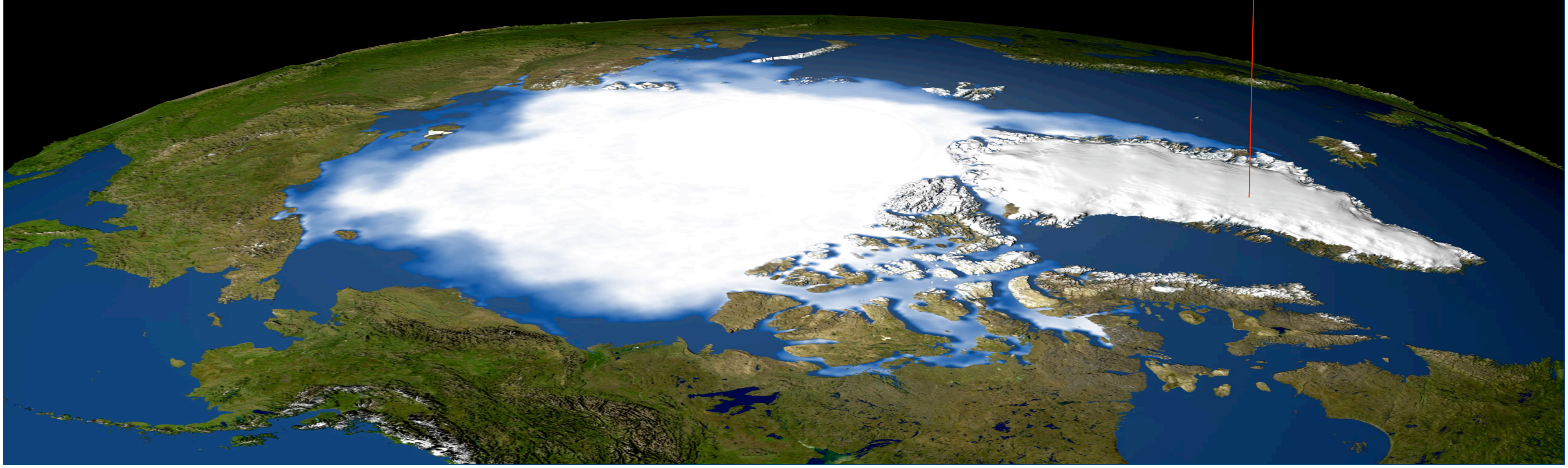
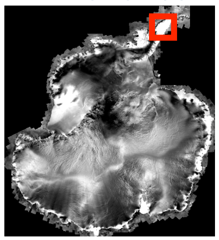
NASA's Ice Cloud and land Elevation Satellite (ICESat)

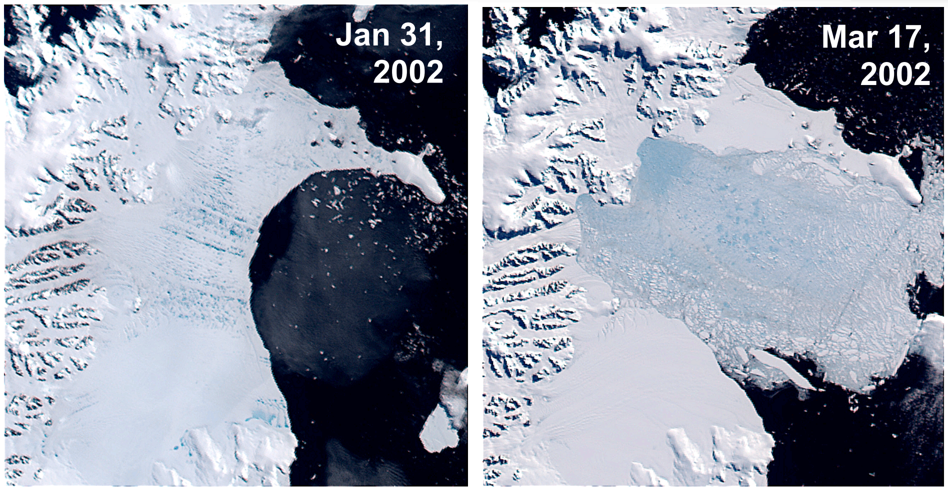
Waleed Abdalati
Earth Science and Observation Center
CIRES, University of Colorado



The Earth's Ice is Changing Dramatically With Significant Societal Implications

Antarctica





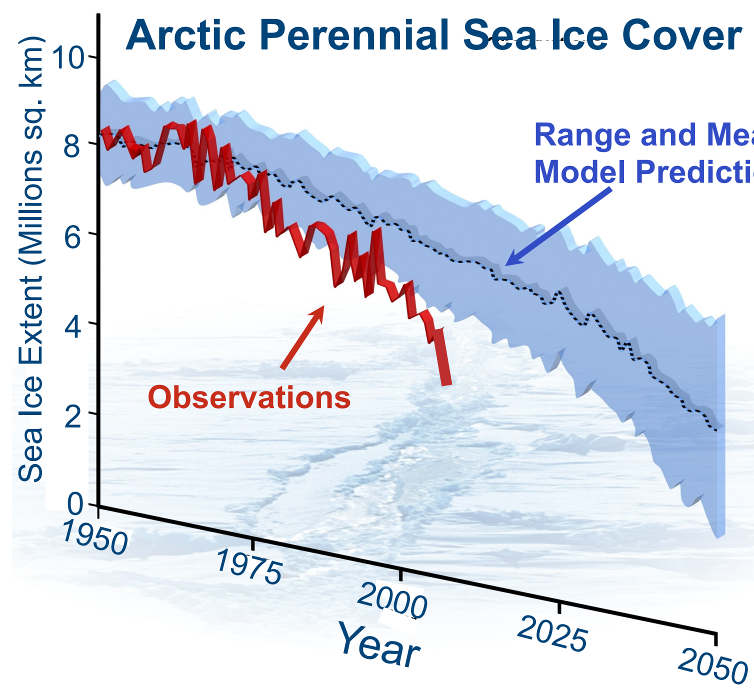
T. Scambos, NSIDC

<u>Ice Sheet Stability</u>
10,000 year old ice, thousands of km in area, hundreds of meters thick, gone in weeks! Glaciers rapidly accelerated in response

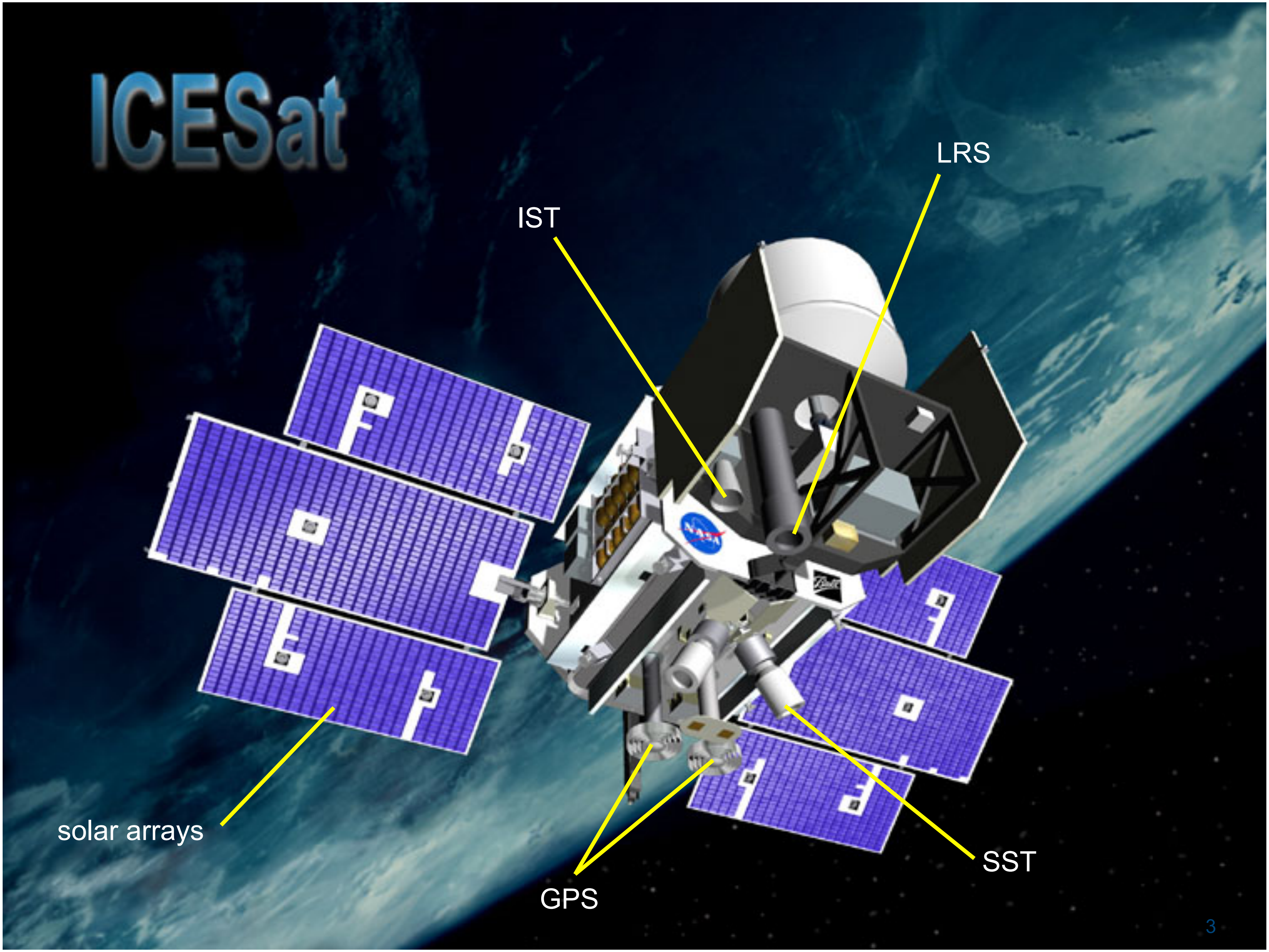
The amount and nature of ice sheet change are manifest in its topographic change

<u>Disappearing Arctic Sea Ice</u>
Arctic sea ice is disappearing faster than nearly all of the world's most widely accepted climate models predict.

