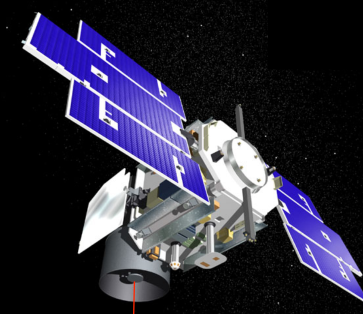
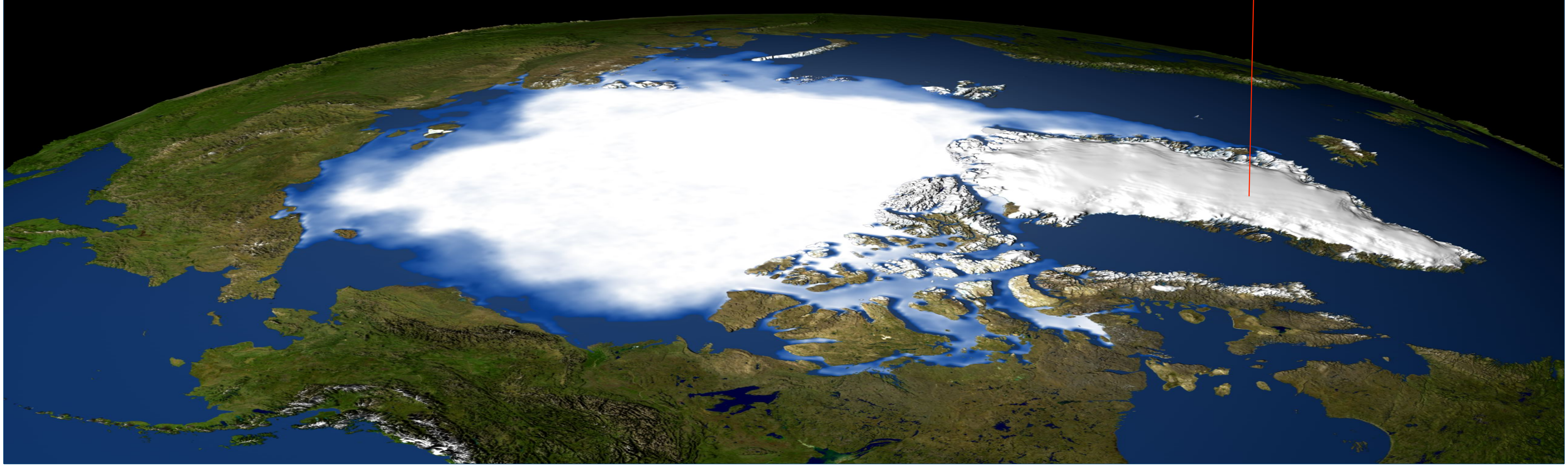
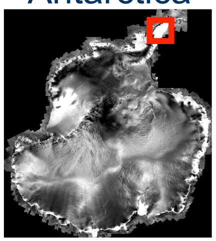
# NASA's Ice Cloud and land Elevation Satellite (ICESat)

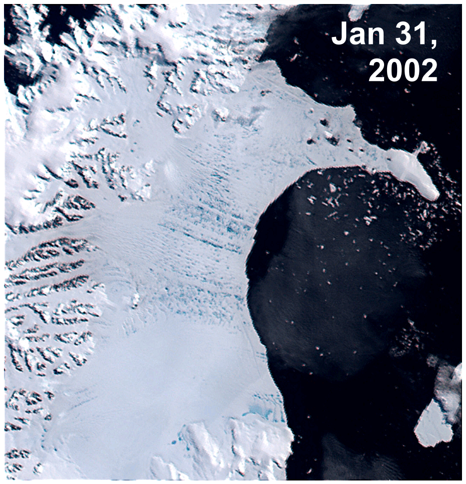


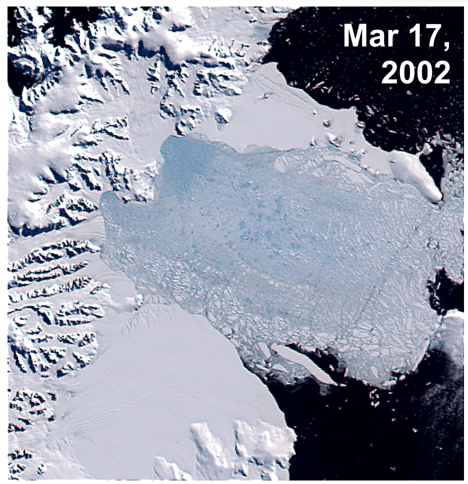
**Waleed Abdalati**
**Earth Science and Observation Center**
**CIRES, University of Colorado**



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




T. Scambos, NSIDC

<u>Ice Sheet Stability</u>

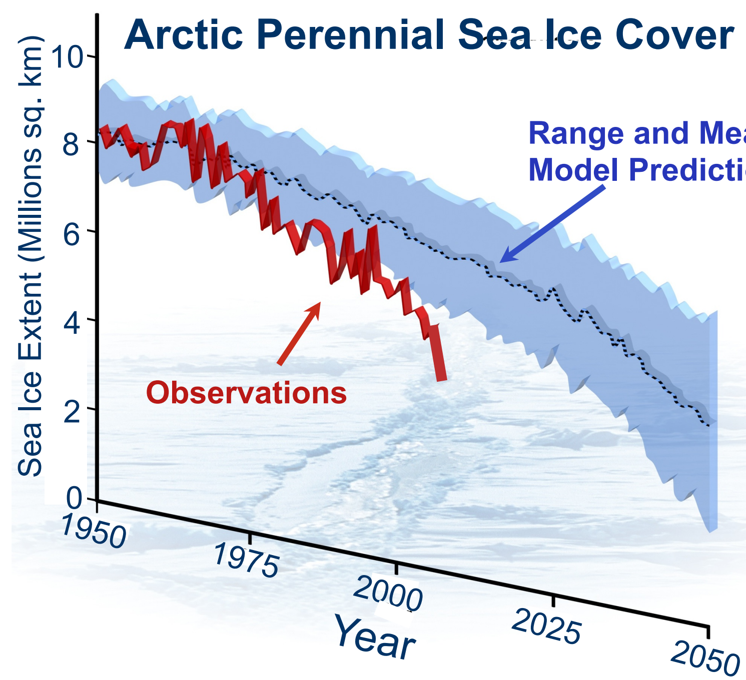
10,000 year old ice, thousands of km in area, hundreds of meters thick, gone in weeks! Glaciers rapidly accelerated in response

