# Altimetry theory

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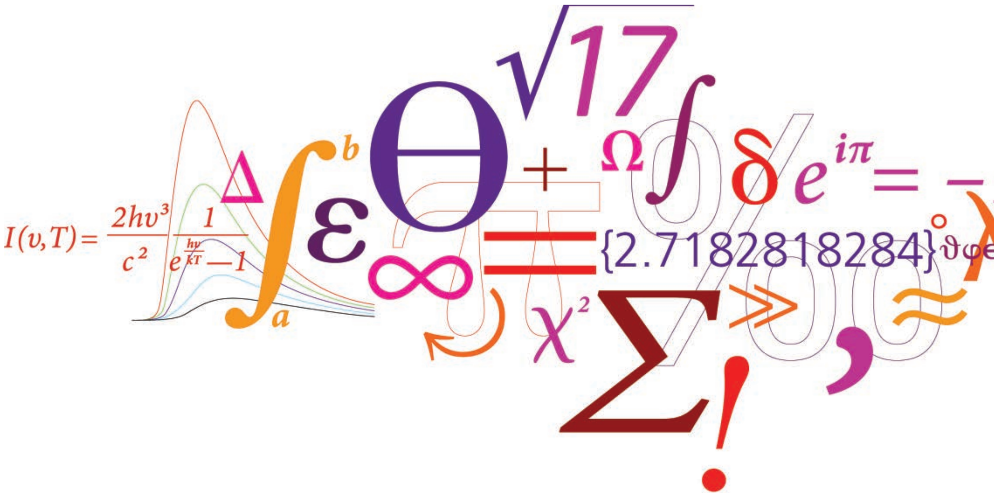


What is an altimeter?

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:

$$distance = velocity * TWT / 2$$

# Principle of satellite altimetry

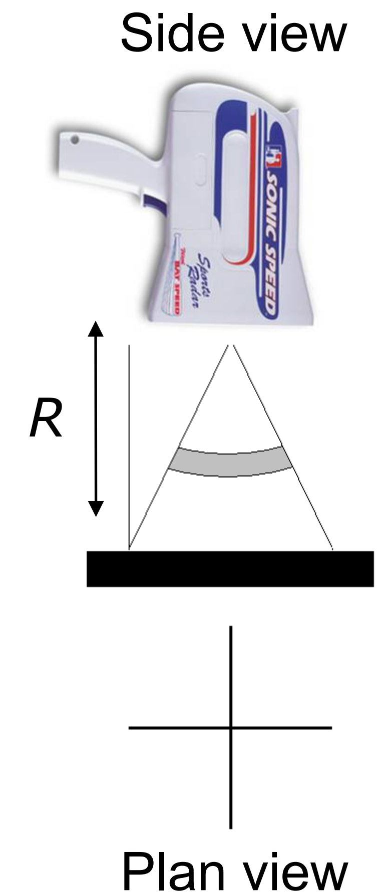
(1) Radars transmit pulses of electromagnetic radiation at radio frequencies

(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.

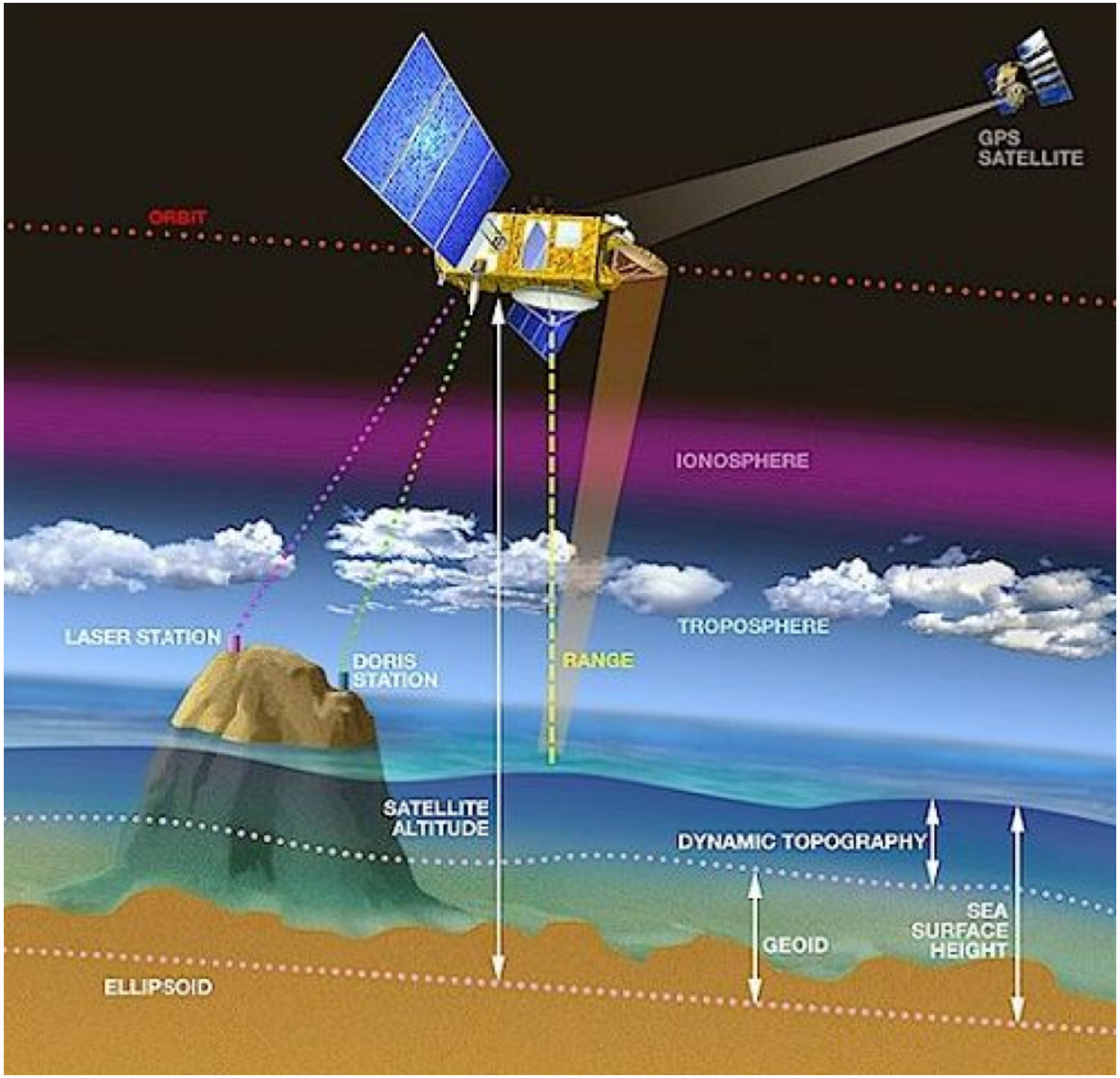
(5) The travel time is converted into the distance (range) separating the radar and the surface.






(Credits A. Shepherd)

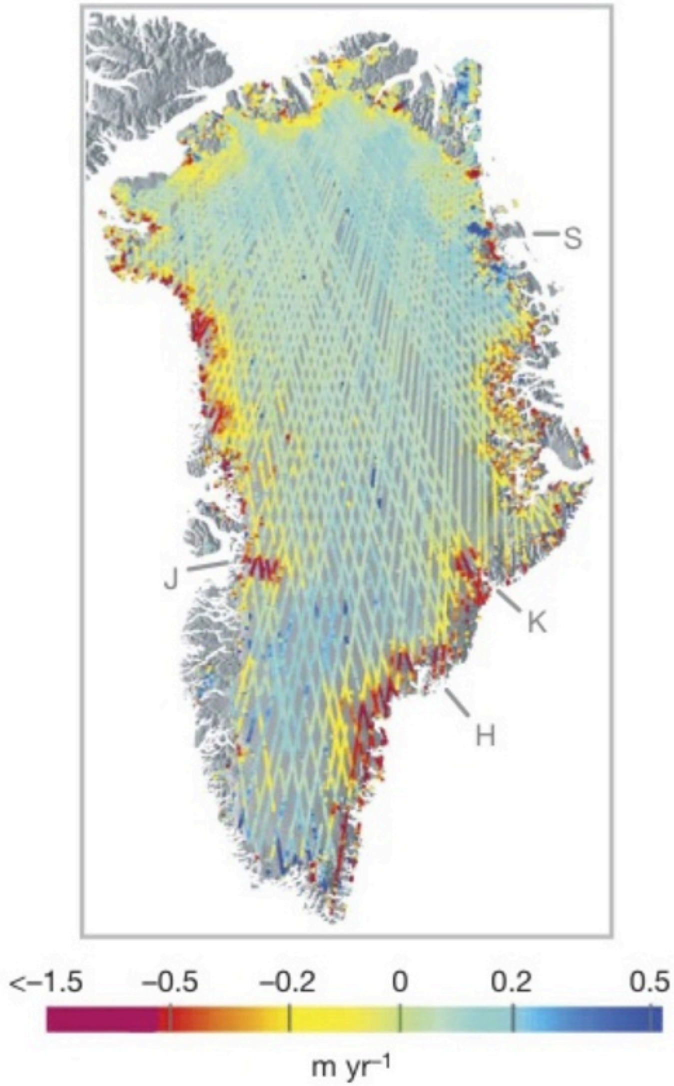
# Principle of satellite altimetry




(Credits CNES/D. Ducros)

## What can we observe with satellite altimeters?

# Altimeters for studying the cryosphere

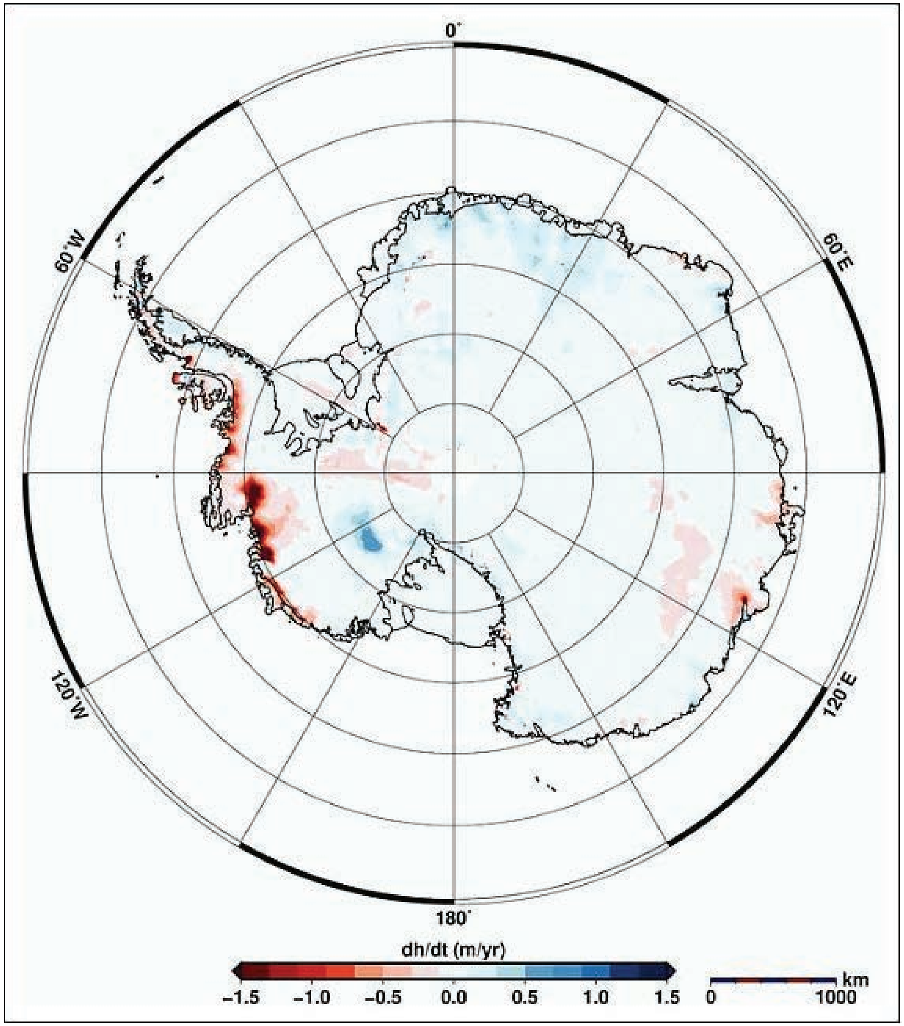



Elevation changes of the Greenland ice sheet.

Derived from ICESat data 2003-08.

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

# Altimeters for studying the cryosphere

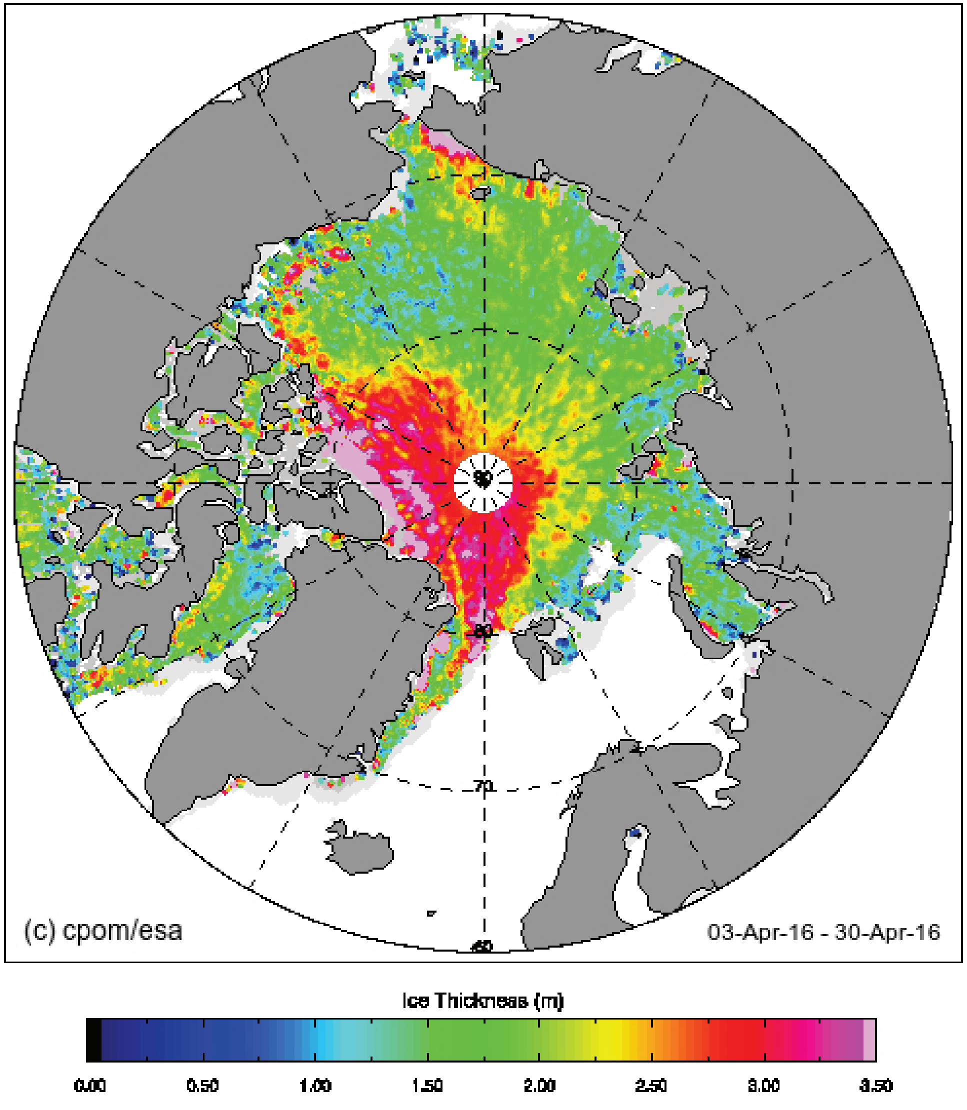



Elevation changes of Antarctica ice sheet

Derived from CryoSat-2 data 2011-14.

