is a slight dependency on the altitude of the satellite (ionosphere above the satellite)
- Order of magnitude: 2-20 cm
- Average value ~ 0.045 m, SD ~ 0.035 m
- Path delay is computed using global TEC measurements or models
  - Dual-frequency altimeters: Ku- and C-/S-band (TOPEX, Jason, Envisat)
  - Operational model: JPL GIM (5º x 2.5º x 2 hours), based on GNSS

Ionospheric correction



After Andersen and Scharroo, 2011

Atmospheric range corrections – summary

–Ionospheric correction: 2-20 cm [+/- 3 cm]

Caused by presence of free electrons in the ionosphere

Use model or measure using dual frequency altimeter

–Dry tropospheric correction: 2.3 m [+/- 1-2 cm]

Caused by oxygen molecules

Model the correction accurately using surface atmospheric pressure

–Wet tropospheric correction: 5-35 cm [+/- 3-6 cm]

Caused by clouds and rain (variable)

Measure H_2O with microwave radiometer

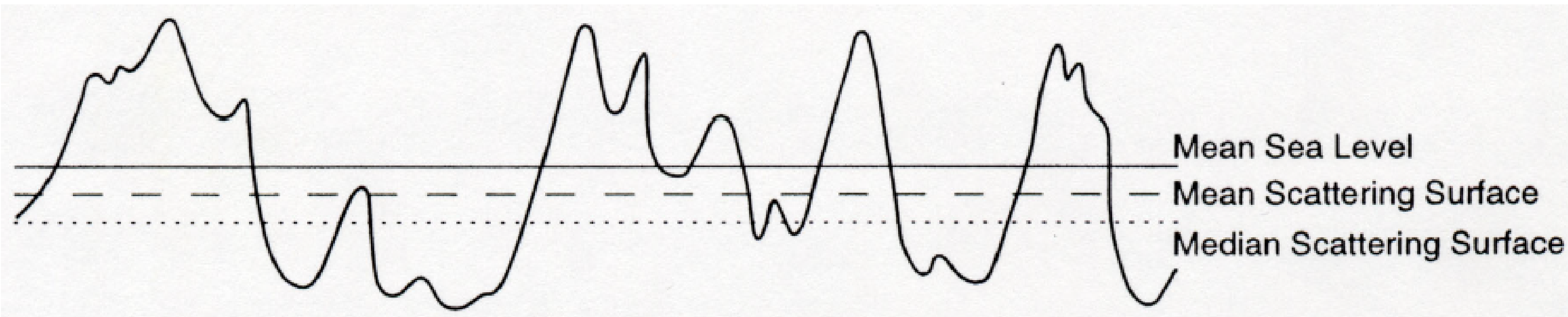
Or use weather model predictions

Sea state bias (SSB) correction

$$\Delta R_{\mathrm{SSB}} = f(\mathrm{SWH}, U)$$

- The onboard tracker determines the two-way travel time from the half power point of the waveform. In the presence of waves, this half power point corresponds to the range to the median scattering surface. However, one wants the range to the mean sea surface. The difference between the two surfaces is the SSB. The SSB is the largest remaining error in altimeter-based mean sea level estimates. The SSB consists of two components:
  - **Electromagnetic bias (EMB):** wave troughs (they are parabolic) backscatter more power per unit area than wave crests (have smaller radius of curvature). This moves the mean scattering surface below the mean sea surface (range is biased towards the troughs). The distance between mean scattering surface and mean sea surface is the EMB.
  - **Skewness bias (SB):** the onboard tracker determines the two-way travel time from the half power point of the waveform. The associated range refers to the **median** scattering surface. Since the waves follow a Rayleigh distribution and the skewness of that distribution is positive, the median scattering surface is below the mean scattering surface. The distance between the two surfaces is the SB.

Sea state bias (SSB) correction



- Sea state bias models:
- Empirical 4-parameter model, e.g., Gaspar et al (1994), JGR 99, 24981-

$$\mathrm{SSB} = \mathrm{SWH}\left(a_0 + a_1 U + a_2 U^2 + a_3\,\mathrm{SWH}\right)$$

- Non-parametric models, e.g.,
  - SSB = tabulated function of U and SWH

- Empirical estimates of SSB corrections are assumed to have 1% error.
- No SSB correction models yet available for delay-Doppler altimeters.

How accurate is it.
The Error budget (Jason-3).

Now SSH = H – Range(corrected) is as accurate as it get.