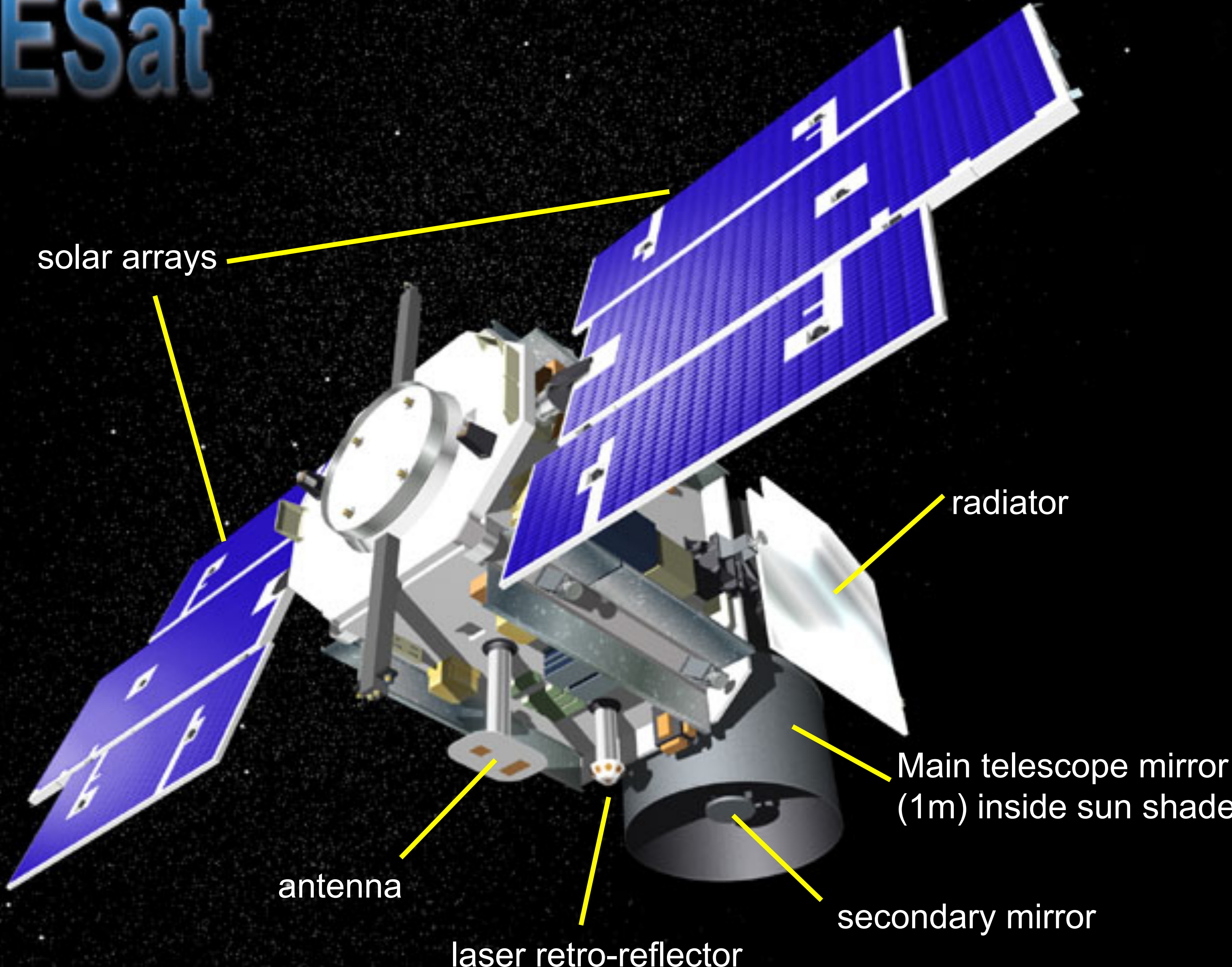
Thickness is the key missing variable



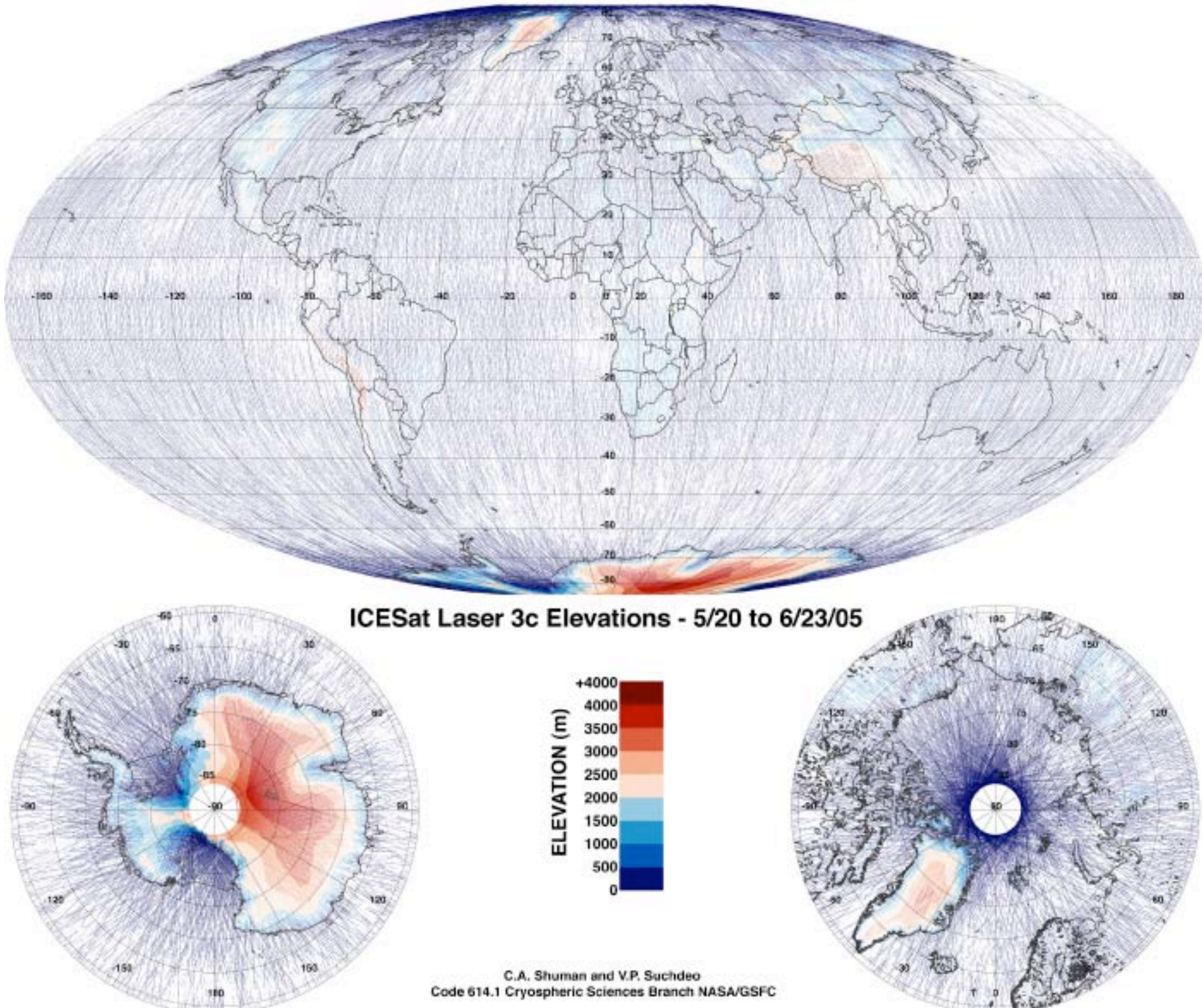
NCAR


ICESat
LRS
IST
solar arrays
GPS
SST

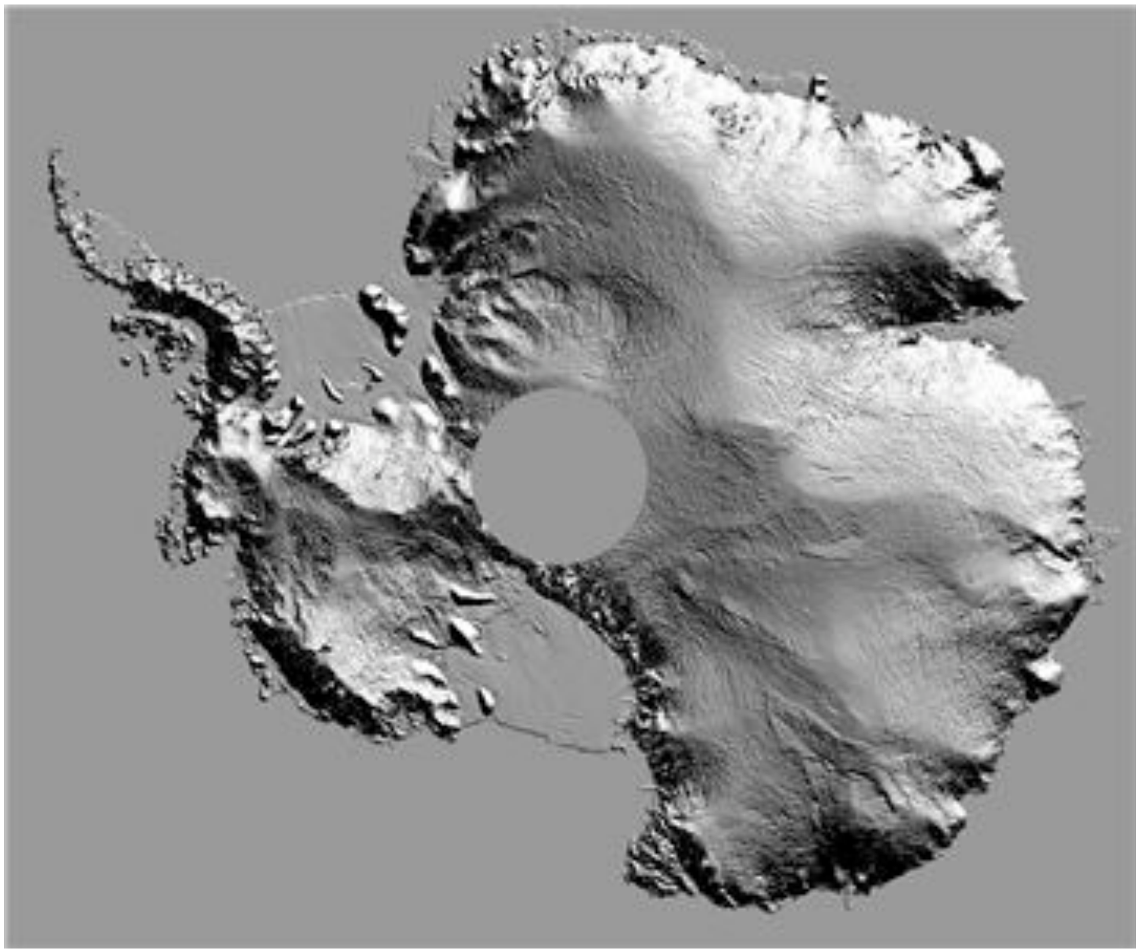
ICESat

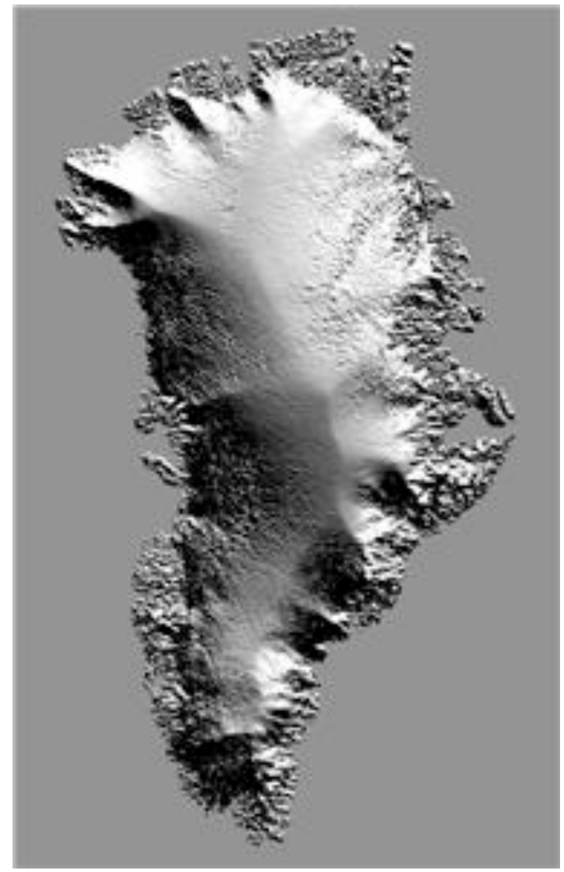

solar arrays
radiator
Main telescope mirror
(1m) inside sun shade
antenna
secondary mirror
laser retro-reflector

33 Days of ICESat Coverage

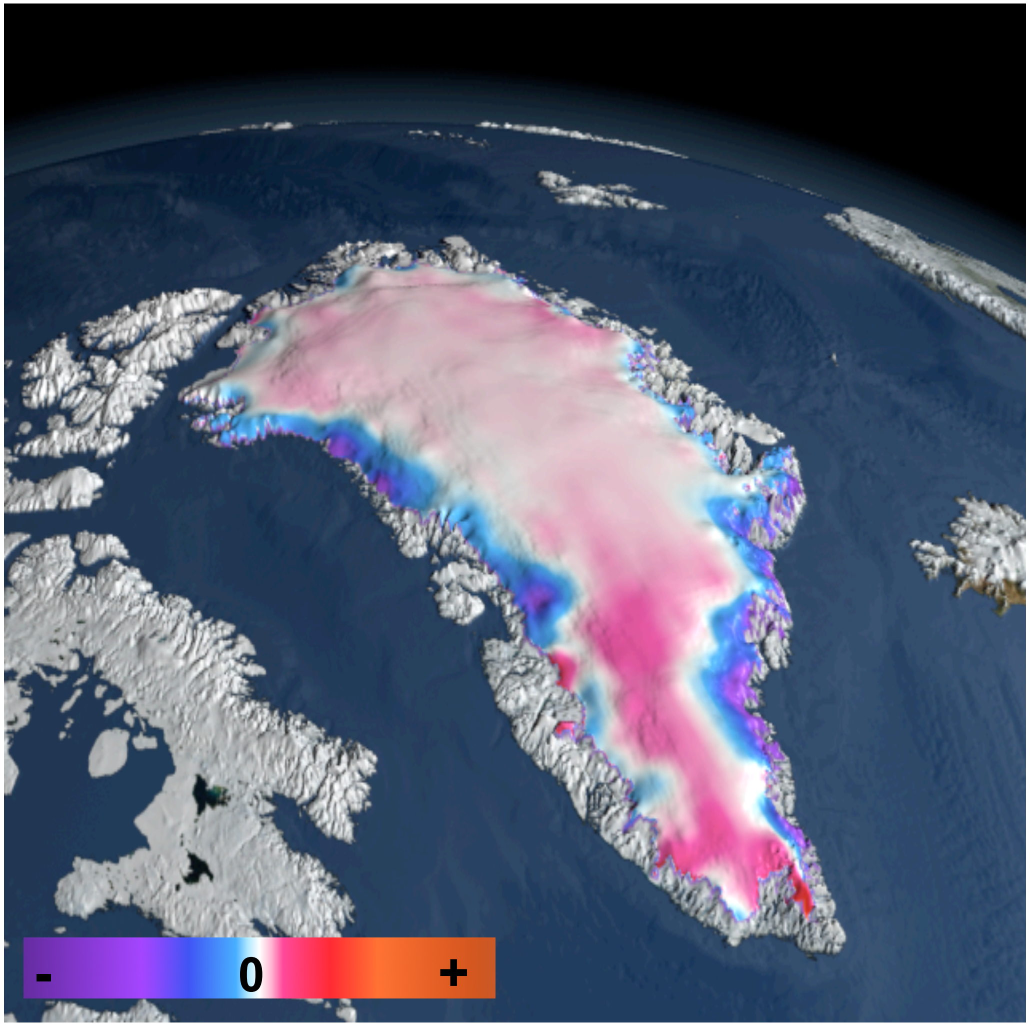


Elevation Measurements Along Ground Tracks Enable the Creation of Digital Elevation Models





But Elevation Change Is the Key Objective



- dh/dt enables assessment of contribution to sea level
- dh/dt holds clues to mechanisms of change
- Ice sheet dh/dt requirement was 1.5 cm/yr on 100 x 100 km^2 scales for slopes < 0.6 deg
- Altimetry has applications to other science disciplines
  - Sea ice
  - Vegetation
  - Hydrology
  - Land processes
  - Atmospheric processes

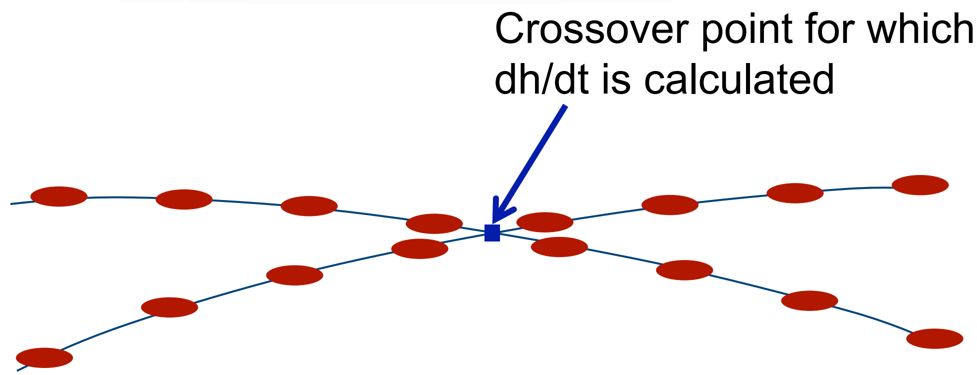
H.J. Zwally, GSFC

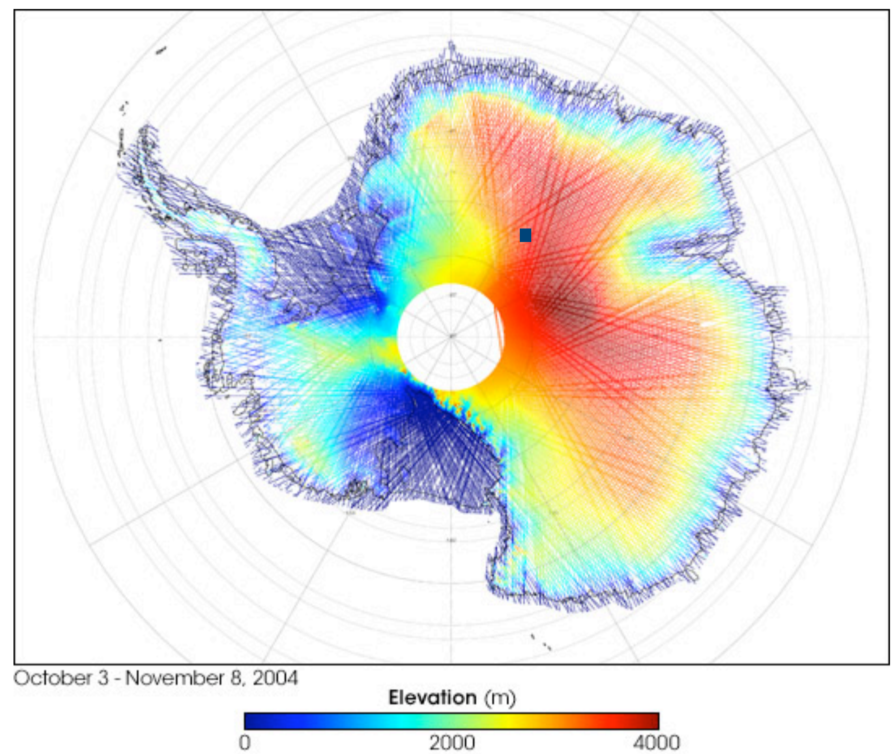
ICESat Mission and Instrument Characteristics