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

# Altimeters for studying the cryosphere

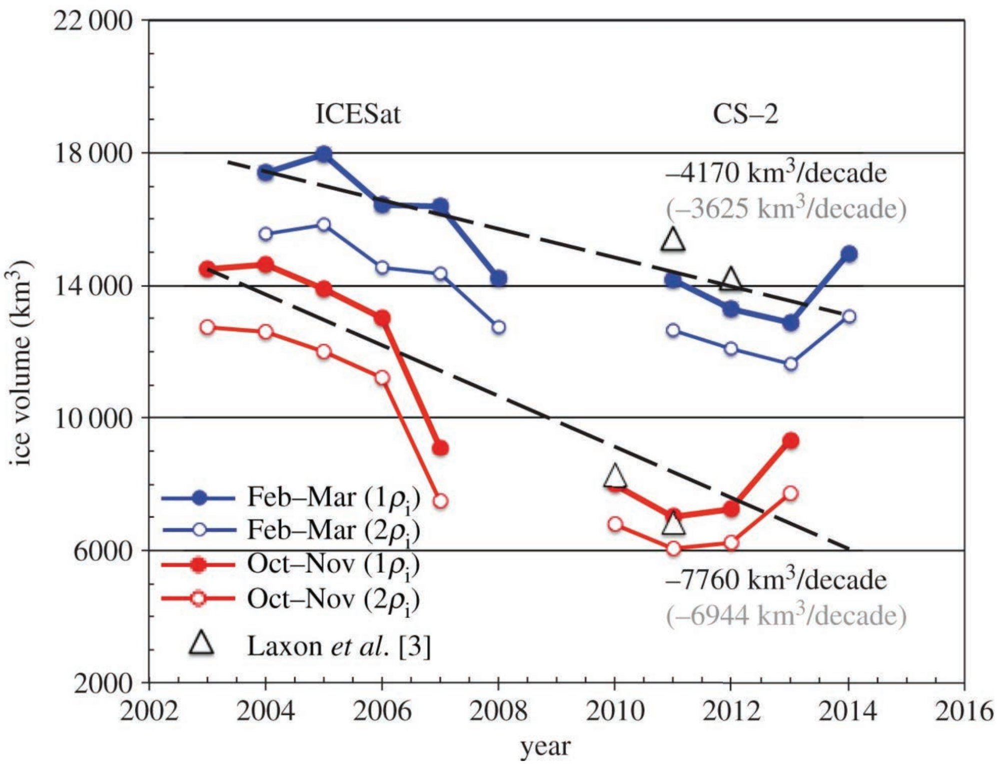



Arctic sea ice thickness

Derived from CryoSat-2 data April 2016.

(credits: CPOM/ESA)

# Altimeters for studying the cryosphere

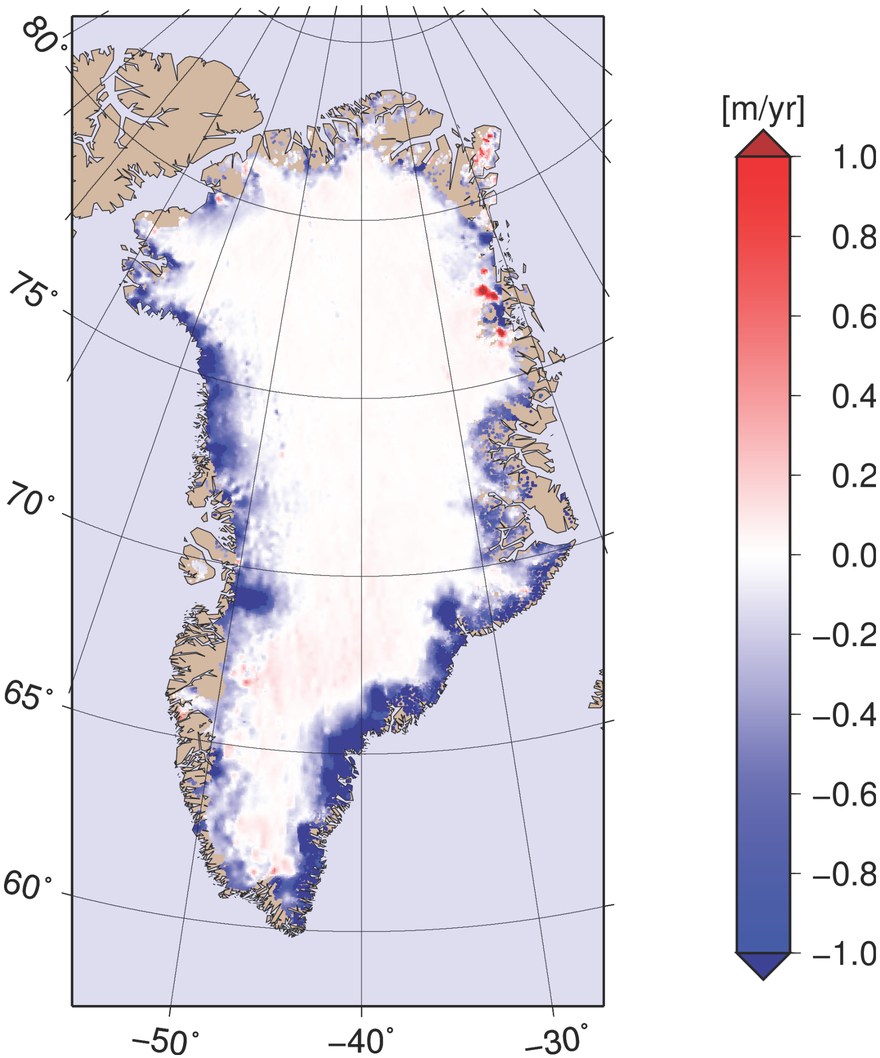



Decline in Arctic sea ice volume

Derived from ICESat and CryoSat-2 data

(credits: Kwok & Cunningham, 2015)

# Altimeters for studying the cryosphere

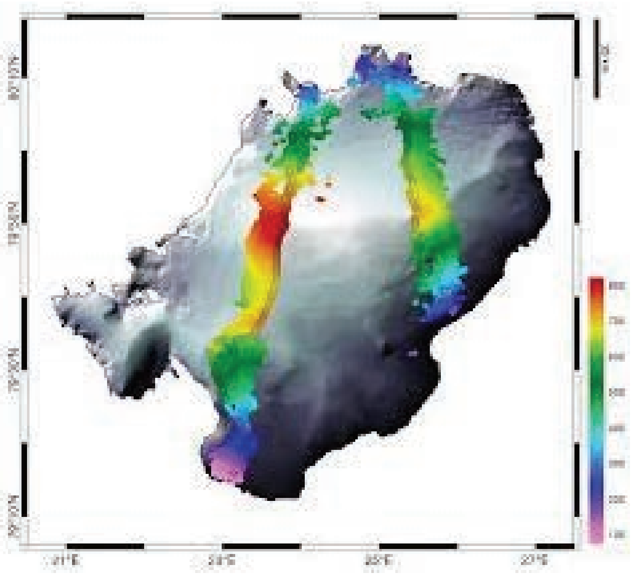



Greenland ice sheet mass changes

Derived from ICESat data 2003-08

(credits: Sørensen et al., 2011, TC)

# Altimeters for studying the cryosphere

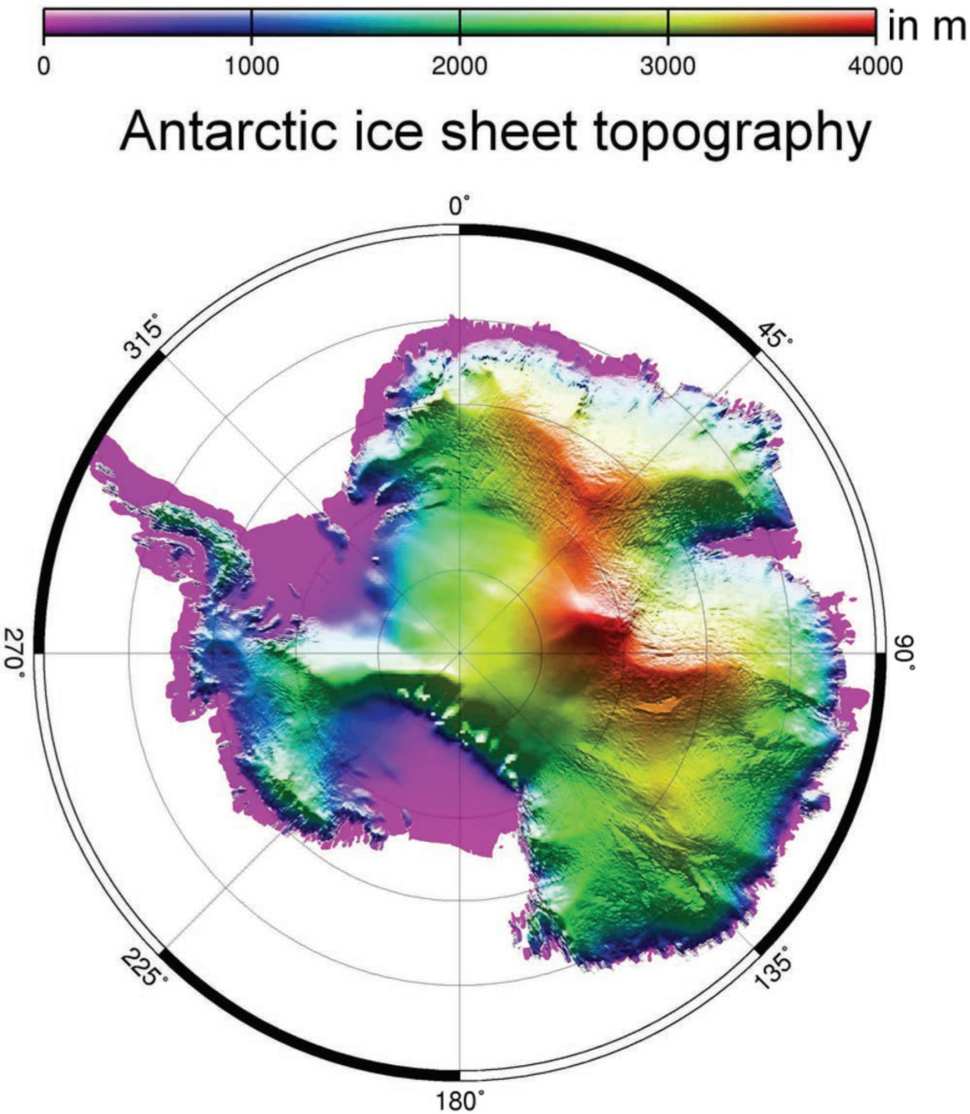


Detailed mapping if ice cap in Iceland

Derived from CryoSat-2 swath processing

(credits: N. Gourmelen & Cryotops cons.)

# Altimeters for studying the cryosphere

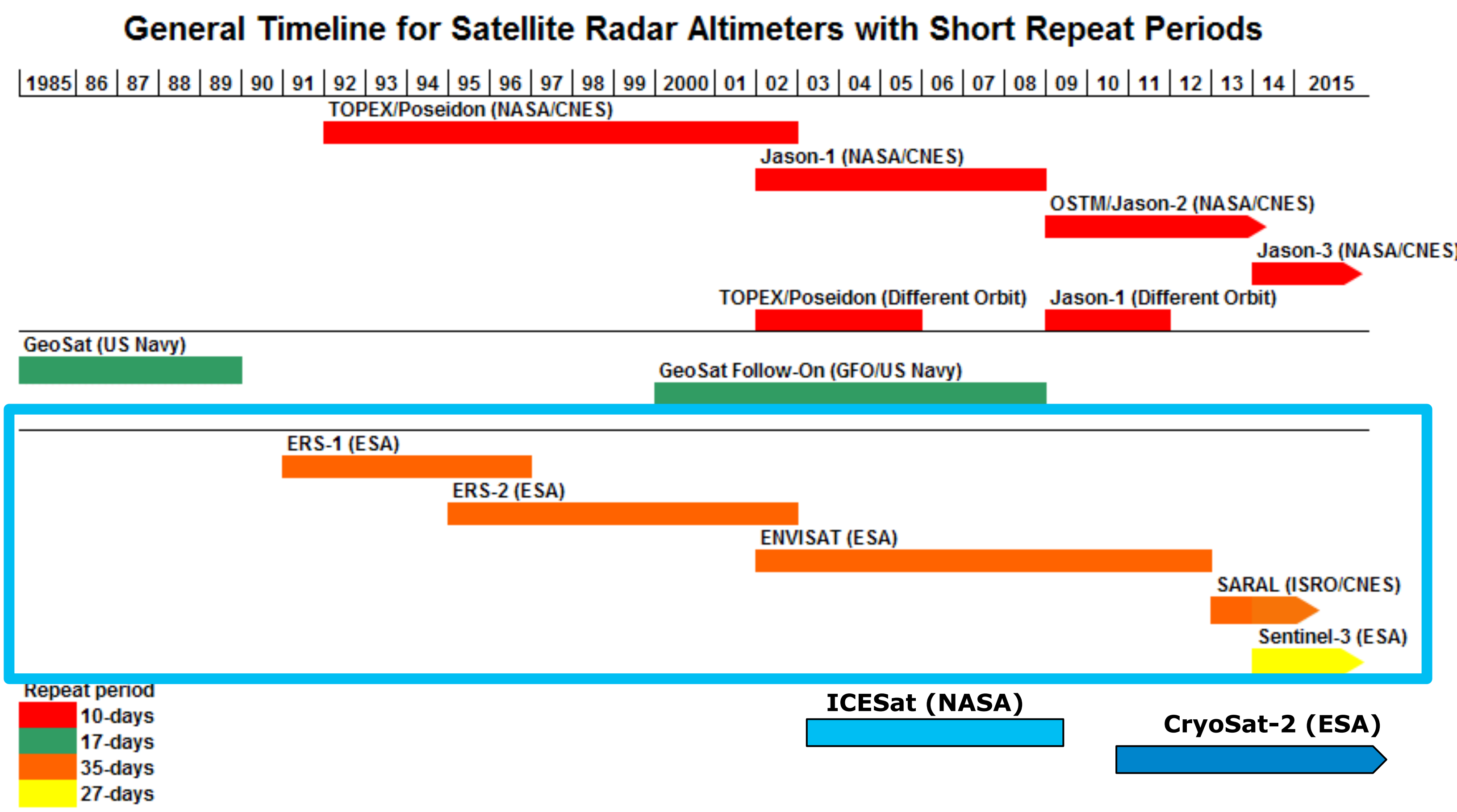



Digital elevation model Antarctica

Derived from ERS-1

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

# Missions




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

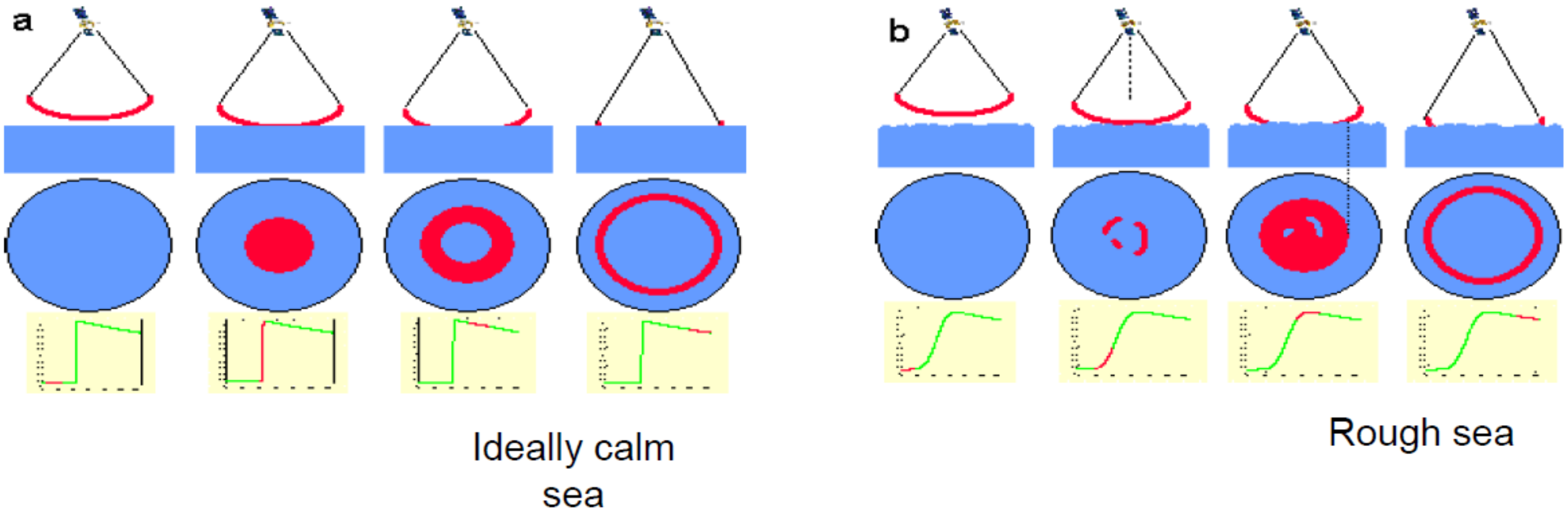
# What is a waveform?