Source of Error	Error Budget (cm)
Altimeter noise	1.5
Ionosphere	0.5
Electromagnetic Bias	1.0
Tracker Bias	0.2
Skewness	0.2
Dry Troposphere	0.7
Wet Troposphere	1.0
Altimeter range Root-Sum-Square	**2.25**
RMS Orbit	1.0
Total RSS Sea Surface Height	**2.5**
Significant Wave Height	25.0
Wind Speed	1.5 m/s
Sigma 0	0.5 dB

Content

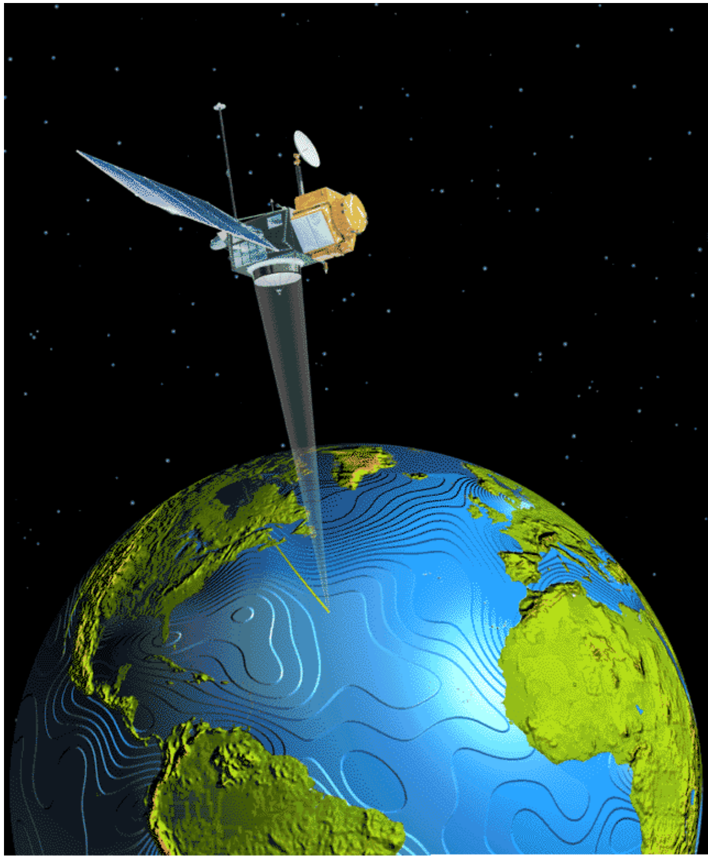
Rationale: Why and whats the benefits.