- Mission
  - 94 degree inclination
  - 33-day subcycle of a 91-day repeat
    - 183-day repeat was planned
- Instrument (Geoscience Laser Altimeter System)
  - Nd:YAG laser
  - 1064 nm output for altimetry
  - 532 nm output for atmospheric measurements
  - Near-nadir viewing at 40 Hz
    - 0.3 deg along-track offset to avoid specular returns
    - Spots separated by 172 m at 600 km altitude
    - Spot size between 50 and 70 m
- Cross-track resolution
  - Intended: 15 km @ equator, 2.5 km @ 80 deg lat (from 183-day repeat)
  - Actual: 90 km @ equator, 15 km@ 80 degrees (from 33-day subcycle of 91-day repeat orbit)

Deriving dh/dt from Cross-Over Analysis

- Measurements are interpolated to the point of intersection
- A time series of elevation differences are accumulated throughout the mission at the crossing nodes.
- Averages within an grid cells (e.g. 50 km x 50 km) are accumulated for sufficient statistics
- Time series for the grid cells are generated
- Sampling density was planned to be 6x greater than shown at right



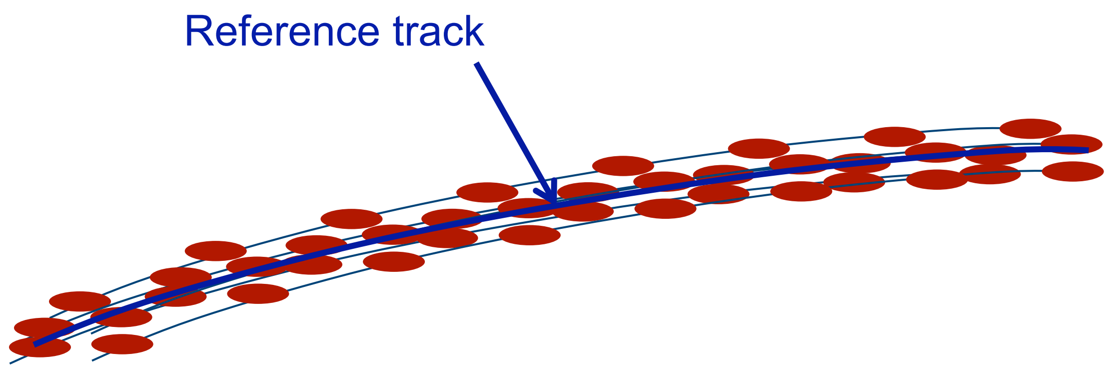


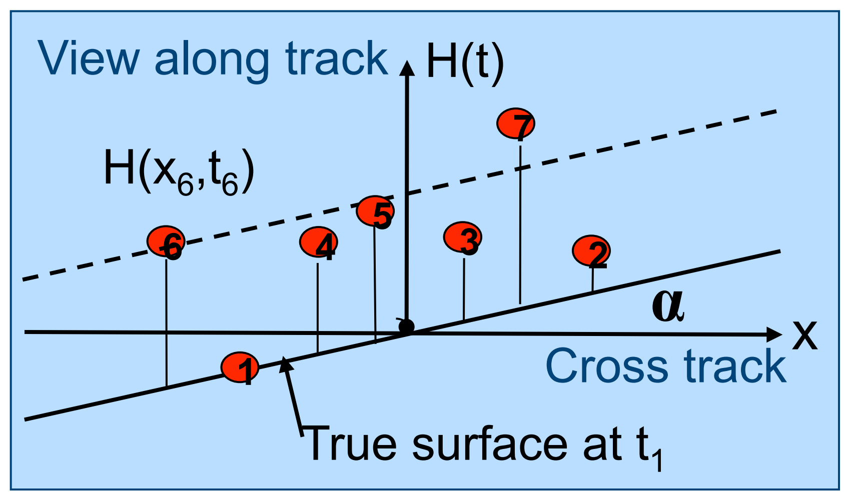
Deriving dh/dt from Repeat-Track Analysis

- Measurements are targeted at a pre-planned reference track.
-
- Offsets from reference track create an apparent dh/dt that must be compensated for
- After a sufficient number of observations, dh/dt and slope are solved for simultaneously:

  $H(X, \alpha, t) = X \tan \alpha + t\,(dH/dt)$

- A dense time series of elevation differences are accumulated throughout the mission along track





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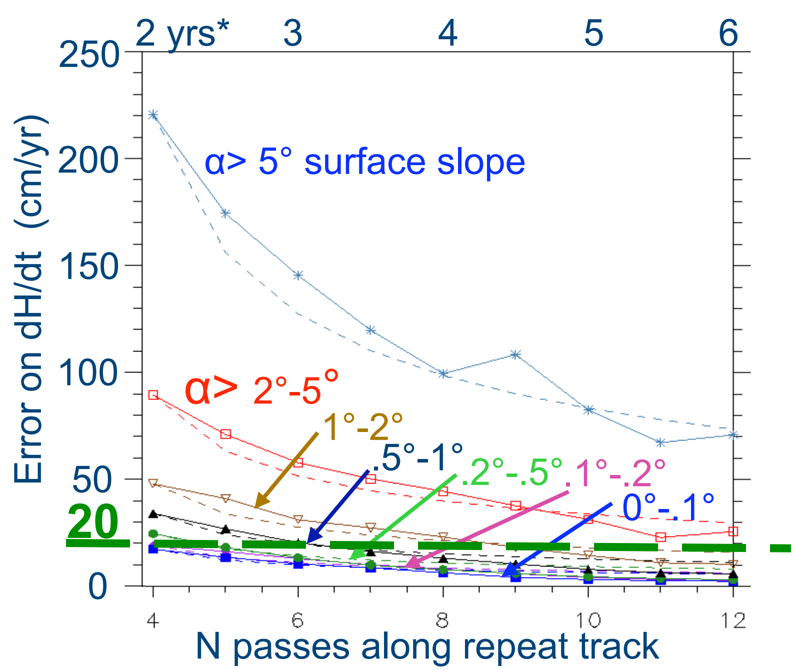
Accuracy is Sensitive to Number of Observations



20 cm/yr accuracy achieved after N= 10 passes for slopes < 2° (e.g. 5 yrs* of continuous operation with 50% cloud loss)

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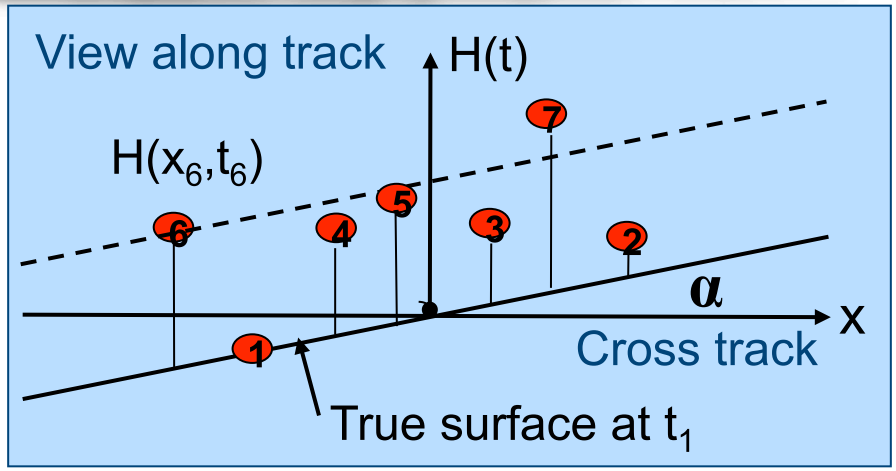
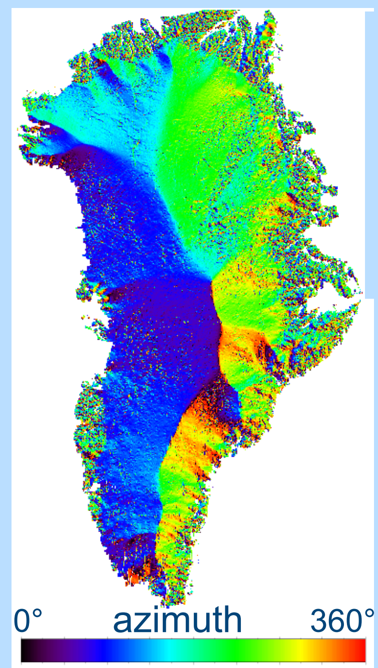
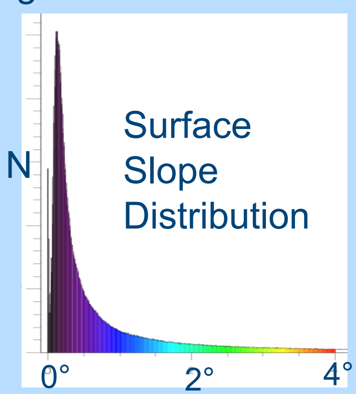


