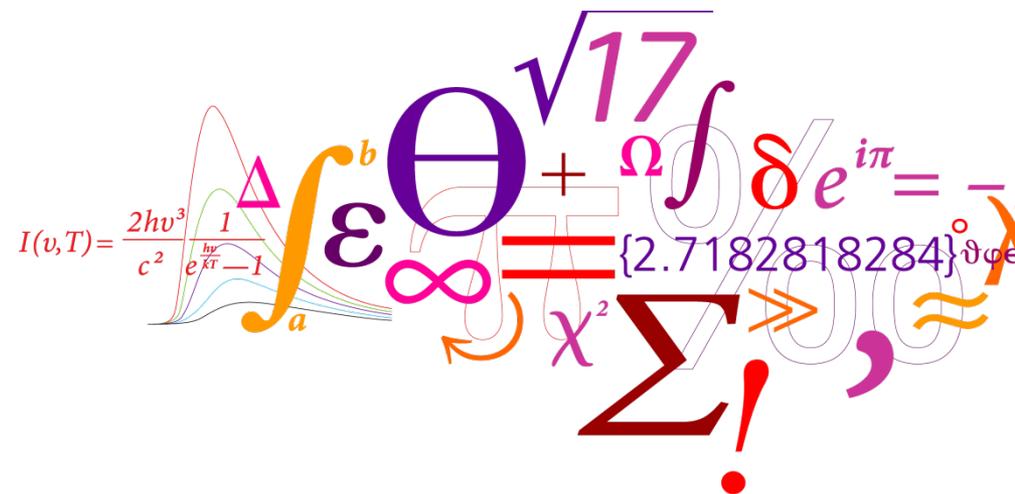


Altimetry theory

Louise Sandberg Sørensen

Senior scientist, Geodynamics, DTU Space, DK

slss@space.dtu.dk



What is an altimeter?

What can they be used for (some nice examples - no details, just introductory for overview).

What is a waveform?

Laser versus radar altimetry

Examples of waveforms from different surfaces

What is a retracker? (not details on individual retrackers)

Corrections (slope, waveform parameters)

What is an altimeter?

What is an altimeter?

altus (latin) - height

metron (greek) – to measure

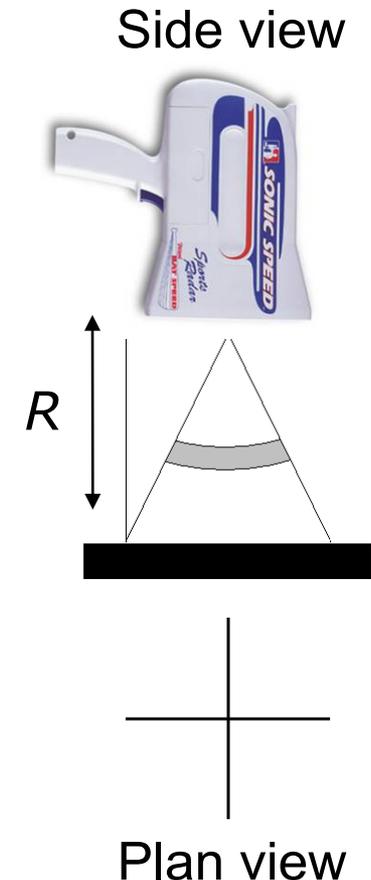
An altimeter is an instrument to measure height, altitude or elevation.

The range altimeter measures the two-way travel time of a signal with a known velocity:

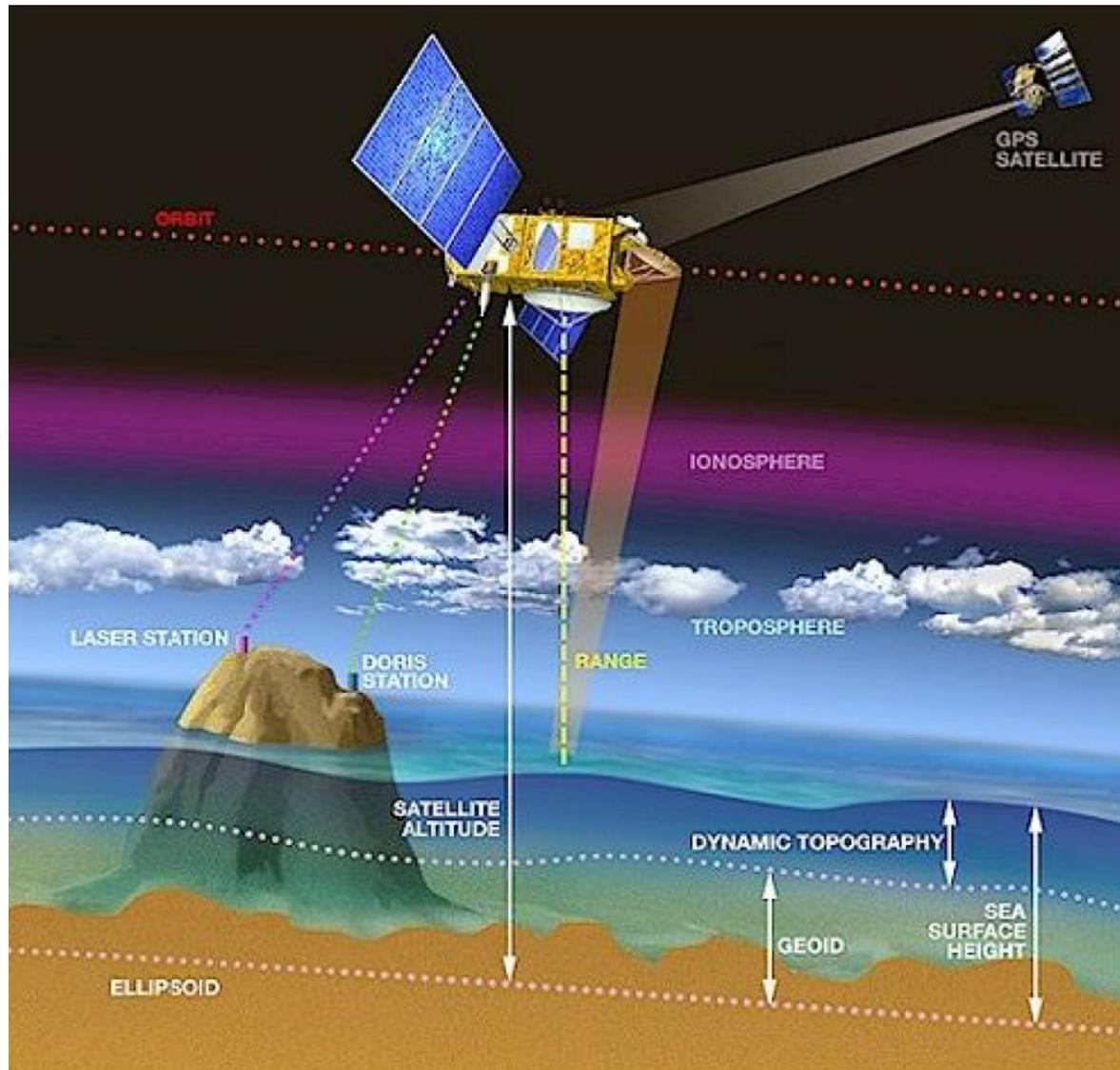
$$\text{distance} = \text{velocity} * \text{TWT} / 2$$

Principle of satellite altimetry

- (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.



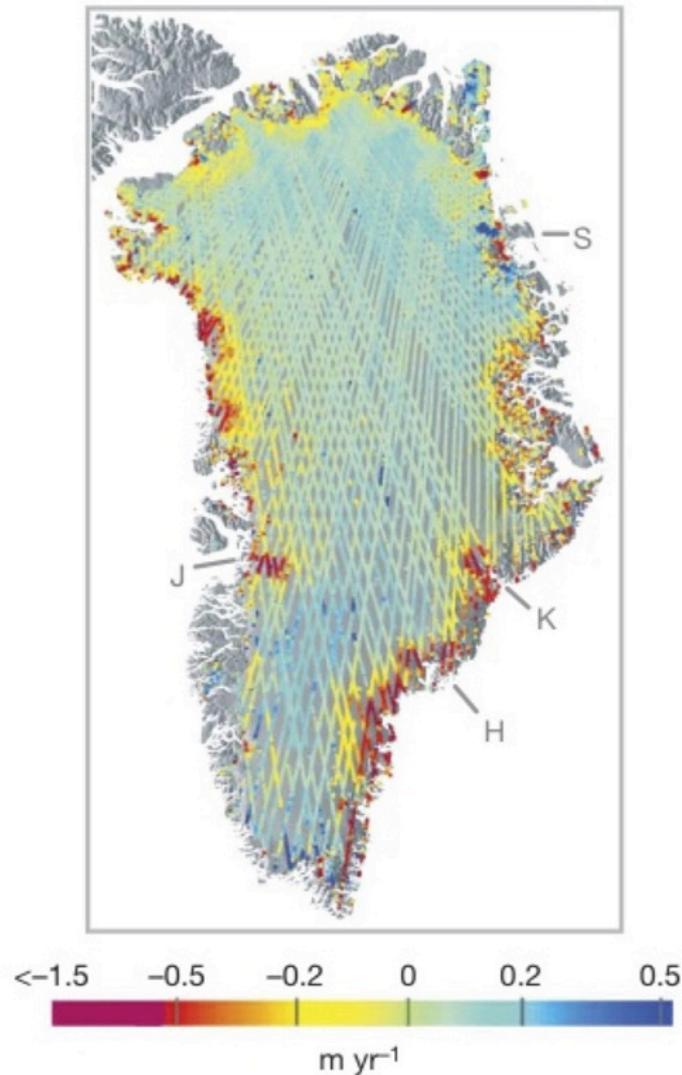
Principle of satellite altimetry



(Credits CNES/D. Ducros)

What can we observe with satellite altimeters?

Altimeters for studying the cryosphere

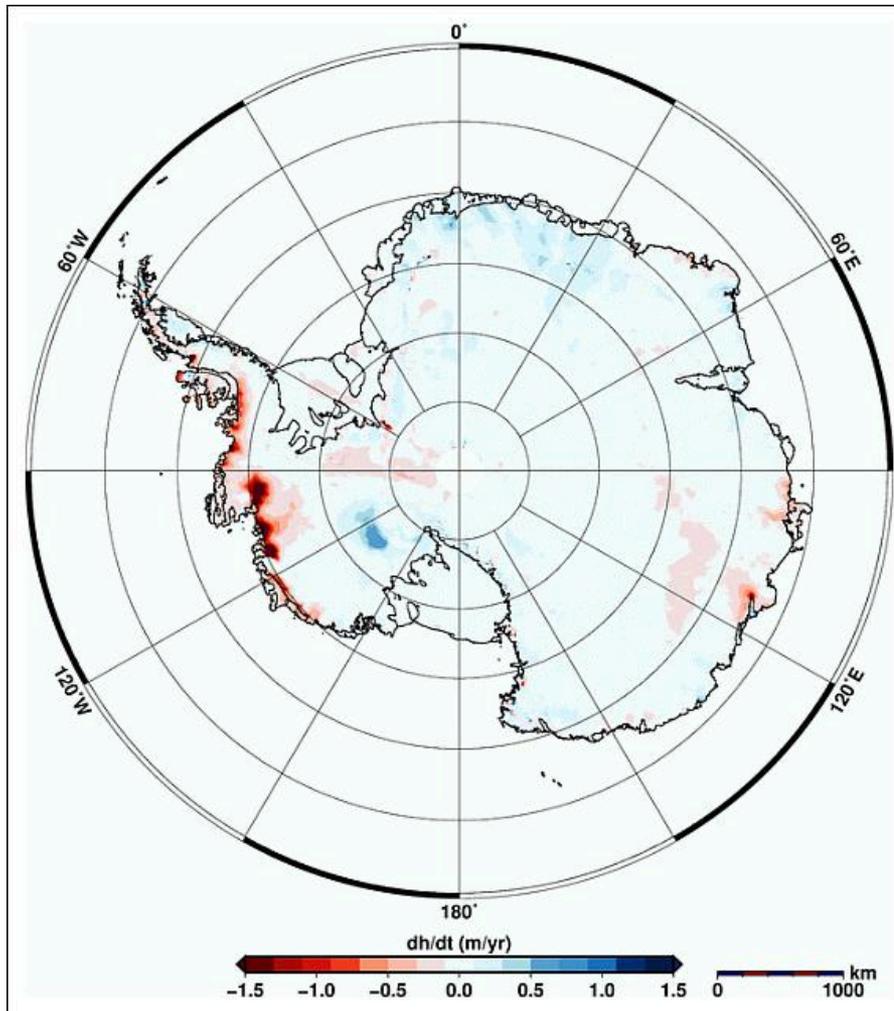


Elevation changes of the Greenland ice sheet.

Derived from ICESat data 2003-08.

(credits: Pritchard et al., Nature, 2009)

Altimeters for studying the cryosphere

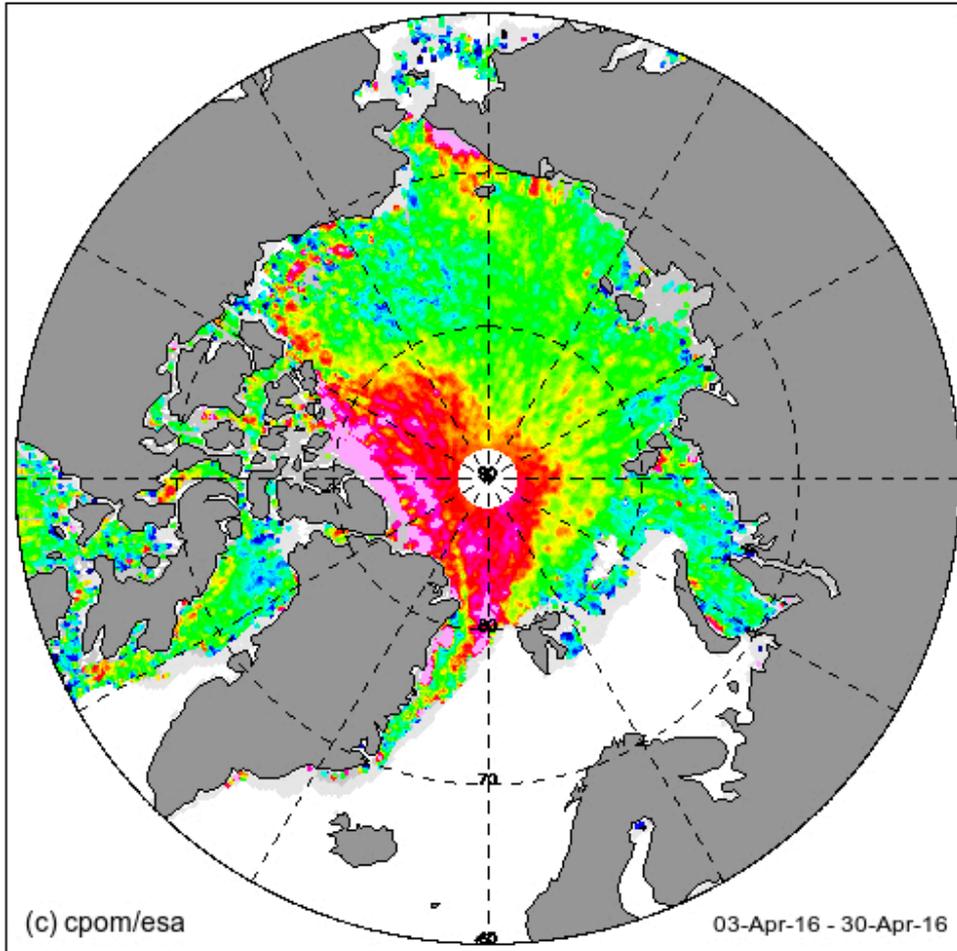


Elevation changes of Antarctica ice sheet

Derived from CryoSat-2 data 2011-14.