Principles: how does it work
Waveform analysis.
orbits

Corrections: how do we make it accurate

Geodetic: What parameters are extracted

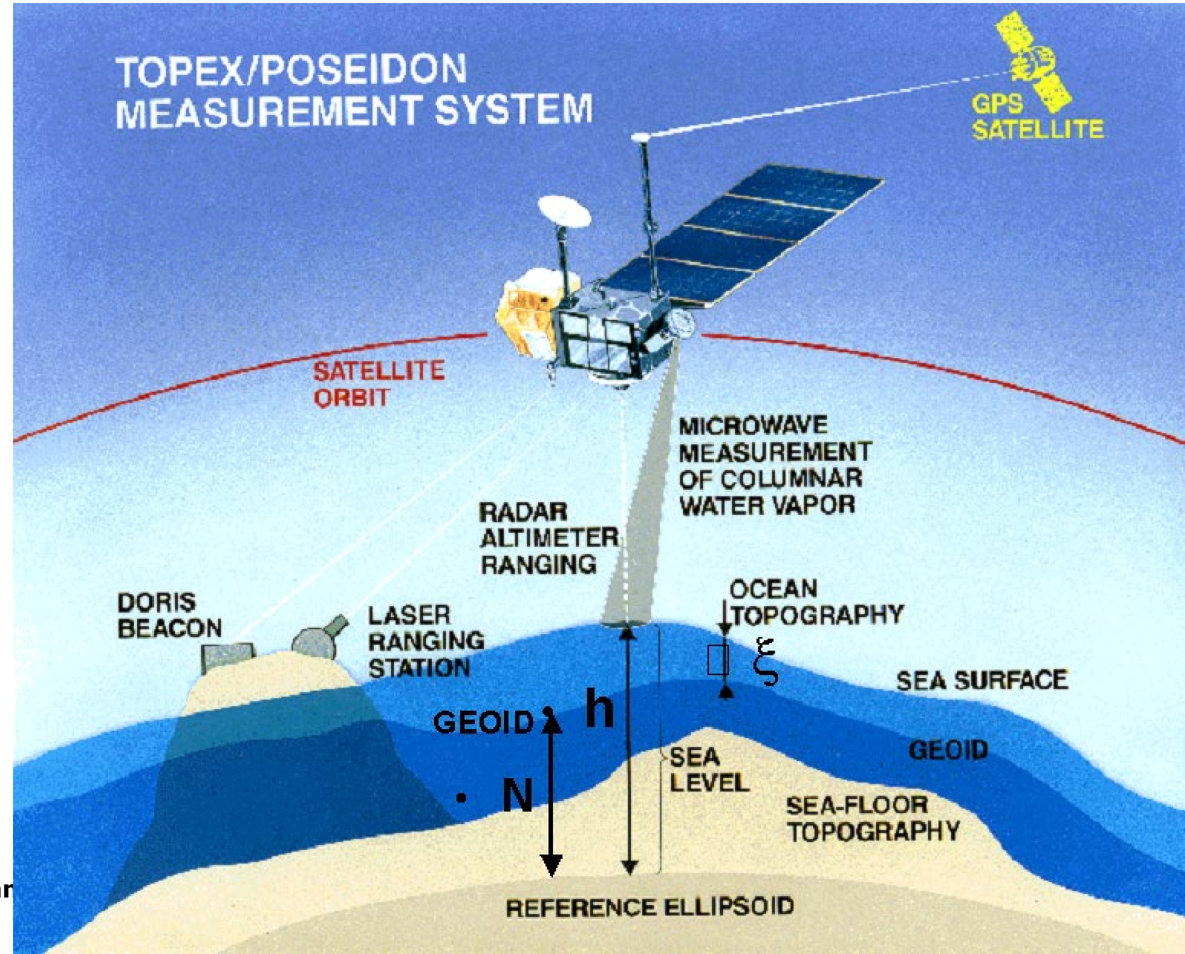
Applications: Next time



Satellite altimetry observes sea level, SWH and wind speed.

Sea Level is key-parameter for geodesy

Sea level is made up from a mean sea level (mean shape of the Earth) + dynamic sea level ξ(t).

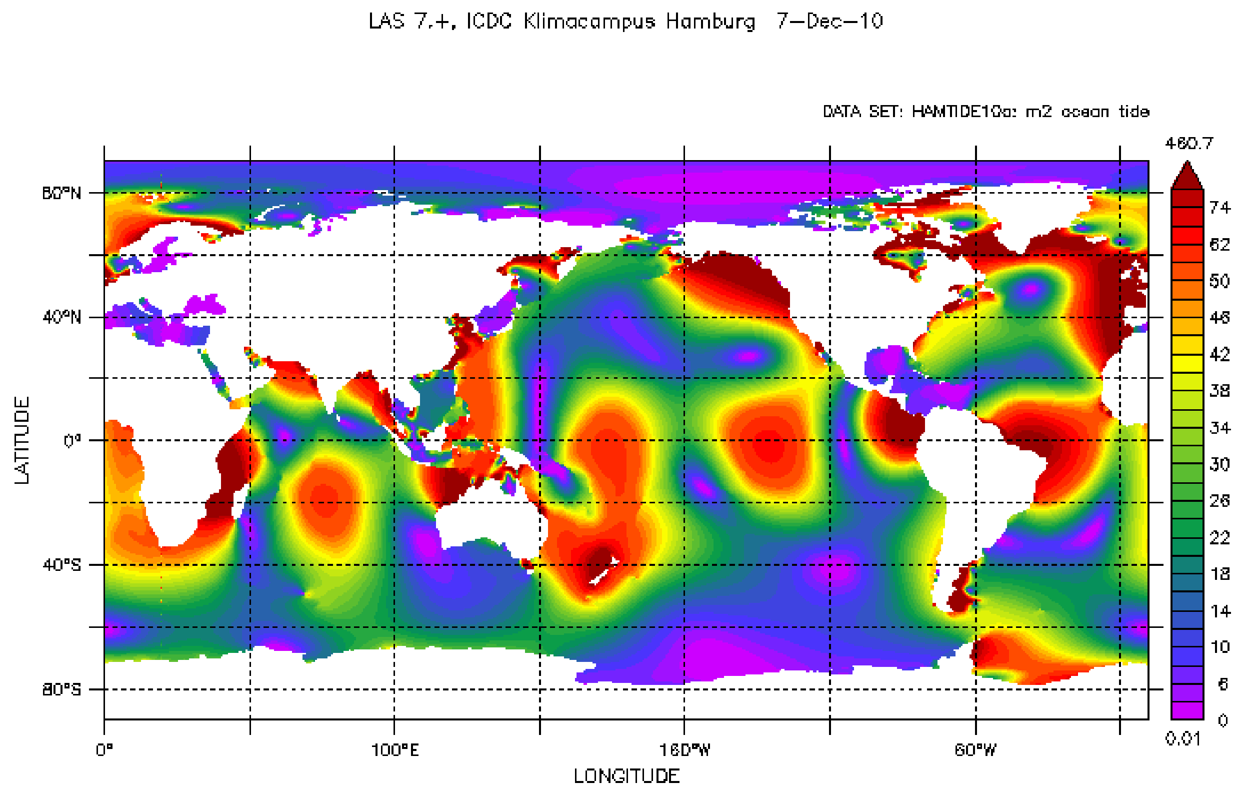


Sea level variations.

More than 70% of sea level variations are caused by ocean tides………
(more to come in later lecture).