# Waveforms

The magnitude and shape of the altimetry return echoes

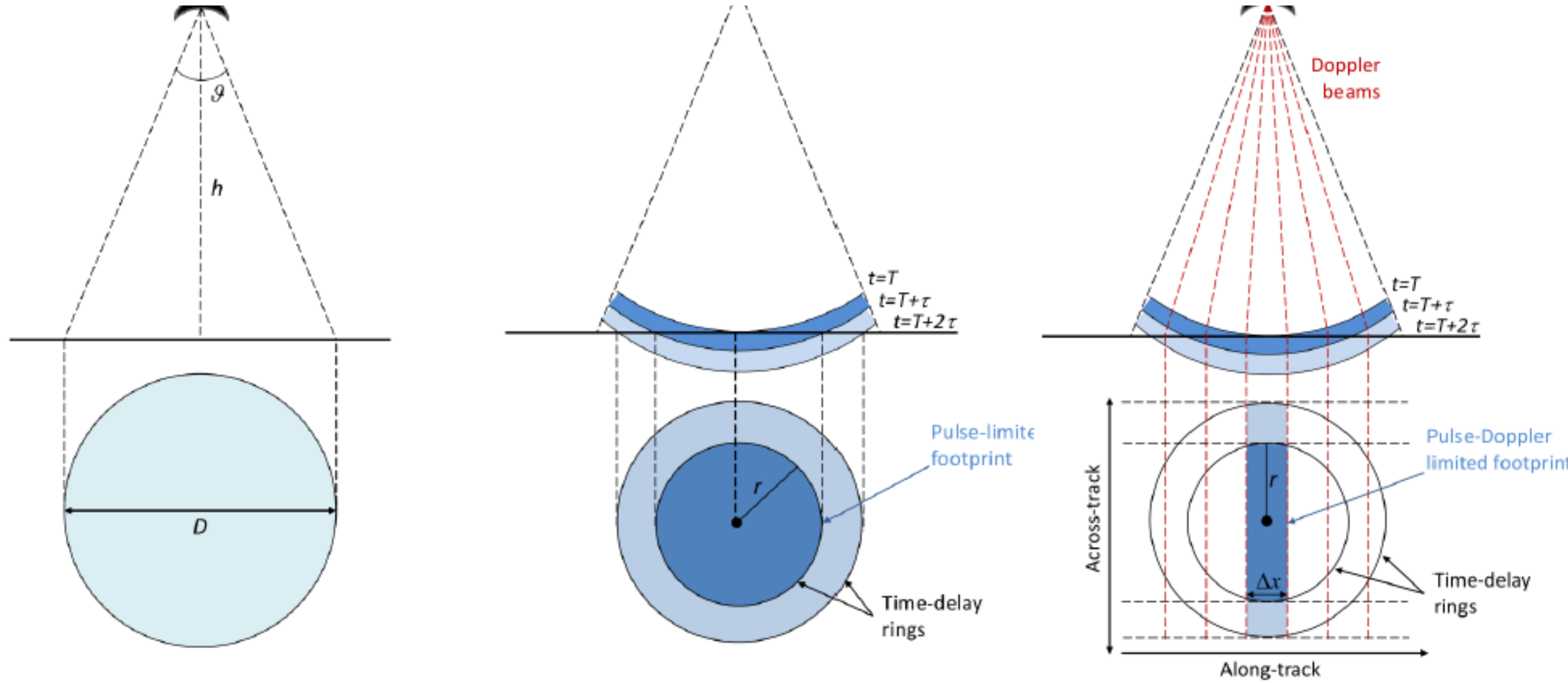
Credit: http://www.altimetry.info/

# Waveforms




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

# Radar footprints




BEAM-LIMITED

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

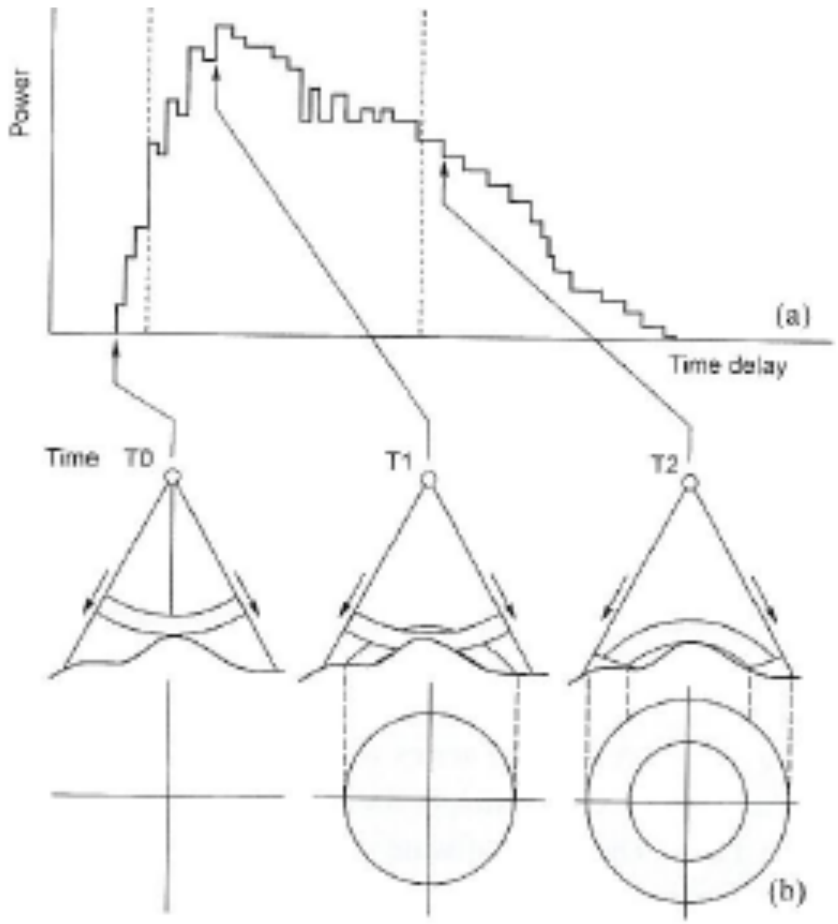
PULSE-LIMITED

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

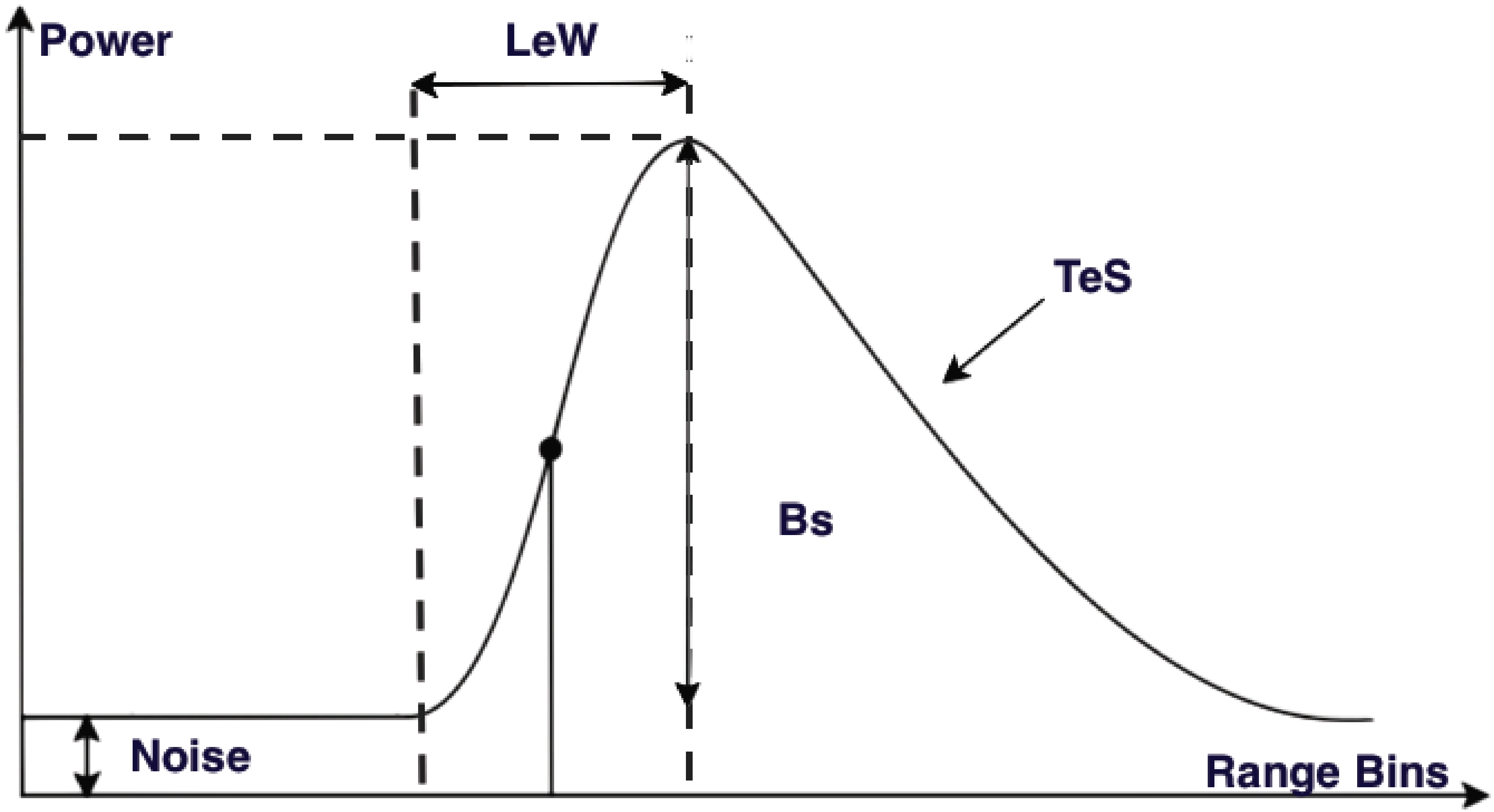
DOPPLER-LIMITED

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

# Waveforms



# Waveform parameters



# Radar or laser altimetry?

# Radar or laser altimetry?

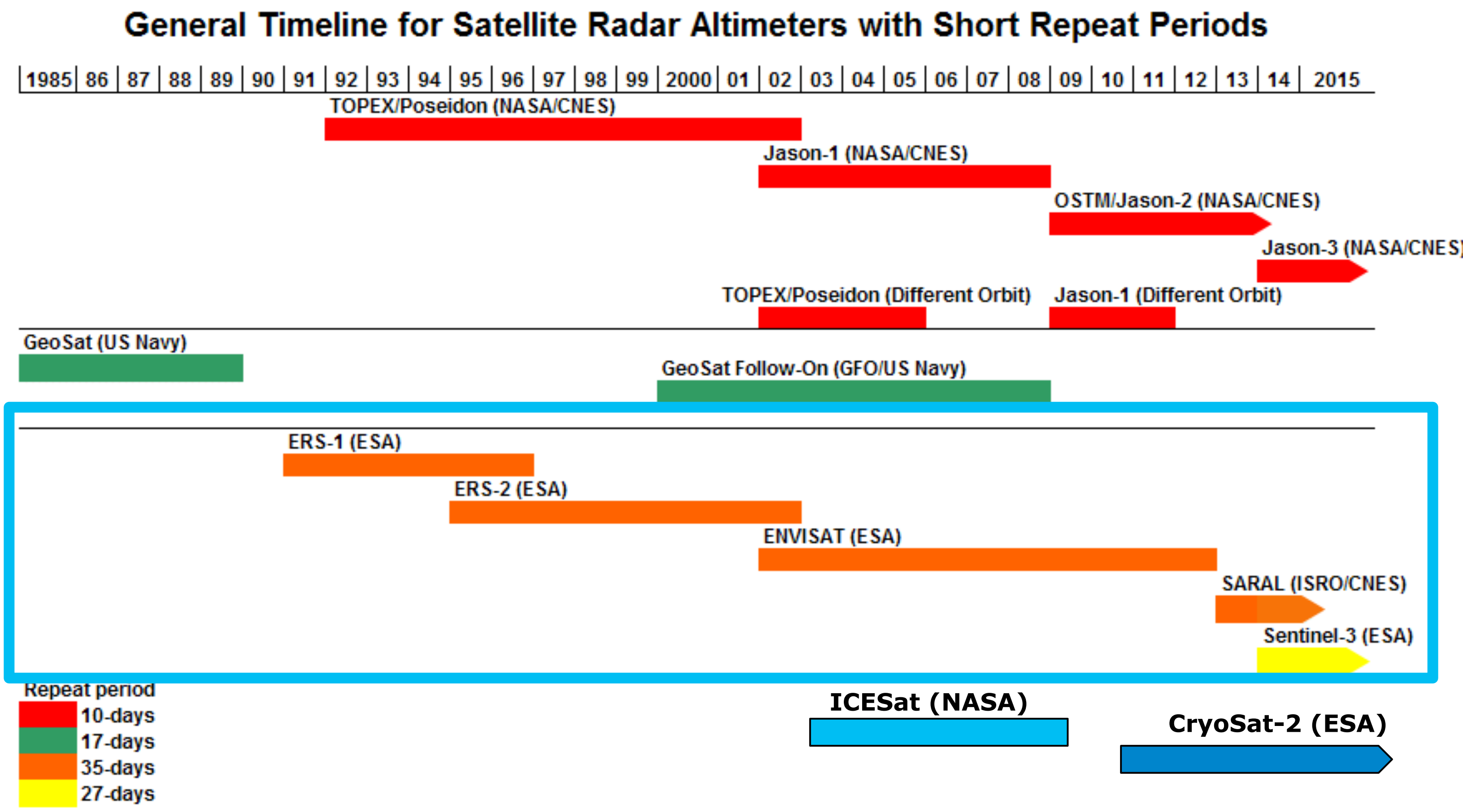
- **Radar altimetry**

✧ 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**

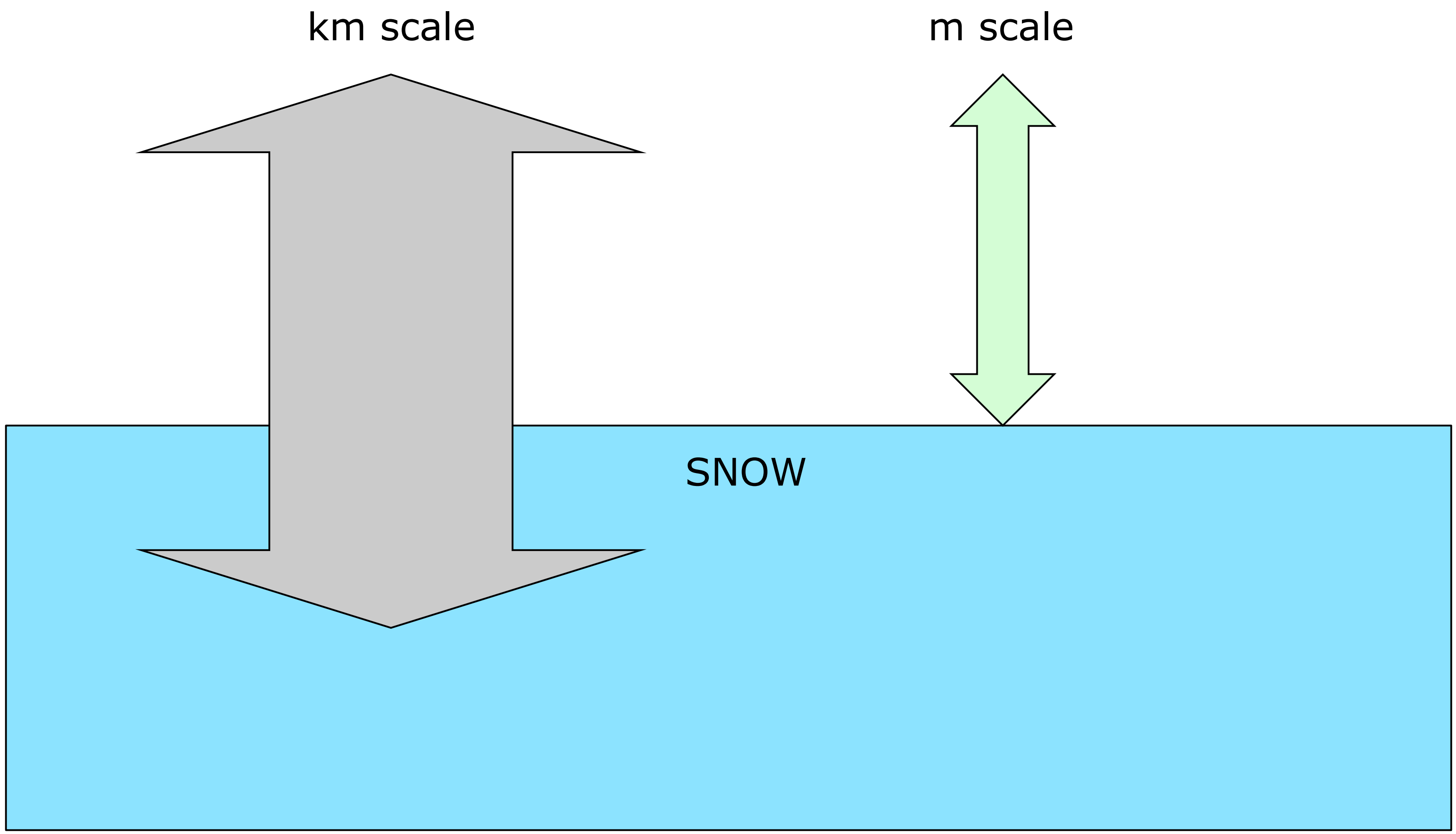
✧ Footprint 40-70 meters
✧ Vertical accuracy < 10cm
✧ Weather dependent, clouds
✧ Energy consuming, not robust
✧ For cryosphere only ICESat (2003-09)
✧ works over water, ice and land