(credits: Helm et al., TC, 2014)

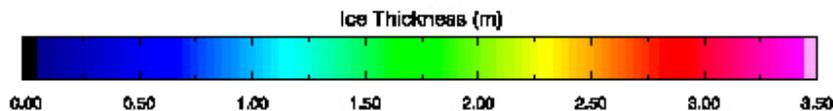
Altimeters for studying the cryosphere



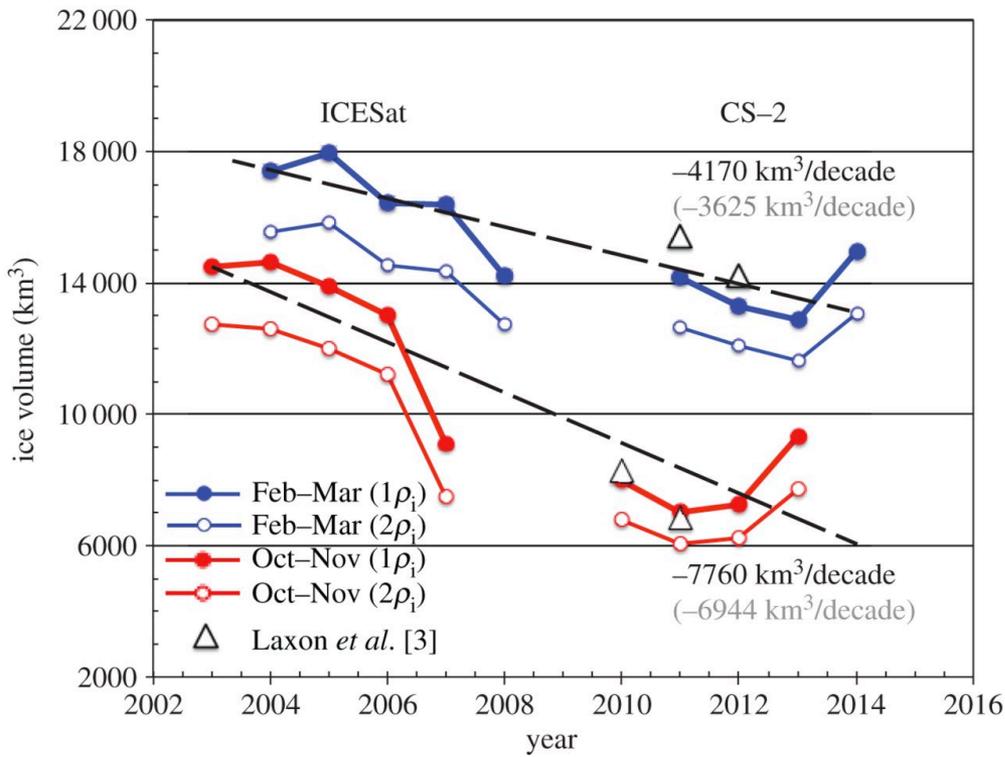
Arctic sea ice thickness

Derived from CryoSat-2 data April 2016.

(credits: CPOM/ESA)



Altimeters for studying the cryosphere

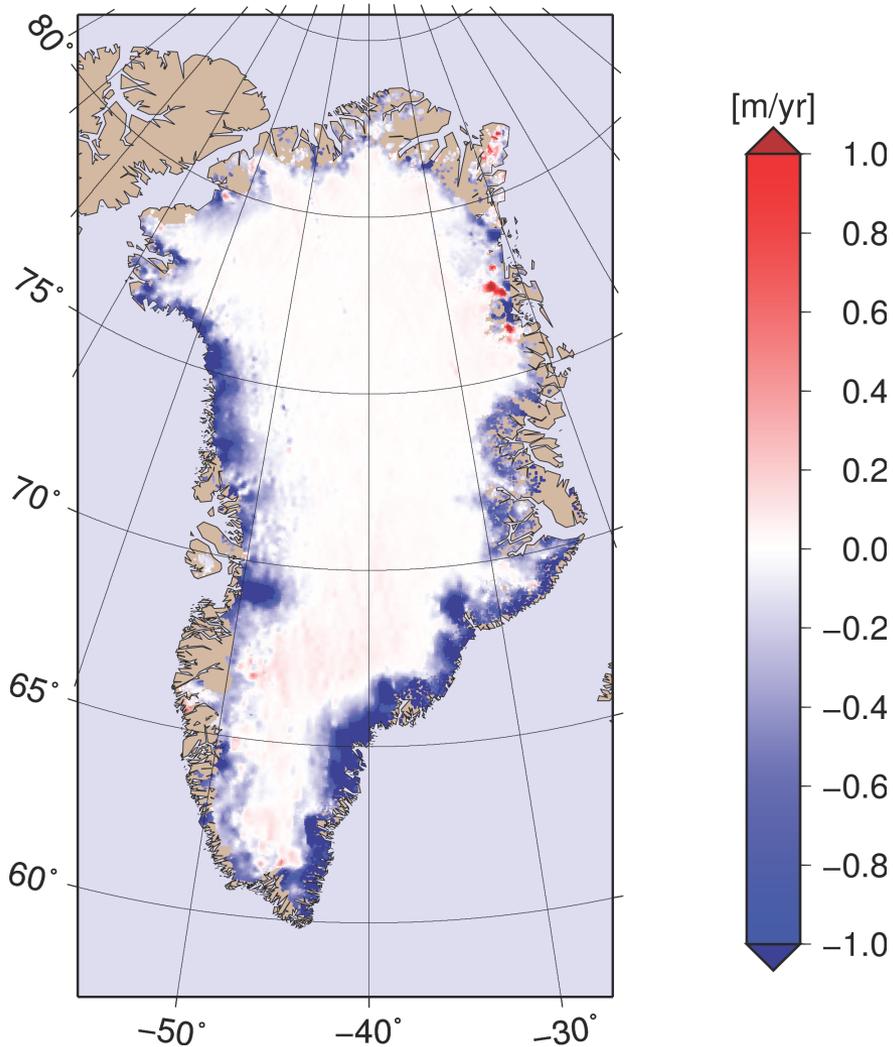


Decline in Arctic sea ice volume

Derived from ICESat and CryoSat-2 data

(credits: Kwok & Cunningham, 2015)

Altimeters for studying the cryosphere

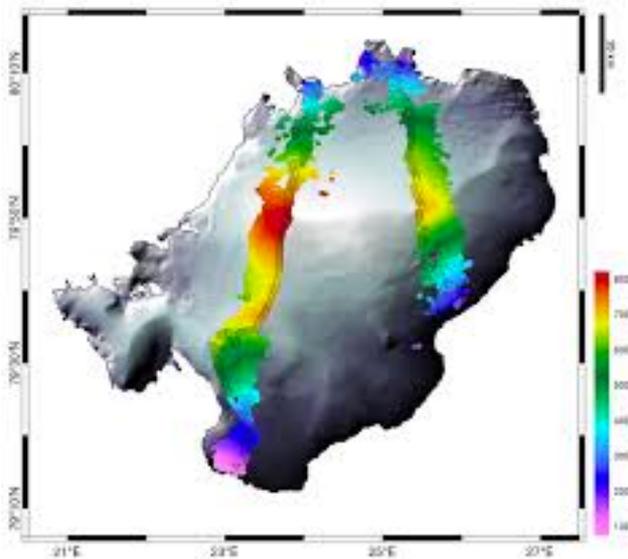


Greenland ice sheet mass changes

Derived from ICESat data 2003-08

(credits: Sørensen et al., 2011, TC)

Altimeters for studying the cryosphere



Detailed mapping of ice cap in Iceland

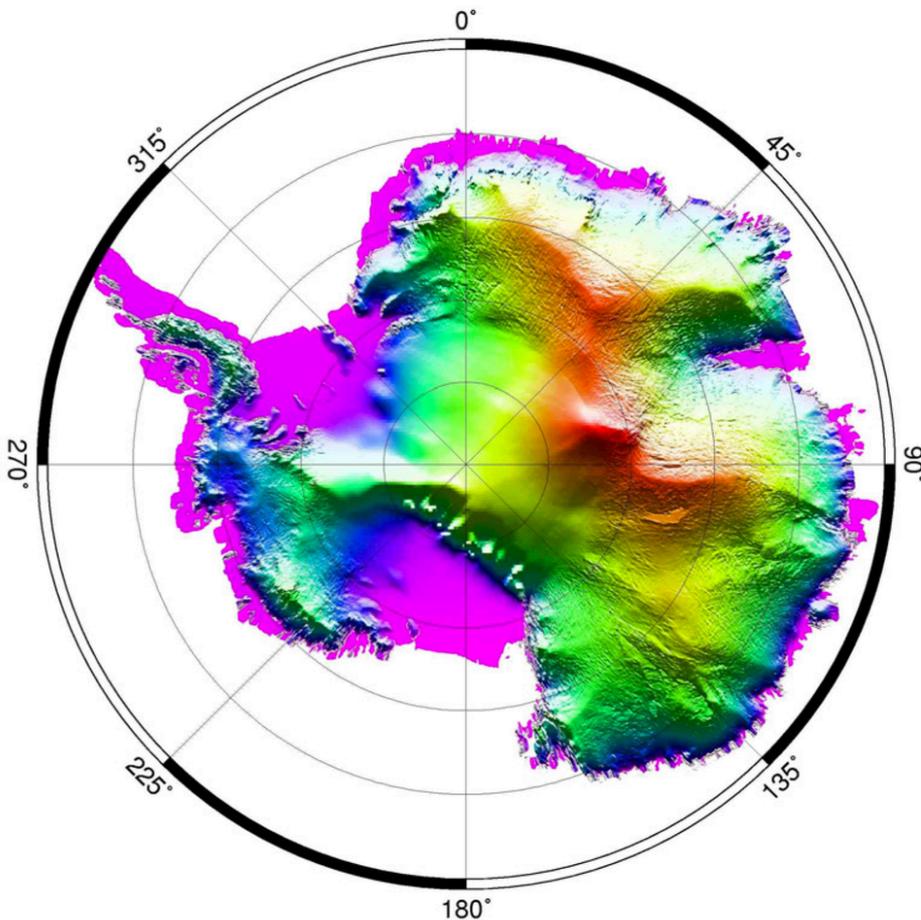
Derived from CryoSat-2 swath processing

(credits: N. Gourmelen & Cryotops cons.)

Altimeters for studying the cryosphere



Antarctic ice sheet topography



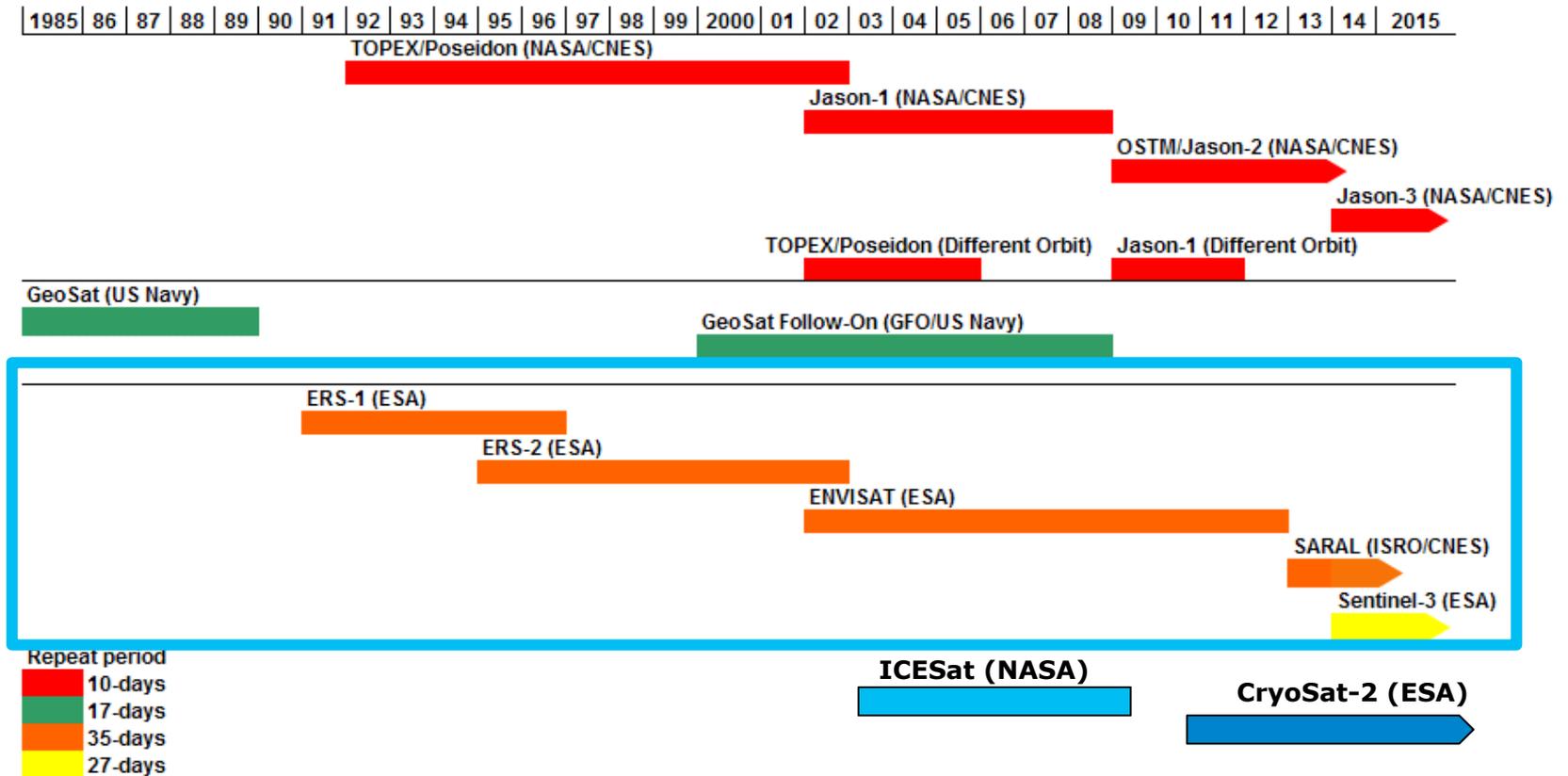
Digital elevation model Antarctica

Derived from ERS-1

(credits: Remy et al., 2006, C. R. Geo.)

Missions

General Timeline for Satellite Radar Altimeters with Short Repeat Periods



From : <http://www.pecad.fas.usda.gov/>

Missions, orbits, frequencies

Mission	Launch	End	Altitude (km)	Inclination (deg)	Orbit repetitivity	Frequency band
Seasat	06/1978	10/1978	800	72	3 d, 17 d	Ku
Geosat	03/1985	01/1990	800	72	17 d	Ku
ERS-1	07/1991	03/2000	785	81.5	3d, 35d, 168d	Ku
Topex-Poseidon	08/1992	01/2006	1336	66	10 d	Ku C
ERS-2	08/1995		785	81.5	35d	Ku
GFO	02/1998	11/2008	800	72	17 d	Ku
Jason-1	12/2001		1336	66	10 d	Ku C
Envisat	03/2002		800	81.5	35 d	Ku S
Jason-2	06/2008		1336	66	10 d	Ku C
Altika	2010		800	81.5	35 d	Ka
Cryosat	2010		717	88	369 d	Ku

Remy and Parouty, 2009, RS

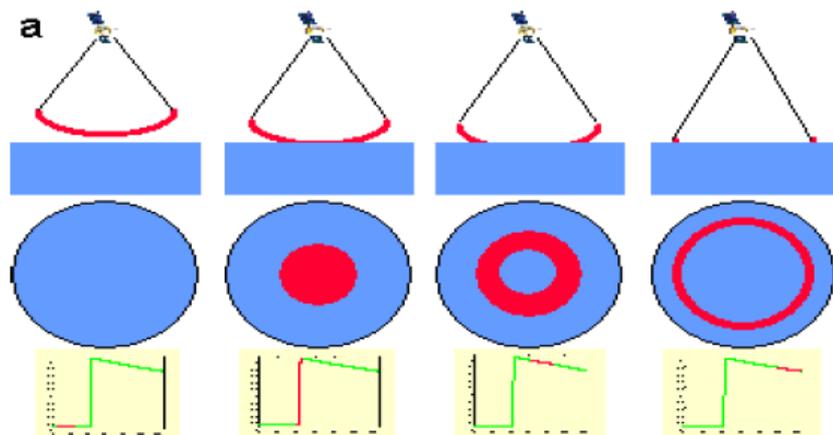
What is a waveform?