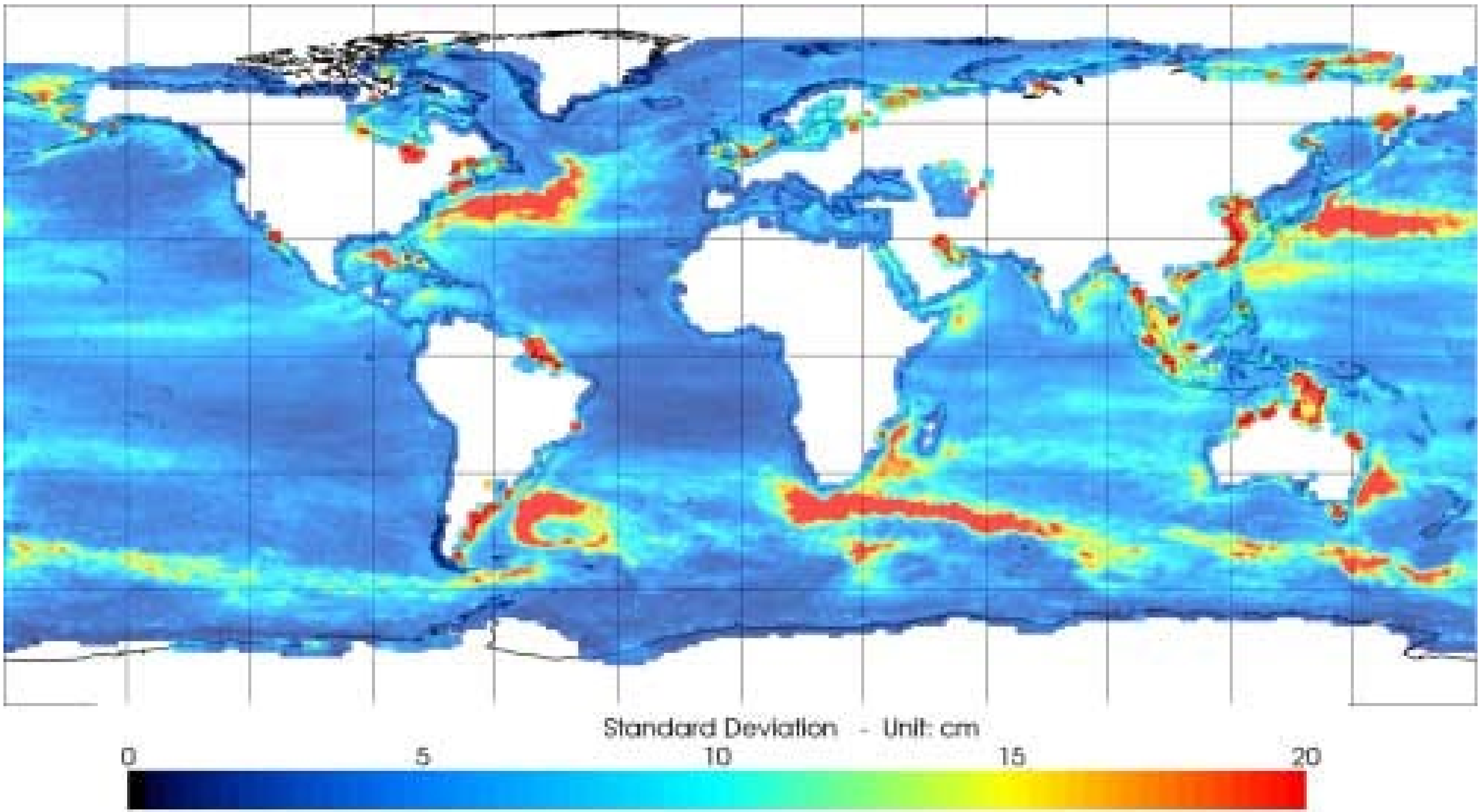
We can remove contribution to se "what is hidden in the signal".

Sea level change on the mm/year is possible from averaging thousands of sea surface observations over 1 month of observations (Later lecture).