# Missions



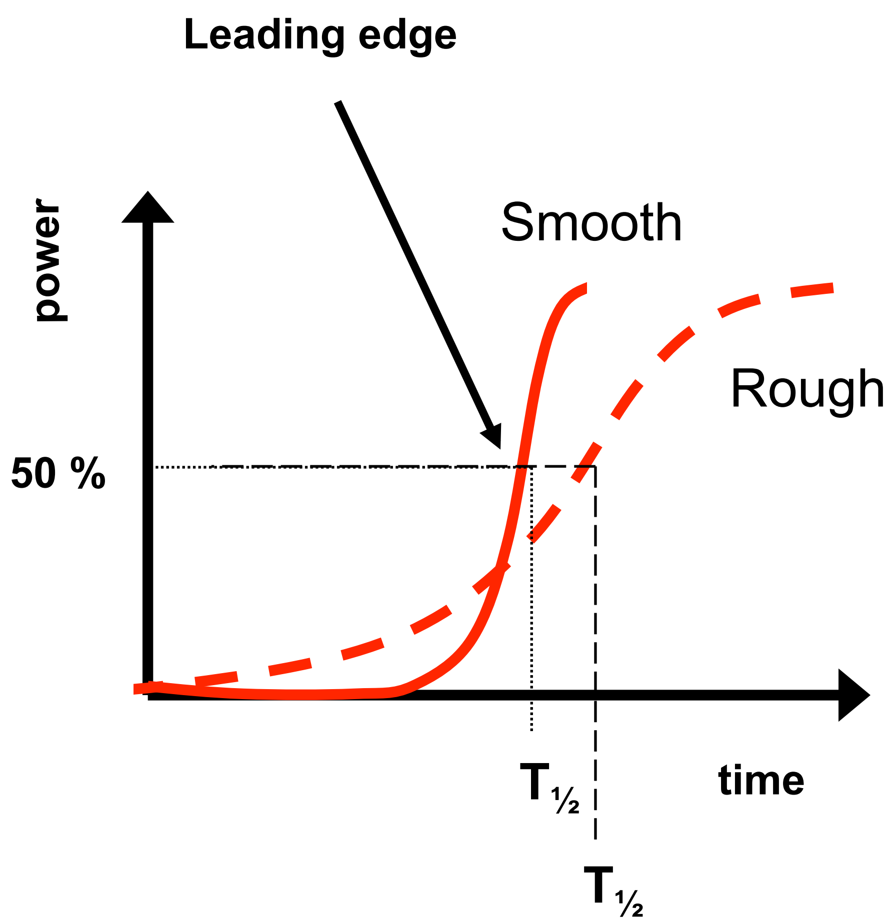

From : http://www.pecad.fas.usda.gov/

# Radar versus laser



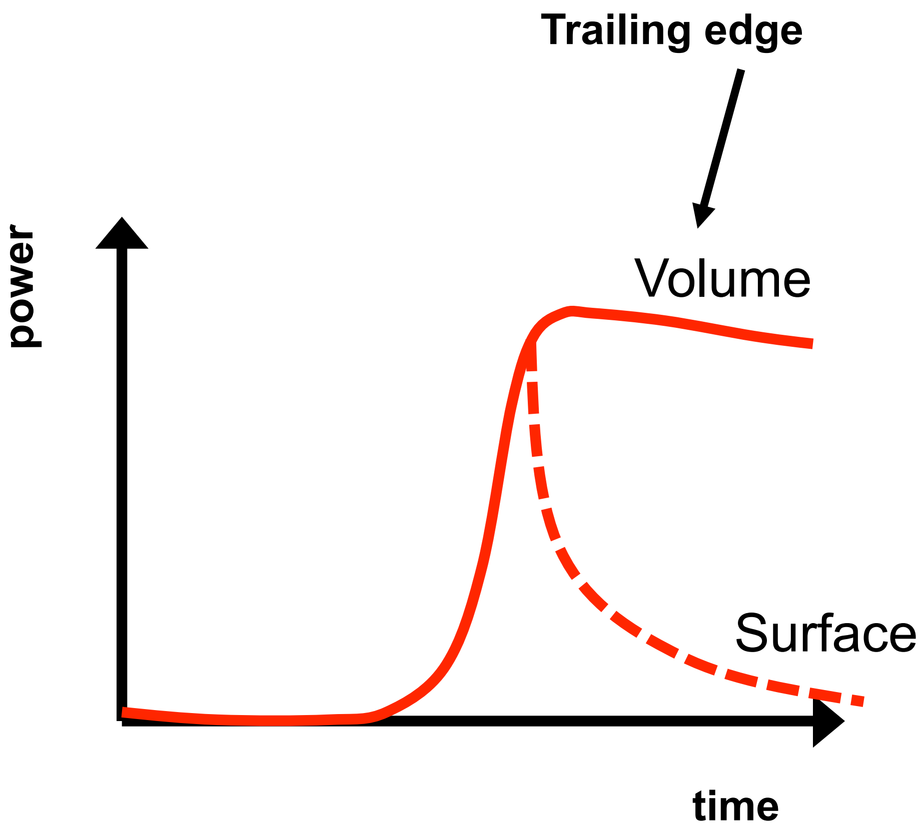
# Radar waveforms from different surfaces

# Radar Waveforms



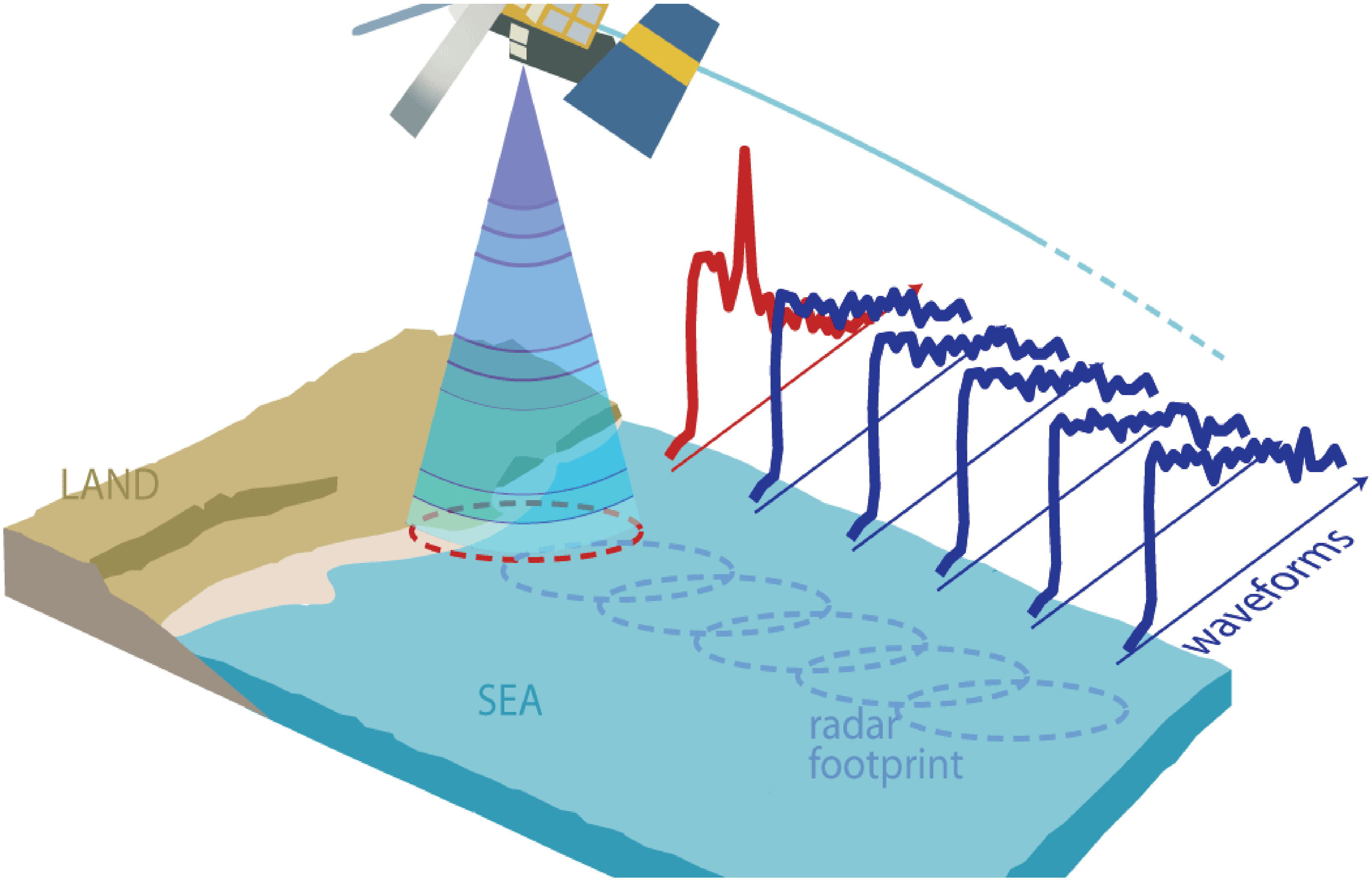

- Leading edge of pulse echo corresponds to first interaction with surface
- Slope of leading edge is related to surface roughness
- Smooth surfaces have steep leading edge, rough surfaces have shallow leading edge
- **Can estimate surface roughness from shape of leading edge**
- **But affects re-tracking**

# Radar Waveforms

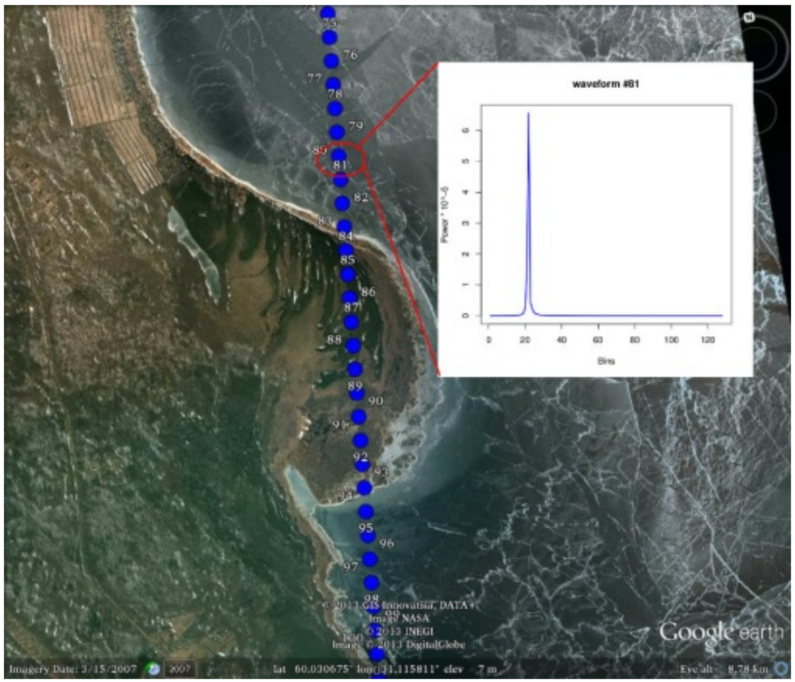


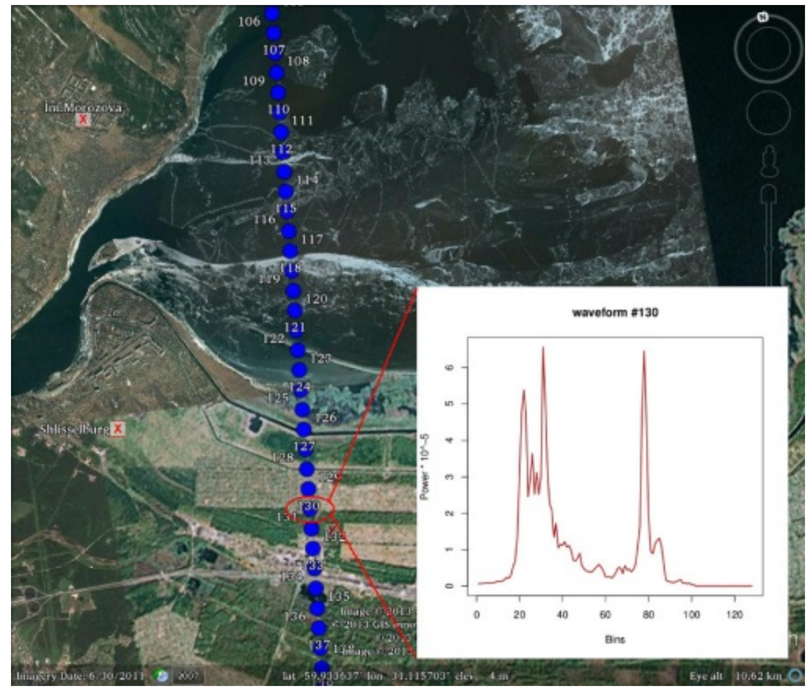

- Trailing edge of pulse is also related to scattering properties of the surface
- Rapid tailing off when scattering is only from surface
- Slow tailing off when additional scattering from depth (due to penetration)
- **Degree of penetration can be characterised by slope of trailing edge**