Waveforms

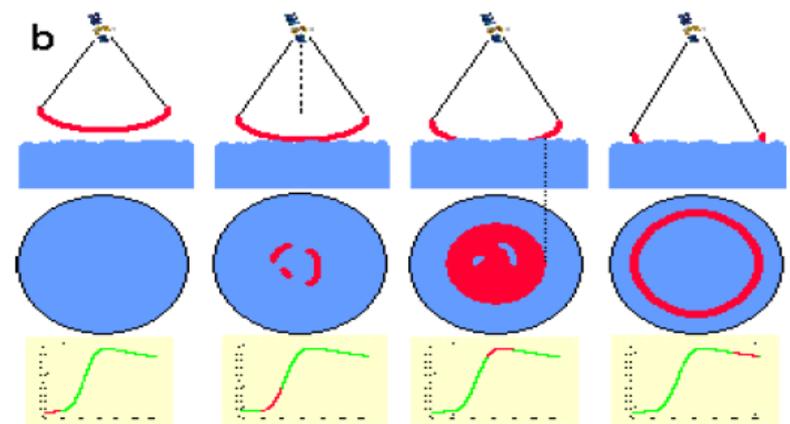
The magnitude and shape of the altimetry return echoes

Credit: <http://www.altimetry.info/>

Waveforms



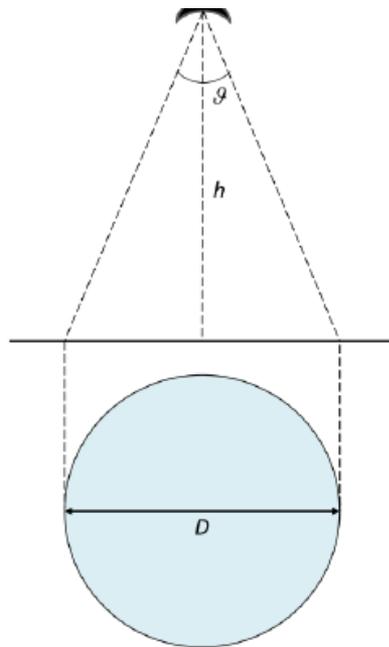
Ideally calm
sea



Rough sea

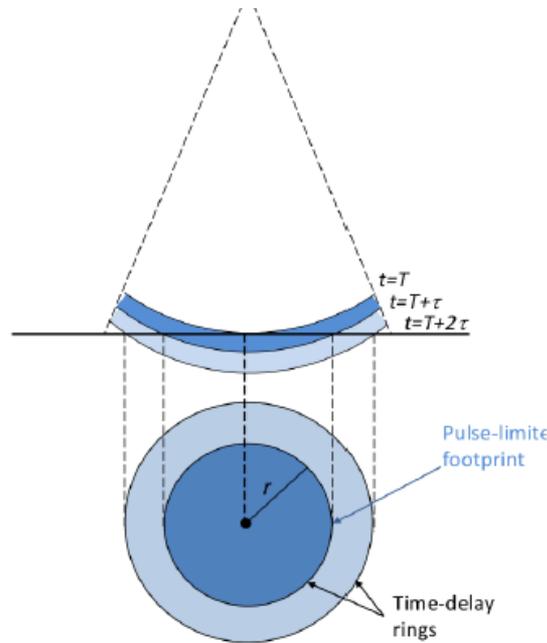
Credit: <http://www.altimetry.info/>

Radar footprints



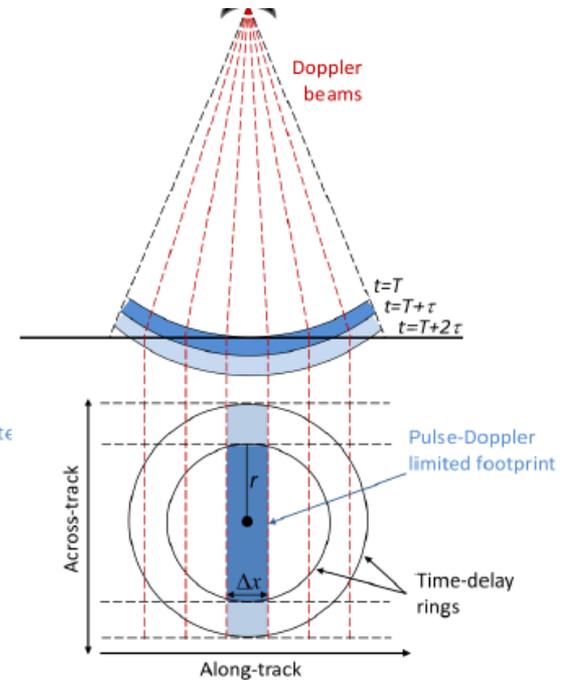
BEAM-LIMITED

$$D = 2h \tan \frac{\theta}{2}$$



PULSE-LIMITED

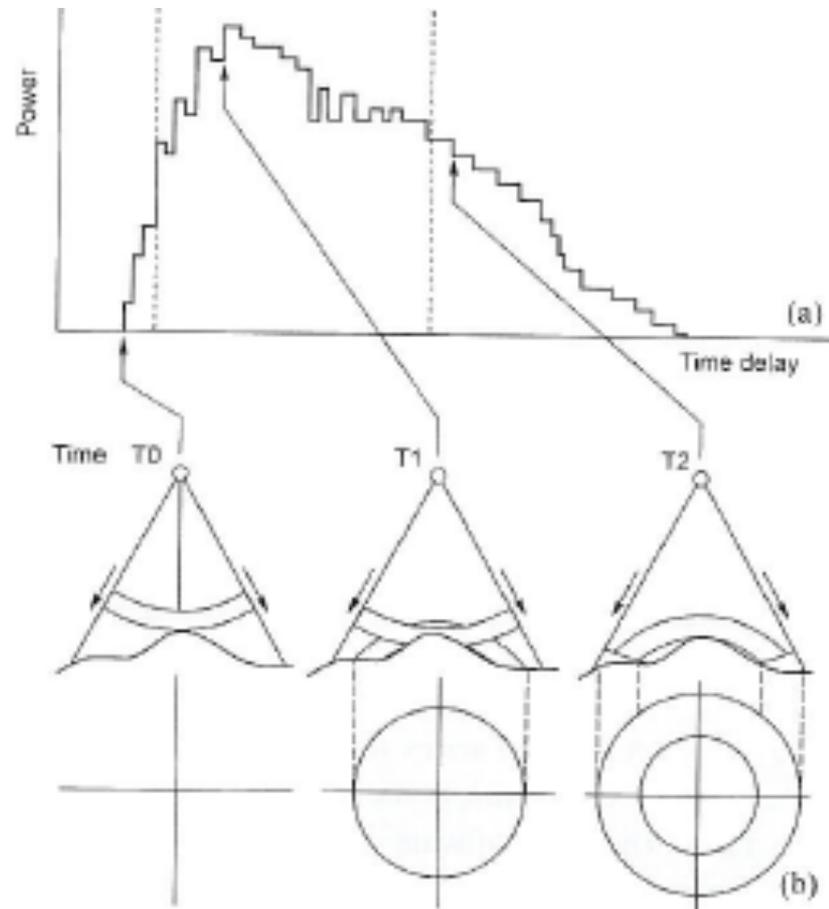
$$r = \sqrt{h c \tau} = \sqrt{h \frac{c}{B}}$$



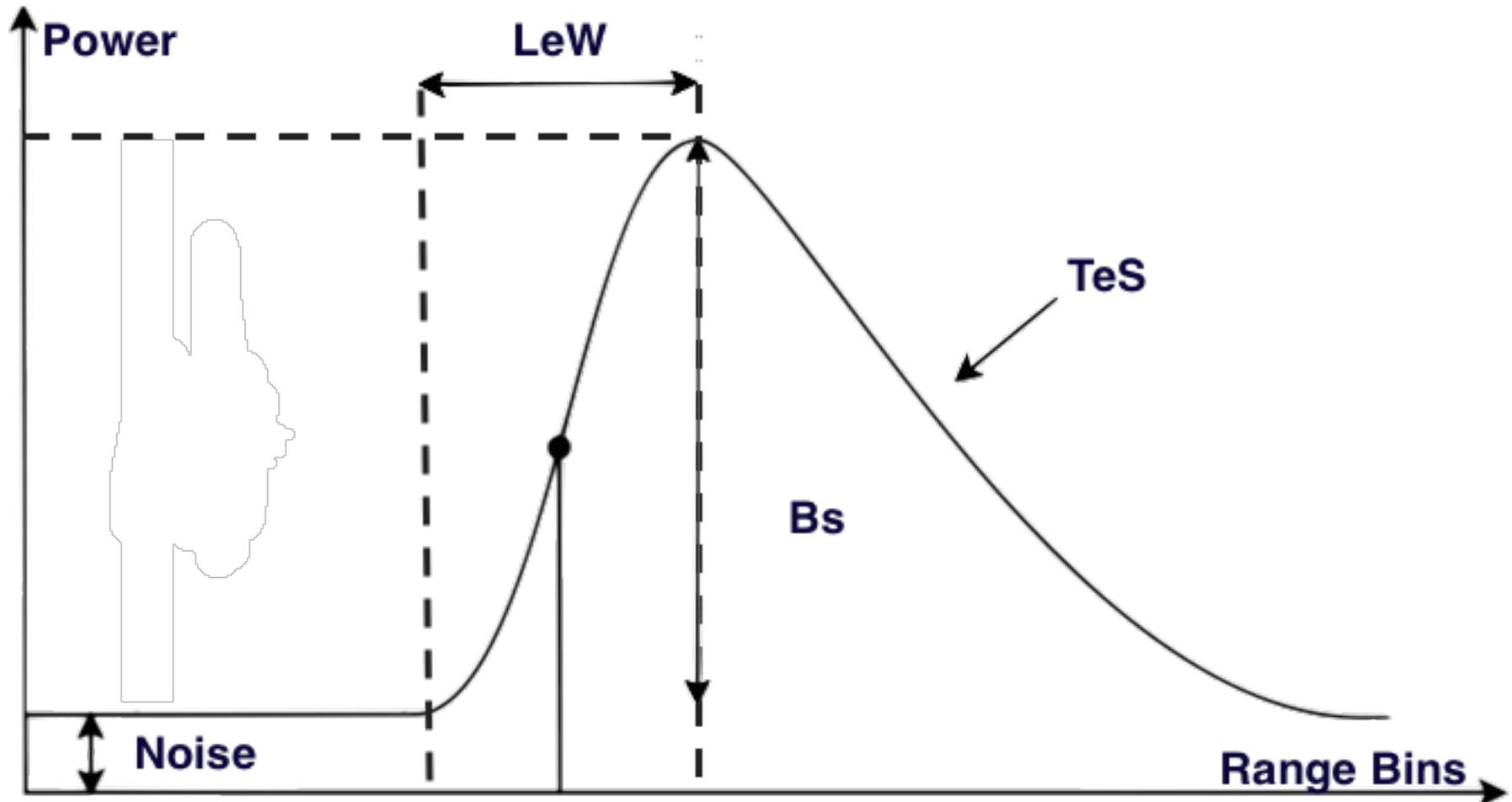
DOPPLER-LIMITED

$$\Delta x = h \frac{\lambda}{2N\nu} \text{PRF}$$

Waveforms



Waveform parameters



Radar or laser altimetry?

Radar or laser altimetry?

• Radar altimetry

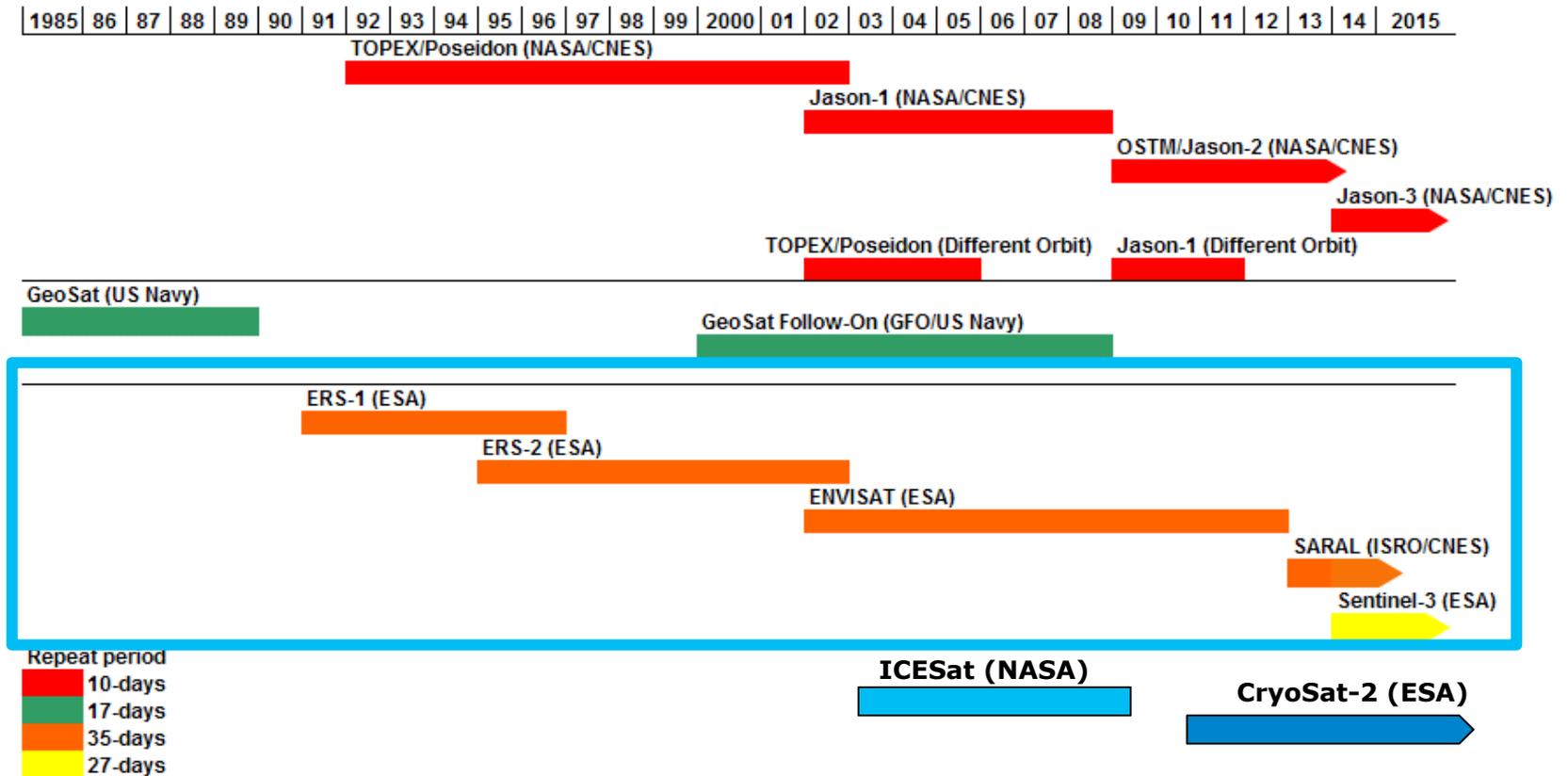
- ✧ Footprint 2-20 km
- ✧ Vertical accuracy < 5cm
- ✧ Weather independent
- ✧ Robust
- ✧ Long history, 18 years
- ✧ Operates on most altimetry missions
- ✧ works over water and ice
- ✧ Possible penetration into snow

• Laser altimetry

- ✧ Footprint 40-70 meters
- ✧ Vertical accuracy < 10cm
- ✧ Weather dependent, clouds
- ✧ Energy consuming, not robust
- ✧ For cryosphere only ICESat (2003-09)
- ✧ works over water, ice and land