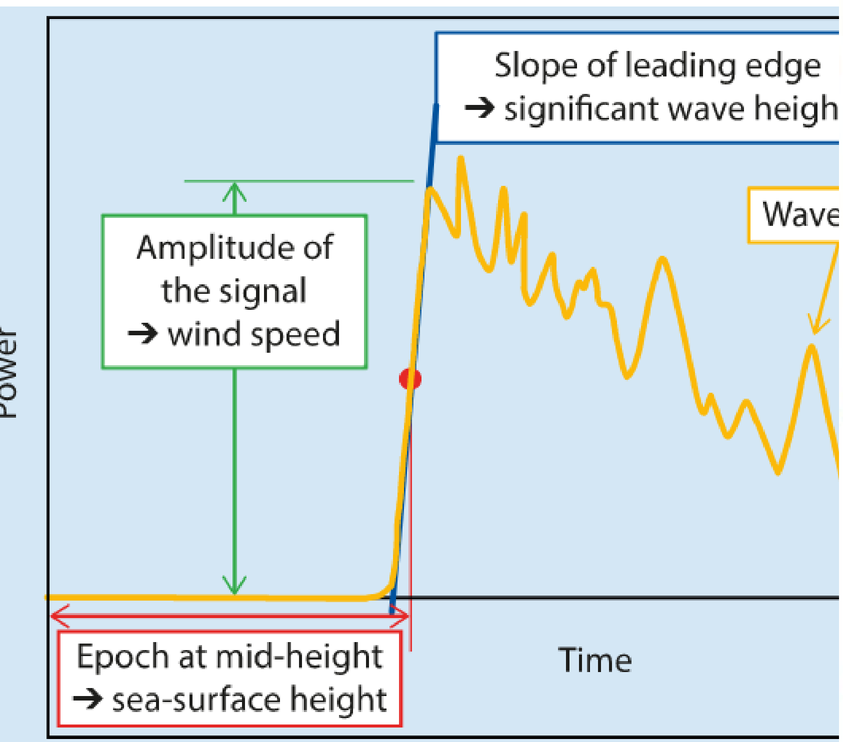


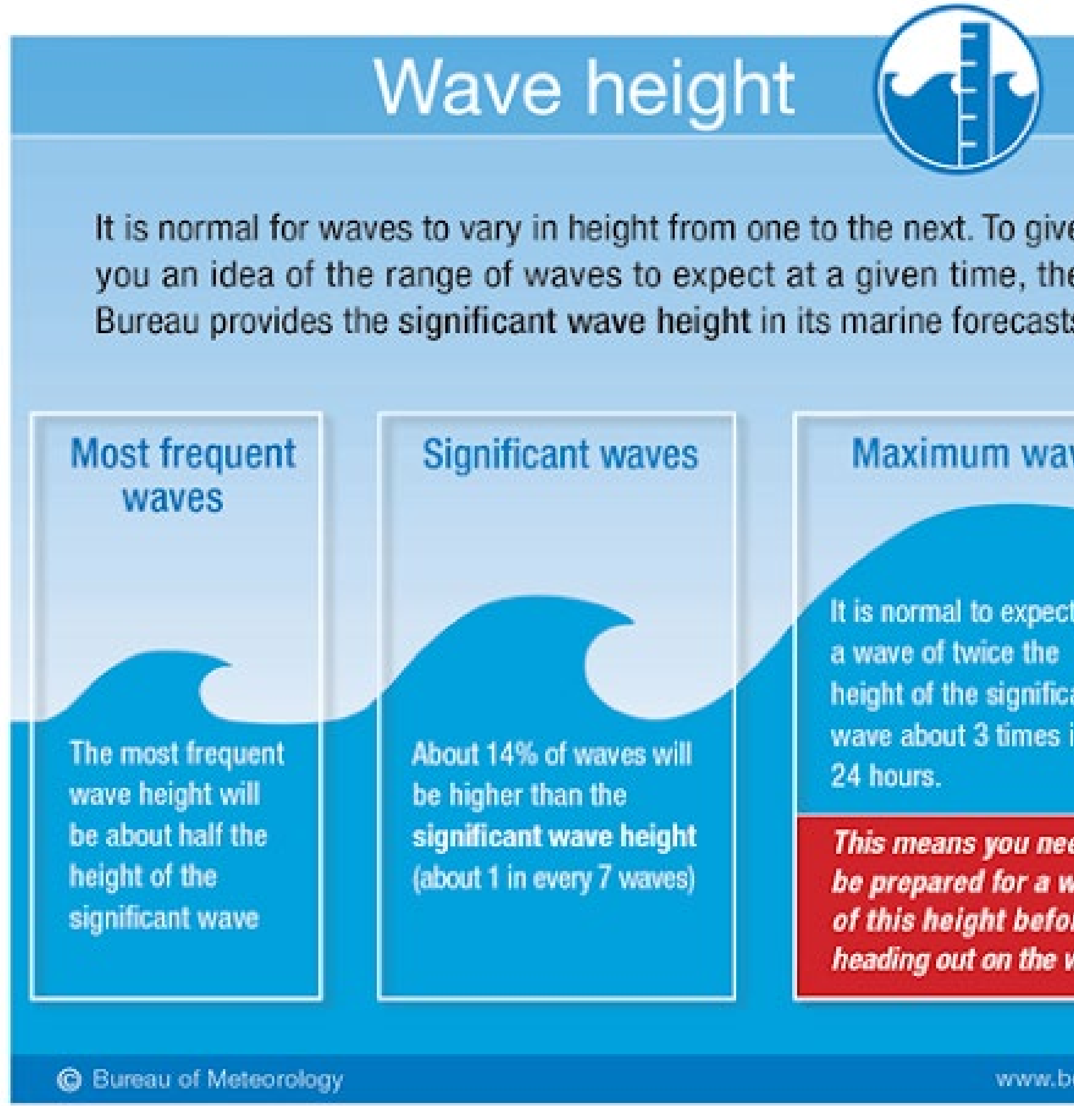
m2 Amplitude (cm)