# Radar waveforms from different surfaces

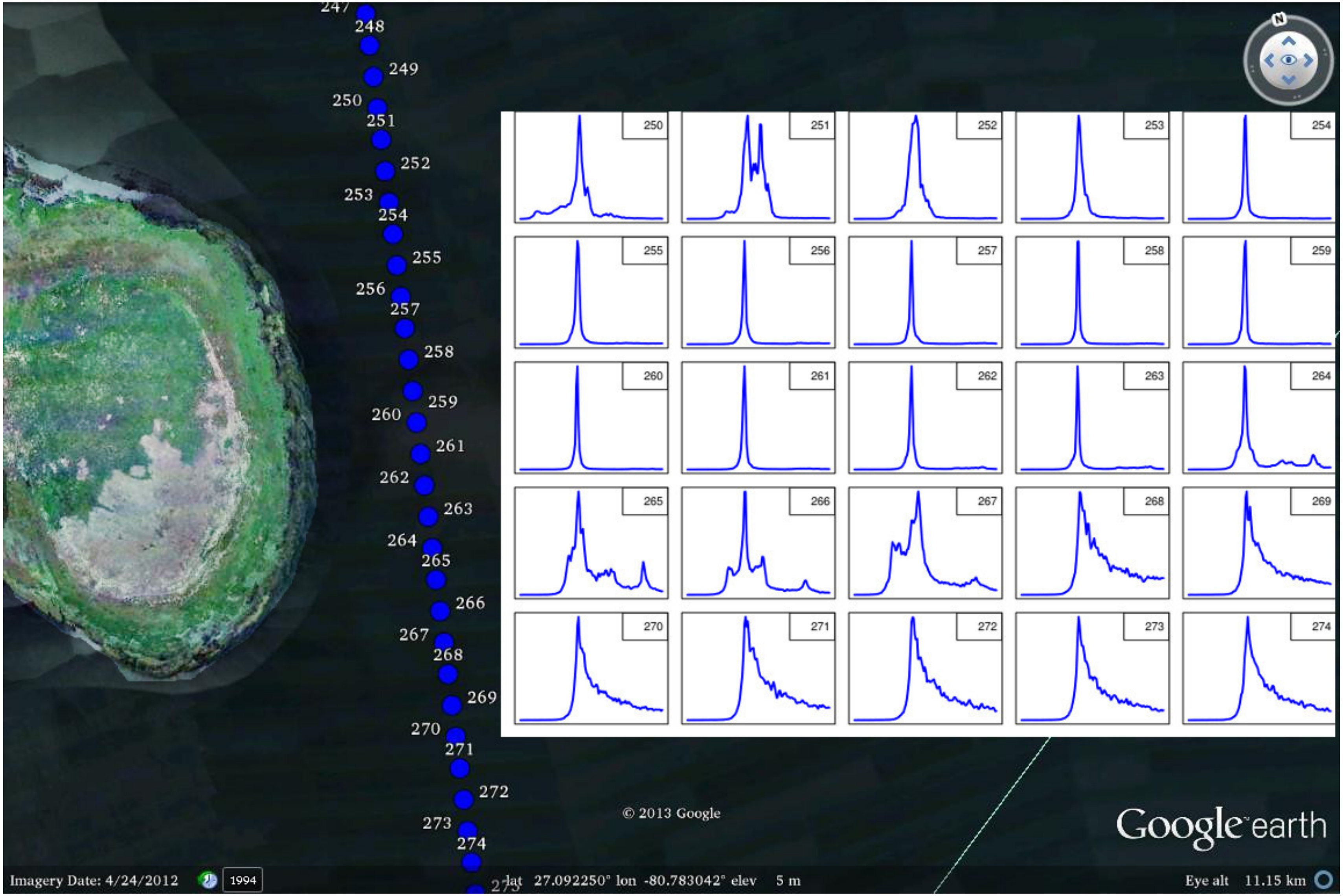


# Radar waveforms from different surfaces

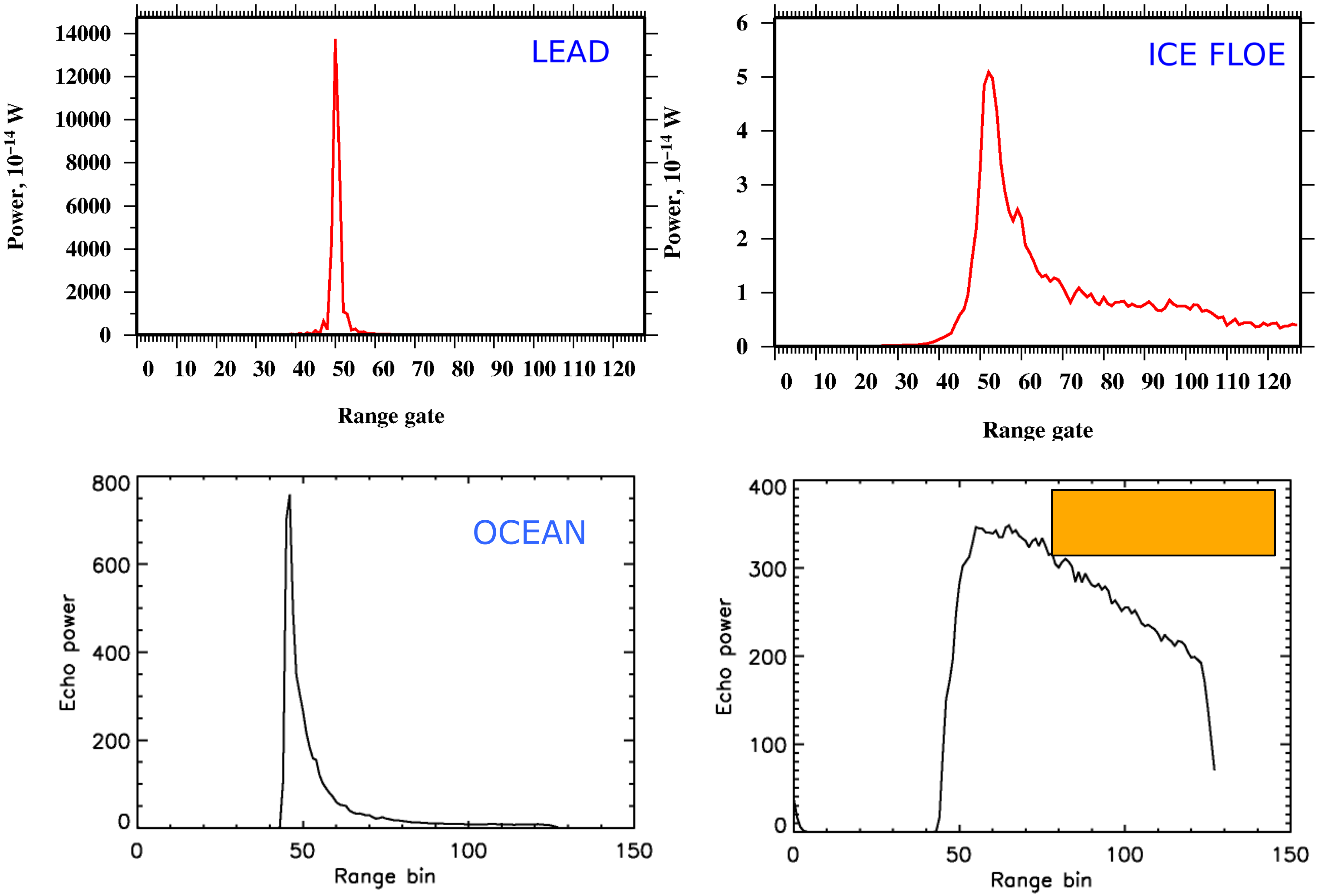


# Radar waveforms from different surfaces

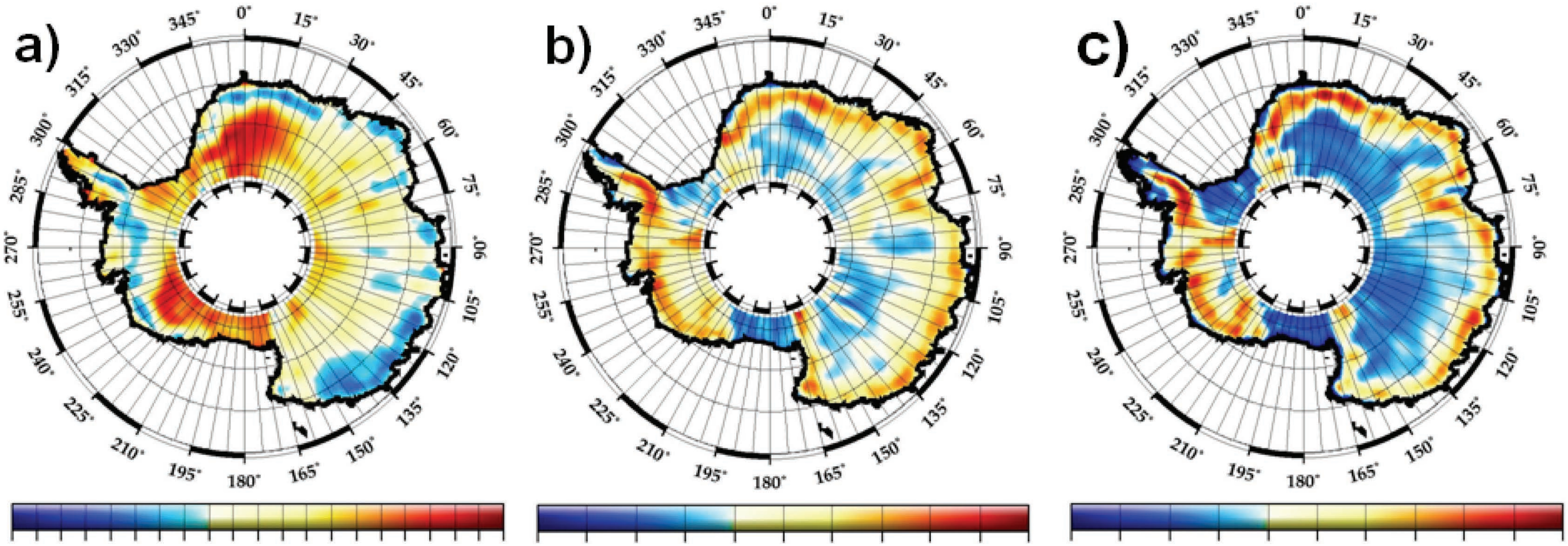


# Radar waveforms from different surfaces



# 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

Retracking is the term used to describe a ground processing estimation technique which attempt to *determine the range to the point of closest approach on the surface*.

OCOG

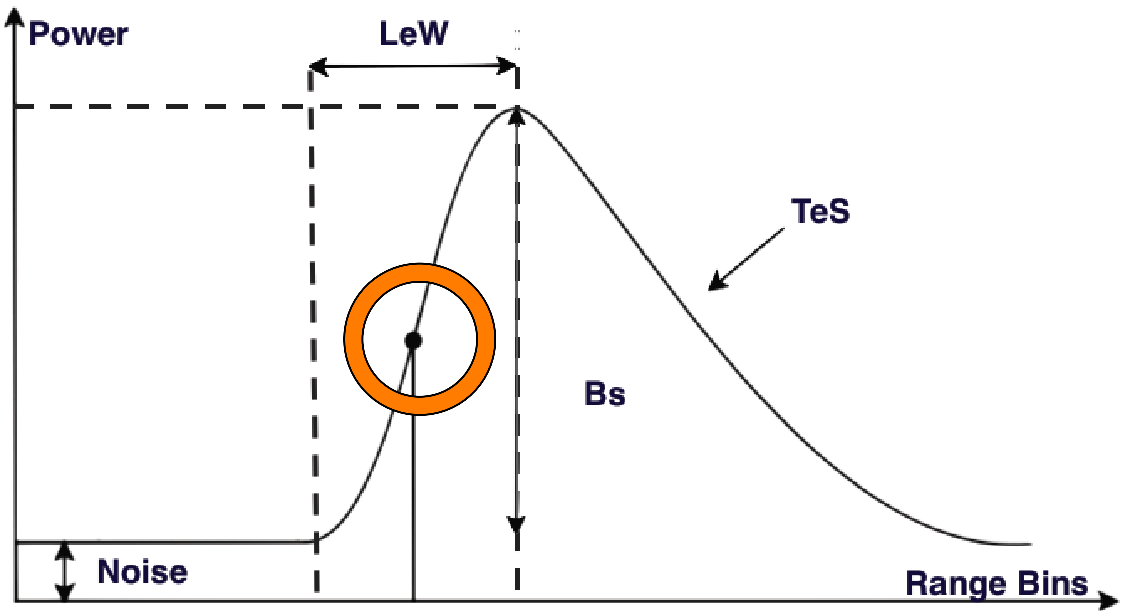
Threshold

Gradient

Ice-1

Ice-2

……



# Retrackers

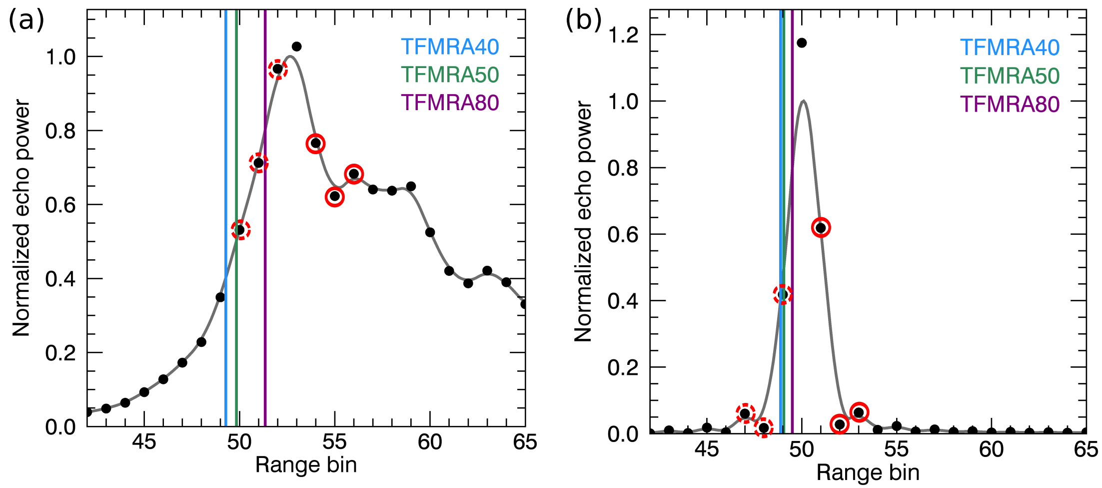
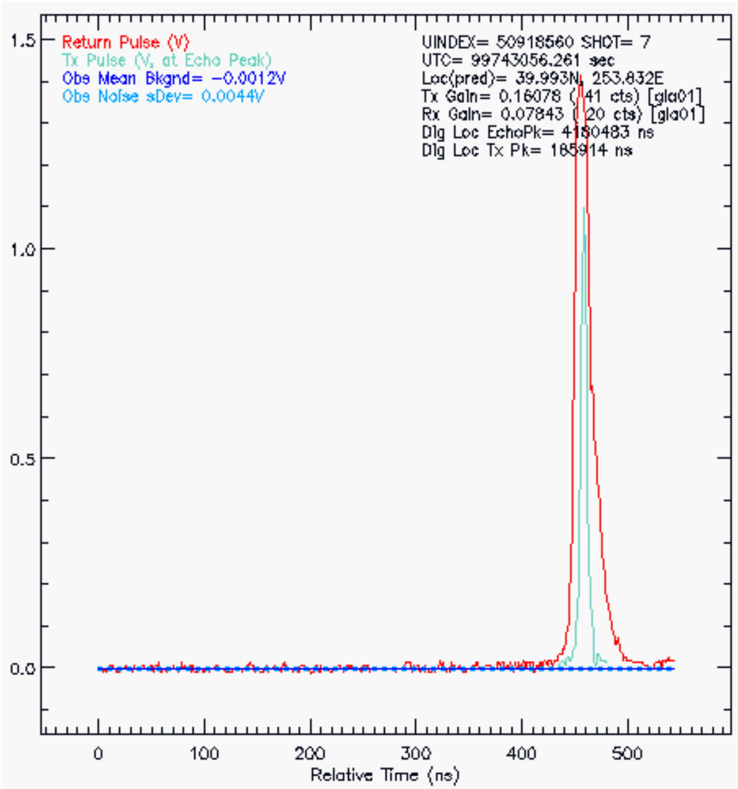



**Figure 3.** Typical CryoSat-2 waveforms for sea ice **(a)** and leads **(b)**. The fitted waveform (grey) is a result of linear interpolation and smoothing of the original CryoSat-2 waveform (black dots). The coloured vertical lines represent the different applied TFMRA (threshold first-maximum retracker 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