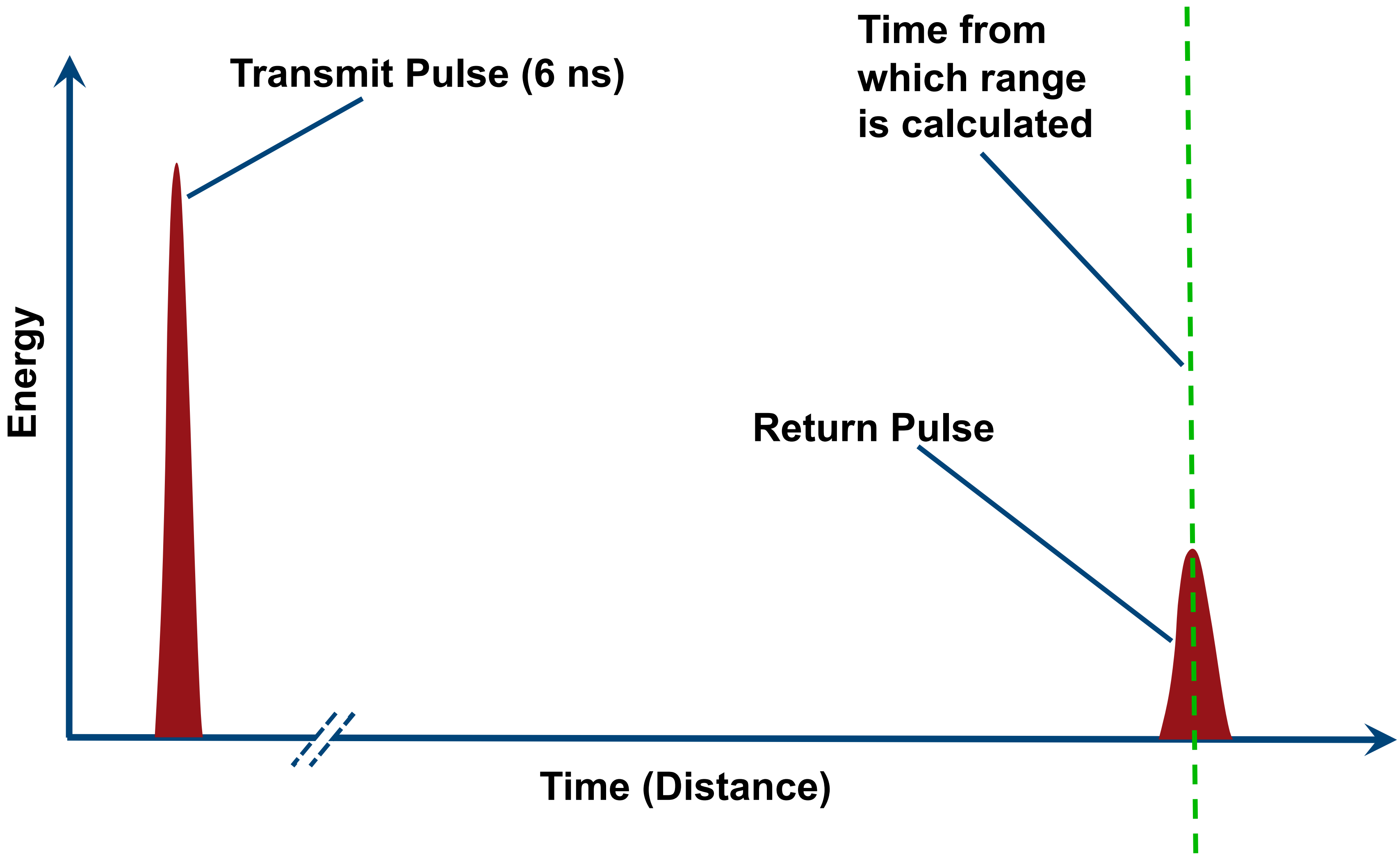


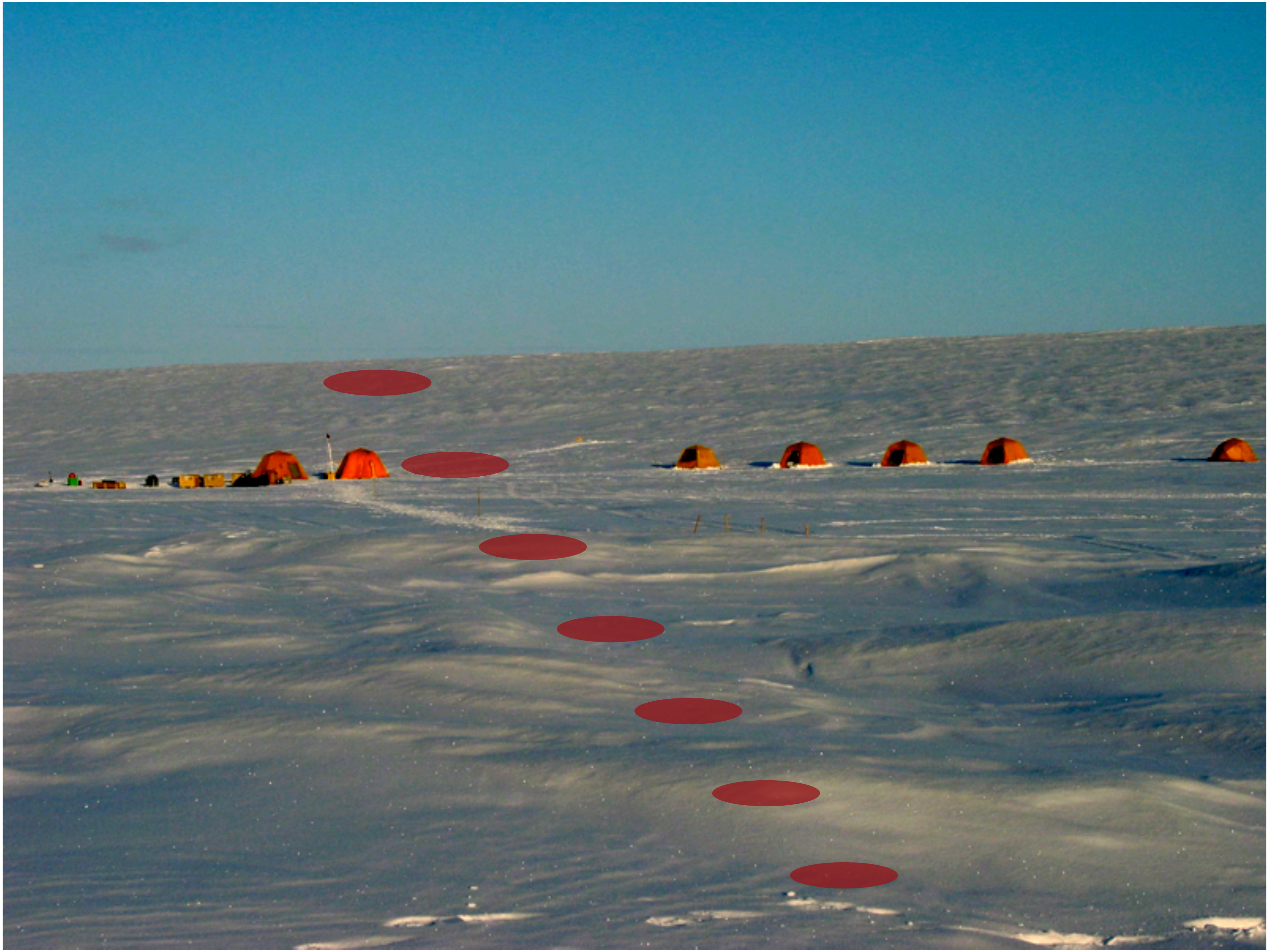
GREENLAND

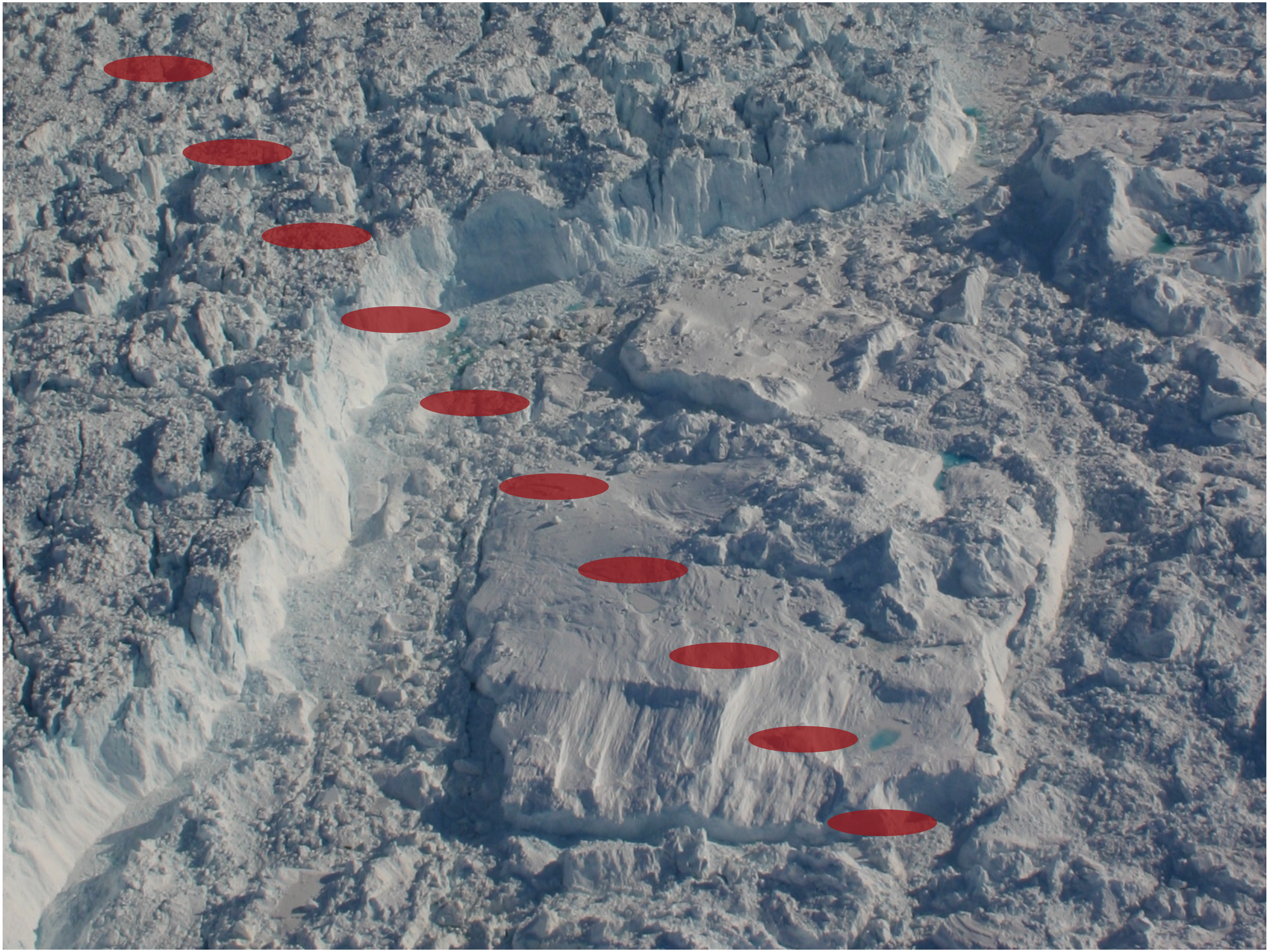
- ❑ Direction and magnitude of ice-sheet slopes is highly variable.
- ❑ Largest slopes at critical margins.