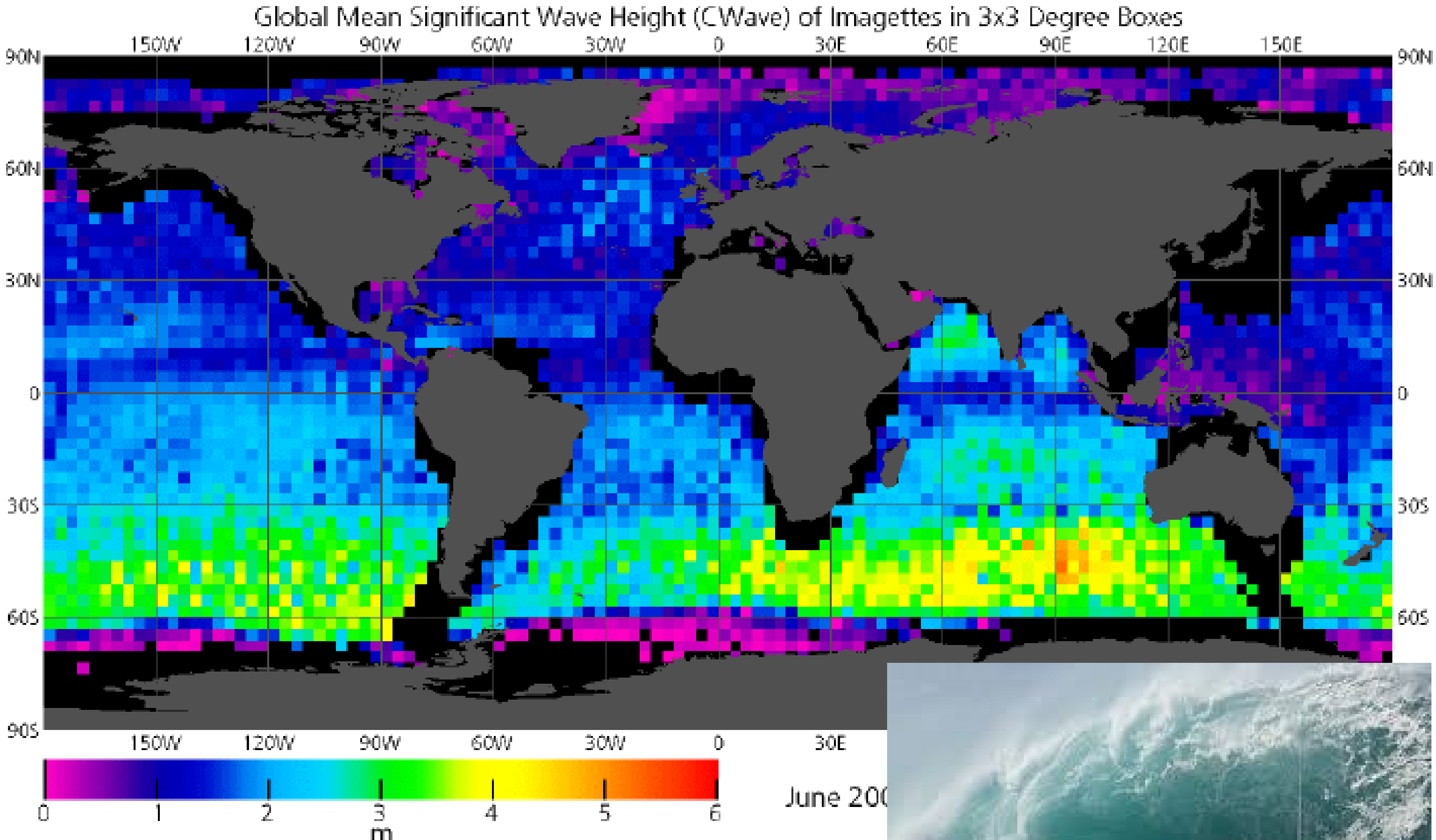
Variability – why we need the 10 cm accuracy