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

<u>Disappearing Arctic Sea Ice</u>

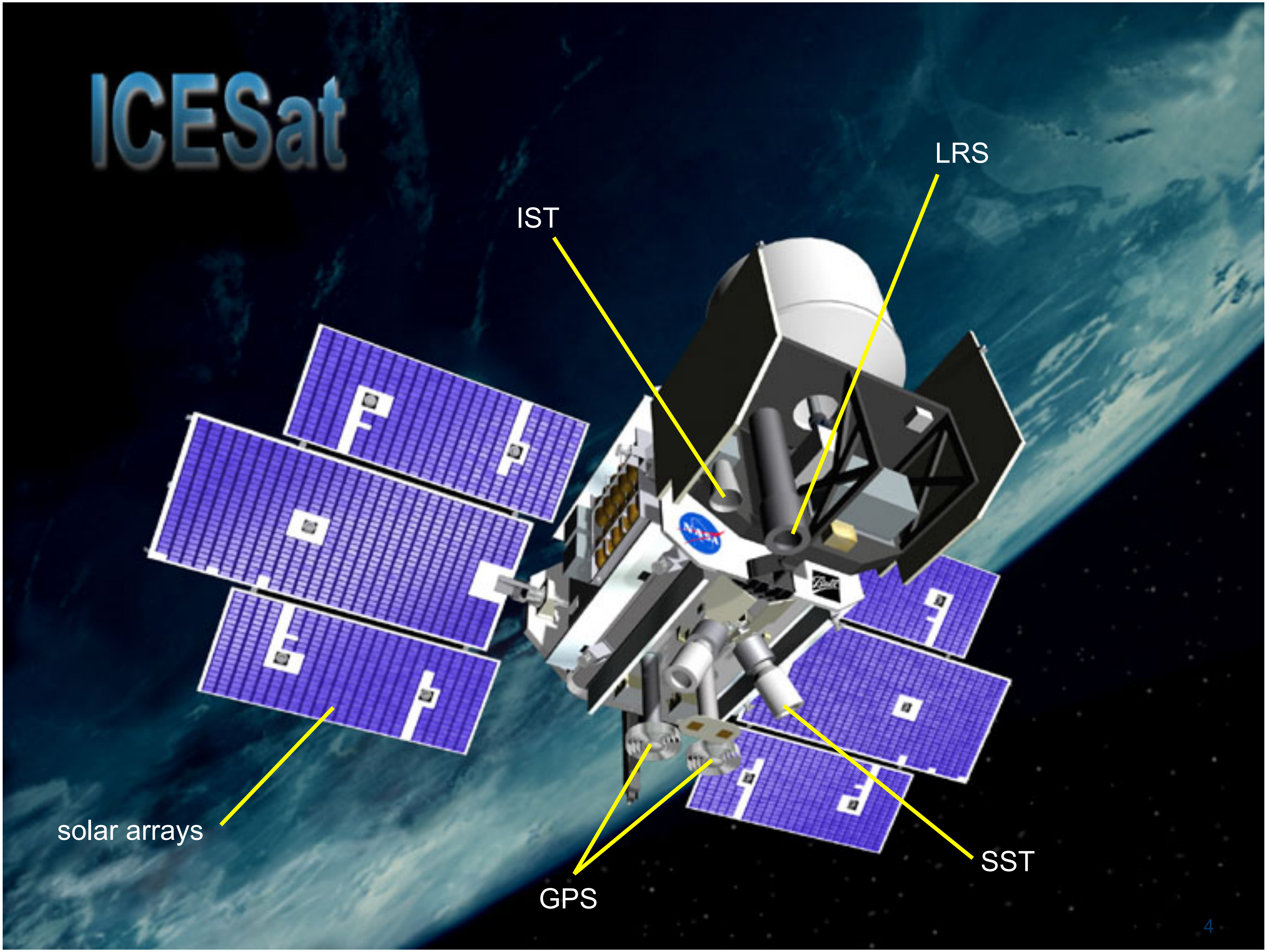
Arctic sea ice is disappearing faster than nearly all of the world's most widely accepted climate models predict.