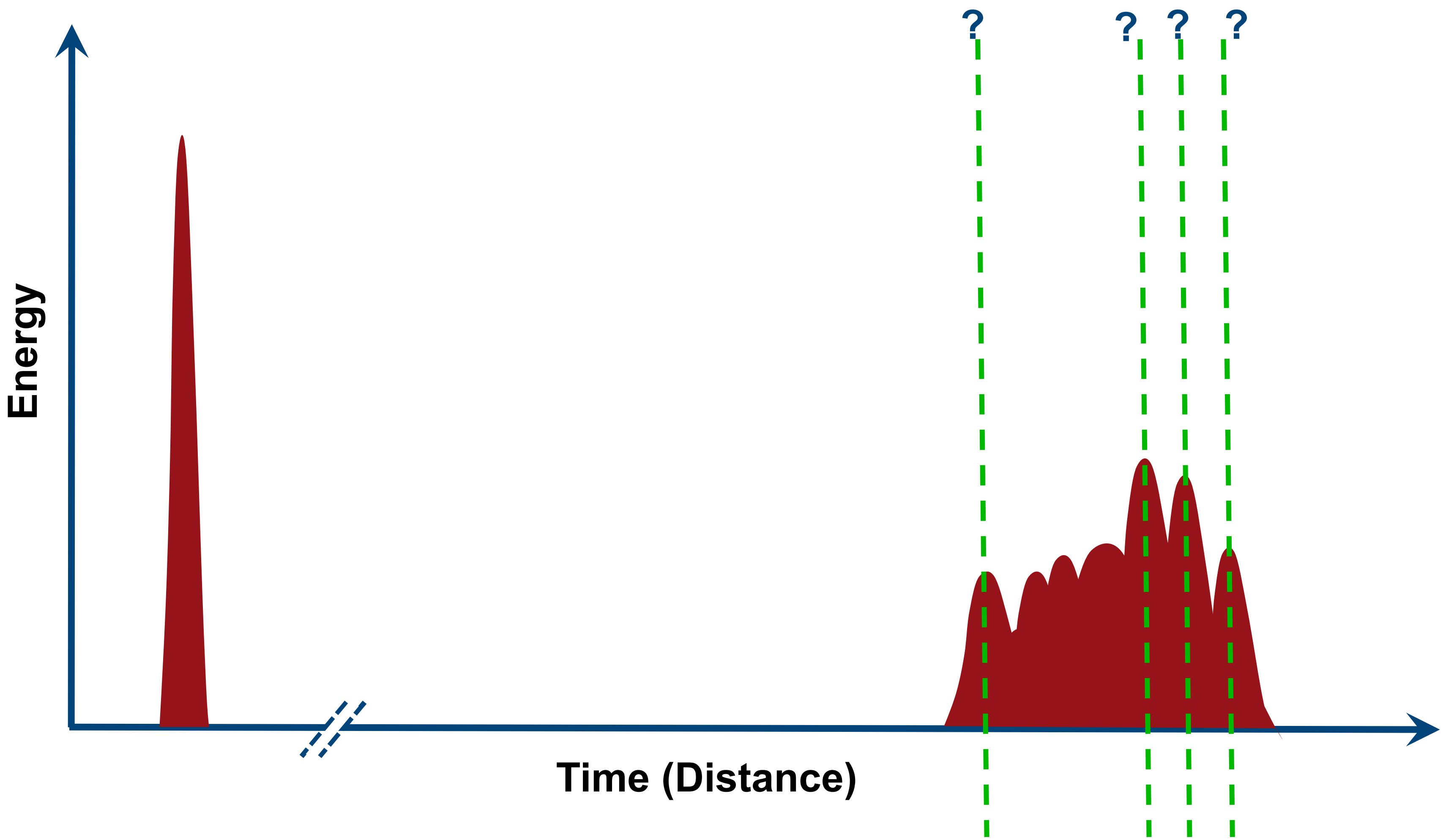
Calculation of Range: Simple Surface



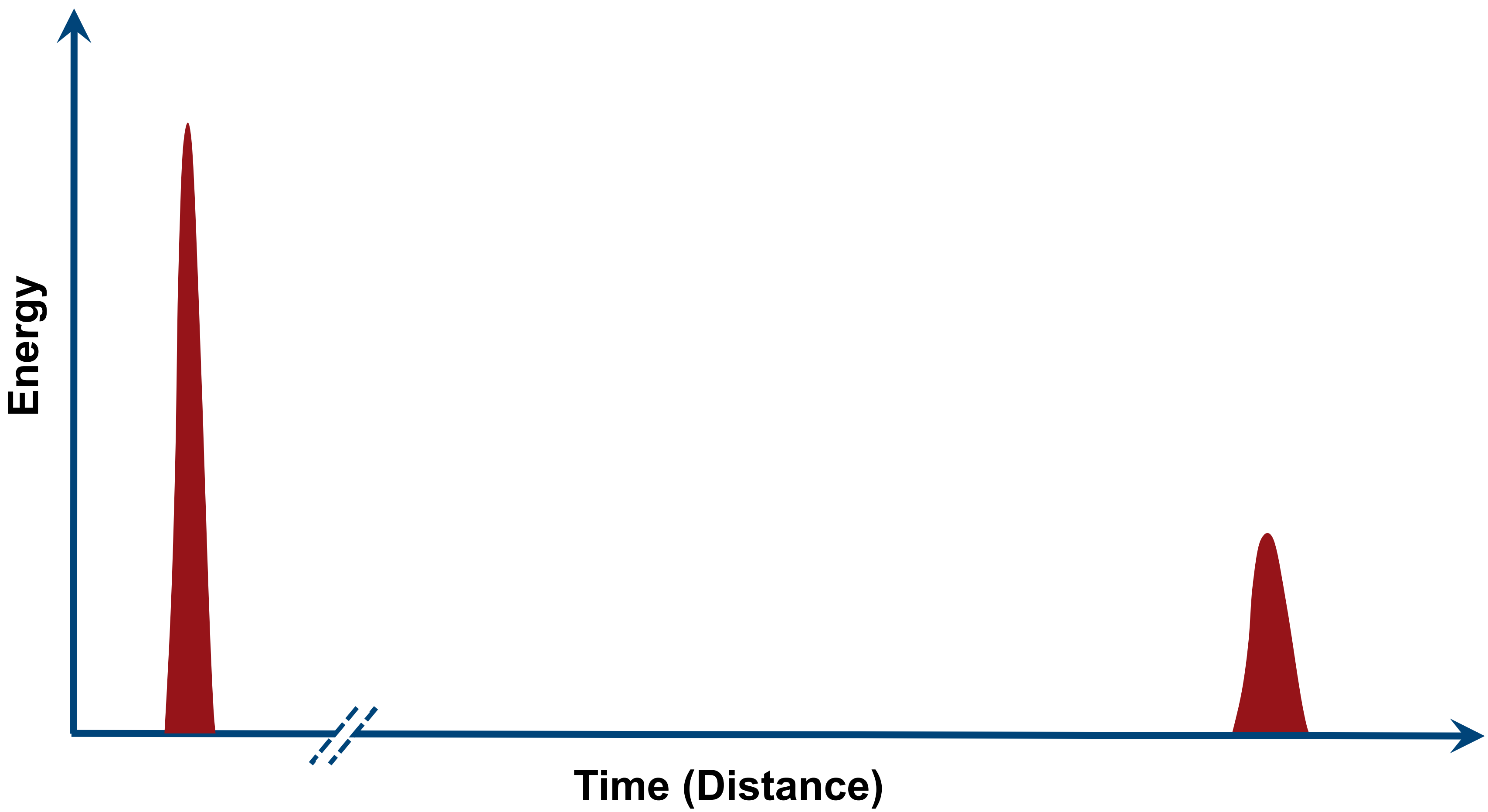




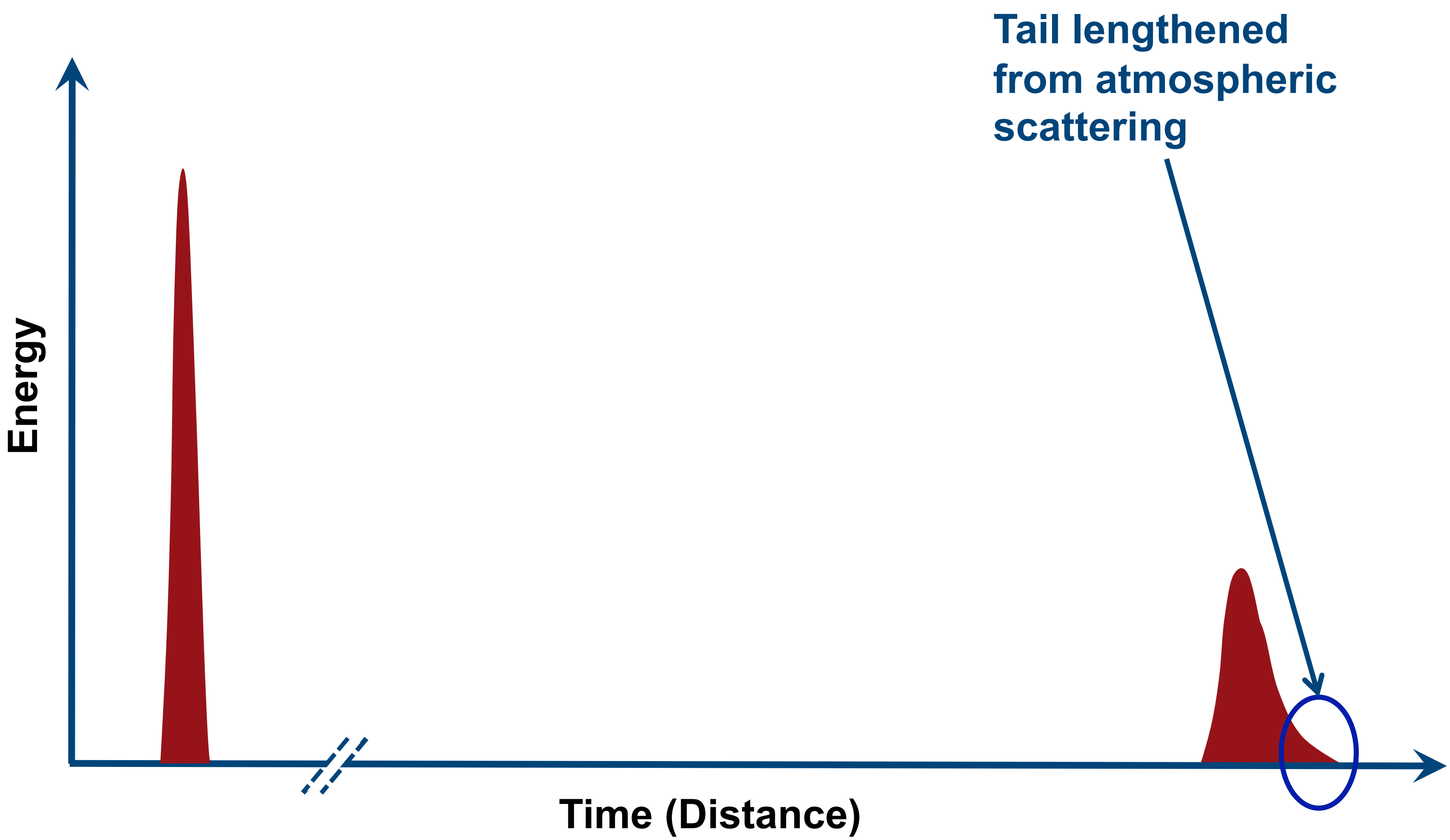
Calculation of Range: Complex Surface



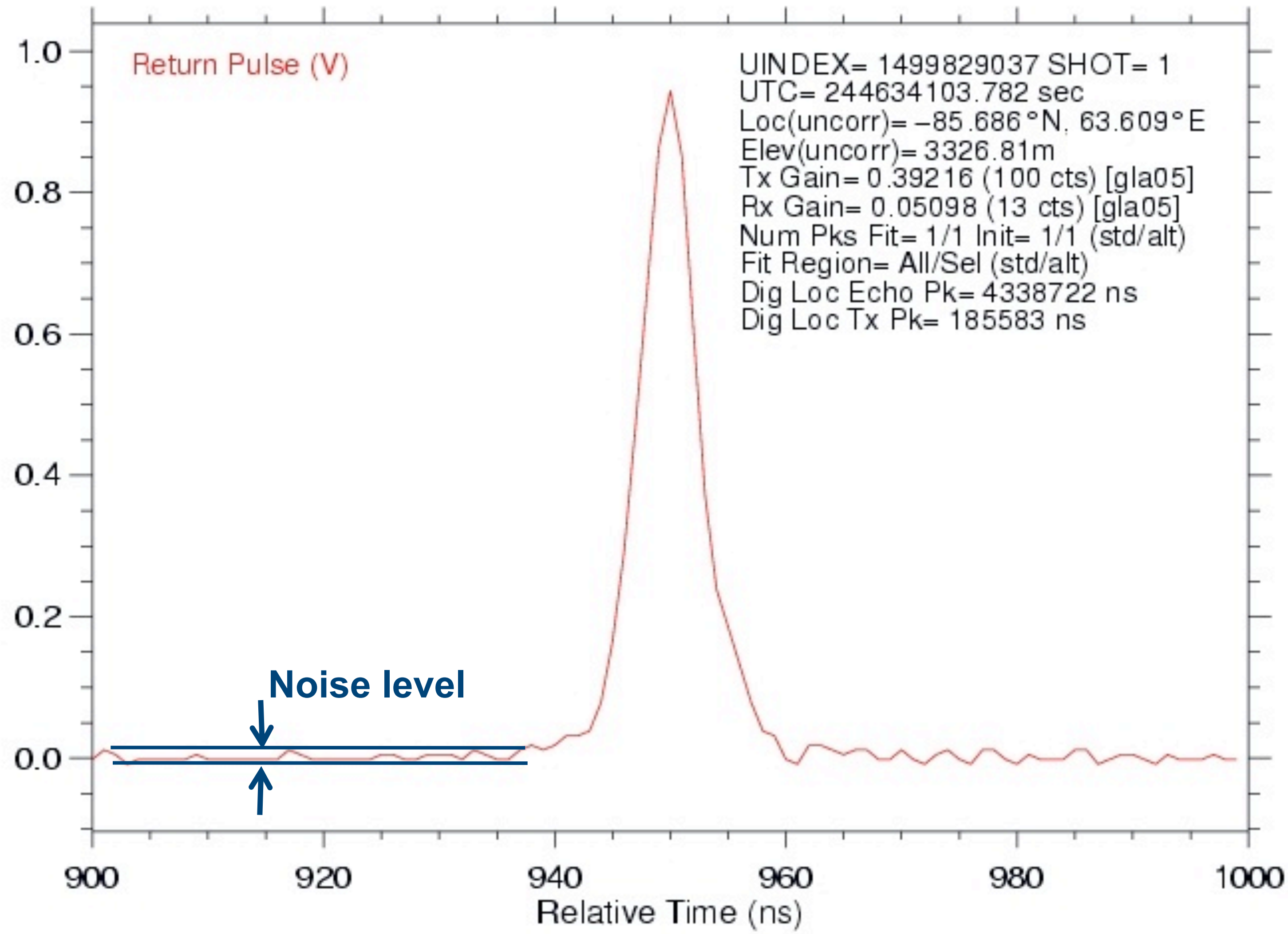
Calculation of Range: Simple Surface



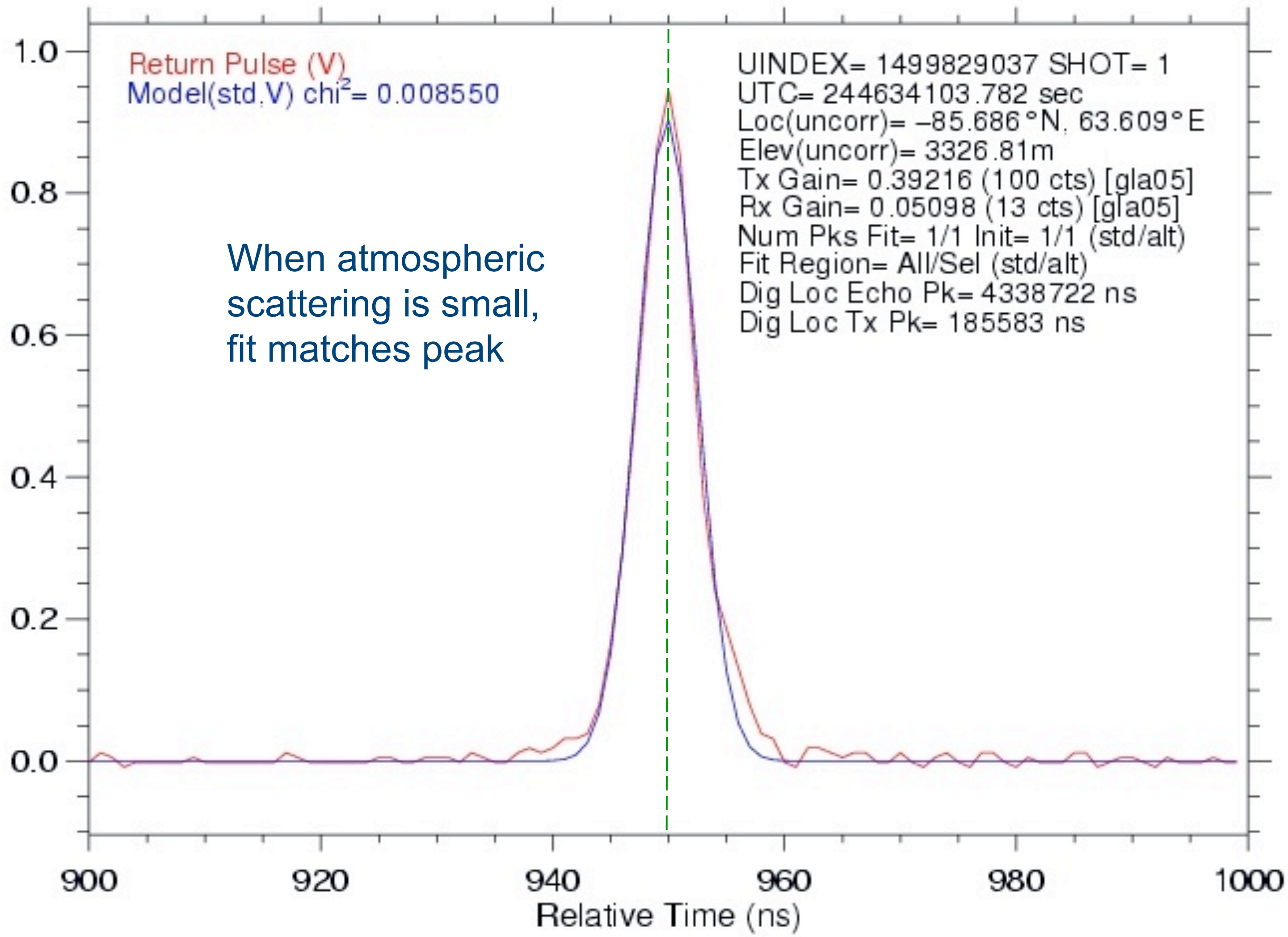
Calculation of Range: Atmospheric Effects



Sample Return Pulse

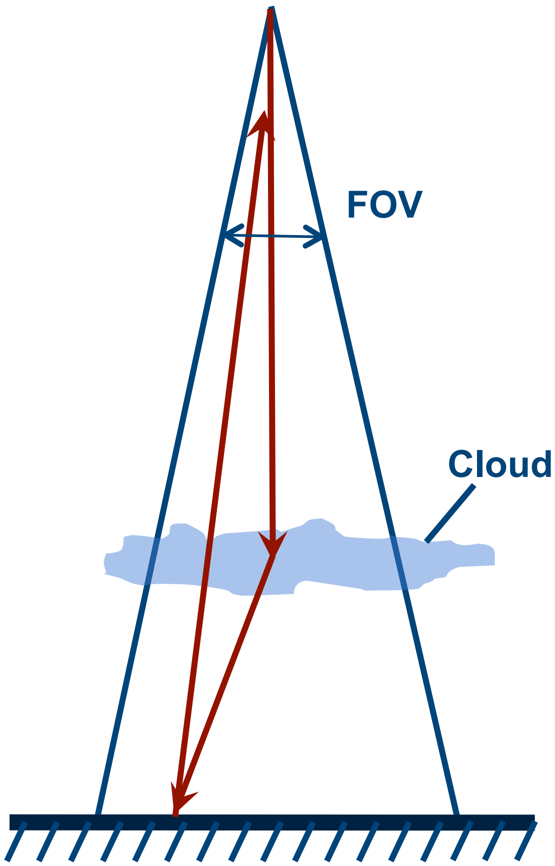


Fitted Return Pulse



When atmospheric scattering is small, fit matches peak

Forward Scattering Effects from Clouds



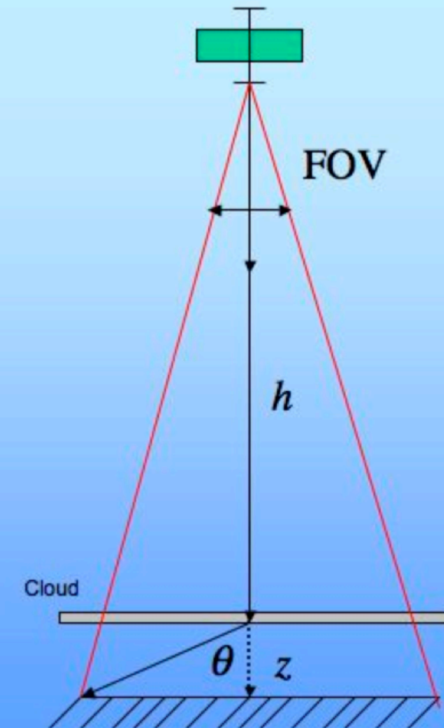
Simple Analytical Approximation

Delay: $$\Delta(z,\theta) = \frac{z}{\cos\theta} - z$$

FOV: $$\mathrm{FOV}(\theta) = \frac{2z}{h}\tan(\theta)$$

Total Delay

$$\frac{\tau \int_{z_{base}}^{z_{top}} \int_{0}^{\theta} \Delta(z,\theta')P(\theta')\sin\theta' d\theta' dz}{1 + \tau \int_{0}^{\theta} P(\theta')\sin\theta' d\theta'}$$