Significant wave height

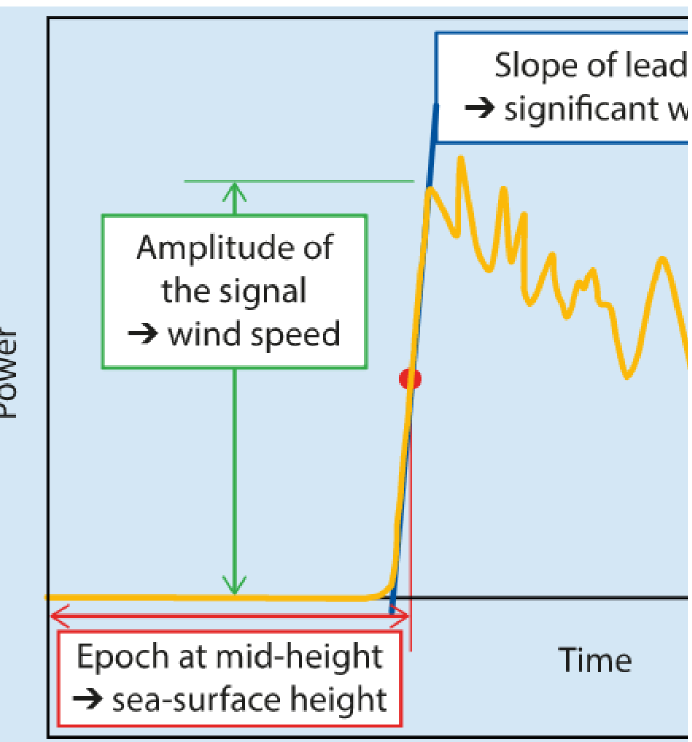


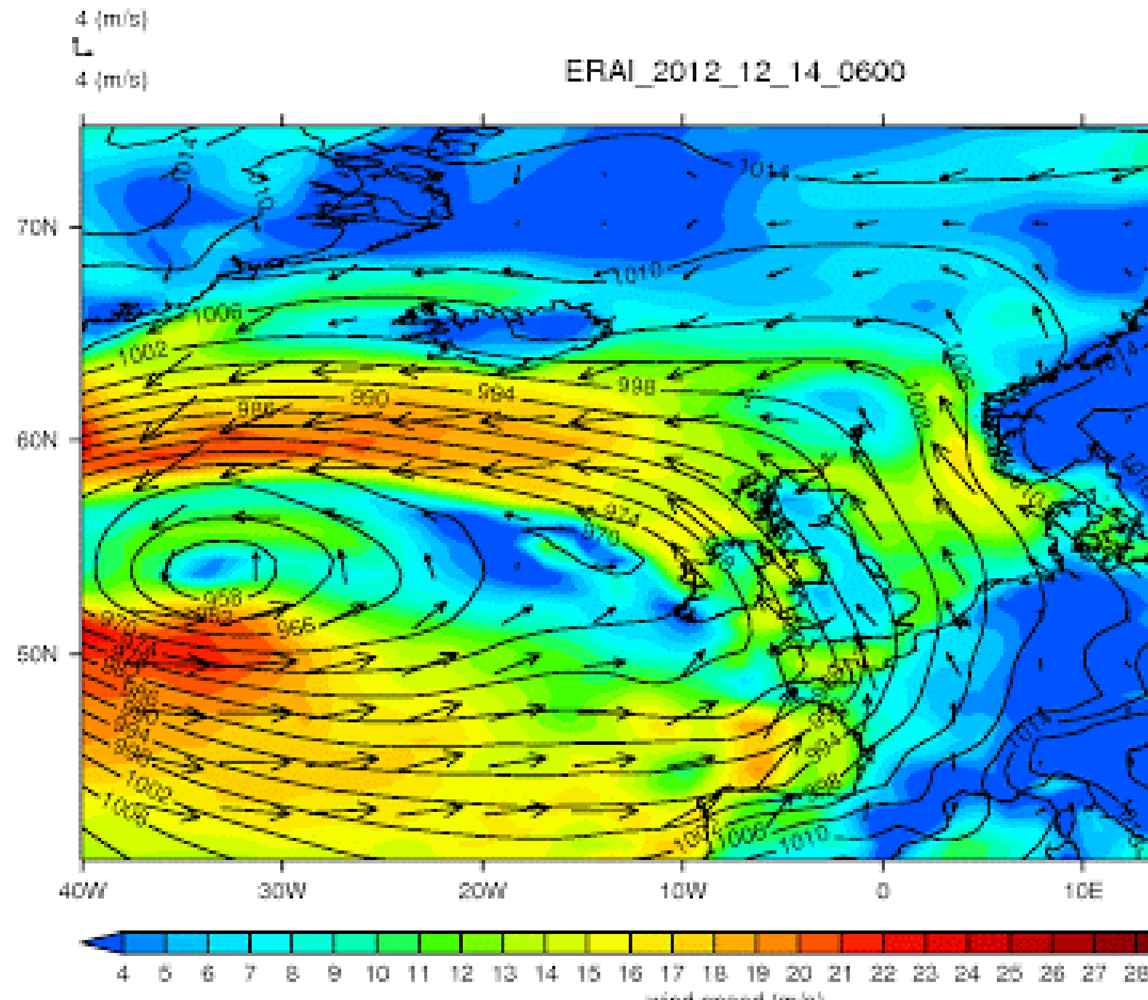



Global Mean Significant Wave Height (CWave) of Imagettes in 3x3 Degree Boxes
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
90N
60N
30N
0
30S
60S
90S
0
1
2
3
4
5
6
m