**Thickness is the key missing variable**

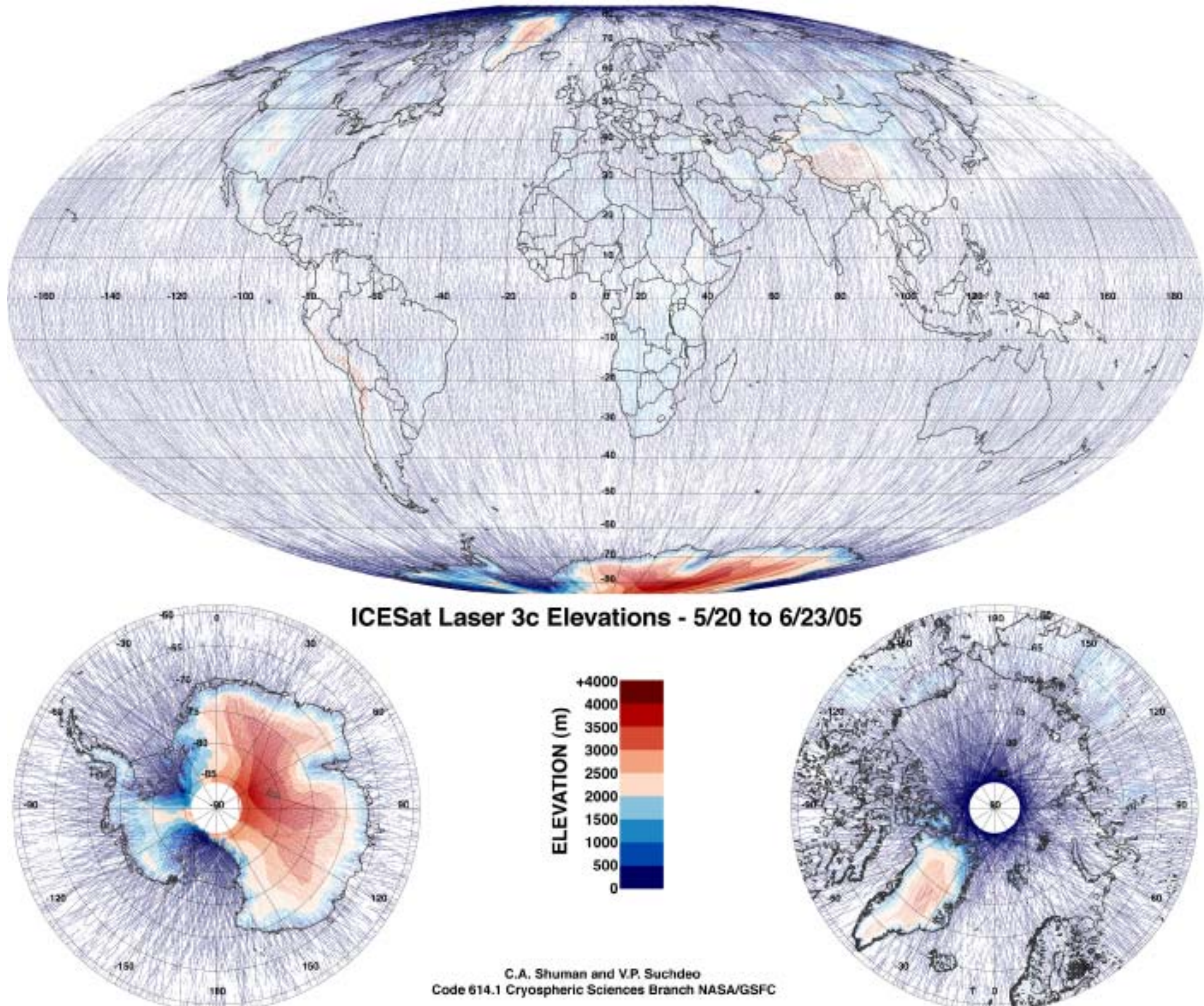



NCAR

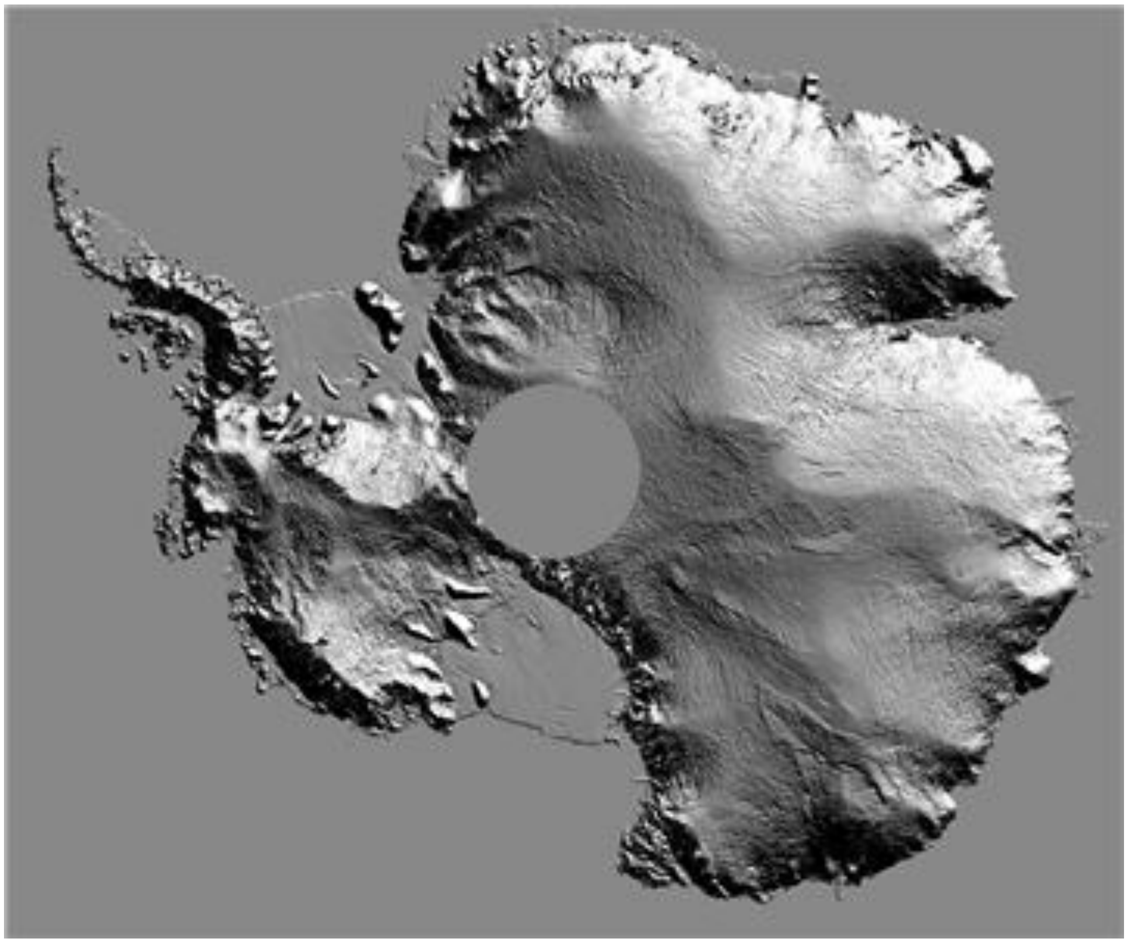

ICESat
solar arrays
radiator
Main telescope mirror
(1m) inside sun shade
antenna
laser retro-reflector
secondary mirror