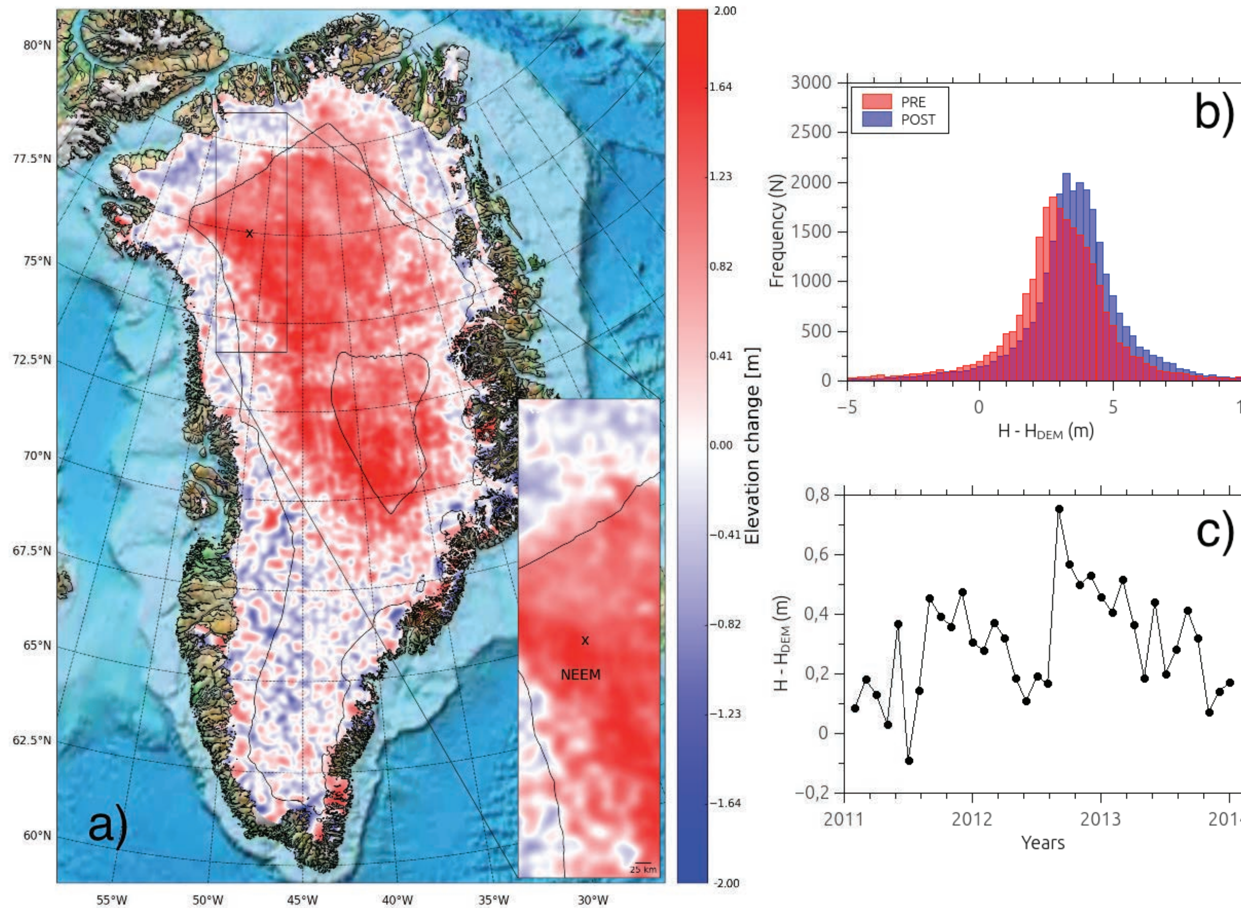
# Retrackers

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



# Changes in surface properties

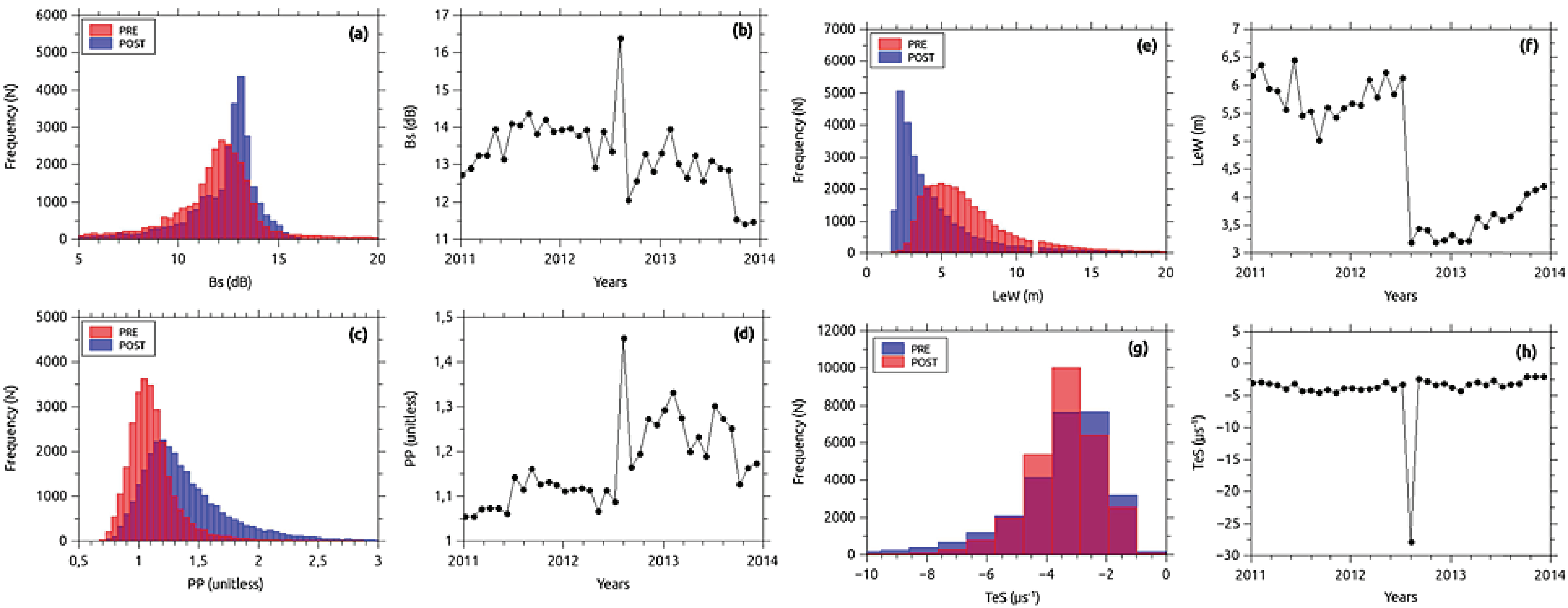
- Trend analysis of 2012 Cryosat-2 data showed anomalous thickening in the interior parts of the GrIS.
- The 2012 event was credited to be the most viable source, after processing errors were discarded.
- Based on CryoSat data near NEEM before and after melt event




Cryosat-2 derived elevation changes from 2012

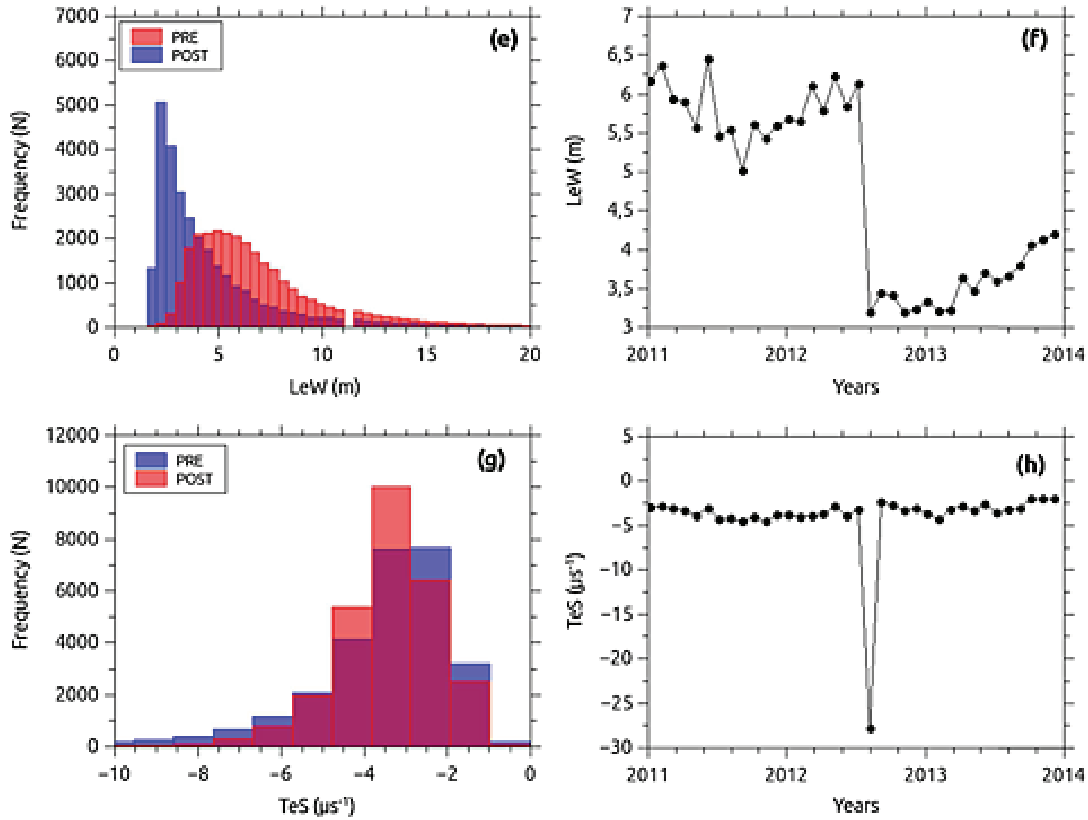
(Nilsson et al. 2015)

# 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

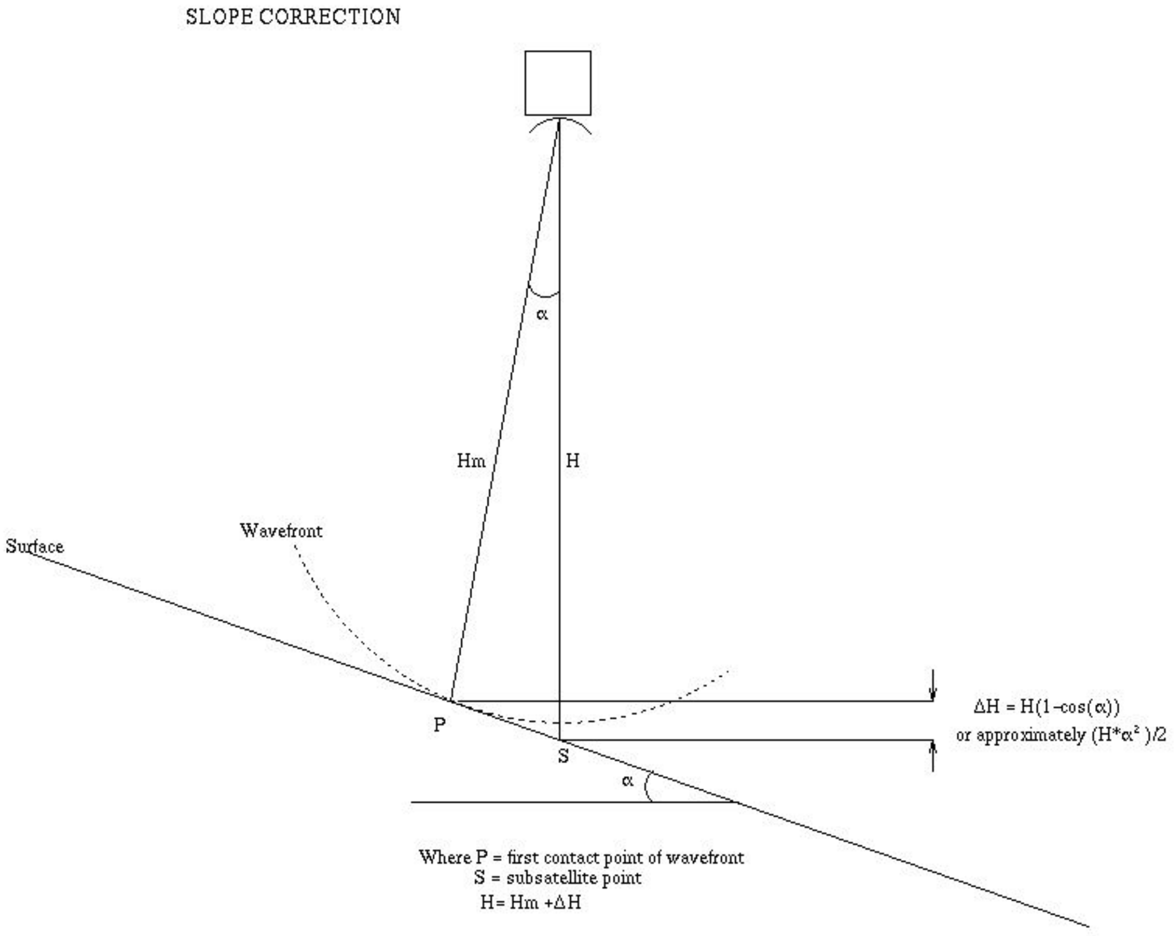
Altimetric waveforms can be seen as the histogram of the backscattered energy with respect to the return time.

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).

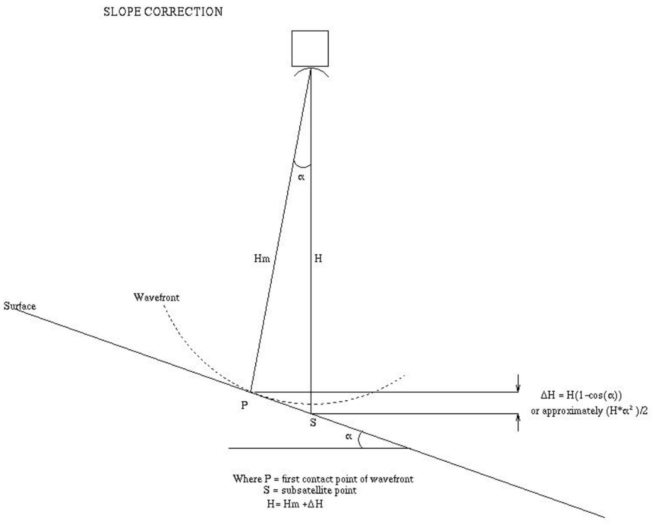
**The main issue in altimetric measurements interpretation is to distinguish between all these effects.**