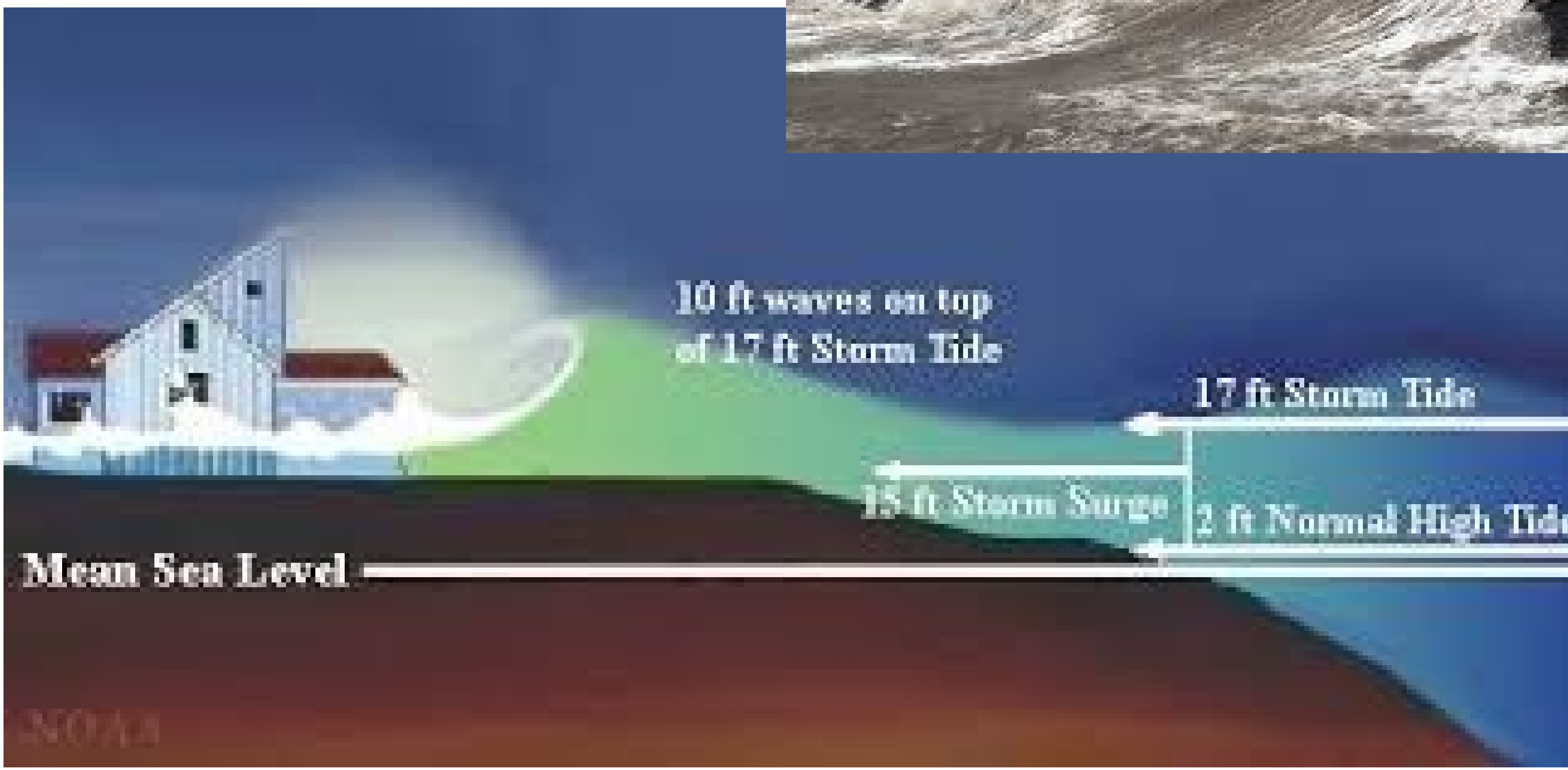
Wind speed

- But No direction....





Storm surges



End of Today.

Back up slides.

Two types of altimeters:

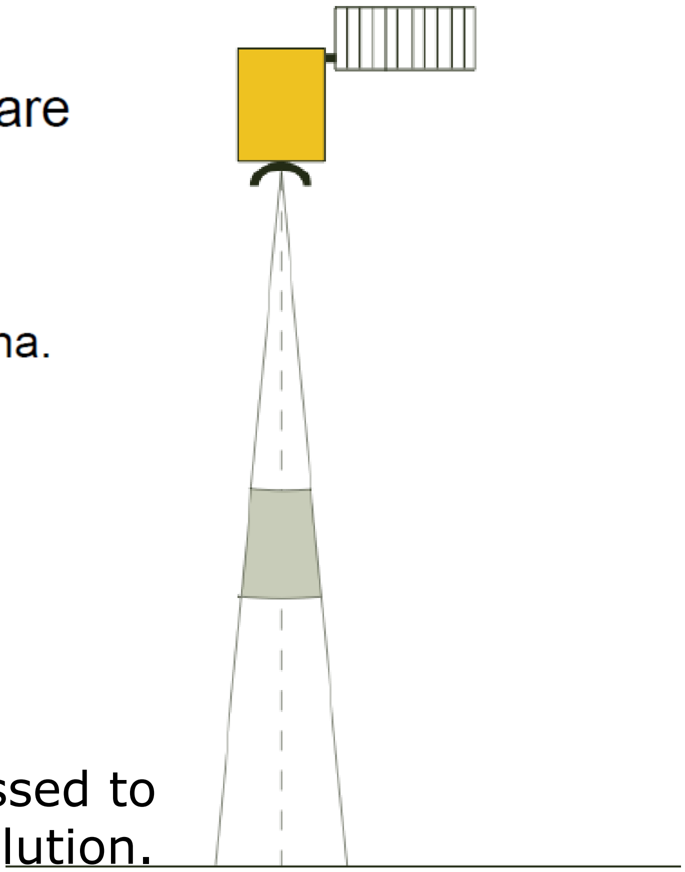
- **Beam limited (typical lasers)**

- **Pulse limited (typical radars)**

- **Course on measurement technology on ESPE gives many more technical details**

Beam limited (constant beam).

- Narrow beams require very large antennae and are impractical in space
  - For a **5 km** footprint a beam width of about **0.3°** is required.
  - For a 13.6 GHz altimeter this would imply a **5 m** antenna.
- Even more important: highly sensitivity to mispointing, which affects both amplitude and measured range



Beam limited Radars are the fundament of SAR Syntetic Aperture Radars where data are processed to Increase “antenna” or aperture to increase resolution.