Missions

General Timeline for Satellite Radar Altimeters with Short Repeat Periods

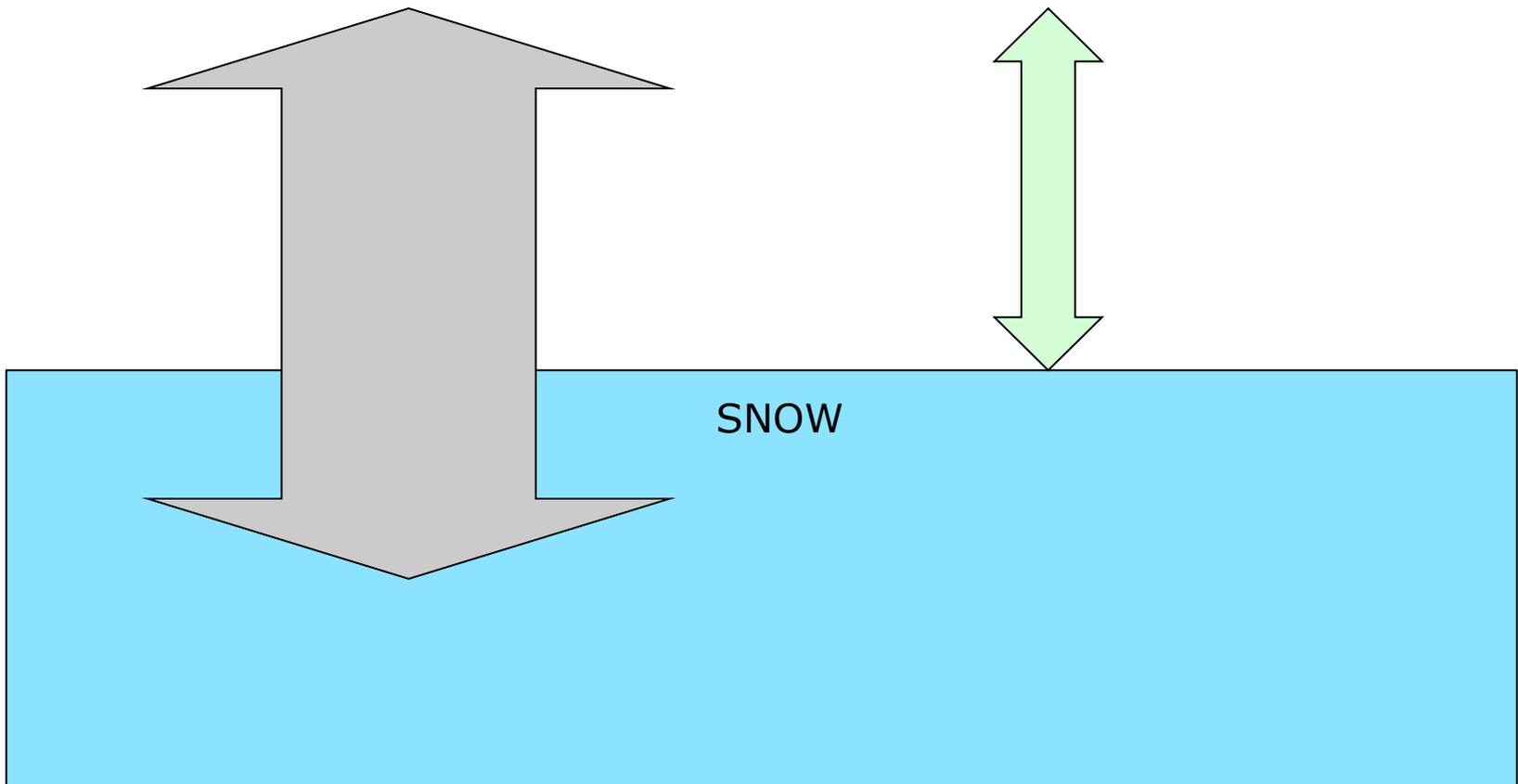


From : <http://www.pecad.fas.usda.gov/>

Radar versus laser

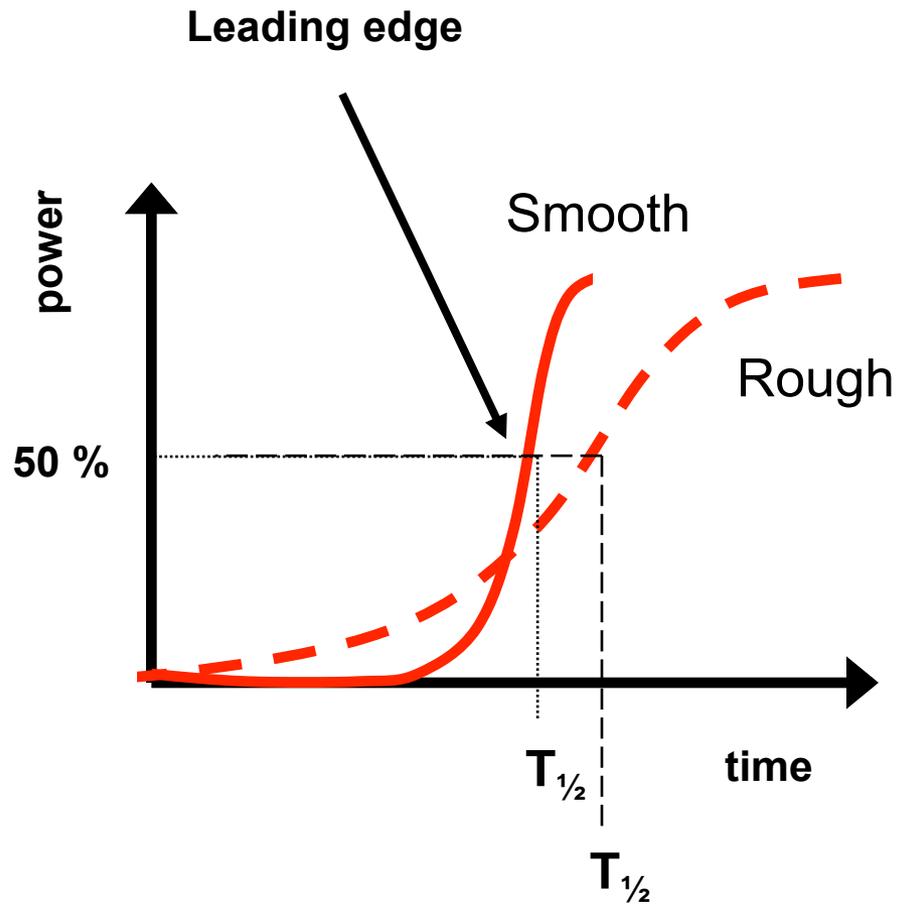
km scale

m scale



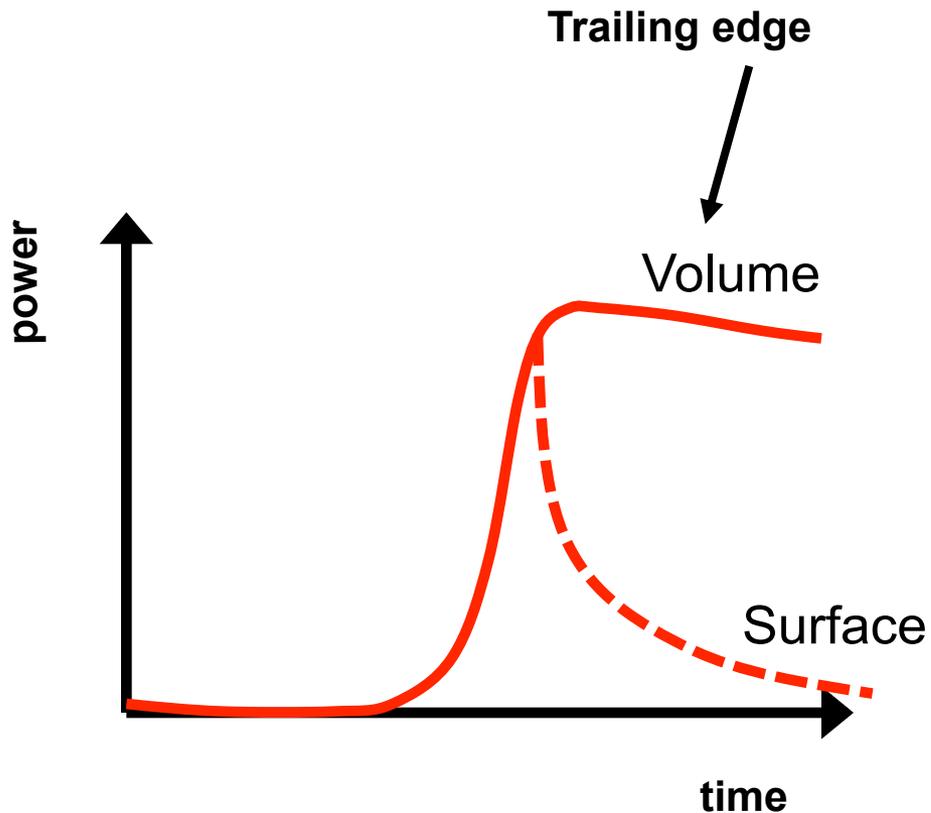
Radar waveforms from different surfaces

Radar Waveforms



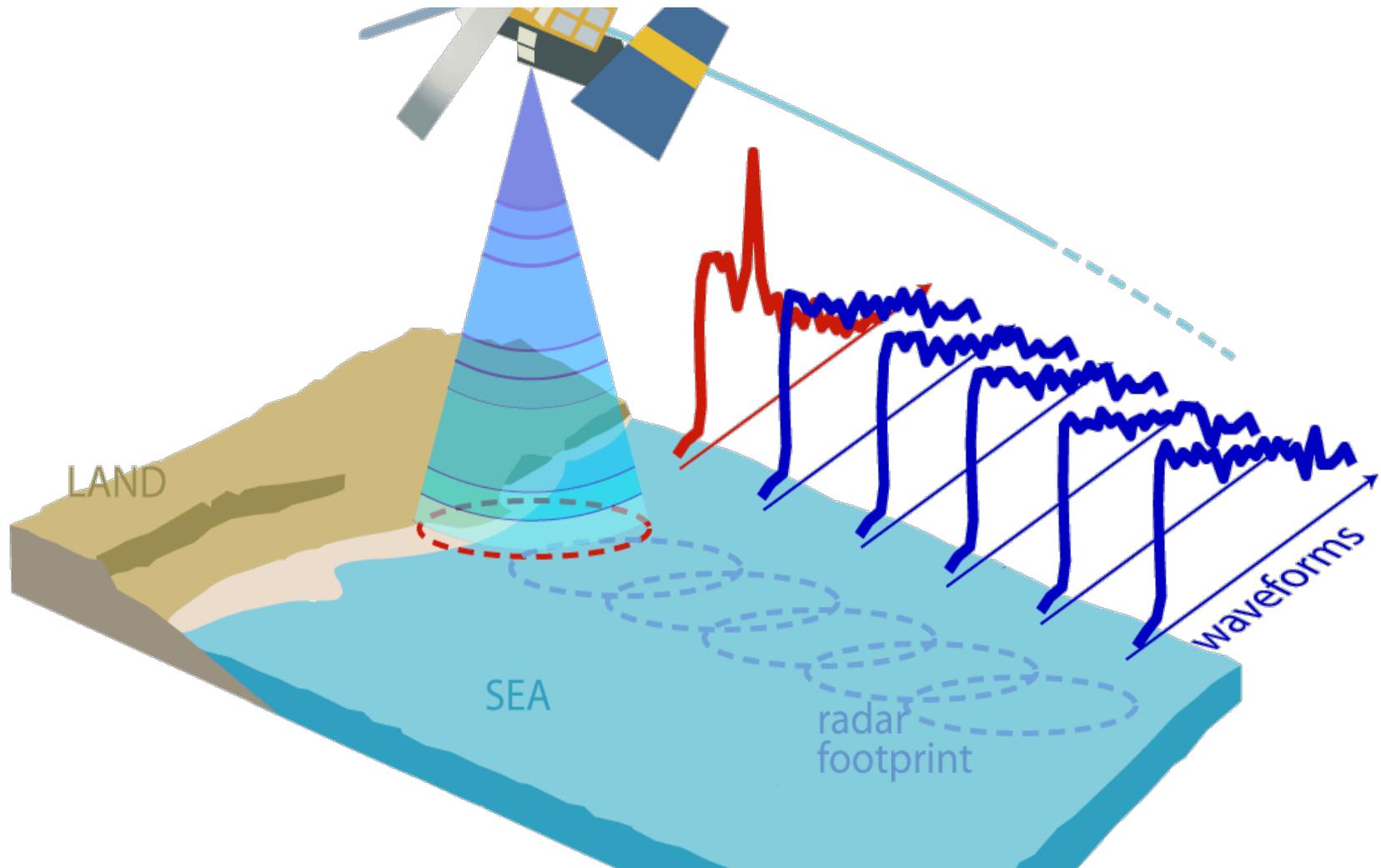
- Leading edge of pulse echo corresponds to first interaction with surface
- Slope of leading edge is related to surface roughness
- Smooth surfaces have steep leading edge, rough surfaces have shallow leading edge
- **Can estimate surface roughness from shape of leading edge**
- **But affects re-tracking**

Radar Waveforms

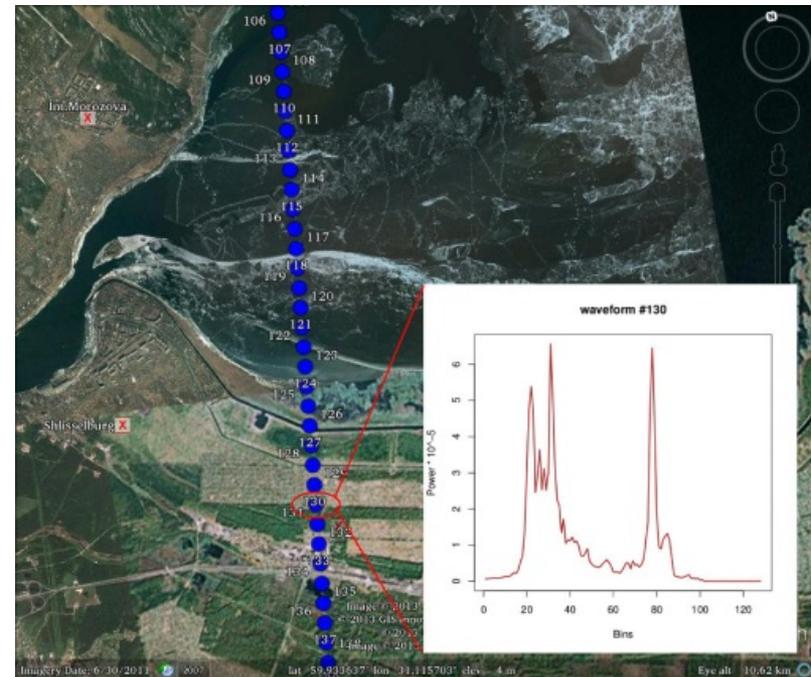
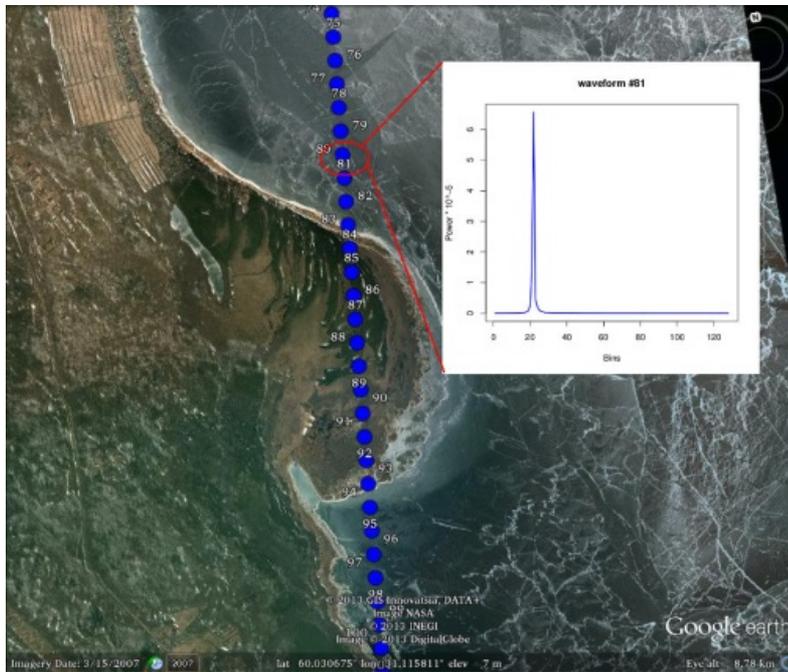


- Trailing edge of pulse is also related to scattering properties of the surface
- Rapid tailing off when scattering is only from surface
- Slow tailing off when additional scattering from depth (due to penetration)
- **Degree of penetration can be characterised by slope of trailing edge**