A. Marshak, GSFC

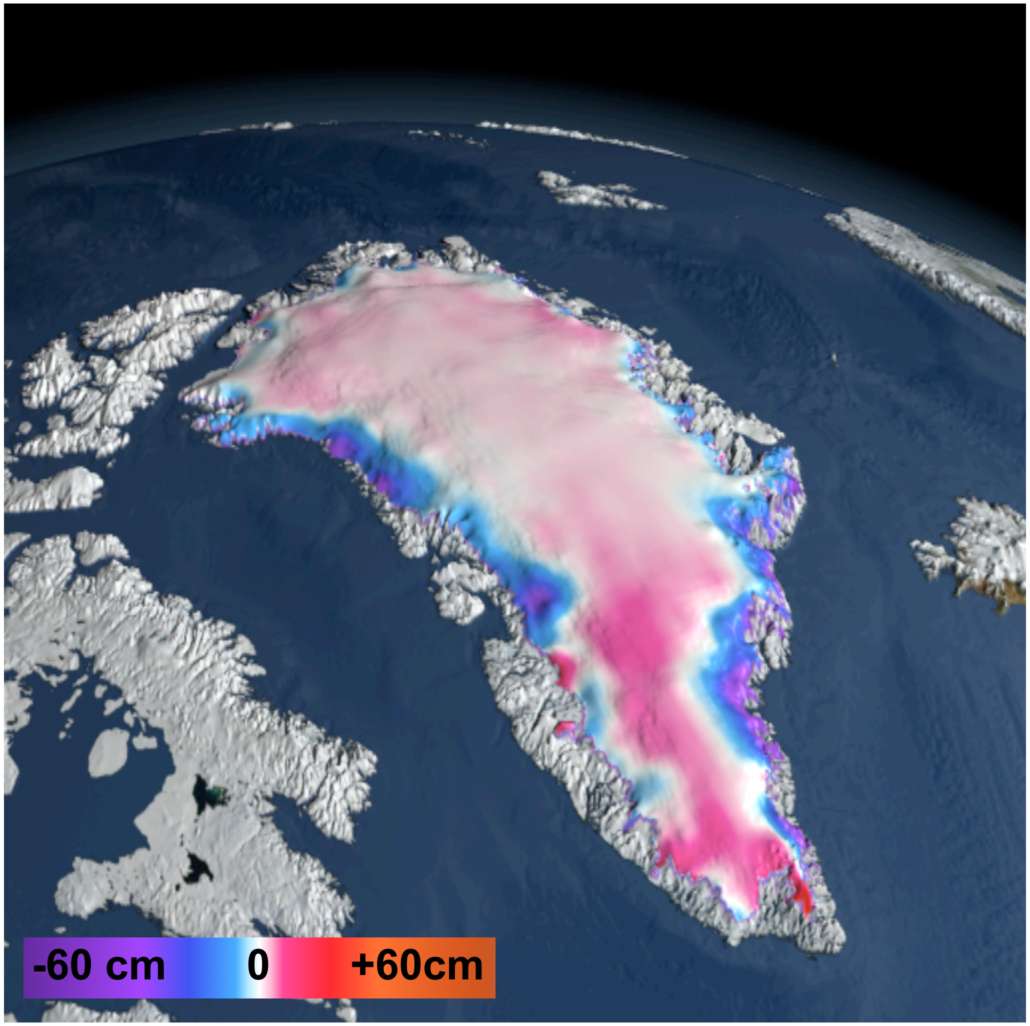
Key Factors Contributing to Error

- Pointing knowledge
  - ICESat was designed with state-of-the-art attitude determination system
- Pointing angle
  - Off-nadir pointing possible to 5 degrees to targets of opportunity, but for ice, we try to keep it under a few tenths of a degree
  - Orbit control to within $\pm$1 km of reference track to minimize pointing
  - Pointing control to within 30 m
- Spacecraft position
  - Radial component currently determined to within about 5 cm

Key Factors Contributing to Error

- Footprint Size
  - Accuracy increases when we smooth out over roughness elements within the footprint
- Along-track sampling density
  - Minimizes interpolation errors
- Pulse width
  - 6 ns transmit pulse width
- Beam shape
  - We seek to achieve gaussian beam with 86% of the return from within 70 m
- Transmit and return energy
  - Number of samples improves with ability to penetrate clouds
  - Better-defined waveforms with higher energies
- Spacecraft and instrument stability
- Forward scattering

Elevation Change Observations are The Keys to Understanding Ice Sheet Changes

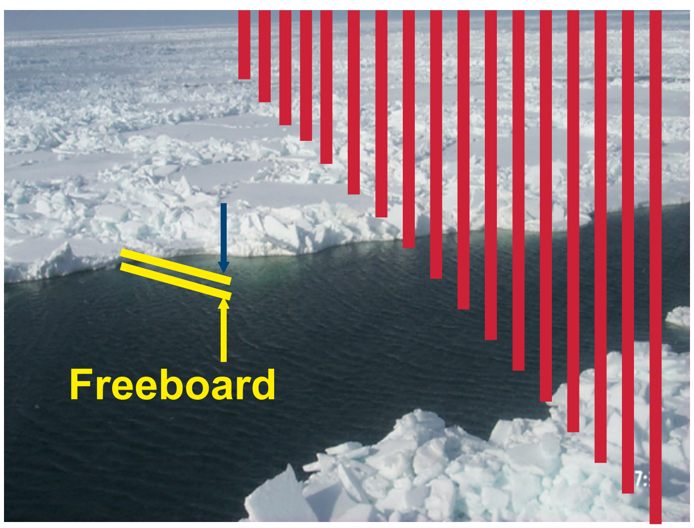


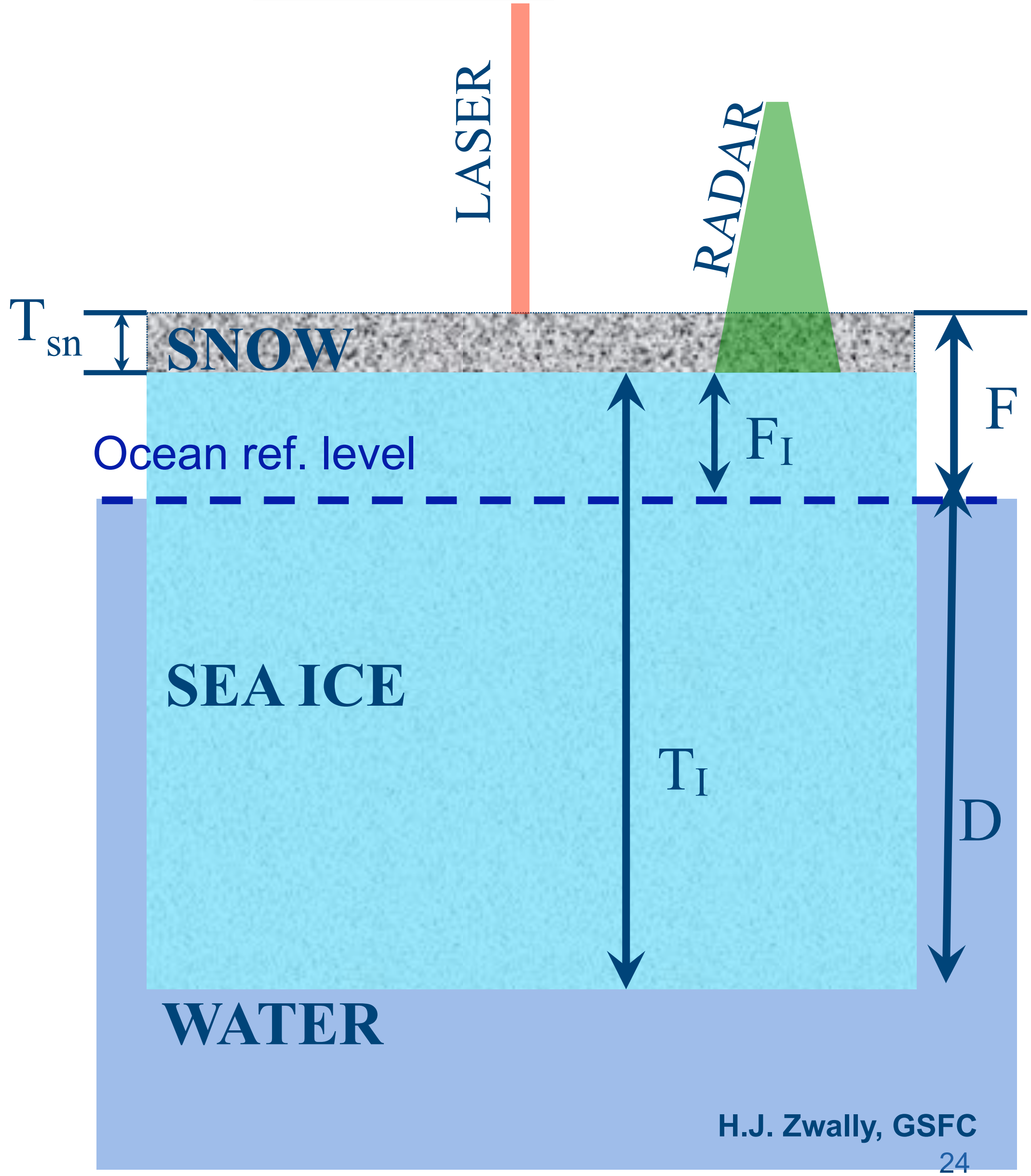
- ICESat is showing dramatic shrinking at the Greenland ice sheet margins and slight growth in the interior.
  - Interior growth over very large areas offsetting some but not all of the losses at the margins
  - Greenland contributing ~160 GT per year (0.35 mm) to sea level
- Antarctica also shows significant thinning in margins, and growth in much of the interior for a net loss of ice.

H.J. Zwally, GSFC

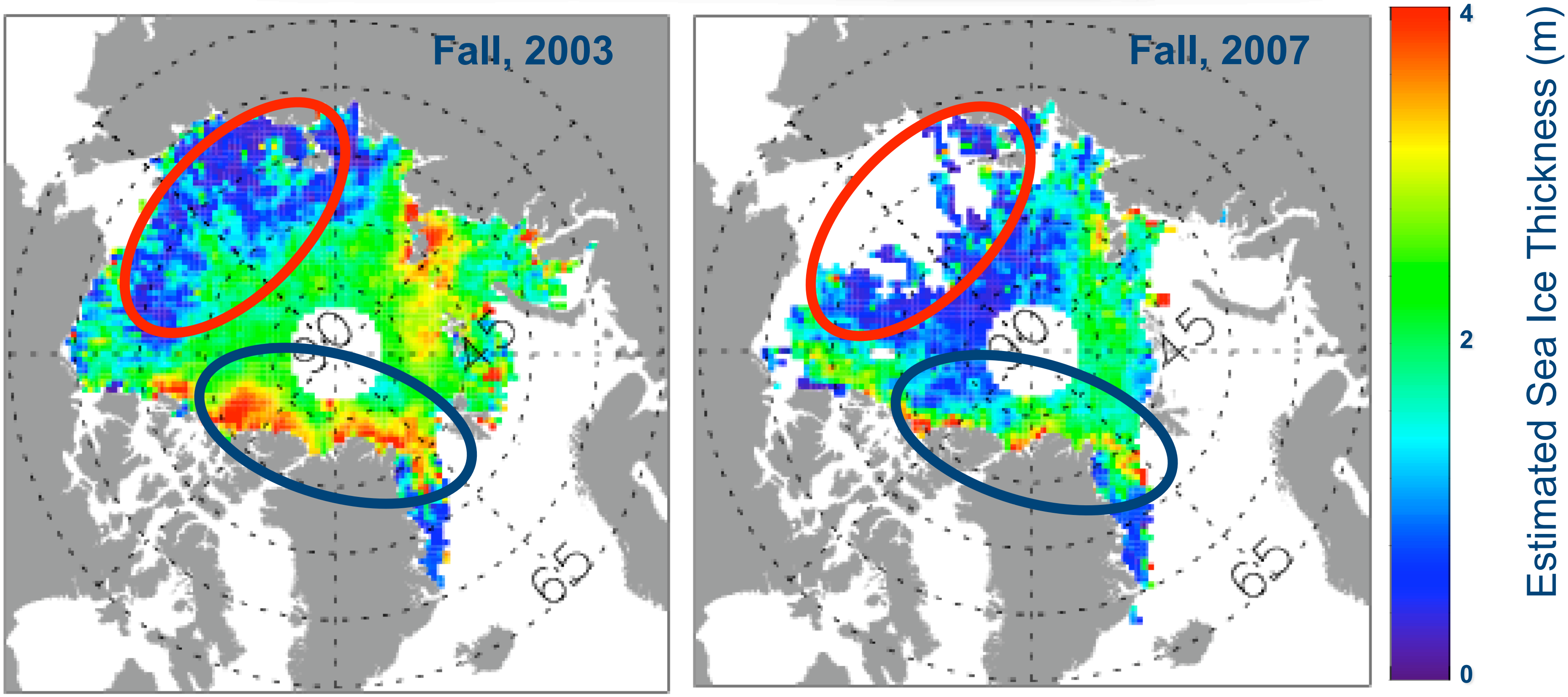
ICESat Enables Estimates of Sea Ice Thickness

- ICESat's precision allows measurement of difference between water and sea ice surface heights
- Adjusting for snow depth and buoyancy yields ice thickness estimates