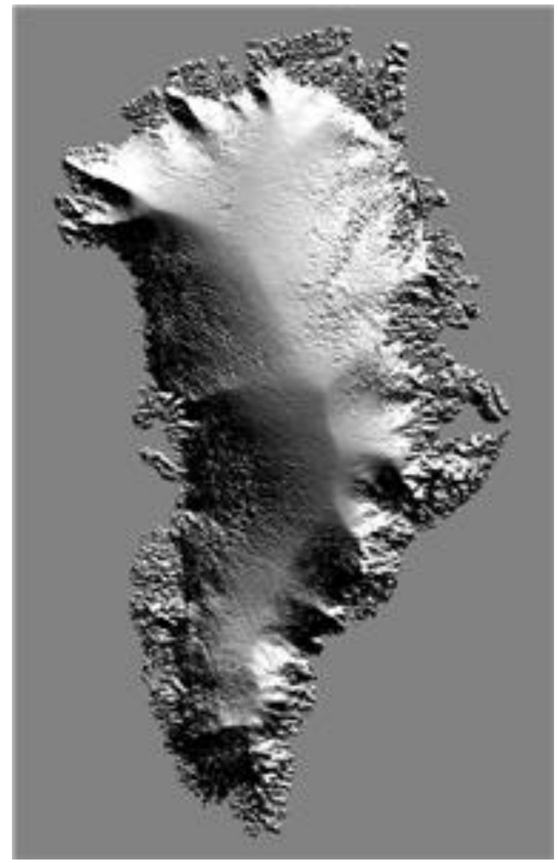

ICESat
LRS
IST
solar arrays
GPS
SST

# 33 Days of ICESat Coverage

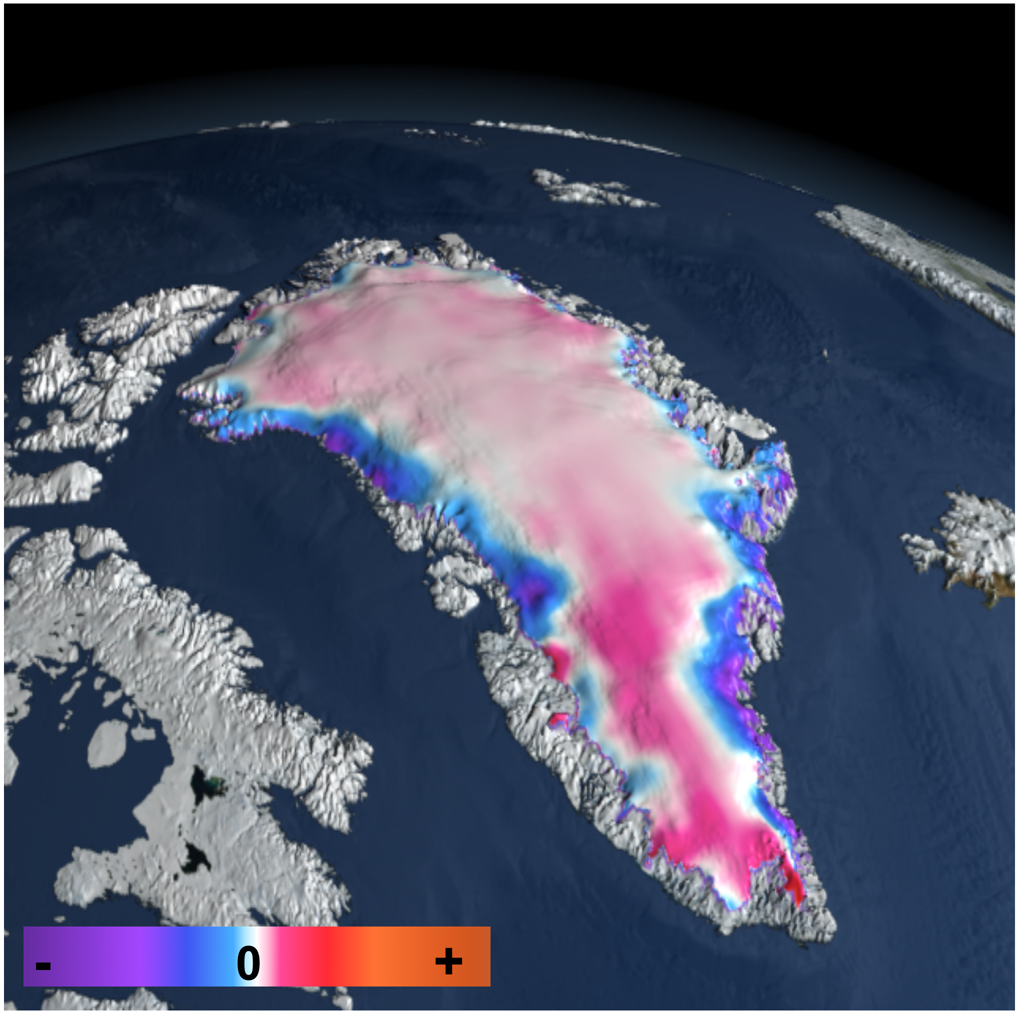


# Elevation Measurements Along Ground Tracks Enable the Creation of Digital Elevation Models





# 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

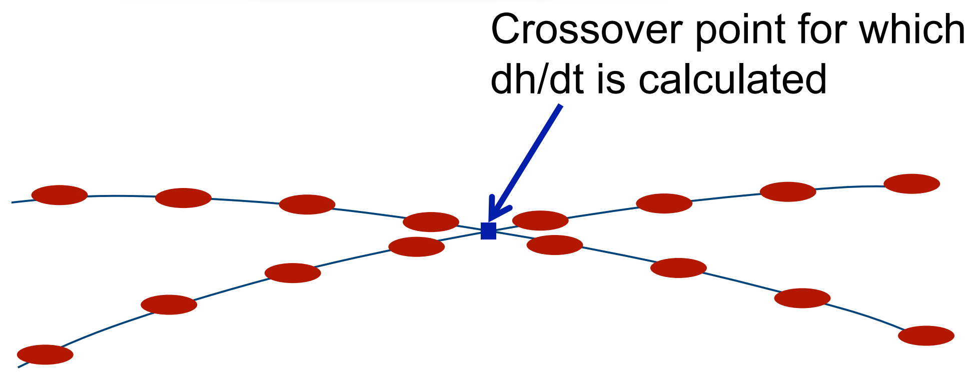
H.J. Zwally, GSFC

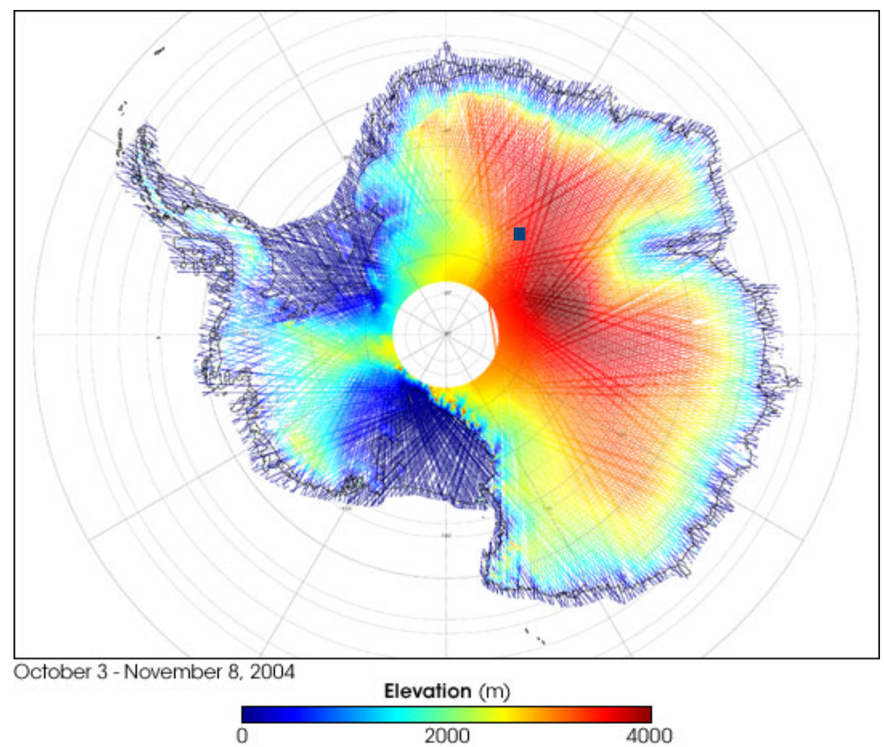
# ICESat Mission and Instrument Characteristics

- 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



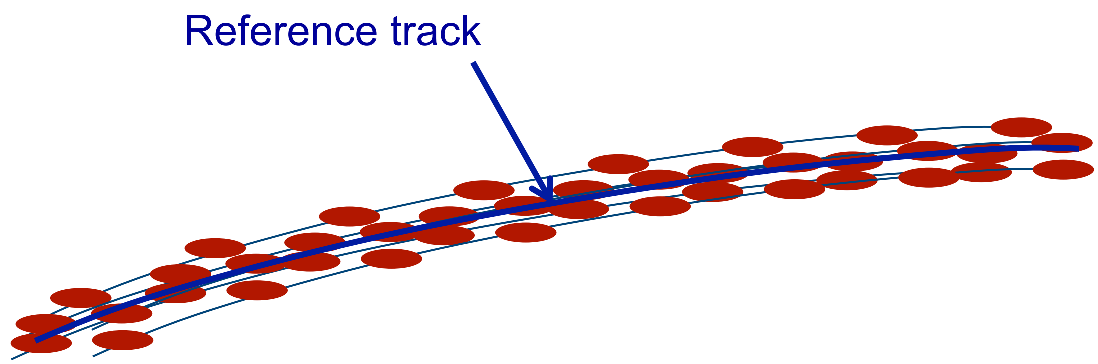



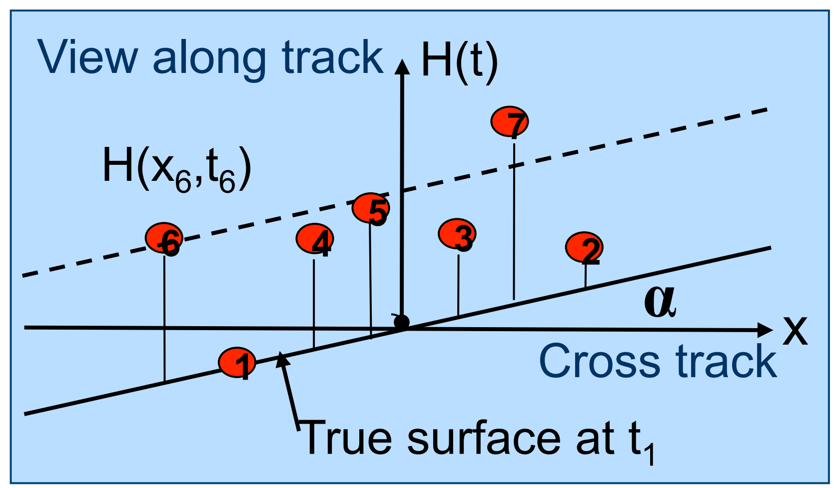
# Deriving dh/dt from Repeat-Track Analysis

- 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:

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

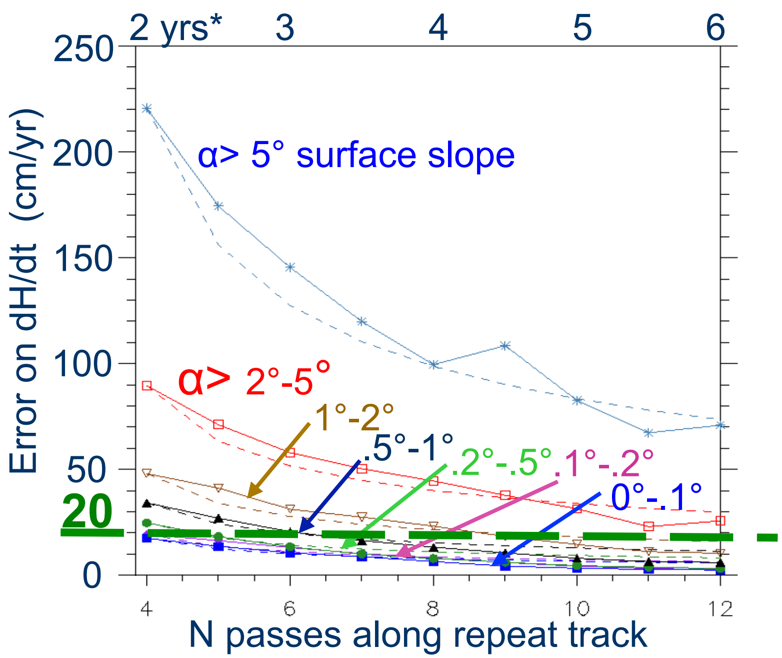
- A dense time series of elevation differences are accumulated throughout the mission along track