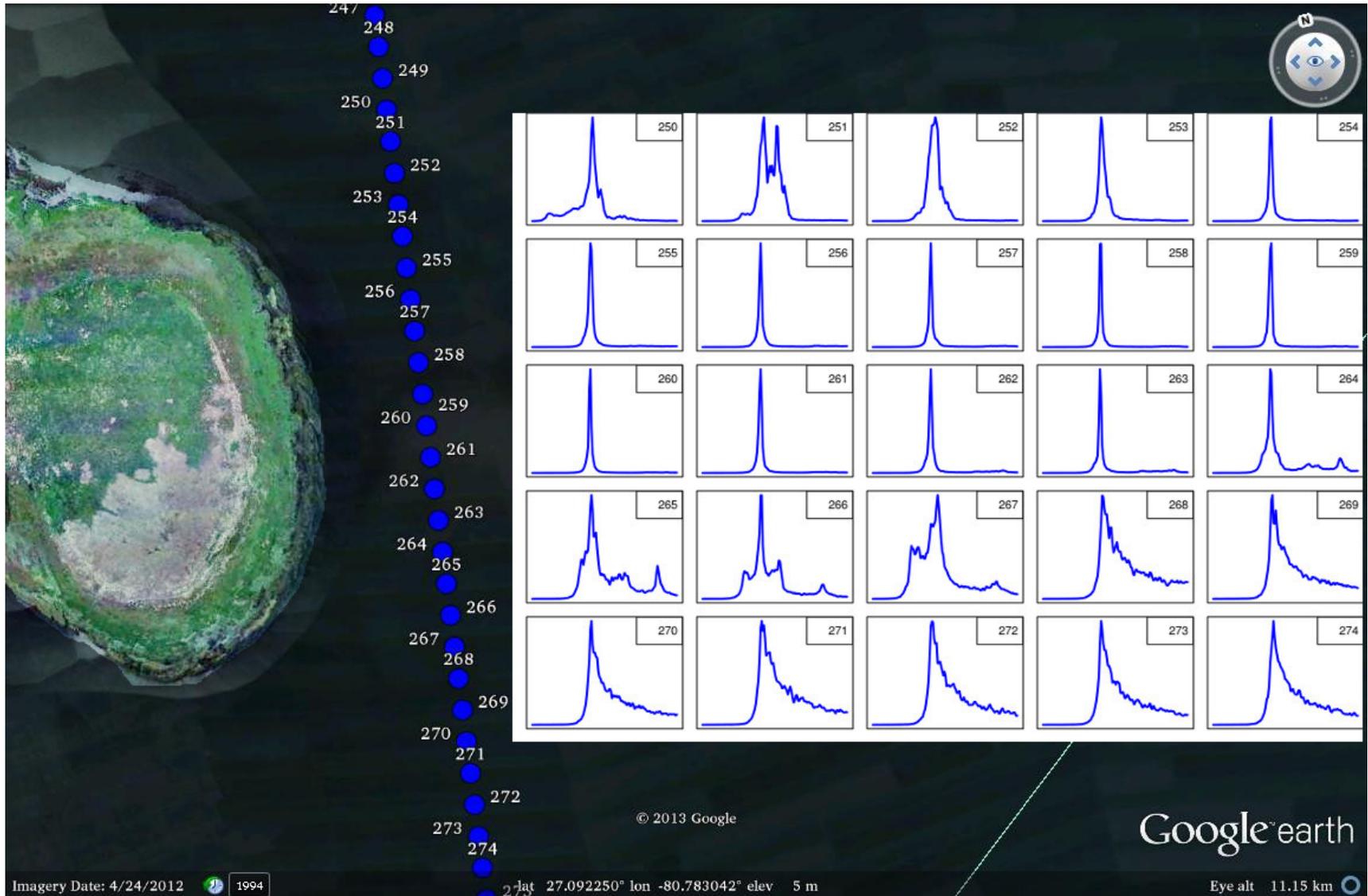
Radar waveforms from different surfaces



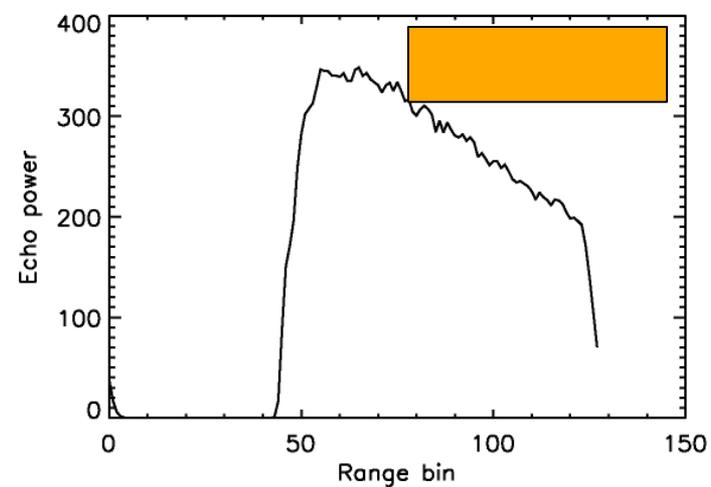
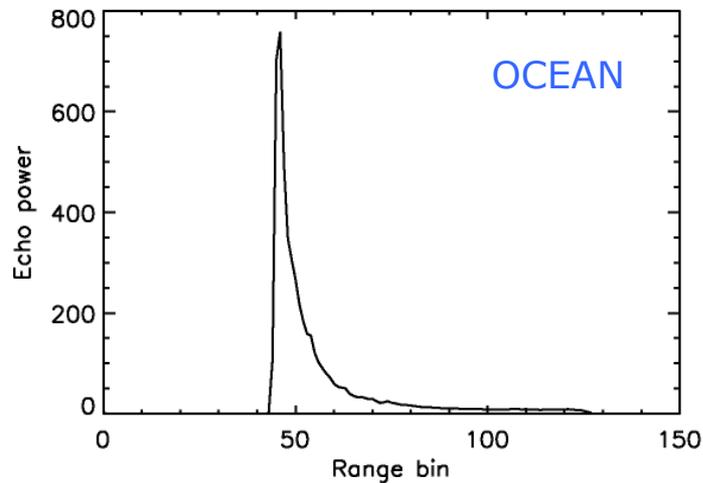
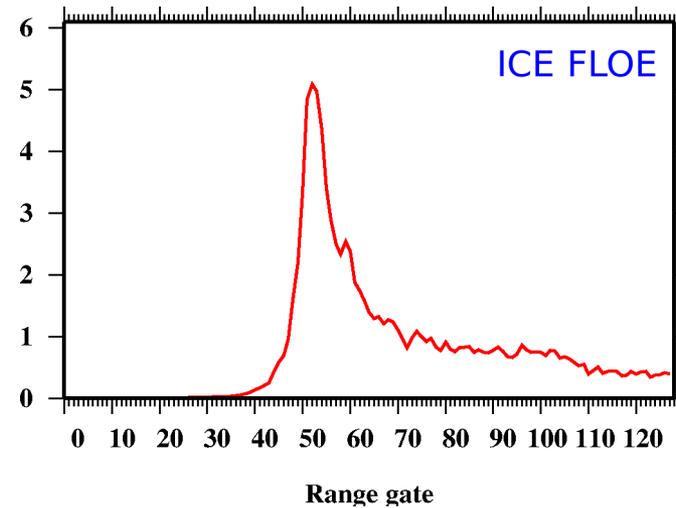
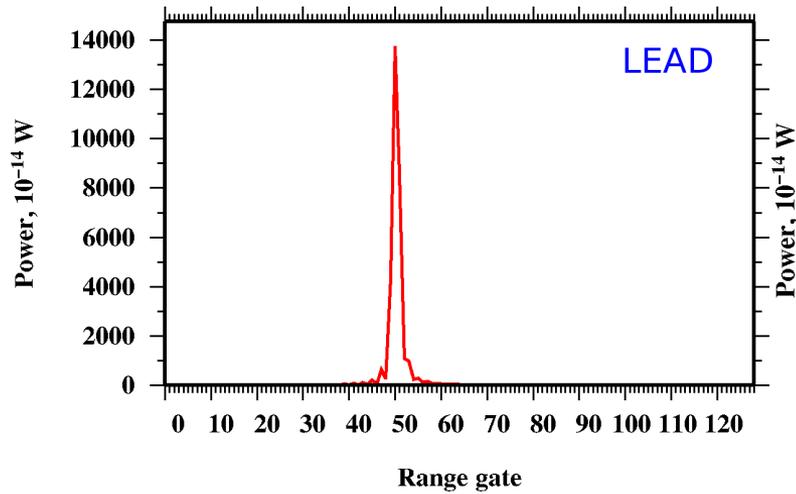
Radar waveforms from different surfaces



Radar waveforms from different surfaces

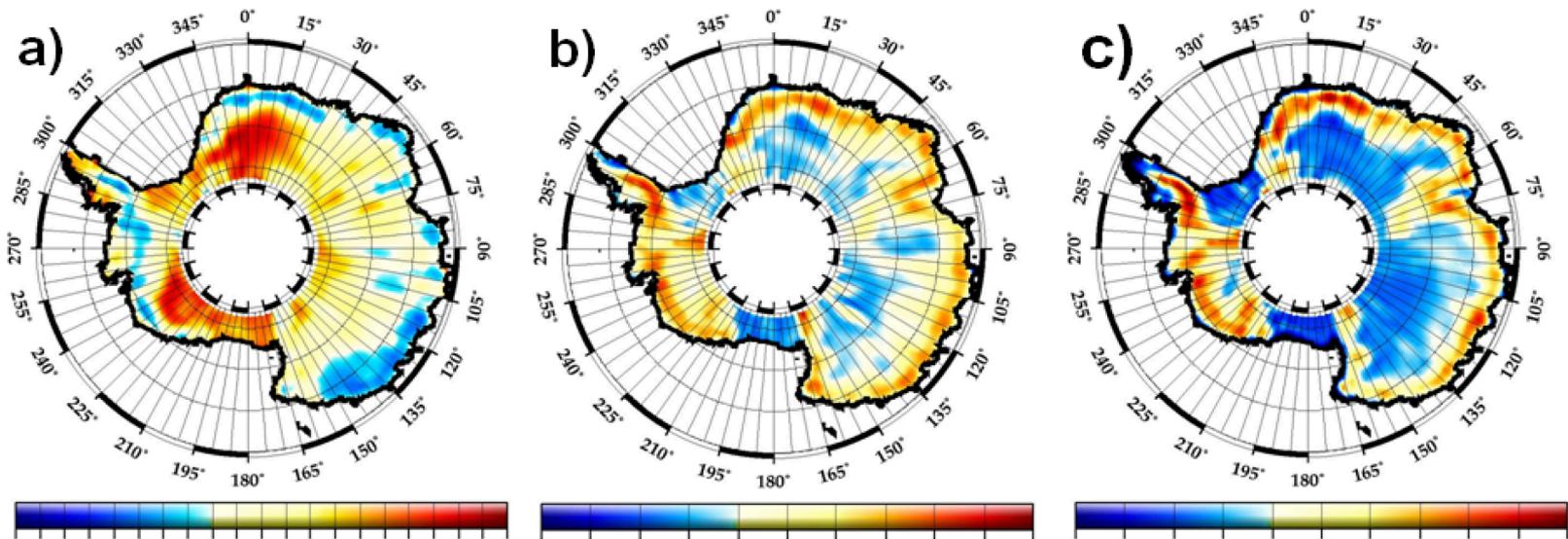


Radar waveforms from different surfaces



Waveform parameters

Mean altimetric waveform parameters mapped over Antarctica in Ku-band from 2003 to 2007.



(a) Backscattering coefficient (dB)

(b) Leading edge width (m)

(c) Trailing edge slope expressed in 10^6 s^{-1} .

What is a retracker?

Retrackers

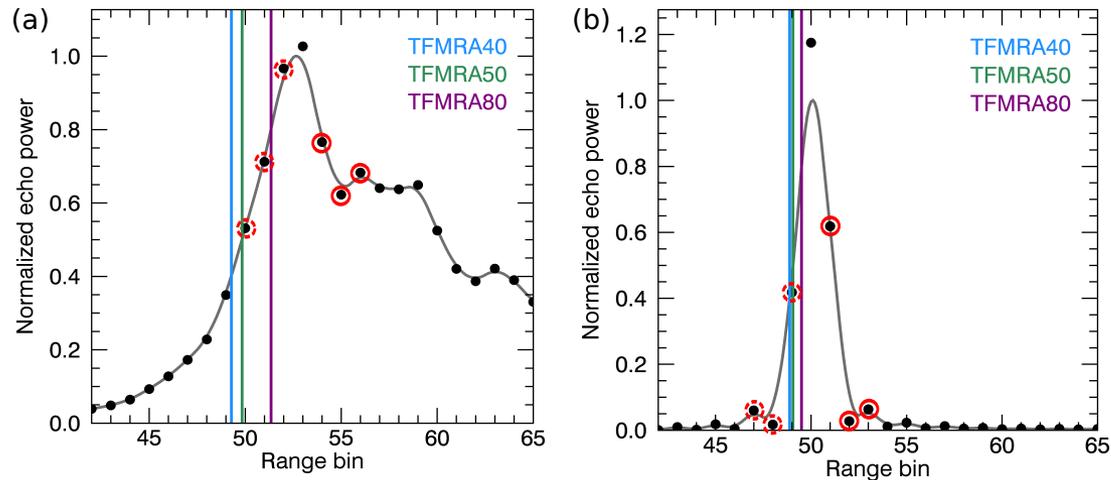
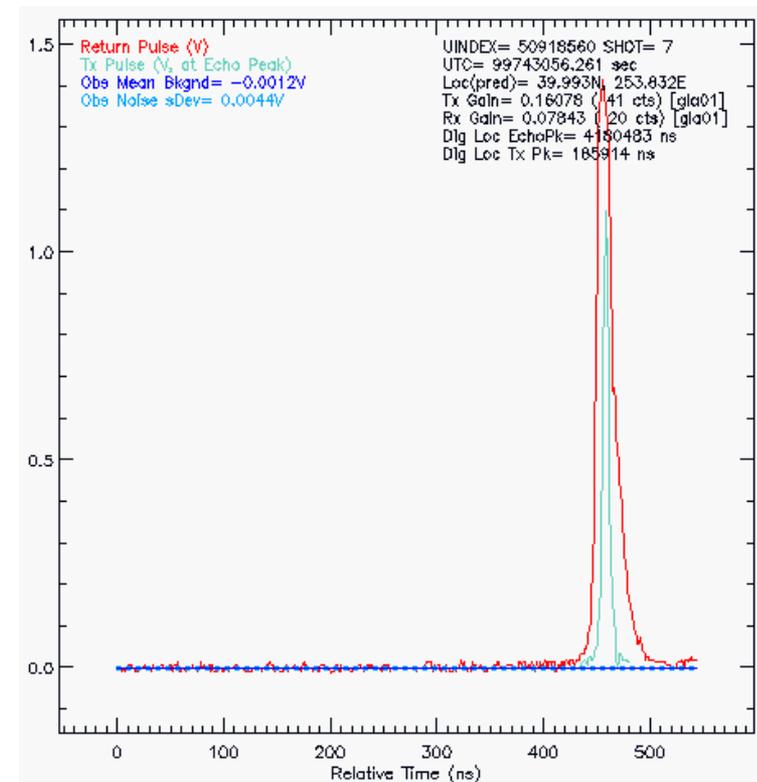


Figure 3. Typical CryoSat-2 waveforms for sea ice (a) and leads (b). The fitted waveform (grey) is a result of linear interpolation and smoothing of the original CryoSat-2 waveform (black dots). The coloured vertical lines represent the different applied TFMRA (threshold first-maximum retracker algorithm) thresholds in this study: 40 % (TFMRA40), 50 % (TFMRA50) and 80 % (TFMRA80). Red circles mark the range bins that are considered for the “left-hand” (dotted) and “right-hand” peakiness (solid).

Ricker et al., 2014, TC

Retrackers

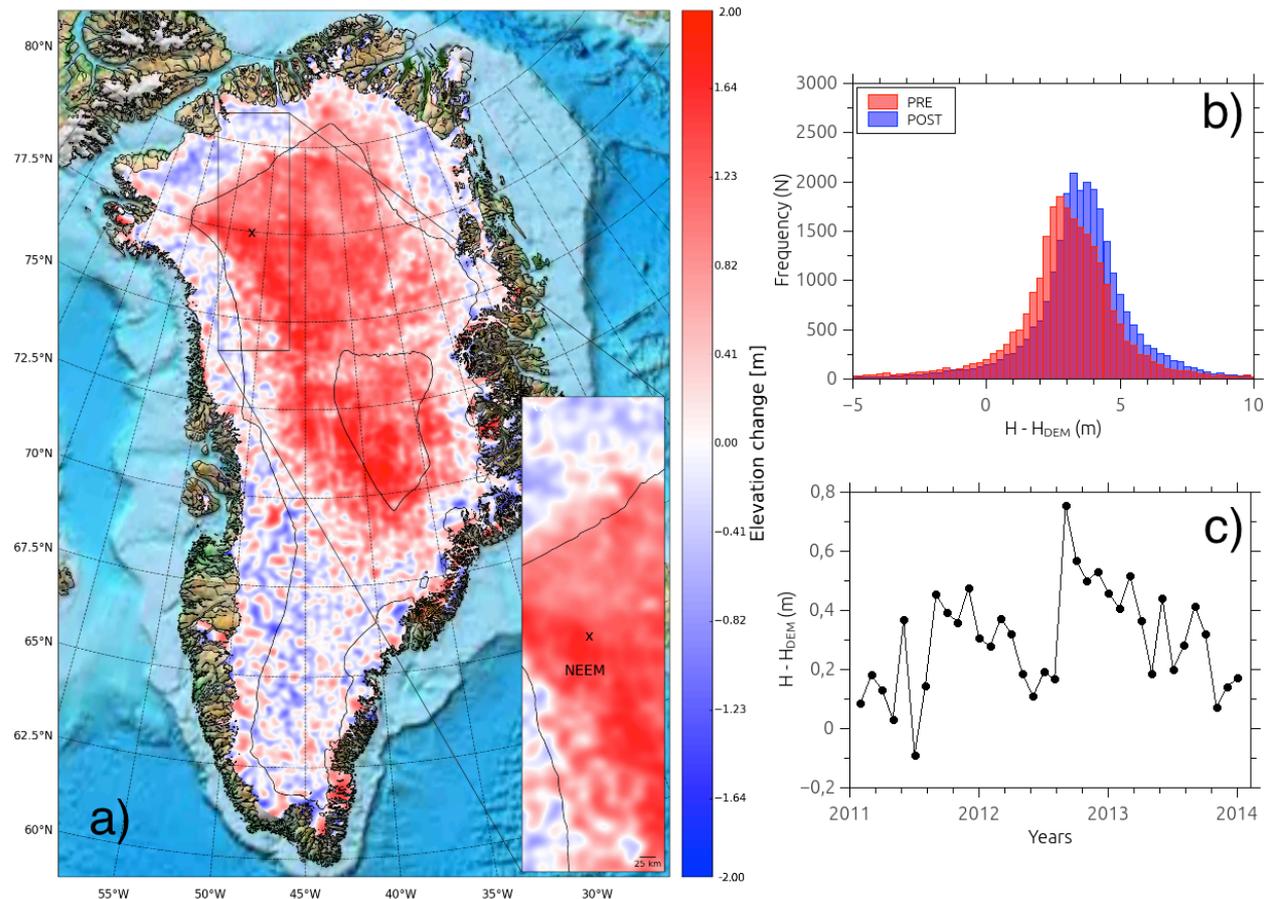
- **Radar altimetry:**
- Many retrackerers available.
- The choice of retracker might affect the height estimate
- Different retrackerers suitable for different surfaces
- **Laser altimetry:**
- The laser return waveforms are much simpler than the radar waveforms.
- The elevation is derived from the maximum peak