# Radar altimetry on slopes

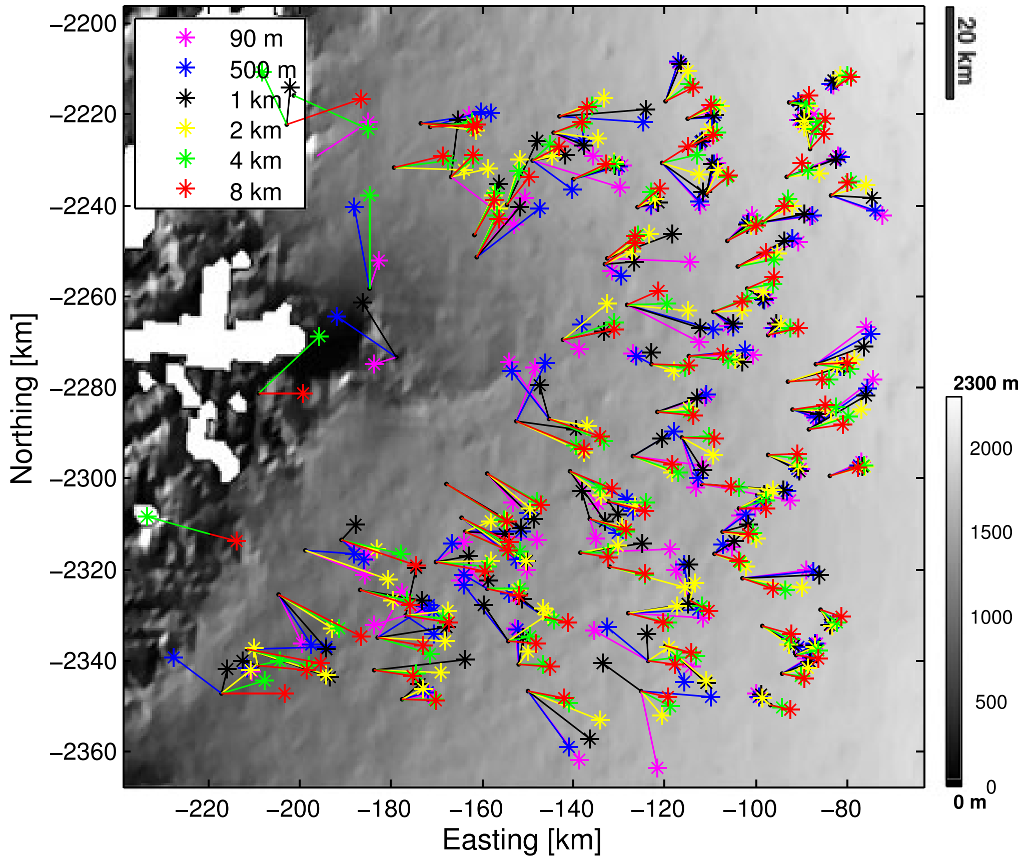


# Radar altimetry on slopes

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



# Radar altimetry on slopes

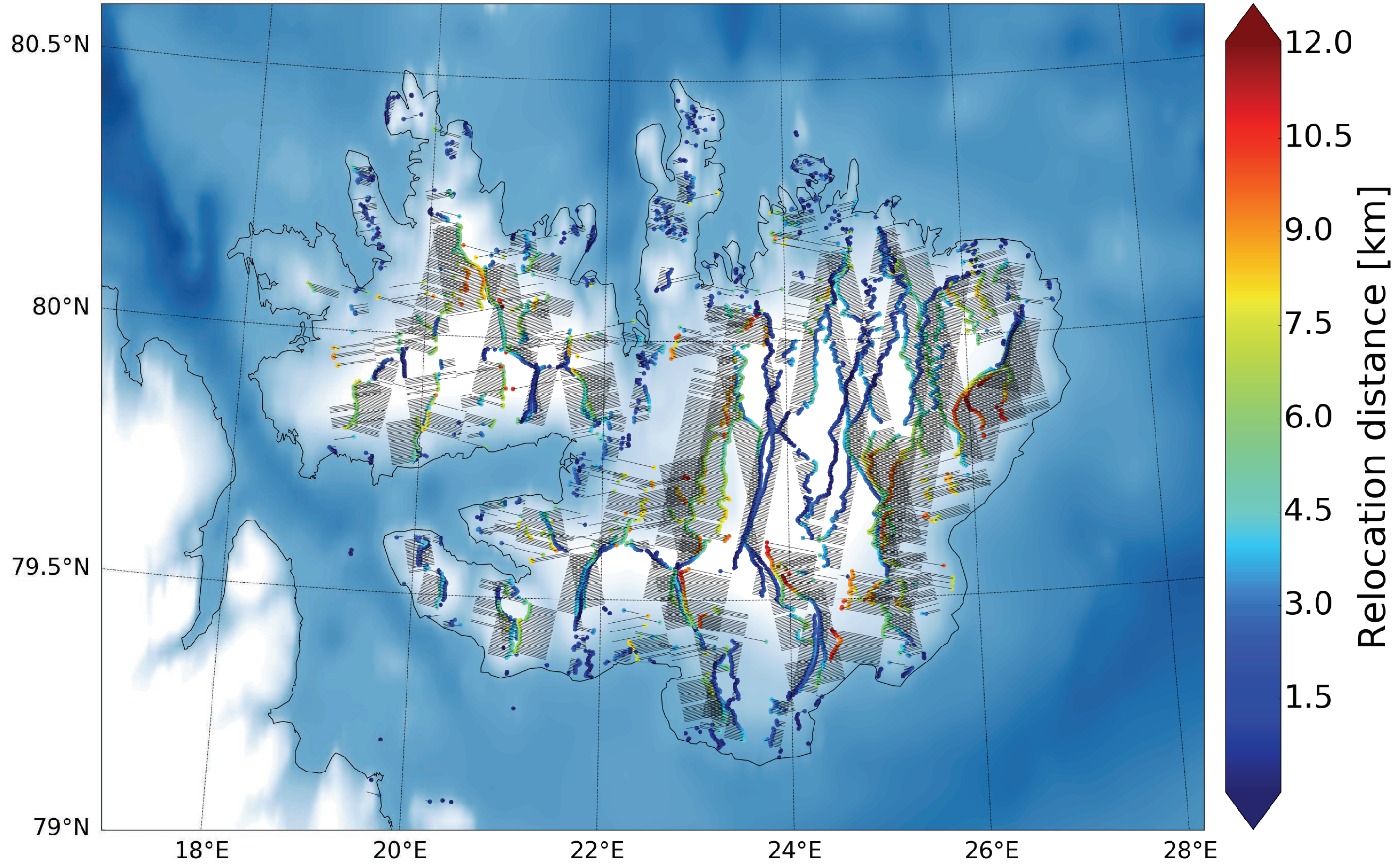



DEM resolution

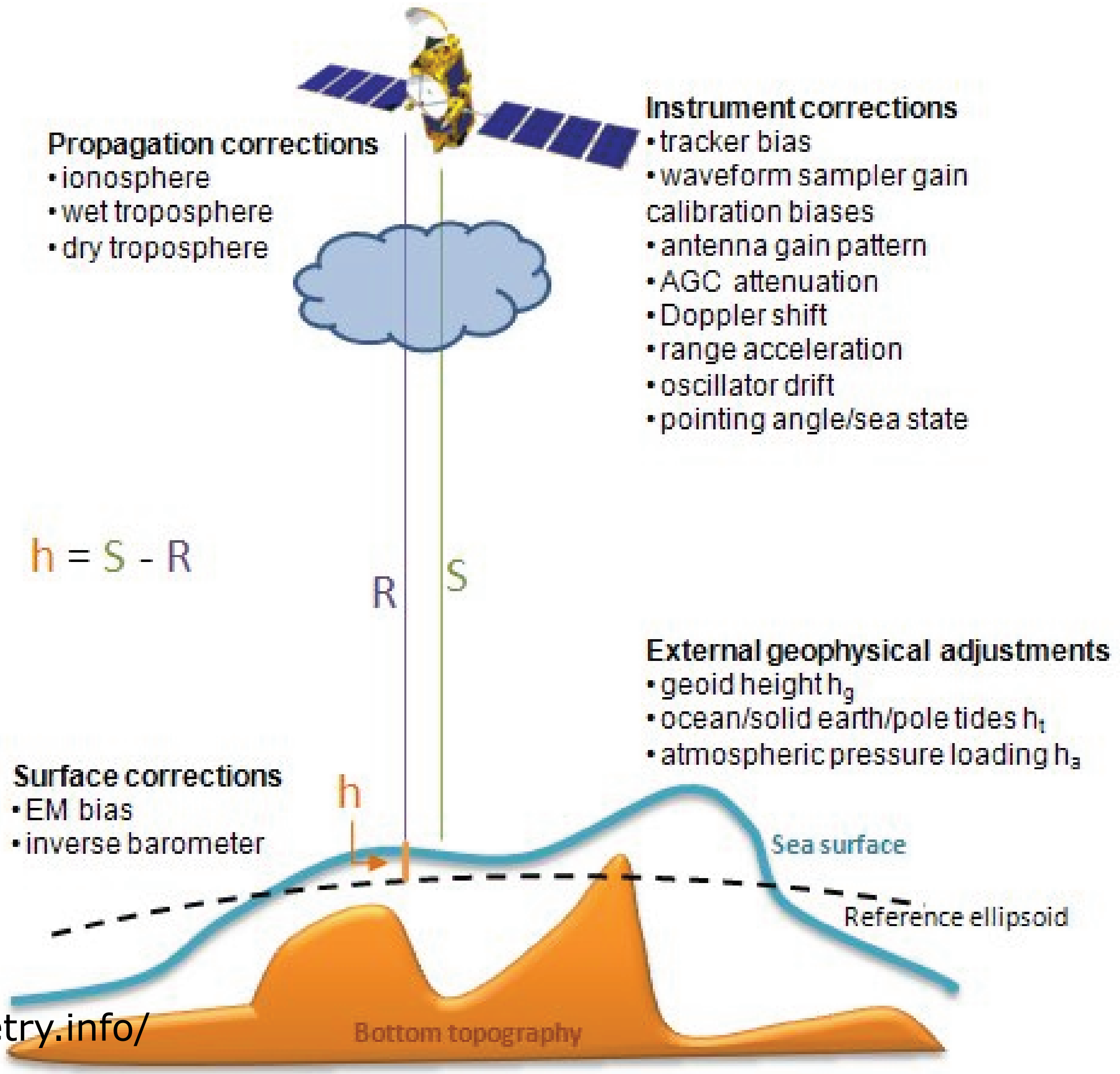
Relocation of Envisat data near Jakobshavn in Greenland

Credits: Levinsen et al, 2016, IEEE

# Radar altimetry on slopes



# Geophysical and propagation corrections




http://www.altimetry.info/

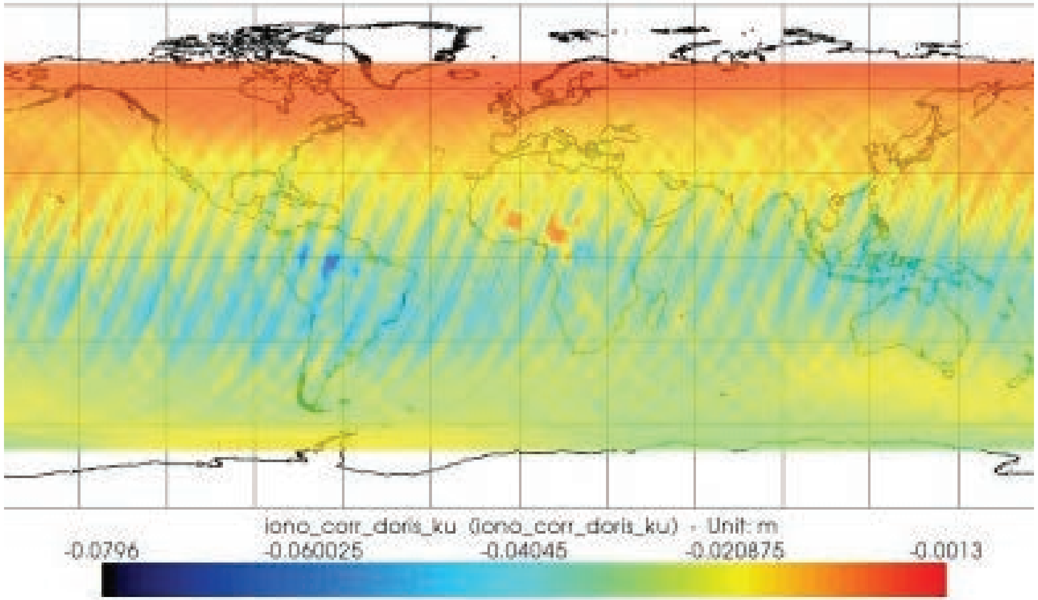
# Ionosphere correction

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

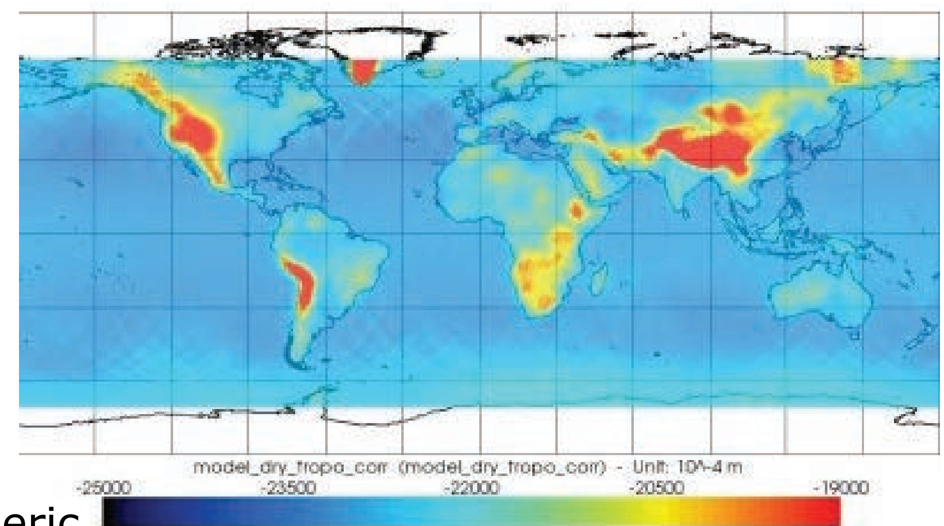
This correction for the dry gas component of the atmosphere refraction takes into account the path delay in the radar return signal due to the atmosphere.

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).



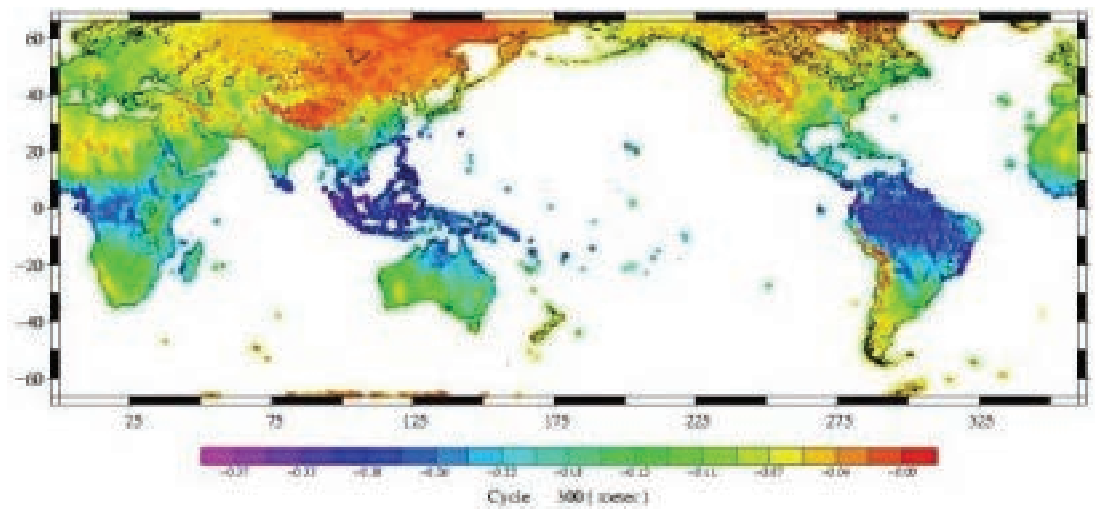

Computed from the ECMWF atmospheric pressures model during the Jason-1 cycle 223.

# 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



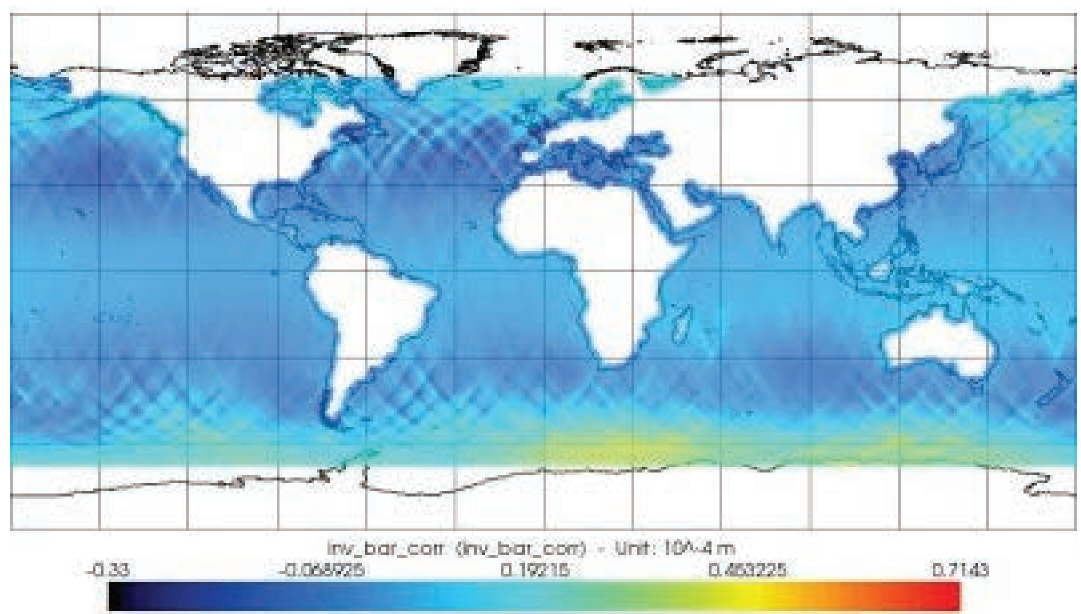

*Amplitude in metres of the wet troposphere correction computed from the NCEP model during Topex/Poseidon cycle 300*

# 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.

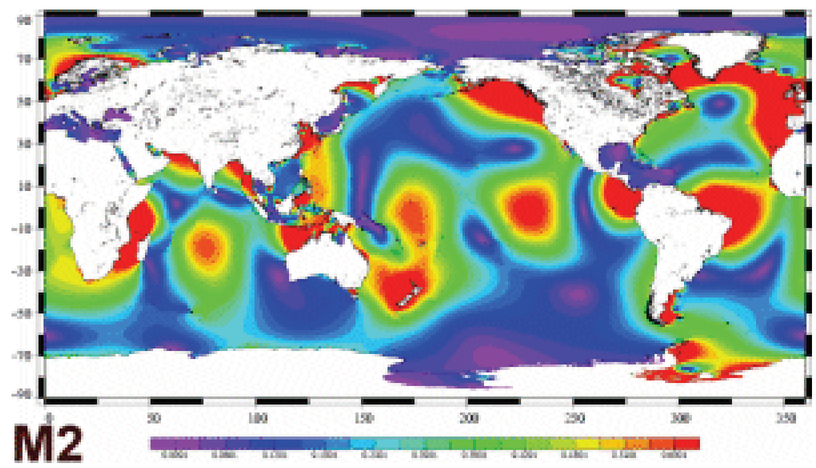
*Amplitude (metres) of Inverse Barometer correction computed from ECMWF atmospheric pressures*



# 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

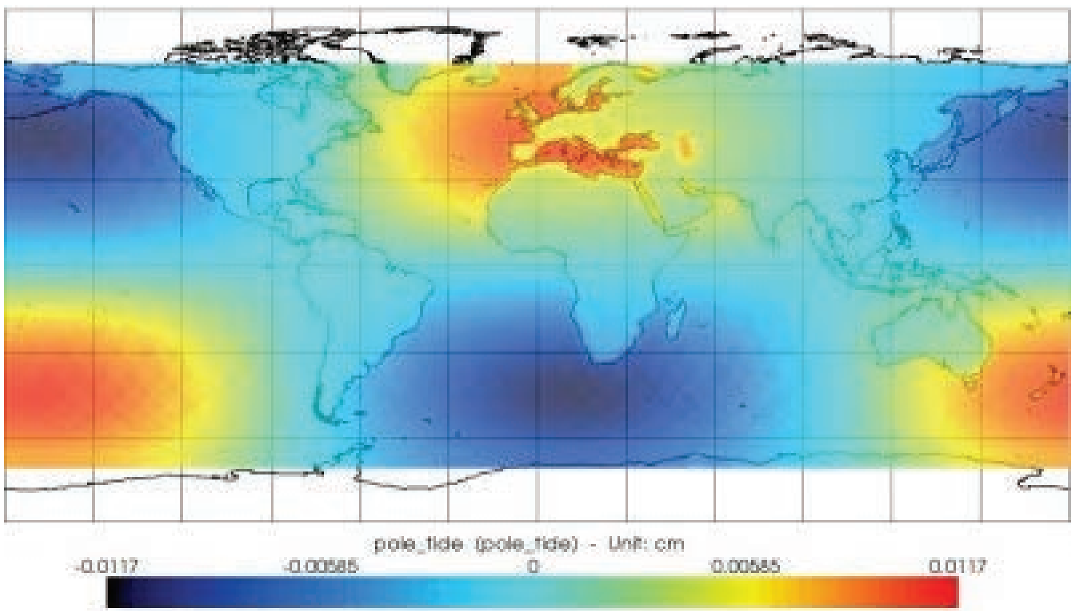



Amplitude (m) of one main tide component from FES2004 model.

(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.