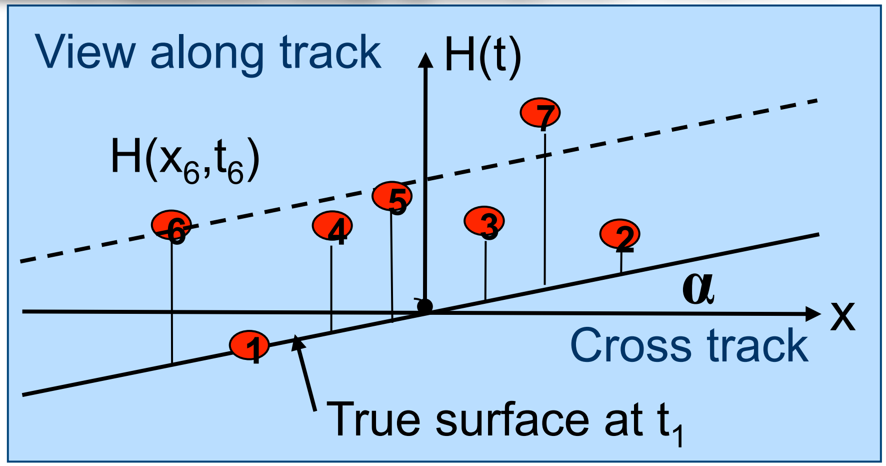

H.J. Zwally, GSFC

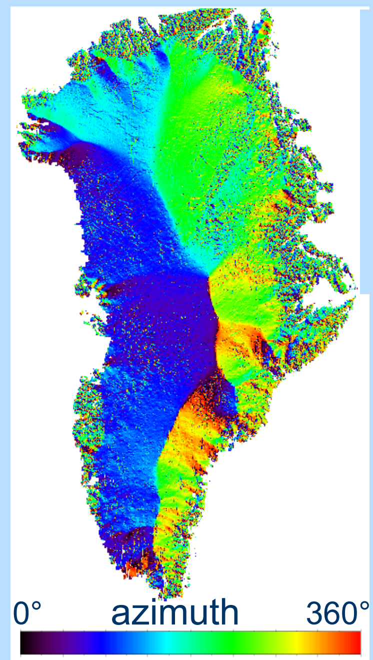
# Accuracy is Sensitive to Number of Observations