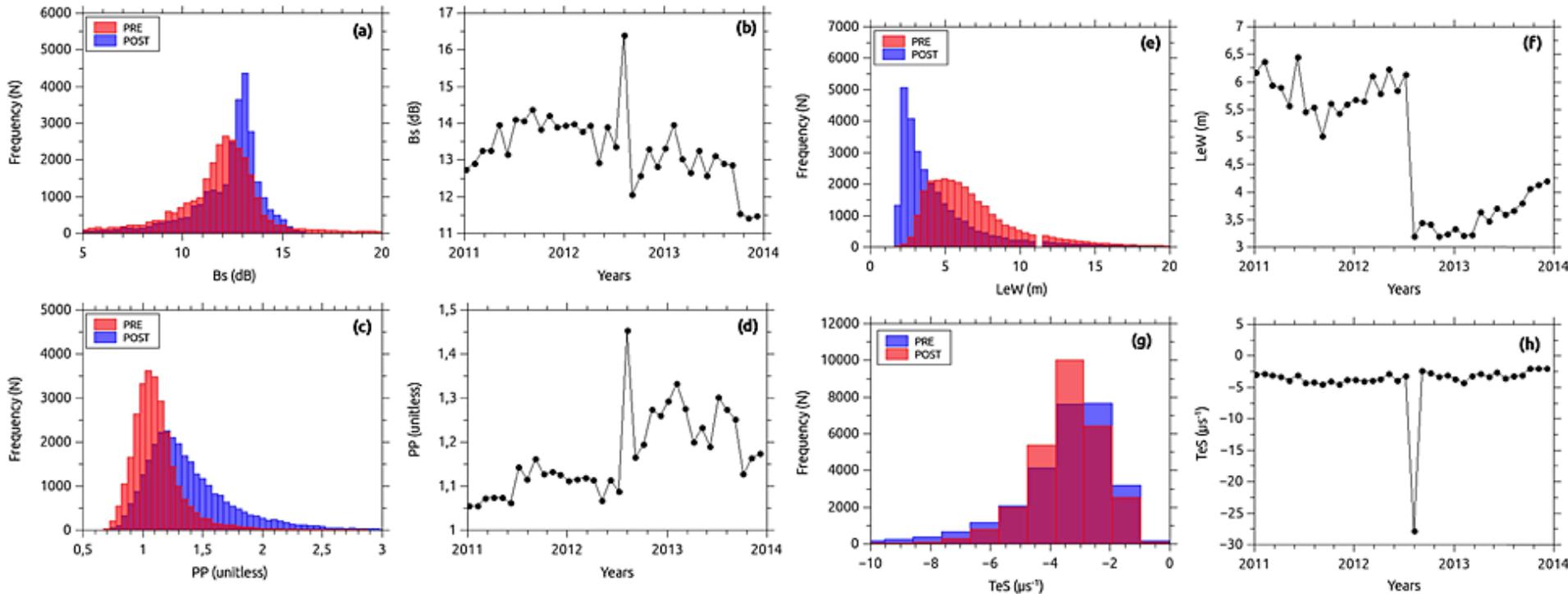
Changes in surface properties

- Trend analysis of 2012 Cryosat-2 data showed anomalous thickening in the interior parts of the GrIS.
- The 2012 event was credited to be the most viable source, after processing errors were discarded.
- Based on CryoSat data near NEEM before and after melt event

Cryosat-2 derived elevation changes from 2012
(Nilsson et al. 2015)

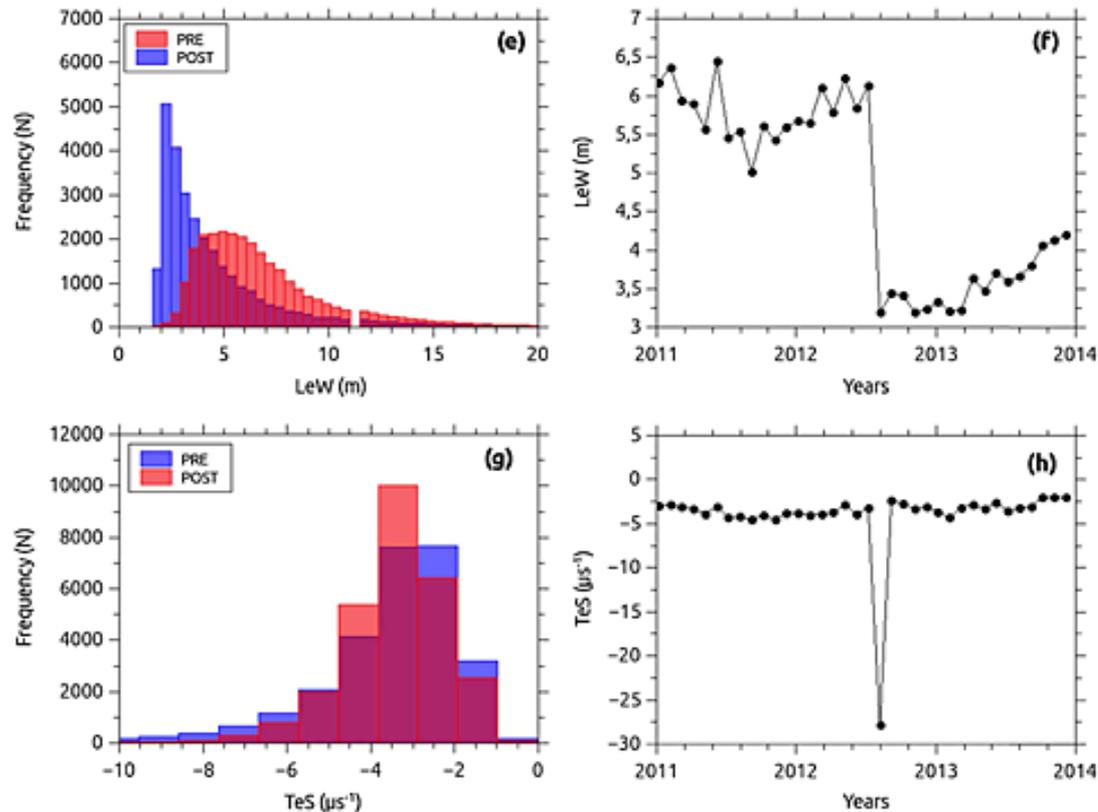


Waveform parameters and retracked heights



Credits: J. Nilsson et al, 2015, GRL

Waveform parameters and retracked heights



Credits: J. Nilsson et al, 2015, GRL

Waveforms

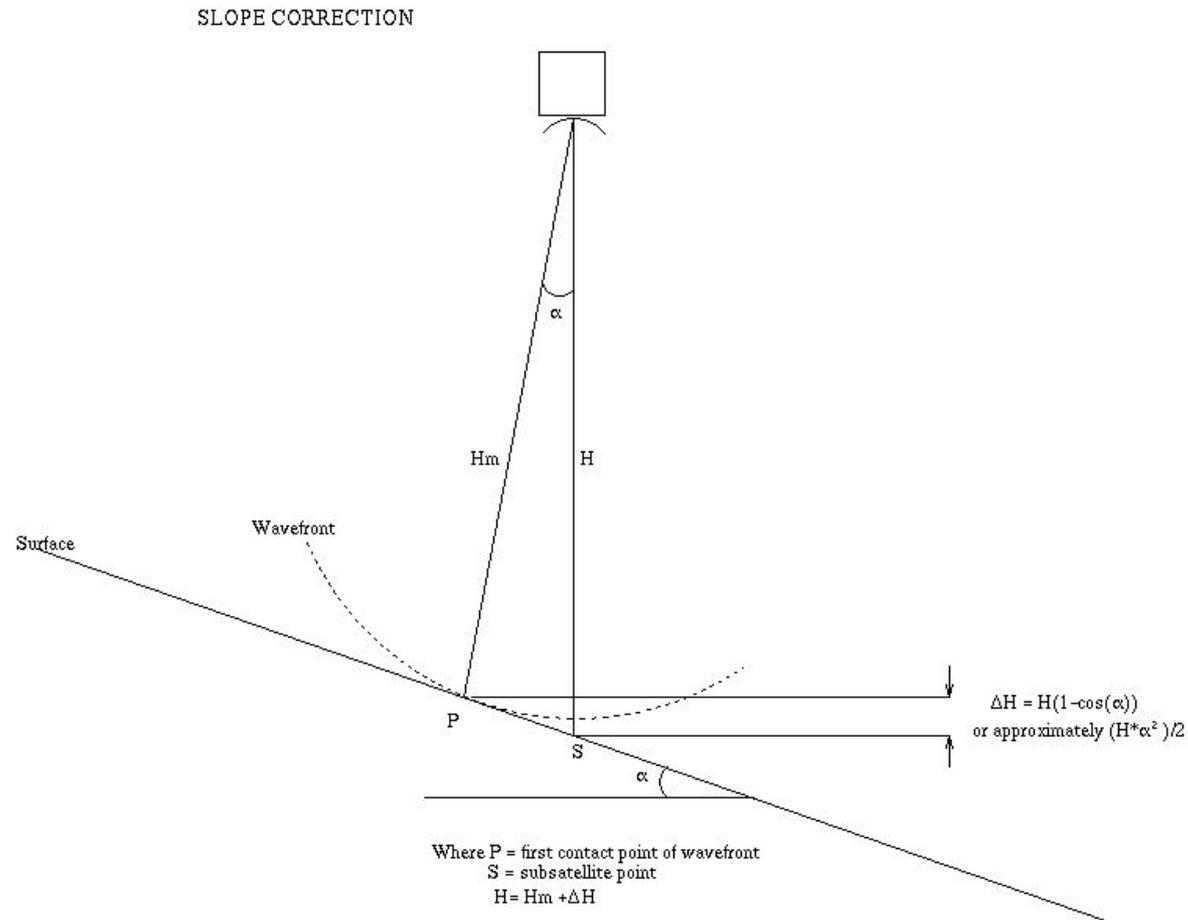
Altimetric waveforms can be seen as the histogram of the backscattered energy with respect to the return time.

The signal is the sum of a surface and of a volume echo.

Thus waveform shape is sensitive to meteorological conditions close to the surface such as winds (through roughness), temperature (through grain size and density) or snowfall events (stratification and density).

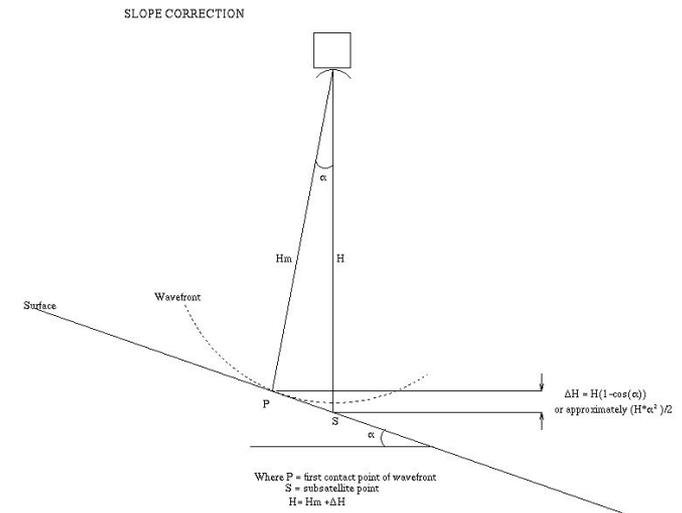
The main issue in altimetric measurements interpretation is to distinguish between all these effects.

Radar altimetry on slopes

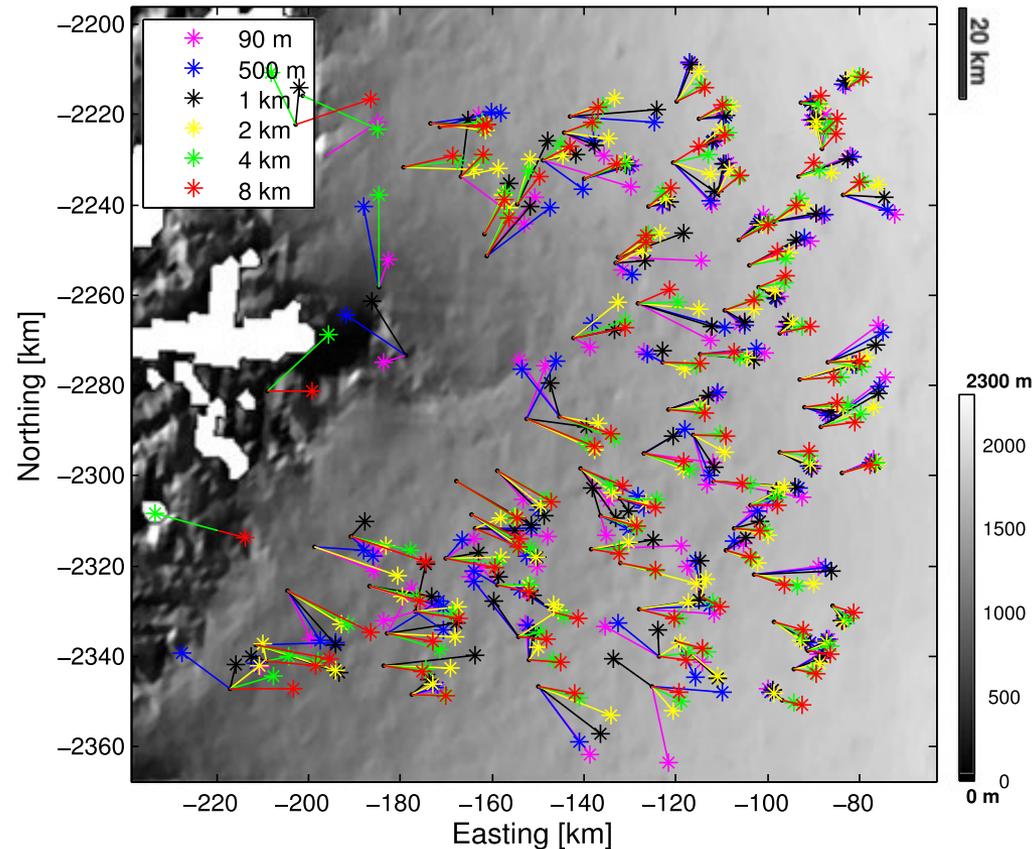


Radar altimetry on slopes

- Slope correction
- Slope in nadir or POCA
- Correct position or height
- DEM resolution (what does the radar see?)