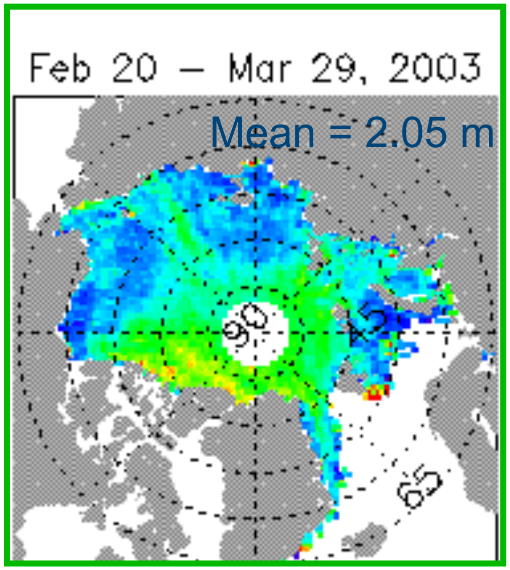
Thinning of Arctic Sea Ice

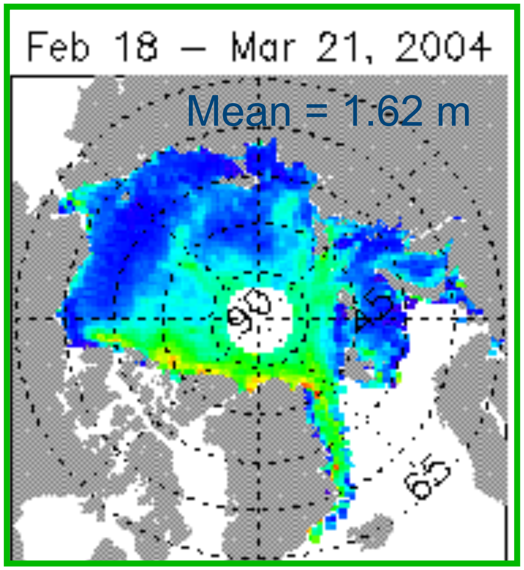


- Arctic Sea ice has thinned substantially since the launch of ICESat making it more vulnerable for rapid loss
  - 1-to-2 m thick ice thinned to <1m between 2003 and 2007 (Red Ovals)
  - Most thick 3-to-4 m ice near Greenland is gone (Black Ovals)

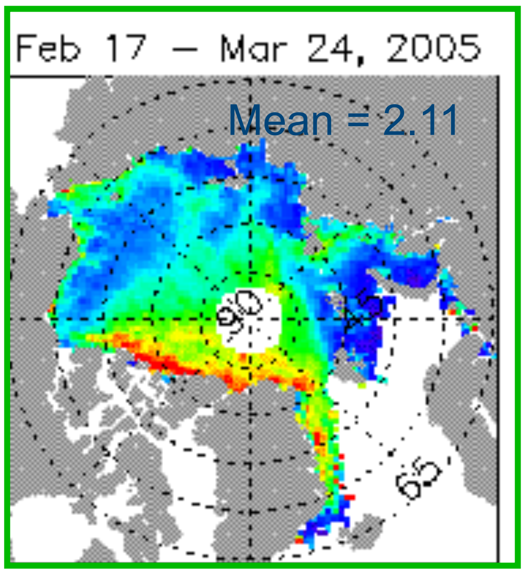
H.J. Zwally, GSFC

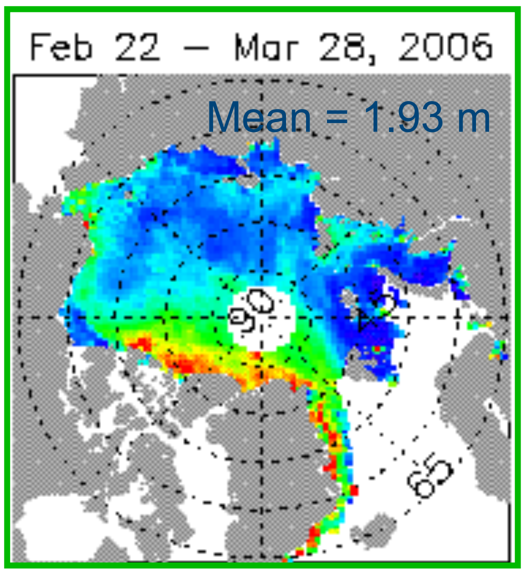
ICESat-I Observations of Changes of Arctic Sea Ice Thickness

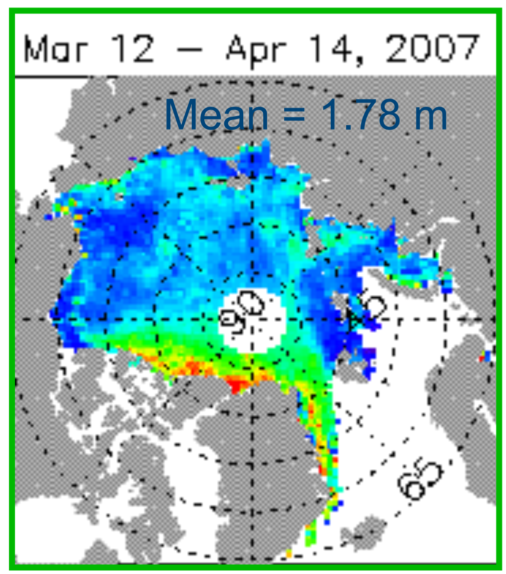


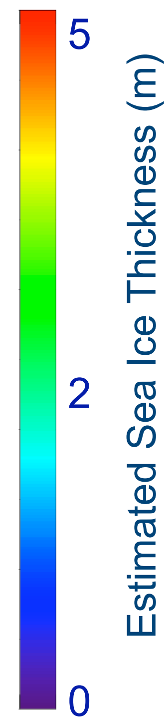


- ❑ 5 years (2003 to 2007) of ICESat measurements in early fall show that the ice VOLUME is rapidly decreasing toward zero (even faster than ice AREA).
- ❑ 3 years provides no valid trend information