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

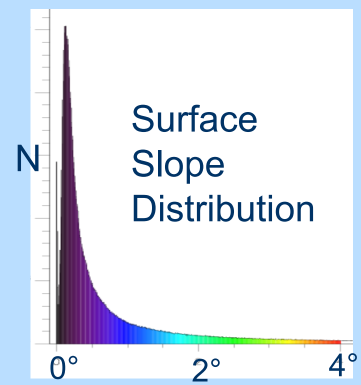
**H.J. Zwally, GSFC**



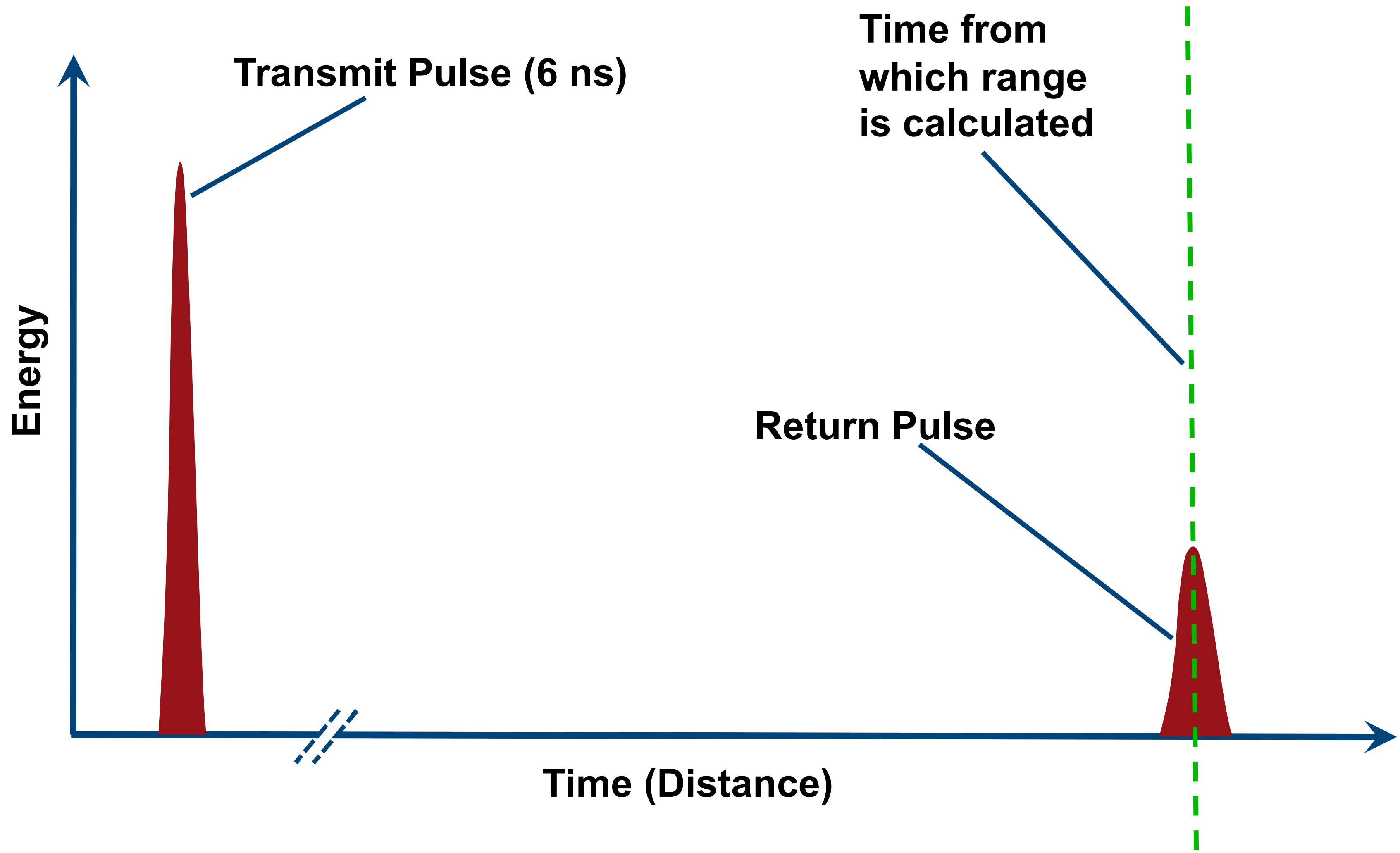



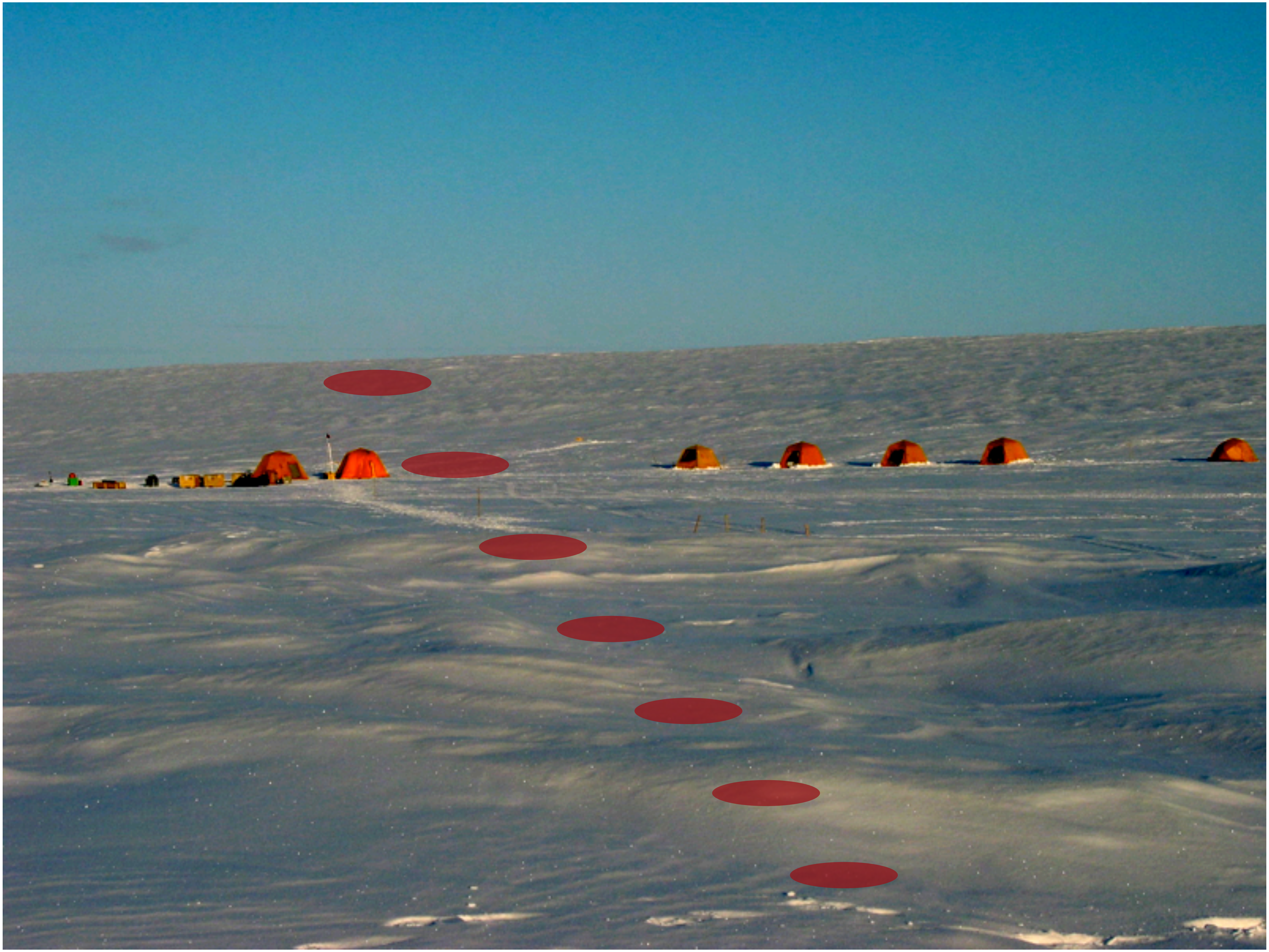

**GREENLAND**

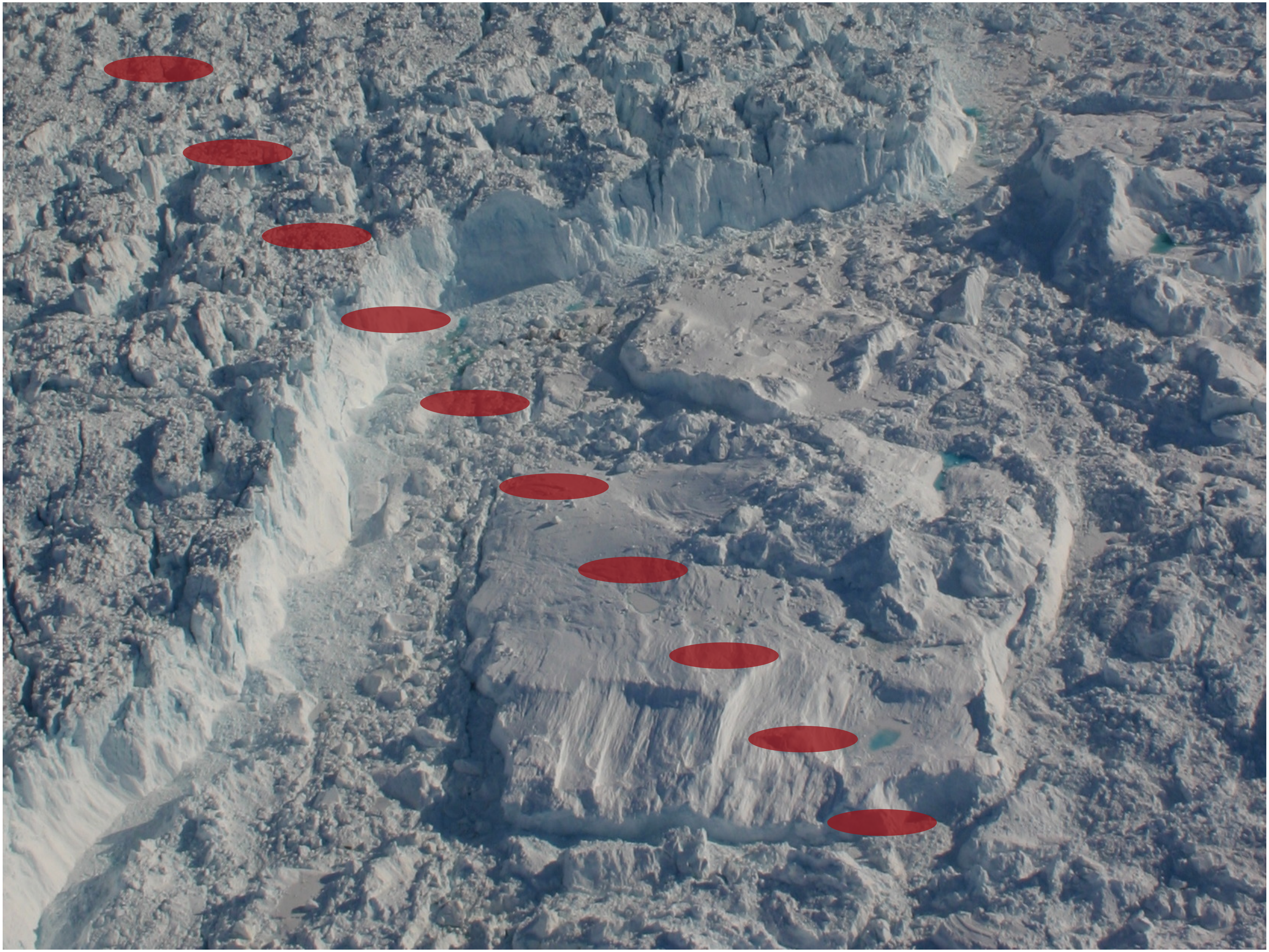
- Direction and magnitude of ice-sheet slopes is highly variable.
- Largest slopes at critical margins.