Radar altimetry on slopes

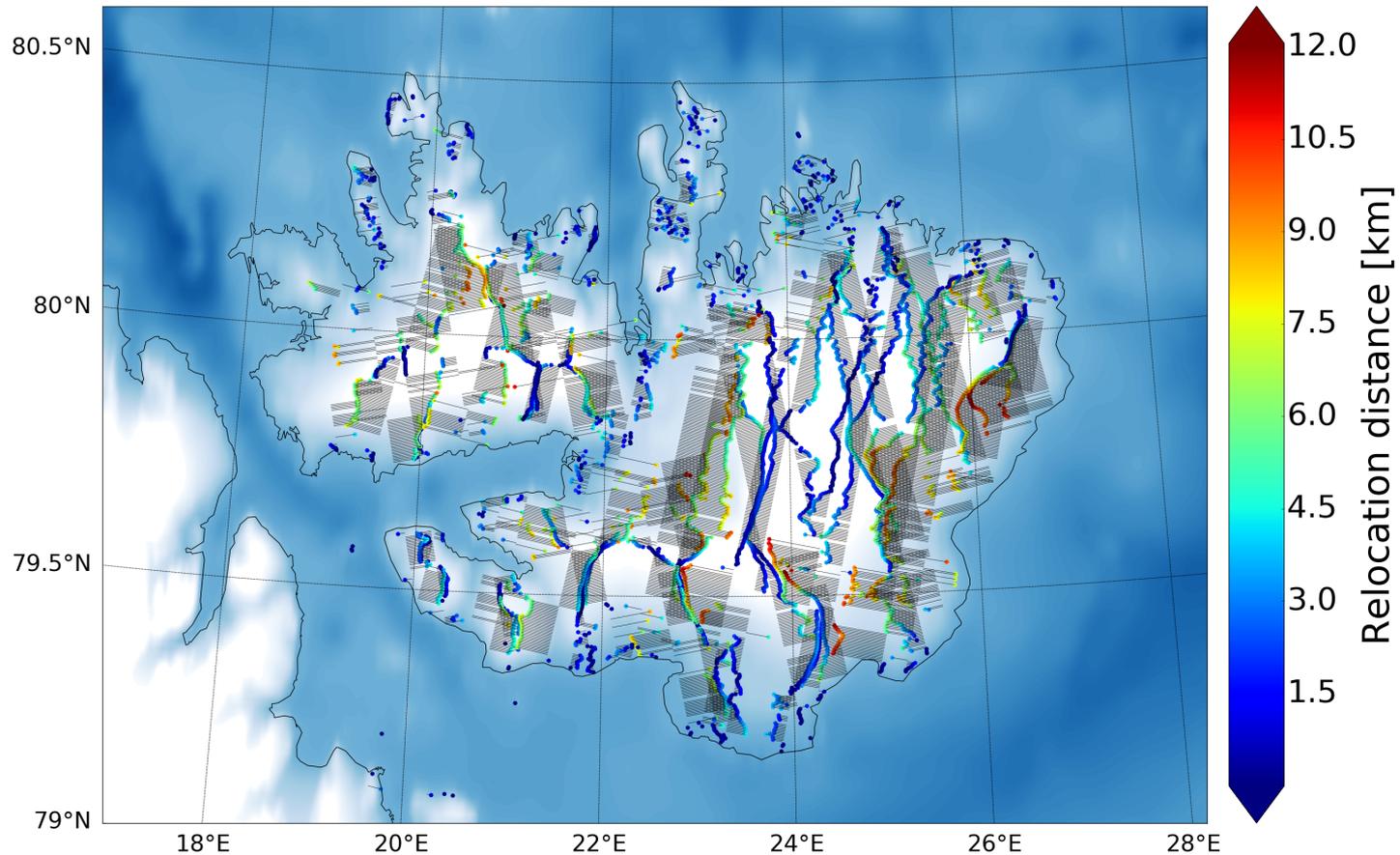


Relocation of Envisat data near Jakobshavn in Greenland

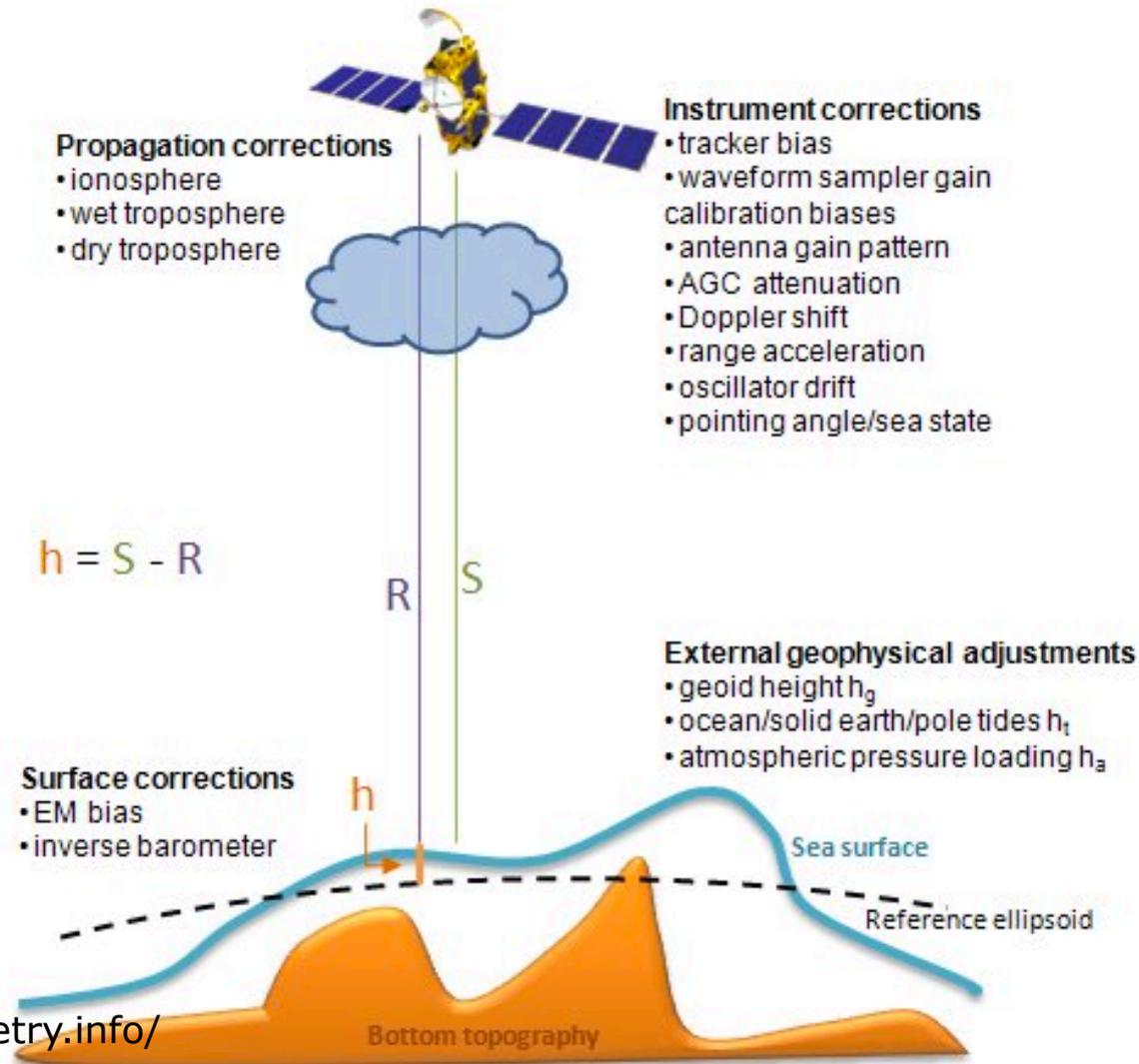
DEM resolution

Credits: Levinsen et al, 2016, IEEE

Radar altimetry on slopes



Geophysical and propagation corrections



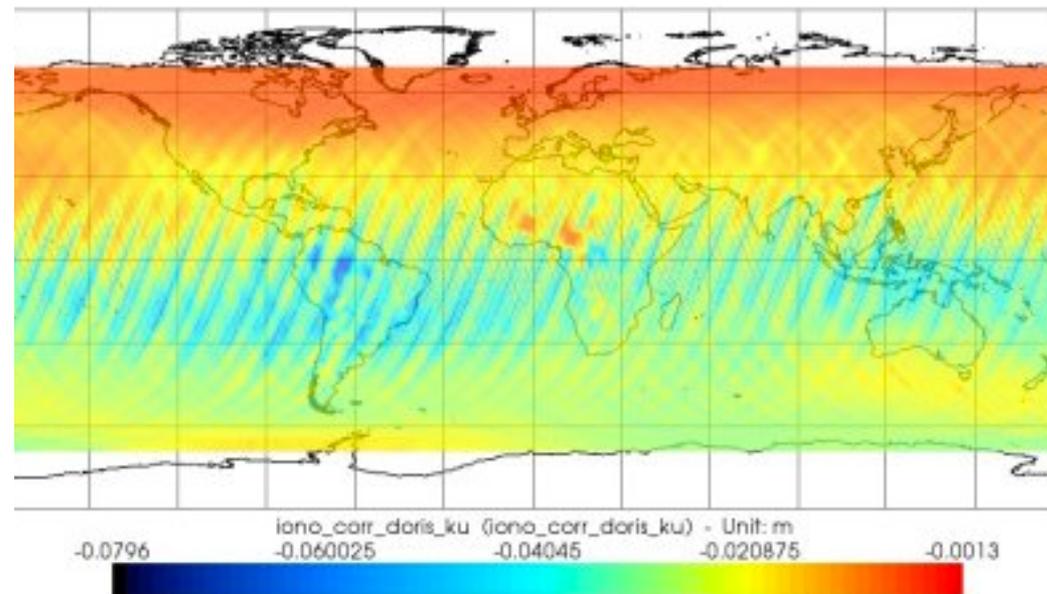
<http://www.altimetry.info/>

Ionosphere correction

The path delay in the radar return signal due to electron content in the atmosphere.

Quantified by e.g. combining two frequency radar altimeter measurements acquired at two separate frequencies (e.g. Ku-band and S-band for Envisat).

Order of magnitude :
0 - 50 cm.



From the Jason-1 GDR products.

<http://www.altimetry.info/>

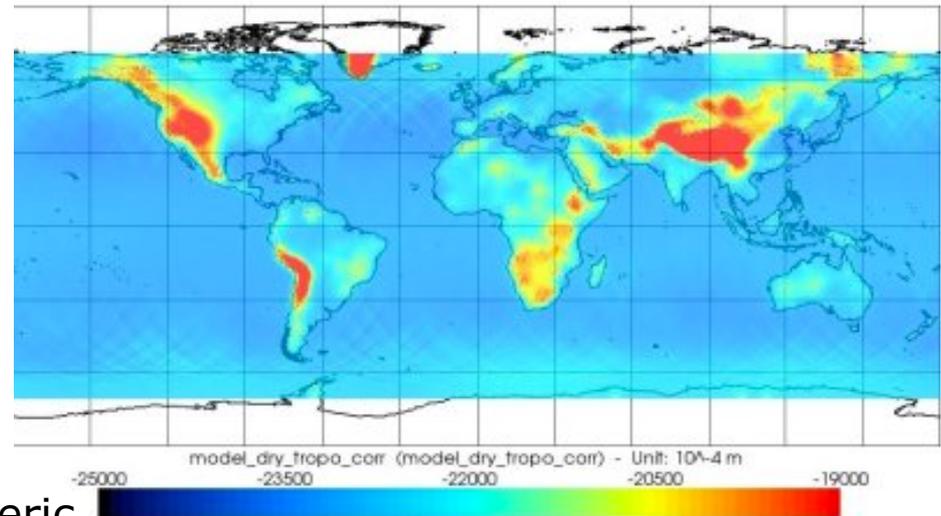
Dry troposphere correction

This correction for the dry gas component of the atmosphere refraction takes into account the path delay in the radar return signal due to the atmosphere.

It is by far the largest adjustment that must be applied to altimeter measurement.

Order of magnitude is about 2.3 m.

Temporal variations are low
(a few centimetres only).



Computed from the ECMWF atmospheric pressures model during the Jason-1 cycle 223.

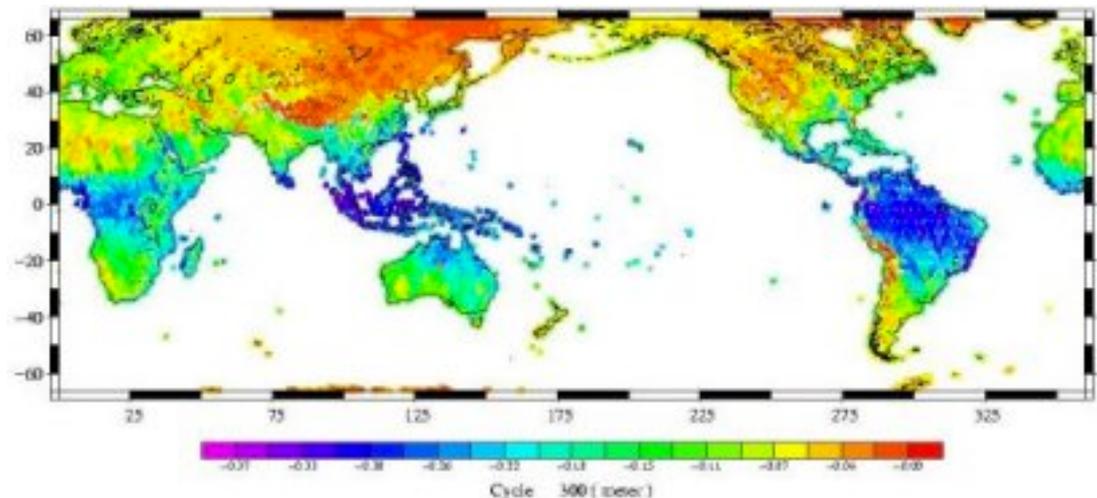
Wet troposphere

The wet troposphere correction is the correction for the path delay in the radar return signal due to liquid water in the atmosphere.

It is calculated from radiometer measurements and meteorological models.

Its order of magnitude is about 0 to 50 cm

Amplitude in metres of the wet troposphere correction computed from the NCEP model during Topex/Poseidon cycle 300

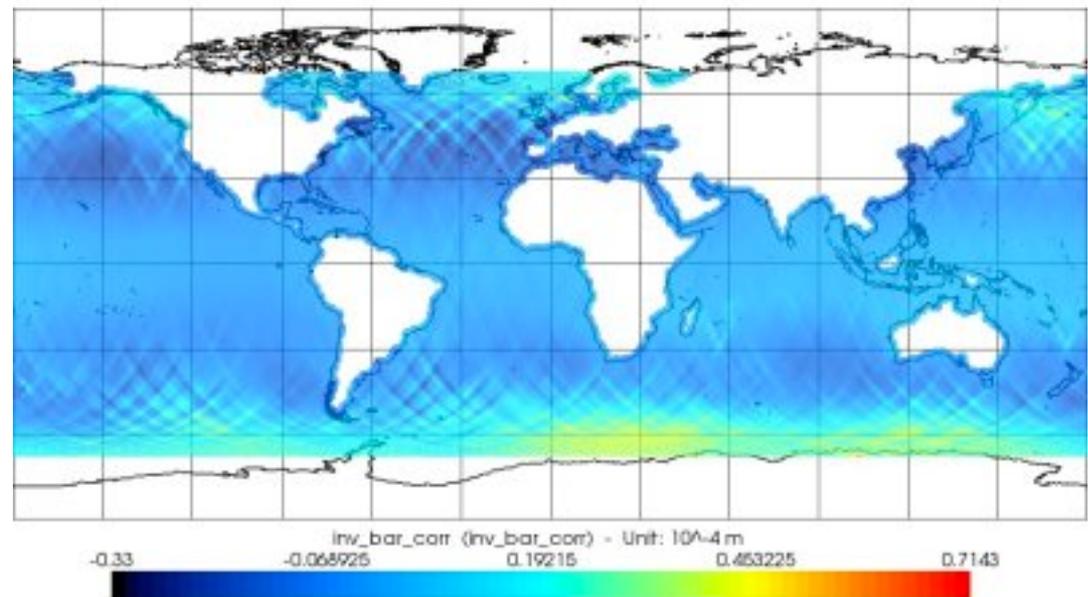


Inverse barometer

Correction for variations in sea surface height due to atmospheric pressure variations (atmospheric loading).

It can reach about ± 15 cm and it is calculated from meteorological models.

Amplitude (metres) of Inverse Barometer correction computed from ECMWF atmospheric pressures

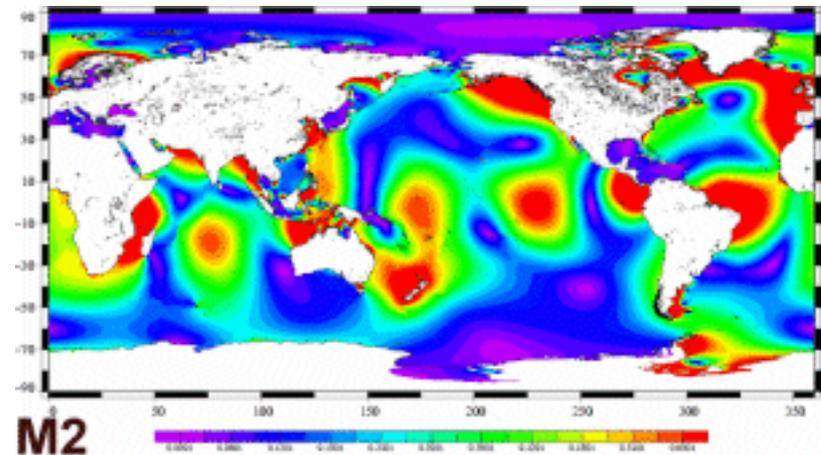


Ocean/Solid Earth tides

The combined attraction of the Moon and the Sun creates the tides and their variations.

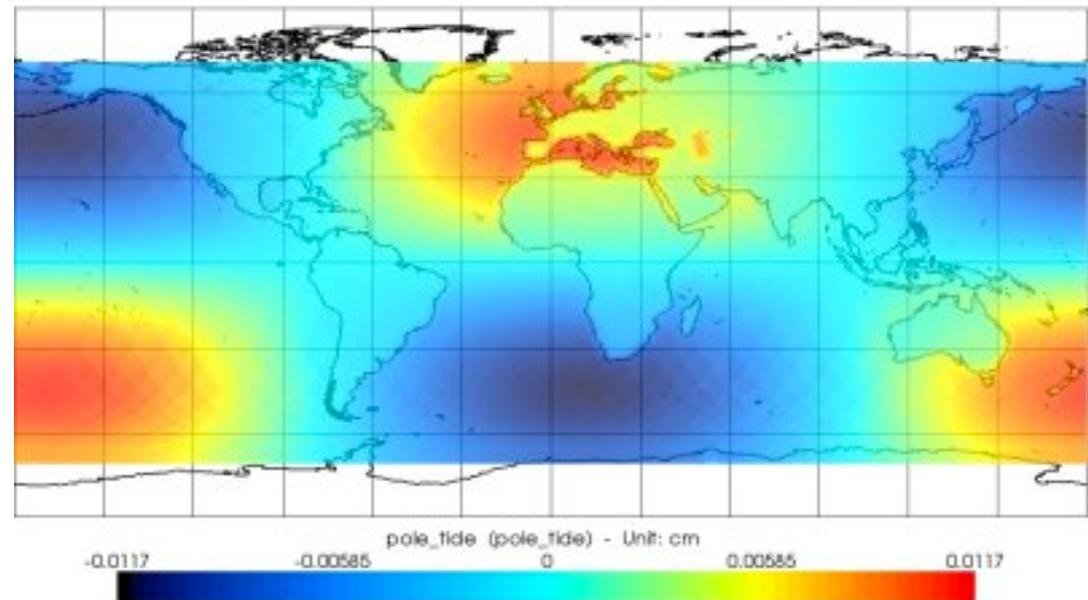
The standard deviations of tidal variations in the open ocean are 10-60 cm

Amplitude (m) of one main tide component from FES2004 model.
(M2)



Pole tides

The ocean pole tide is the ocean response to the variation of both the solid Earth and the oceans to the centrifugal potential that is generated by small perturbations to the Earth's rotation axis.



Amplitude in cm of the pole tide correction during the Jason-1 cycle 223 computed from an equilibrium model.