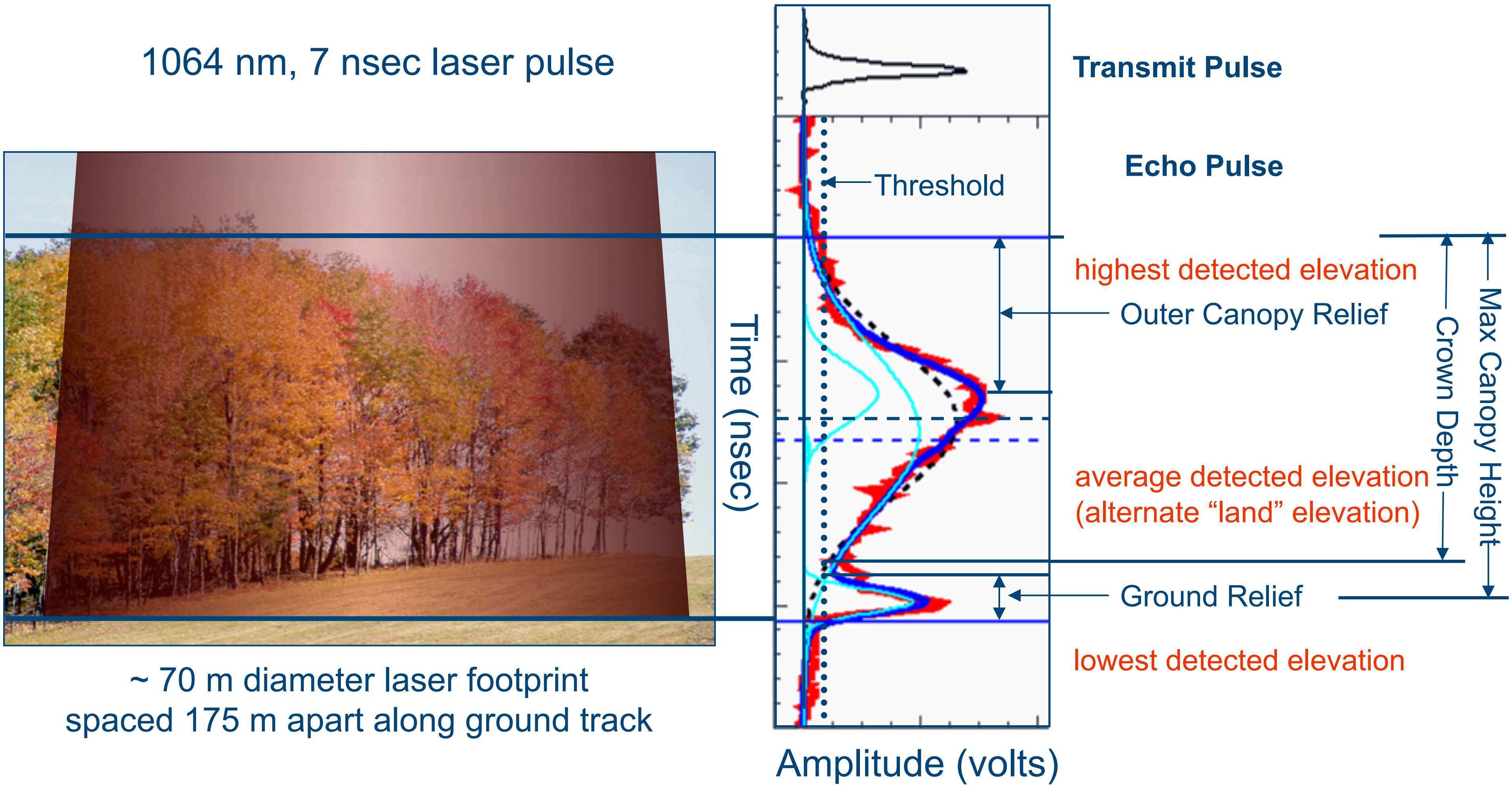




H.J. Zwally, GSFC

GLAS Measurement of Echo pulse from Trees

1064 nm, 7 nsec laser pulse

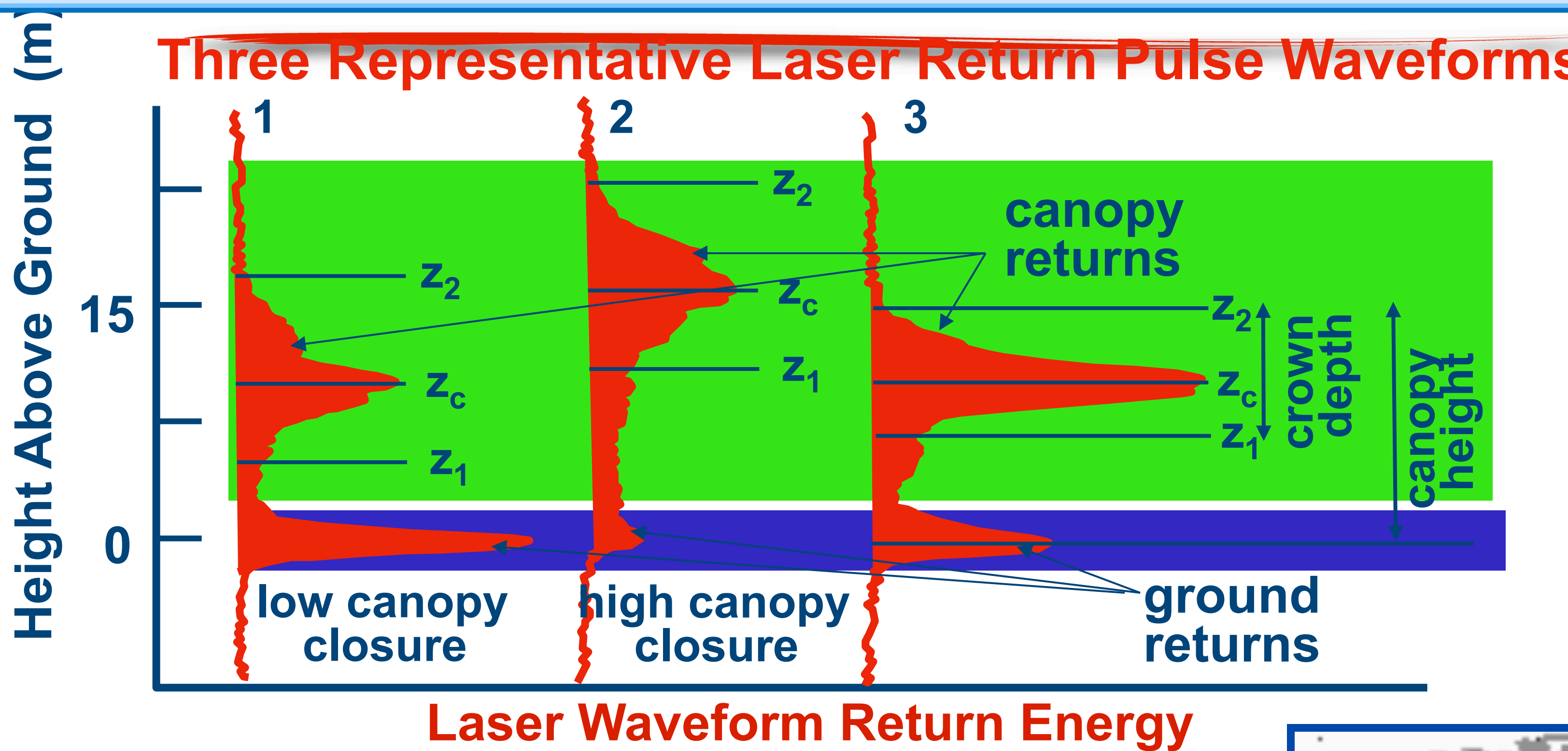


~ 70 m diameter laser footprint
spaced 175 m apart along ground track

Height Distribution of Reflected Laser power with 15 cm Vertical Sampling

D. Harding/NASA- GSFC

Boreal Forest Height and Density from ICESat



Canopy Height = Distance from Start of Signal to Last Peak, z_2

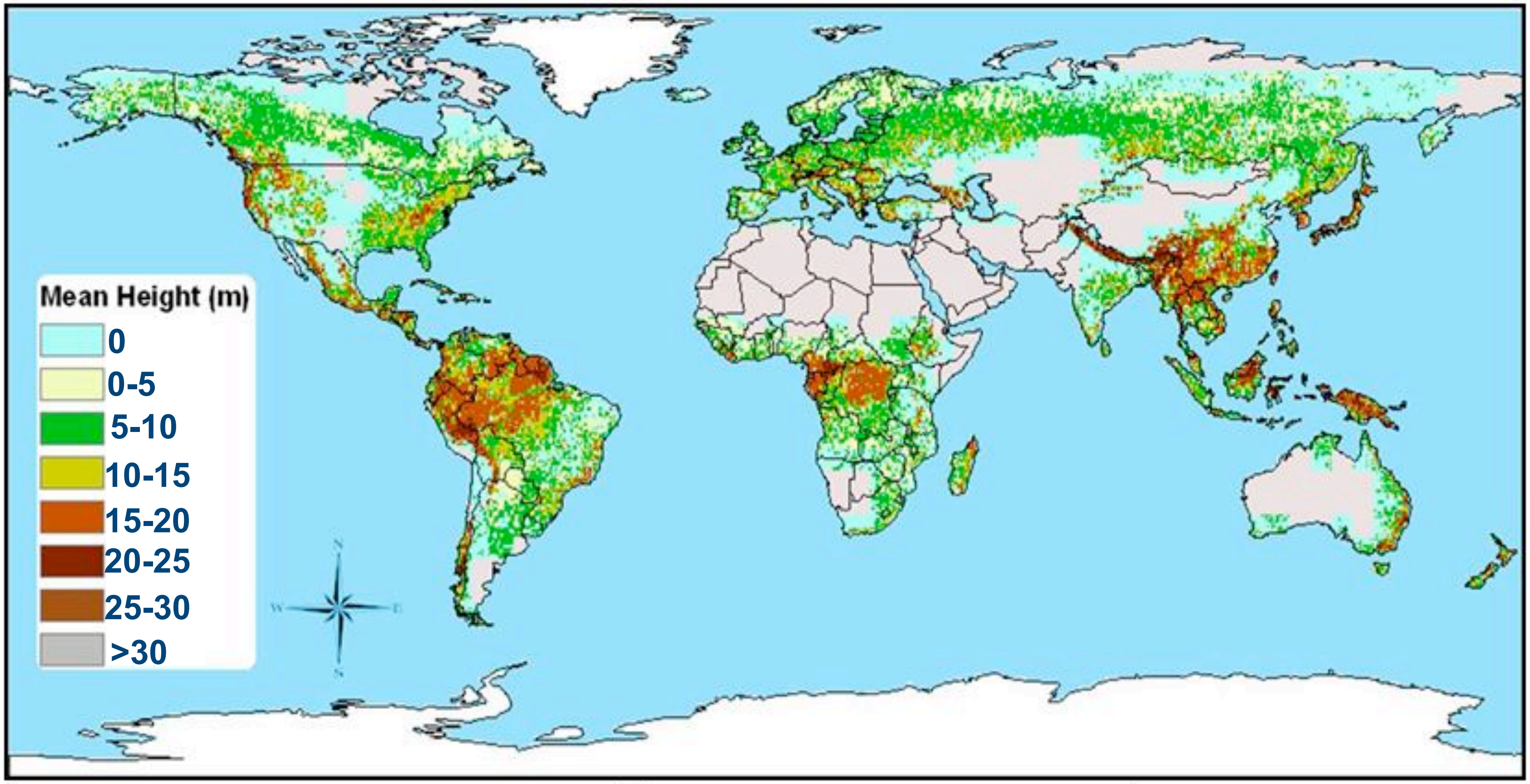
Crown Depth = Width of Upper Part of Canopy Return, $z_2 - z_1$

Roughness of Outer Canopy = Leading Edge Slope from z_2 to z_c

$$\text{Canopy Closure} \sim \frac{\text{Ground Return Energy}}{\text{Total Return Energy}}$$

D. Harding et al., NASA GSFC

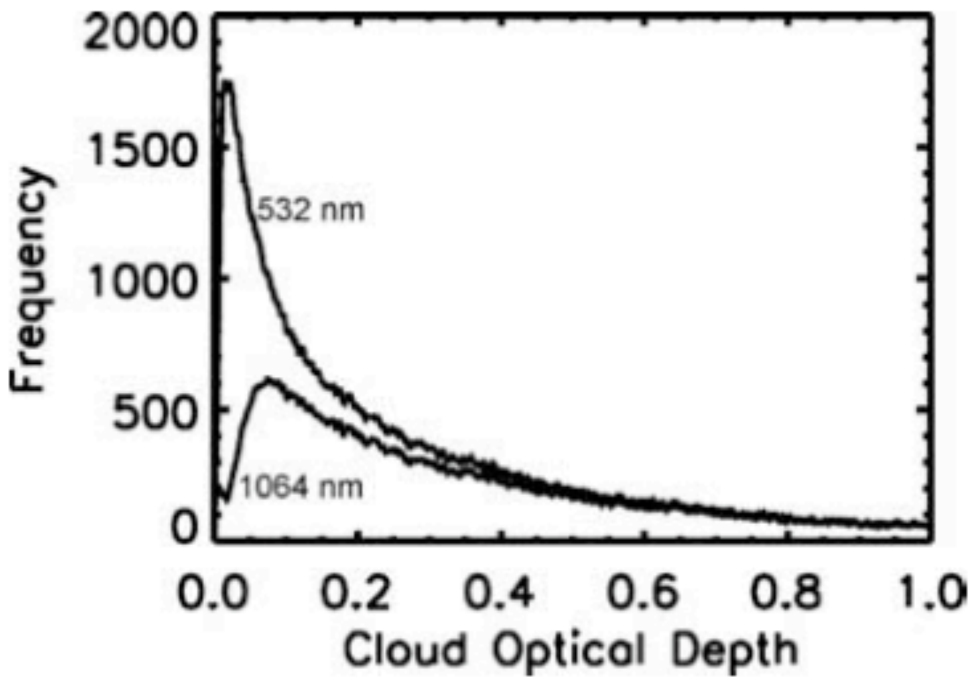
Vegetation Height Measurements



- ICESat's accurate ranging capability enables large-scale biomass estimates from canopy height
  - 50-70 meter footprint limits assessment to large scales
  - More detail requires smaller footprints

M. Lefsky, Colorado State University

Different Sensitivities of 532 and 1064 nm Channels for Atmospheric Science

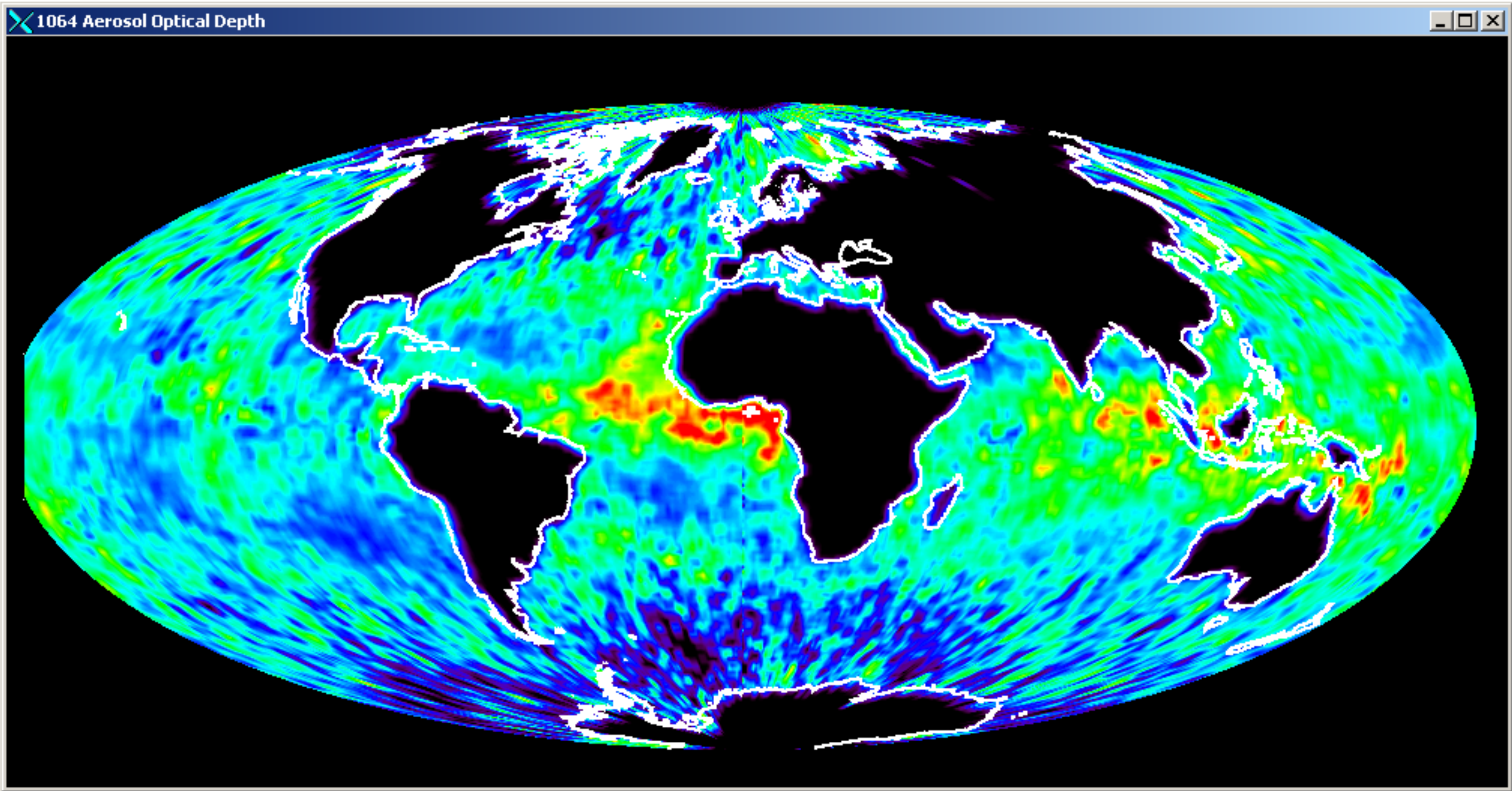


Spinhirne et al., Cloud and Aerosol Measurements from GLAS GRL, 2005

Figure 4. The relative frequency of cloud optical depth retrieval from GLAS for clouds above 4 km altitude from the 532 nm channel for all global observations in October 2003. The lower line indicates the relative frequency clouds are also flagged as detected in analysis of the 1064 nm channel alone. The individual data points are derived from 8 pulse, or 5 Hz, average profiles.

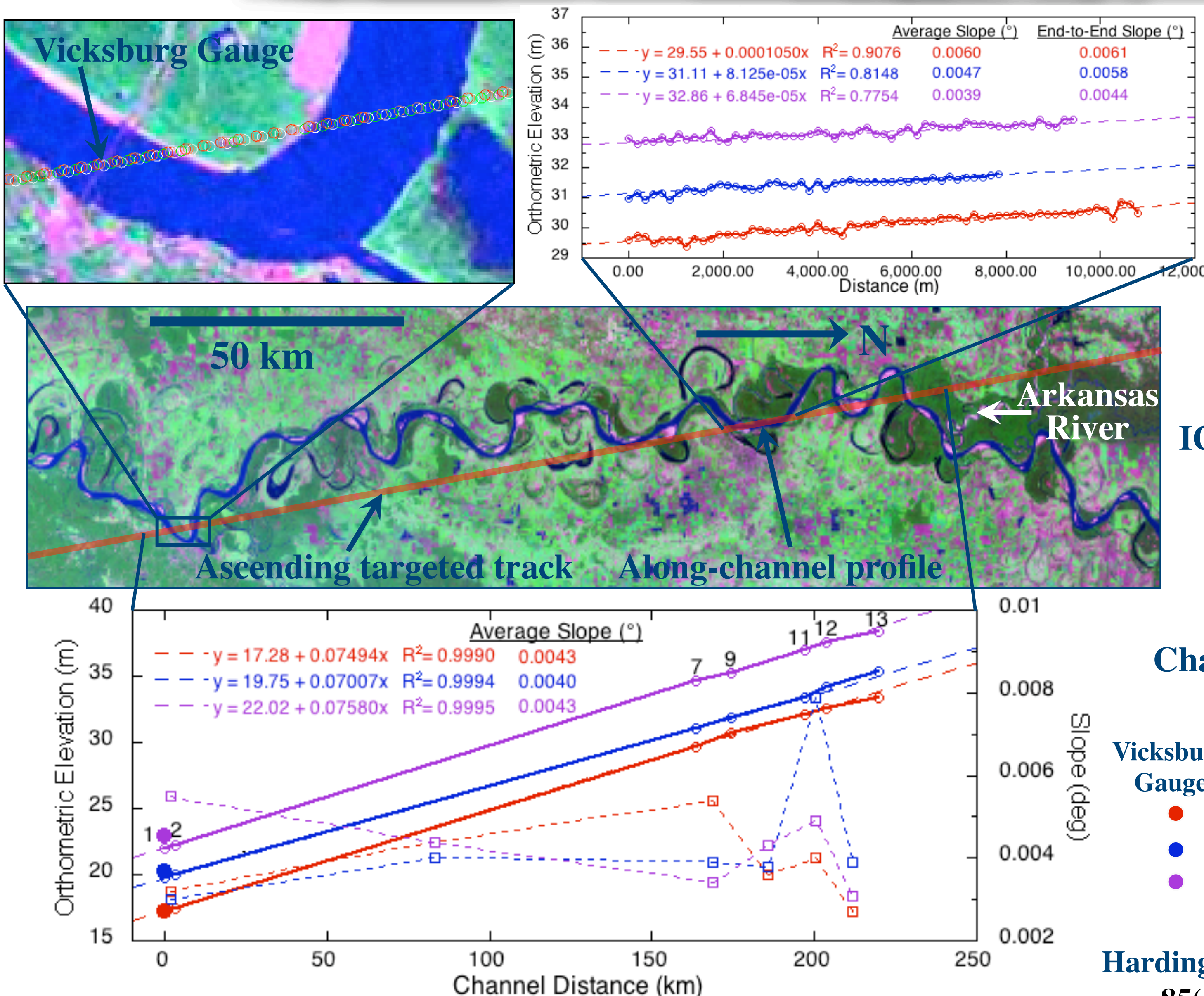
1064 nm Total Column Optical Depth – L3J

Optical Depths range from zero (black) to 1 (white)



S. Palm, SSAI

River & Lake Heights - Profiles of Mississippi River



ICESat Footprint Elevations along Straight Reach and Derived Slopes

Orange: ICESat Targeted Profile on Landsat Image

River Stage at Channel Crossings and Derived Slopes

Vicksburg Gauge	ICESat Average	
●	—o—	Oct. 2, 2003
●	—o—	March 6, 2004
●	—o—	June 5, 2004

Harding et al., *Eos Trans. AGU*, 85(47), C21B-05, 2004.

Summary

- ICESat is uniquely designed to provide essential insights into the world's rapidly changing ice cover
  - Quantity and mechanisms of ice sheet change
  - Estimates of sea ice thicknesses
- Accuracy and precision requirements pose major measurement challenges
- ICESat also supports estimates of vegetation structure and biomass
- The 1064 nm channel provides useful atmospheric science capabilities, though not as good as the 532
- ICESat has applications for other science disciplines as well