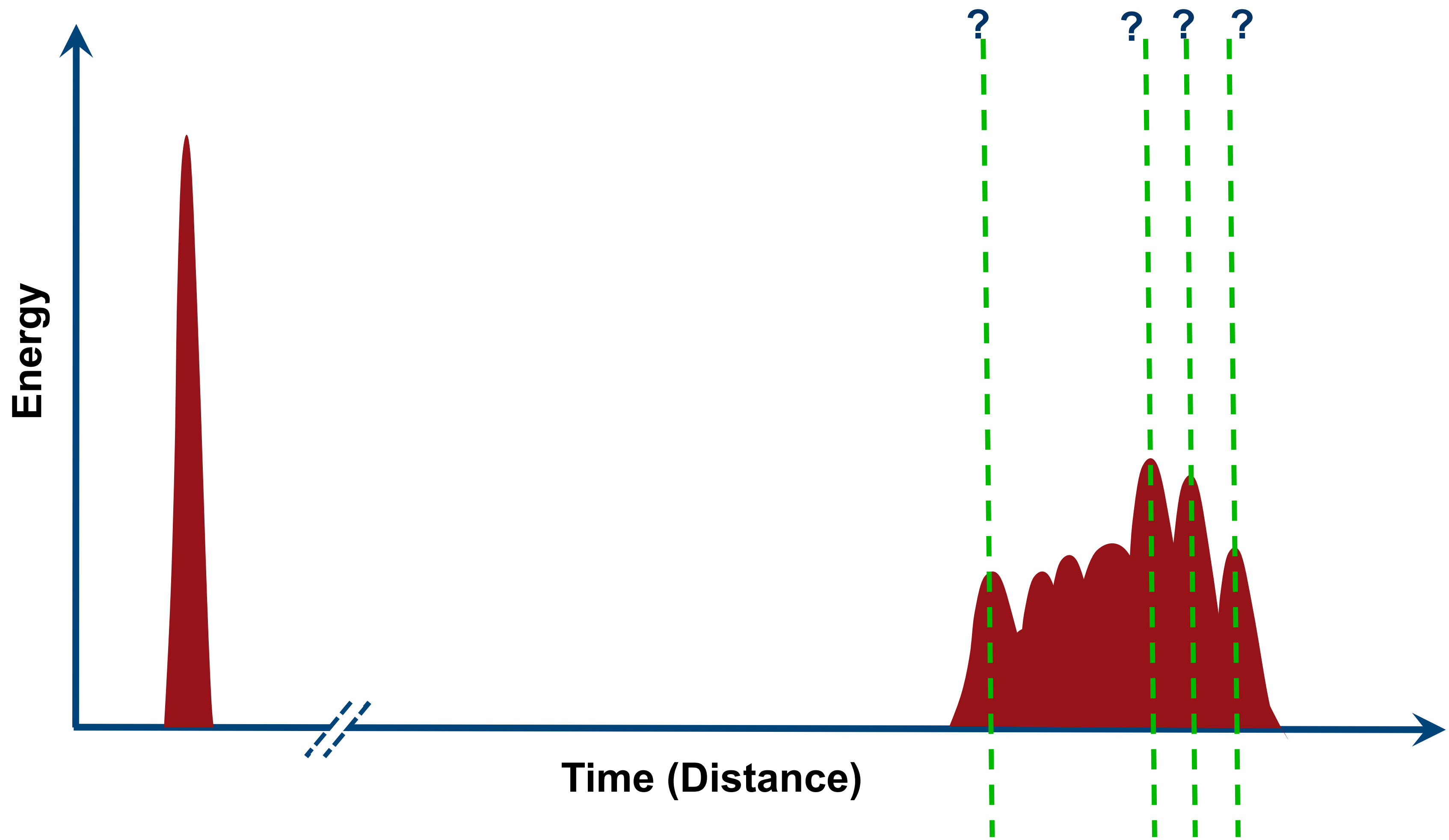
# Calculation of Range: Simple Surface



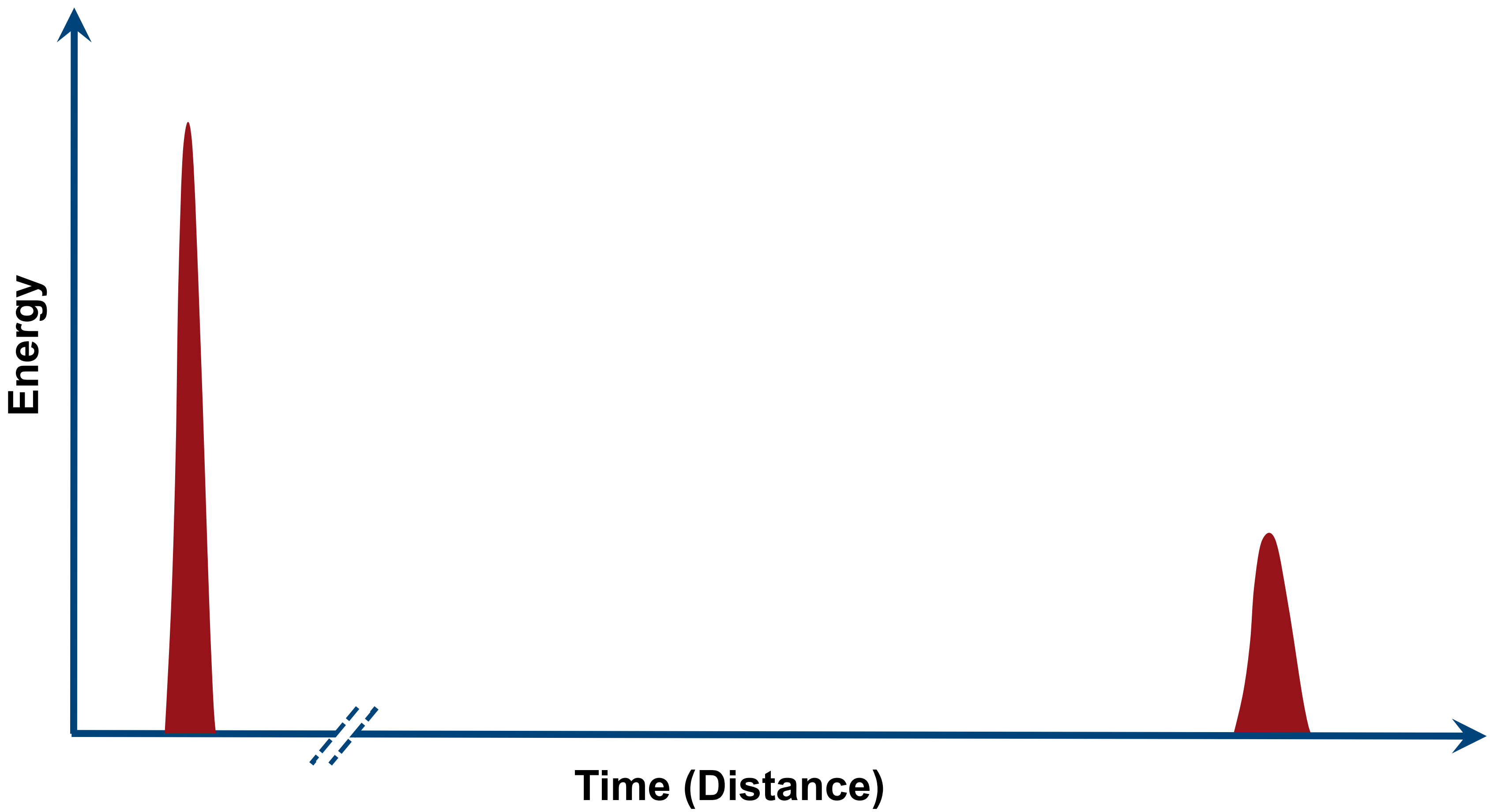