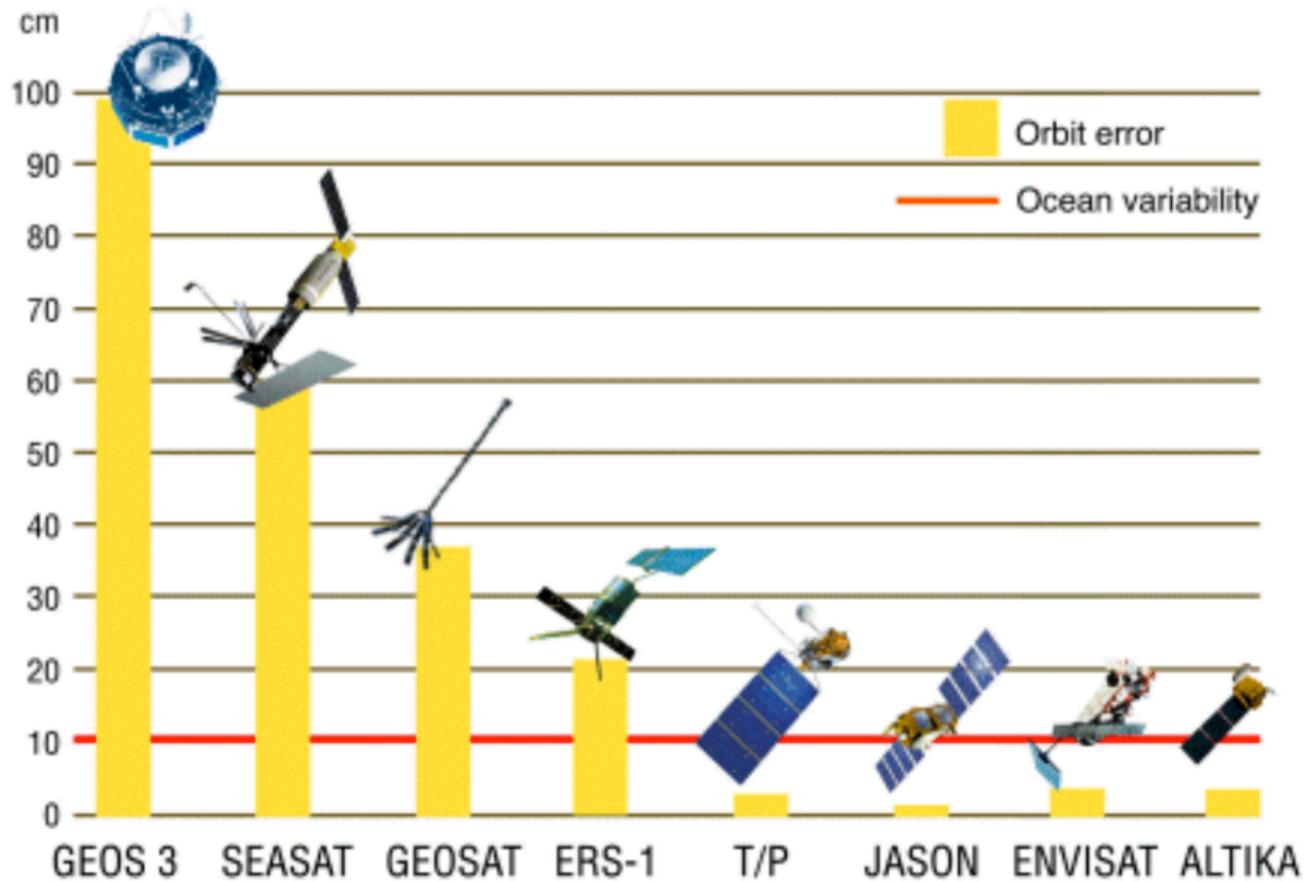
Altimetry error budget

Estimated maximum errors

Signal or Error Source	Length (km)	Height (cm)
Gravity signal	12–400	1–300
Orbit errors ^a	8000–20,000	400–1000
Ionosphere ^{b,c}	>900	20
Wet troposphere ^d	>100	3–6
Sea-state bias ^e	>20	<0.6
Inverse barometer ^f	>250	<5
Basin-scale circulation (steady) ^g	>1000	100
El Niño, interannual variability, planetary waves ^h	>1000	20
Deep ocean tide model errors ^{d,i}	>1000	3
Coastal tide model errors ^{c,i}	50–100	<13
Eddies and mesoscale variability ^j	60–200	30–50
Meandering jet (Gulf Stream) ^g	100–300	30–100
Steady jet (Florida Current) ^g	100	50–100

Taken from: Sandwell and Smith, 2009

Altimetry error budget

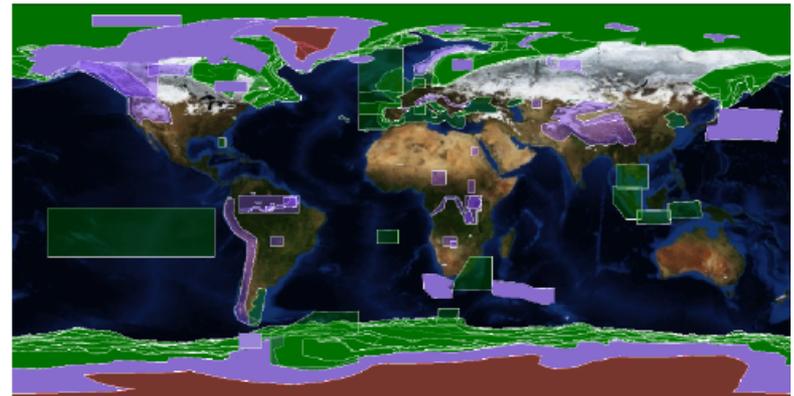


CryoSat-2 radar altimeter

Synthetic Aperture Radar (SAR) (green) is operated over sea-ice areas and over some ocean basins and coastal zones.

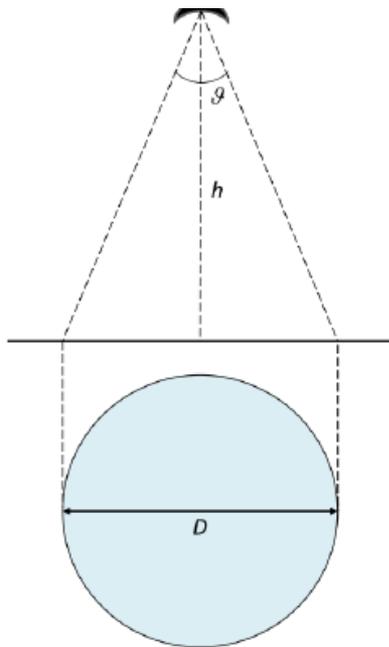
SAR Interferometric (SARIn) (purple) mode is used over steeply sloping ice-sheet margins, over some geostrophic ocean currents and over small ice caps and areas of mountain glaciers. It is also used over some major hydrological river basins.

Low Resolution Mode (LRM) (red) conventional radar altimetry over interior ice sheets



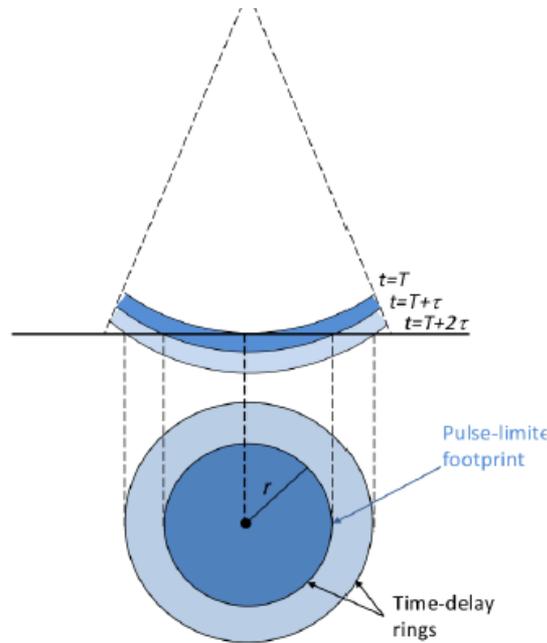
- The end

CryoSat-2 radar altimeter



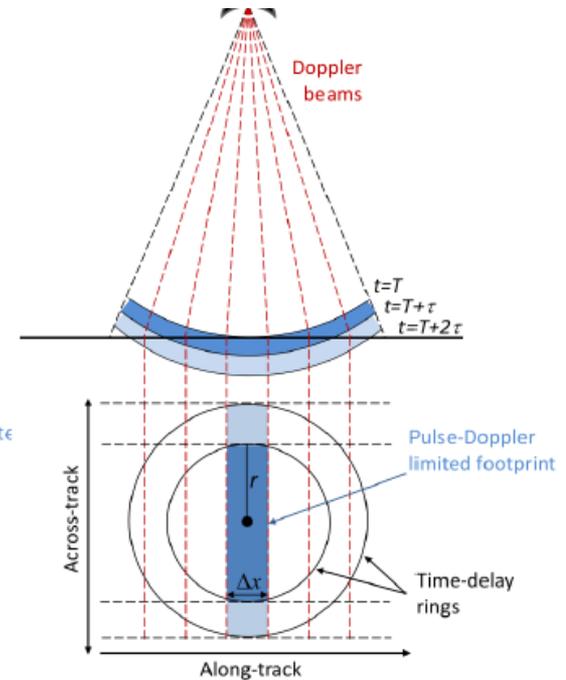
BEAM-LIMITED

$$D = 2h \tan \frac{\theta}{2}$$



PULSE-LIMITED

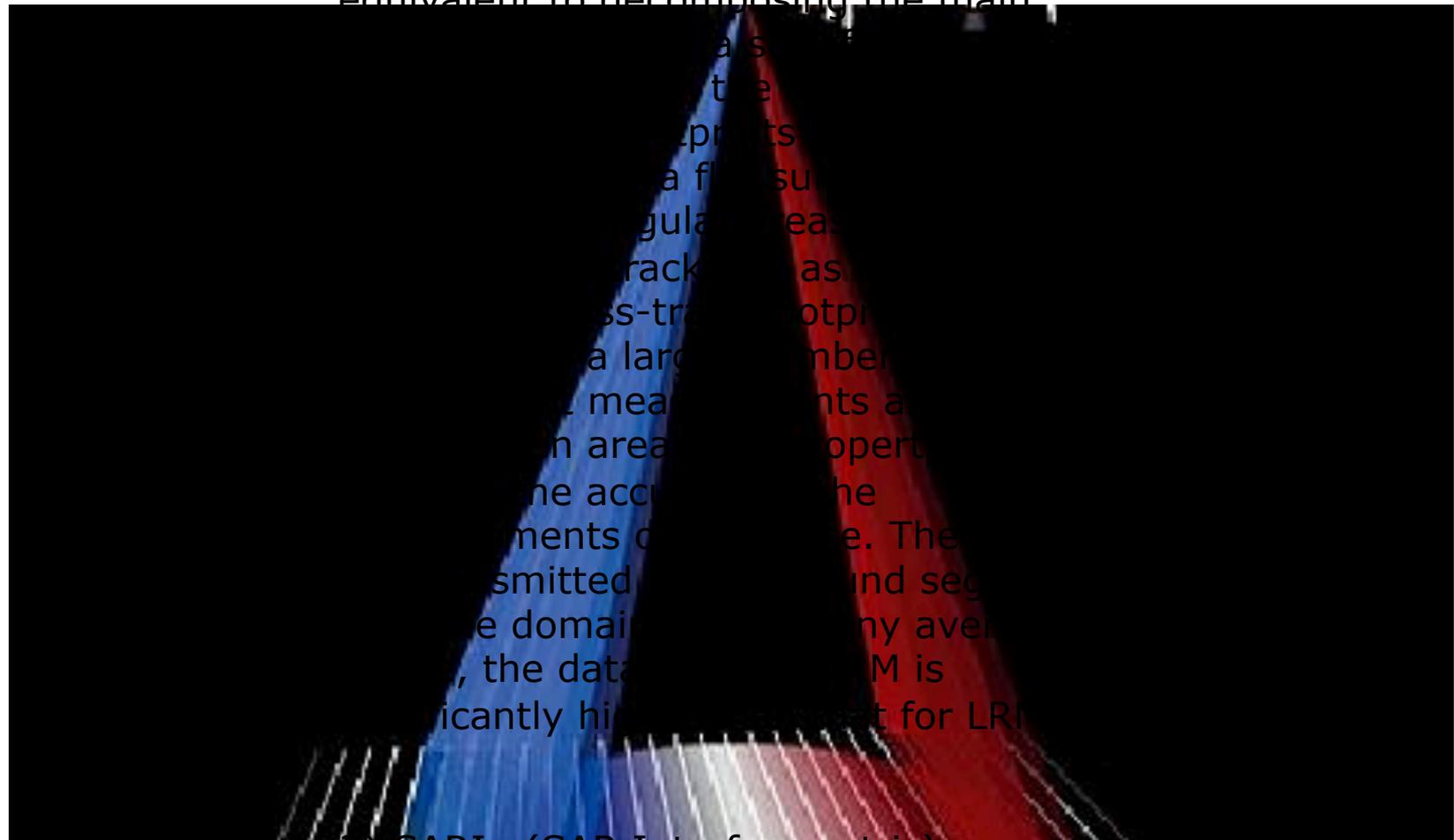
$$r = \sqrt{h c \tau} = \sqrt{h \frac{c}{B}}$$



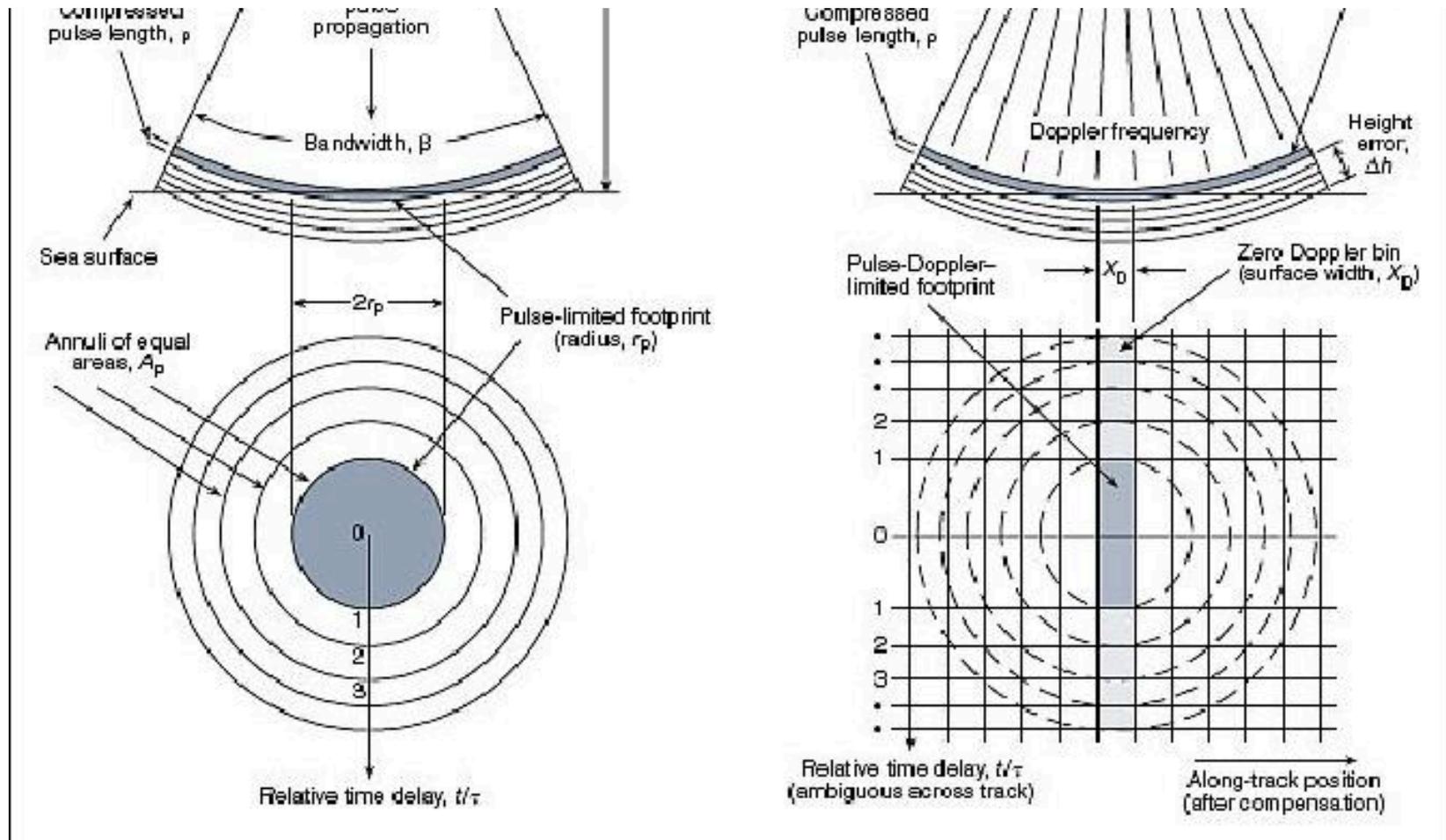
DOPPLER-LIMITED

$$\Delta x = h \frac{\lambda}{2N\nu} \text{PRF}$$

In SAR, the resolution of the radar is improved in the along-track direction. This is achieved by exploiting the Doppler properties of the echoes as they cross the antenna beamwidth. The result is equivalent to decomposing the main



3) SARIn (SAR Interferometric) support mode. The objective is to provide improved elevation estimates over



Beam limited versus pulse limited altimeters



- and a Delay-Doppler Altimeter “can be seen”
- as beam-limited in the along-track direction