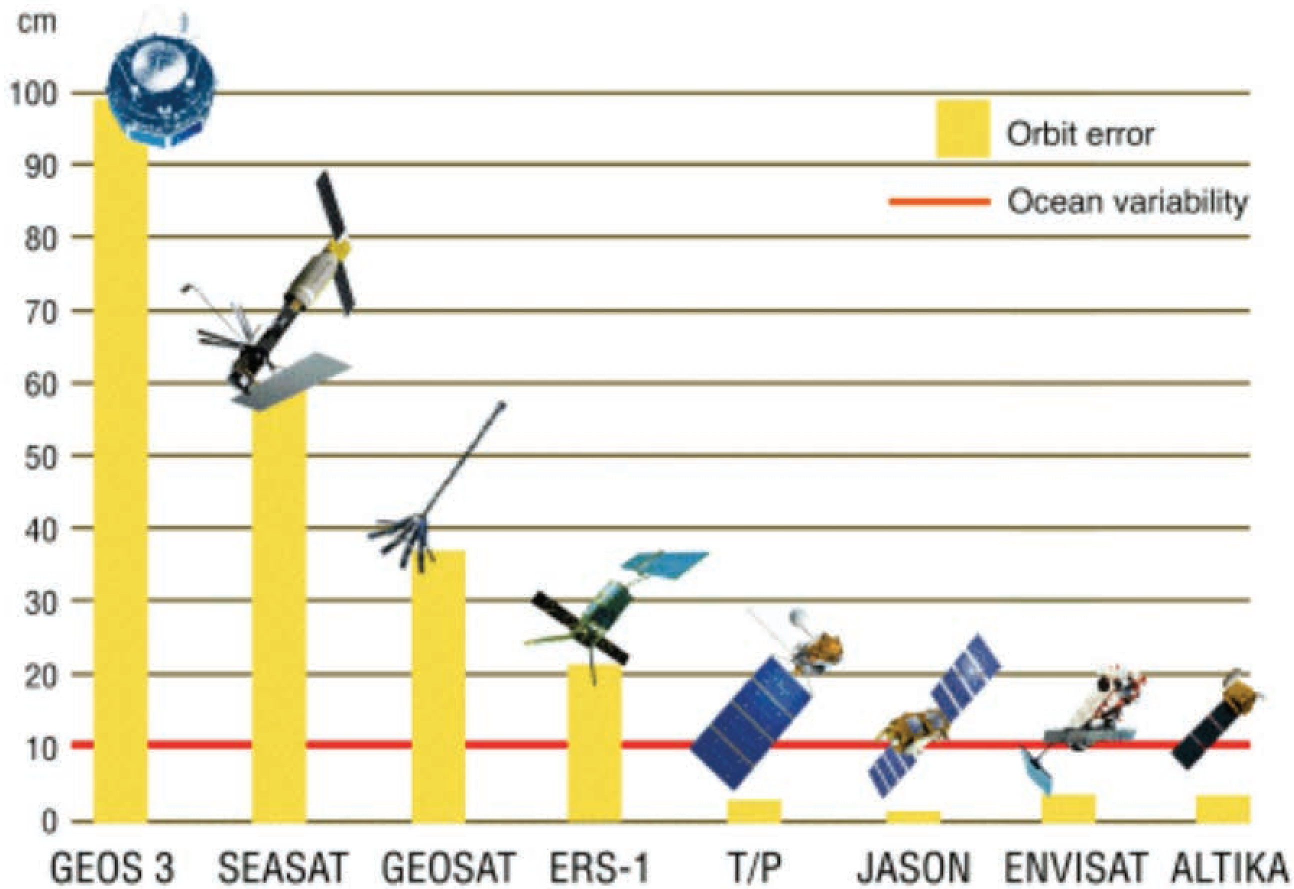
# Altimetry error budget

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 |
| Eddys 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

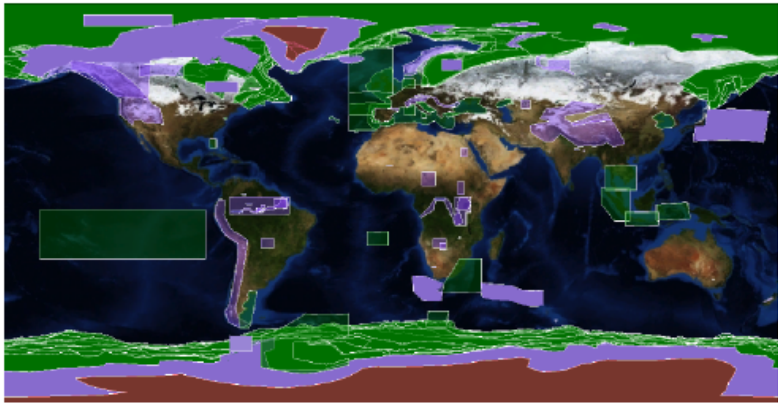
# Altimetry error budget



# CryoSat-2 radar altimeter

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

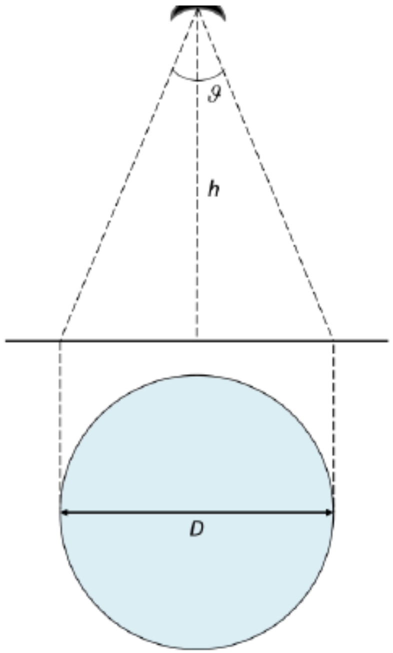
SAR Interferometric (SARIn) (purple) mode is used over steeply sloping ice-sheet margins, over some geostrophic ocean currents and over small ice caps and areas of mountain glaciers. It is also used over some major hydrological river basins.

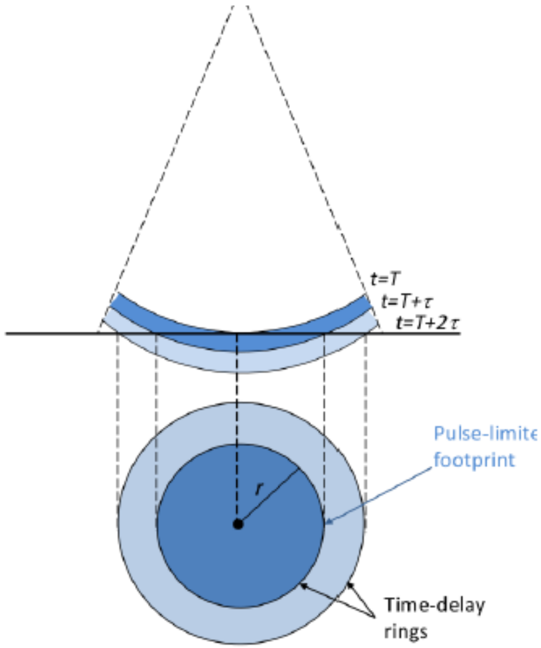


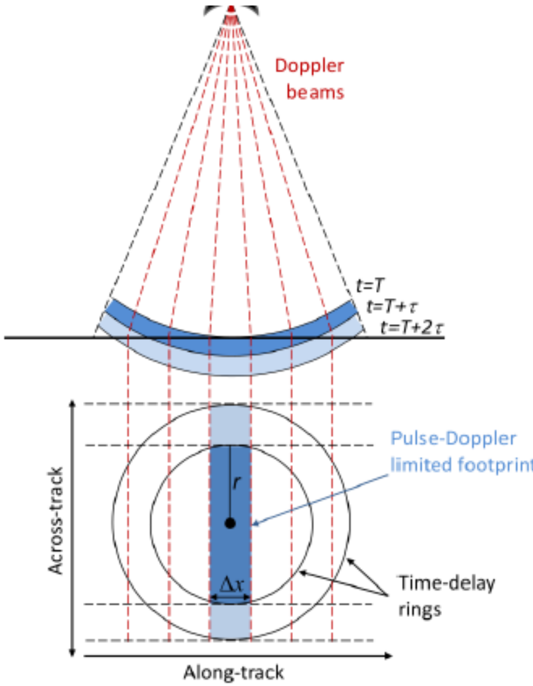
Low Resolution Mode (LRM) (red) conventional radar altimetry over interior ice sheets

- The end

# CryoSat-2 radar altimeter




**BEAM-LIMITED**

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

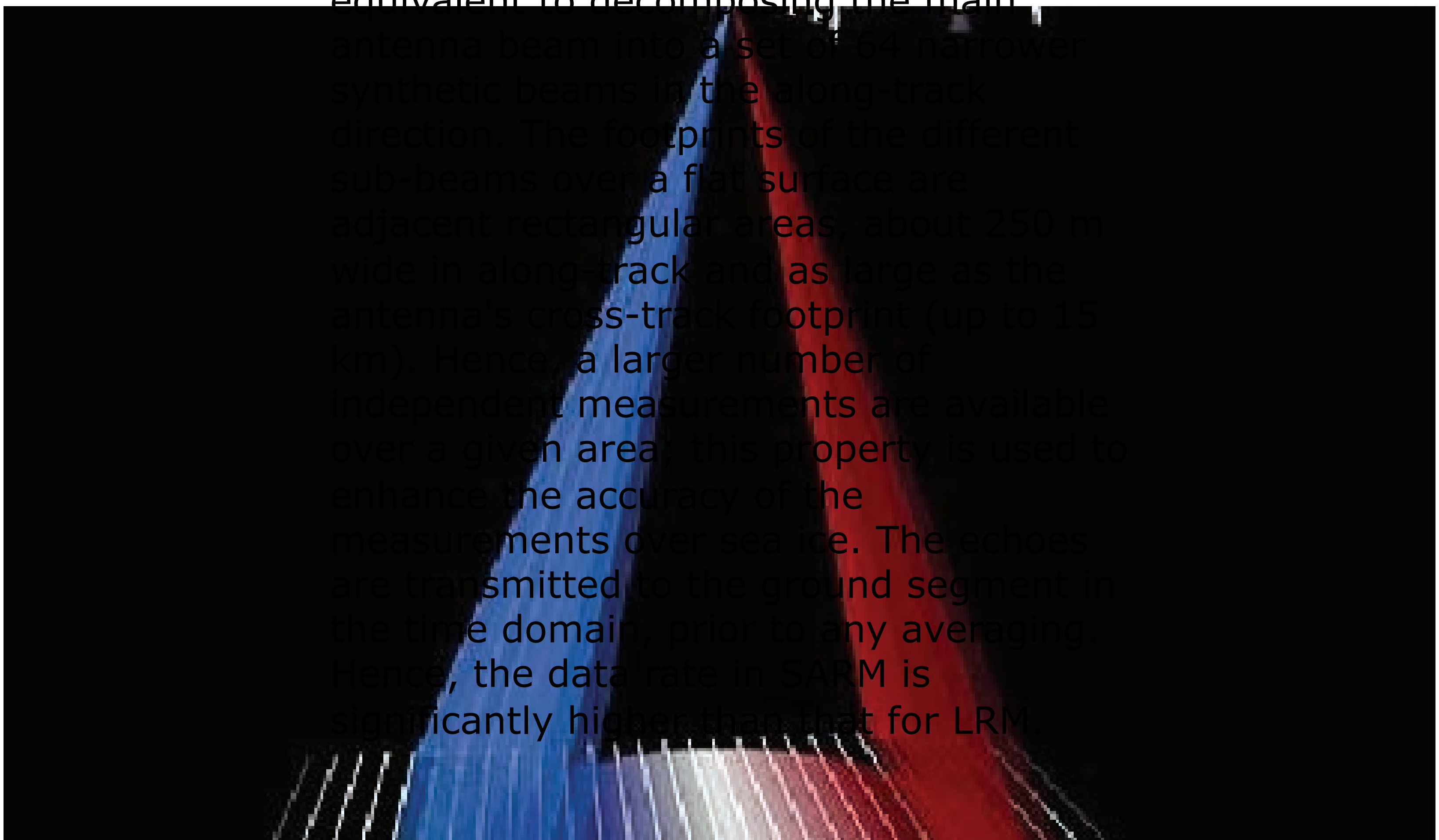
**PULSE-LIMITED**

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

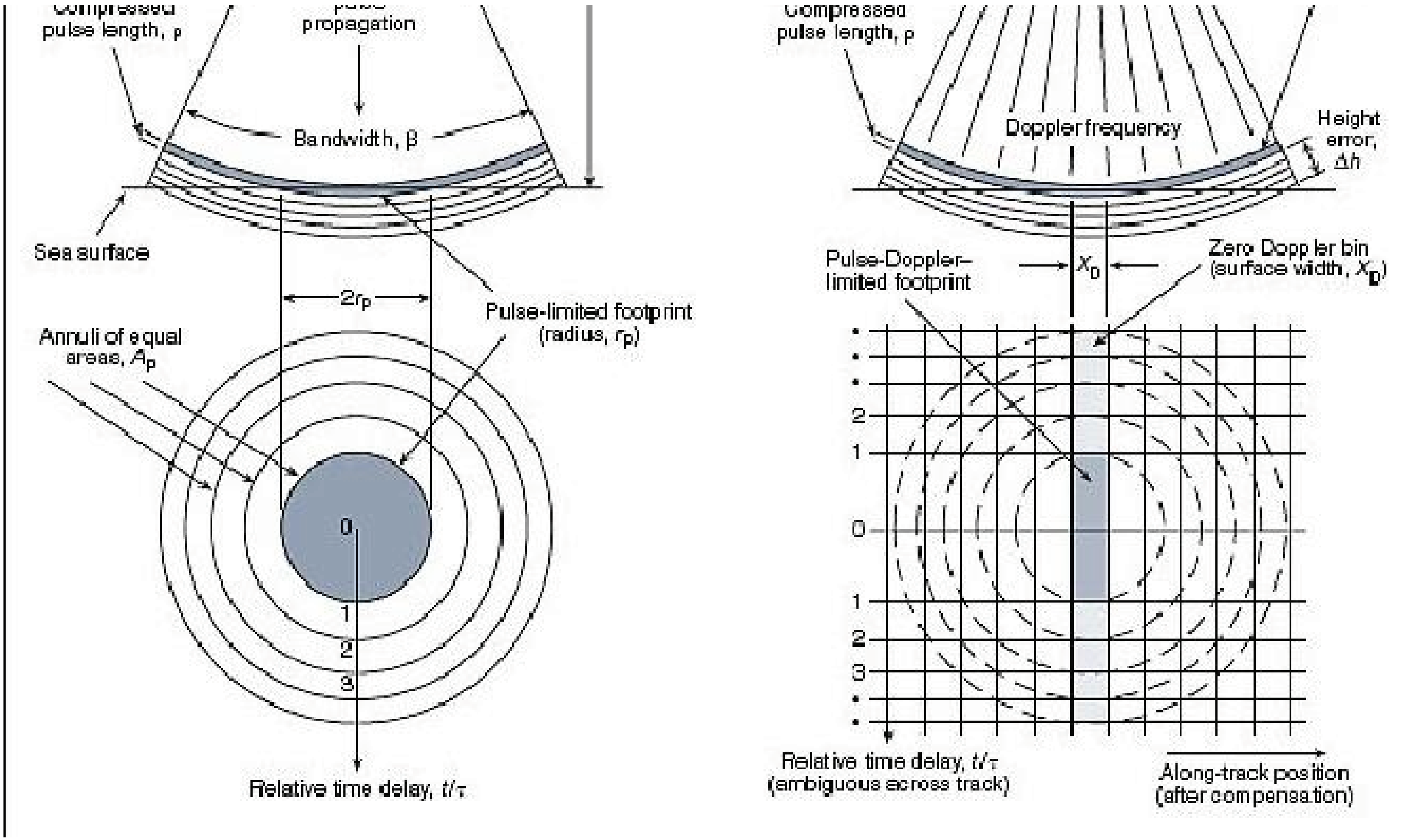
**DOPPLER-LIMITED**

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

In SARM, 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 antenna beam into a set of 64 narrower synthetic beams in the along-track direction. The footprints of the different sub-beams over a flat surface are adjacent rectangular areas, about 250 m wide in along-track and as large as the antenna's cross-track footprint (up to 15 km). Hence, a larger number of independent measurements are available over a given area; this property is used to enhance the accuracy of the measurements over sea ice. The echoes are transmitted to the ground segment in the time domain, prior to any averaging. Hence, the data rate in SARM is significantly higher than that for LRM.



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


pulse length, ρ
propagation
Bandwidth, β
Sea surface
2r_p
Pulse-limited footprint (radius, r_p)
Annuli of equal areas, A_p
0
1
2
3
Relative time delay, t/τ
Compressed pulse length, ρ
Doppler frequency
Height error, Δh
Pulse-Doppler-limited footprint
X_D
Zero Doppler bin (surface width, X_D)
2
1
0
1
2
3
Relative time delay, t/τ (ambiguous across track)
Along-track position (after compensation)

# Beam limited versus pulse limited altimeters

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