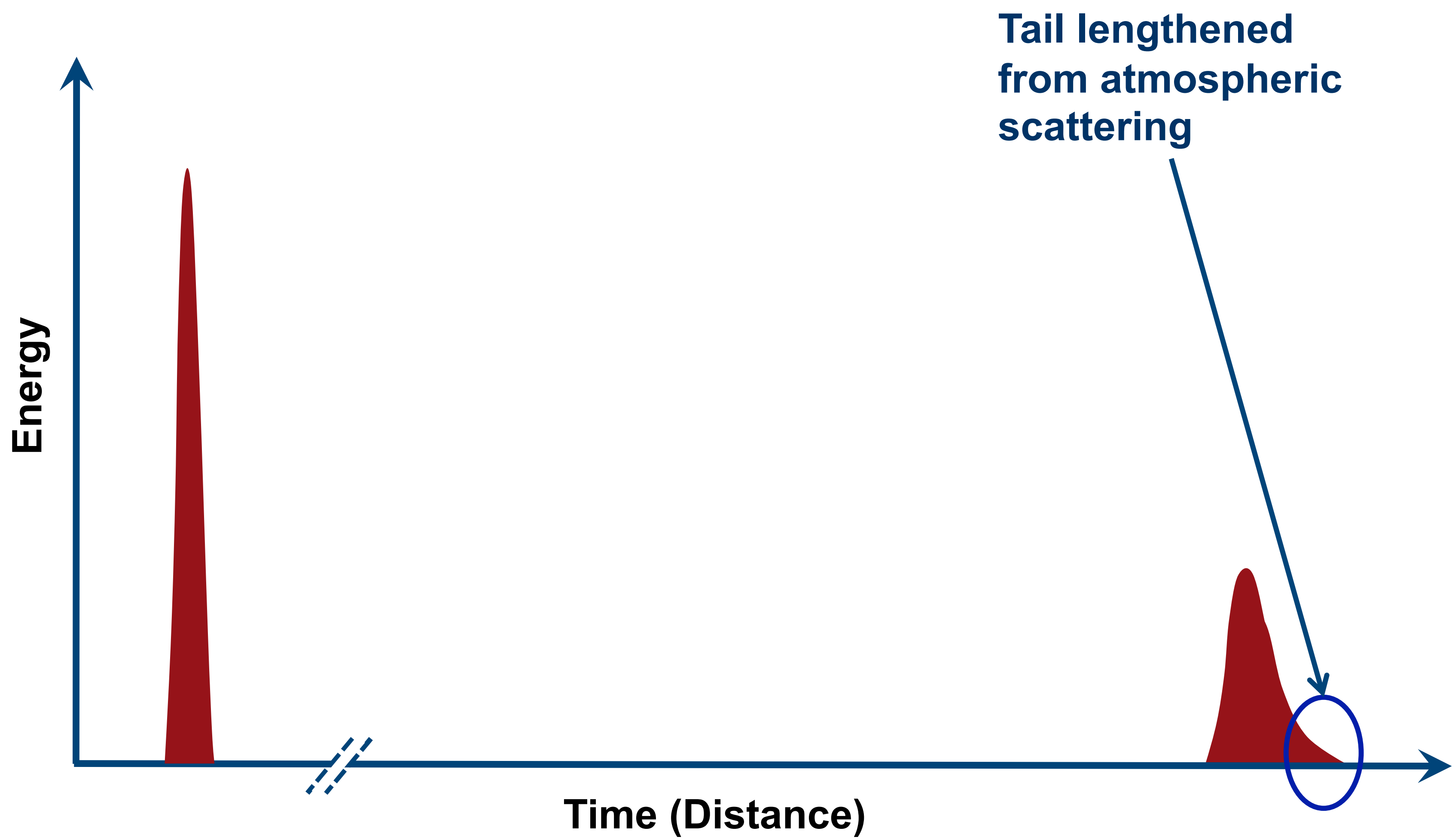
# Calculation of Range: Complex Surface



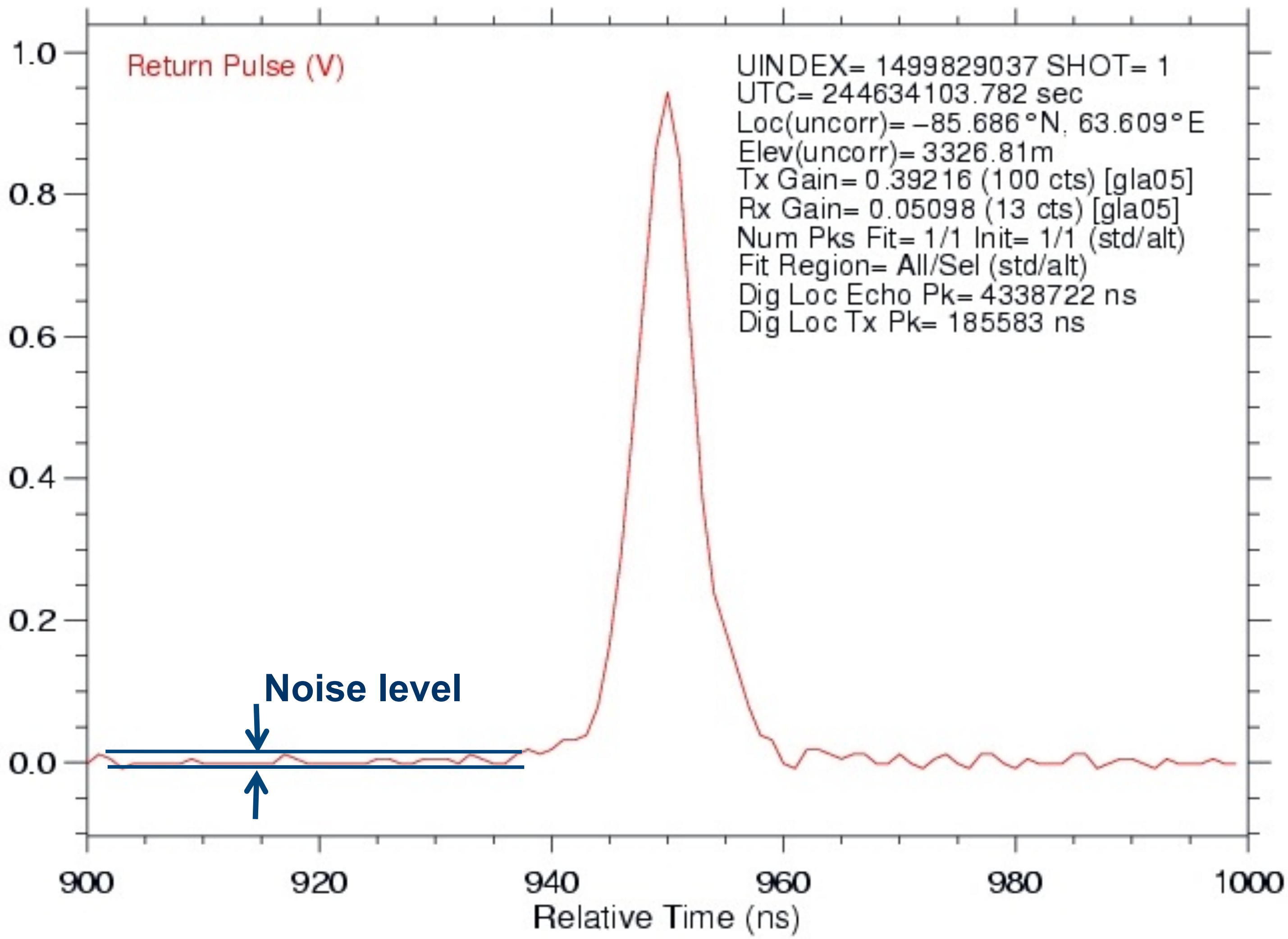
# Calculation of Range: Simple Surface



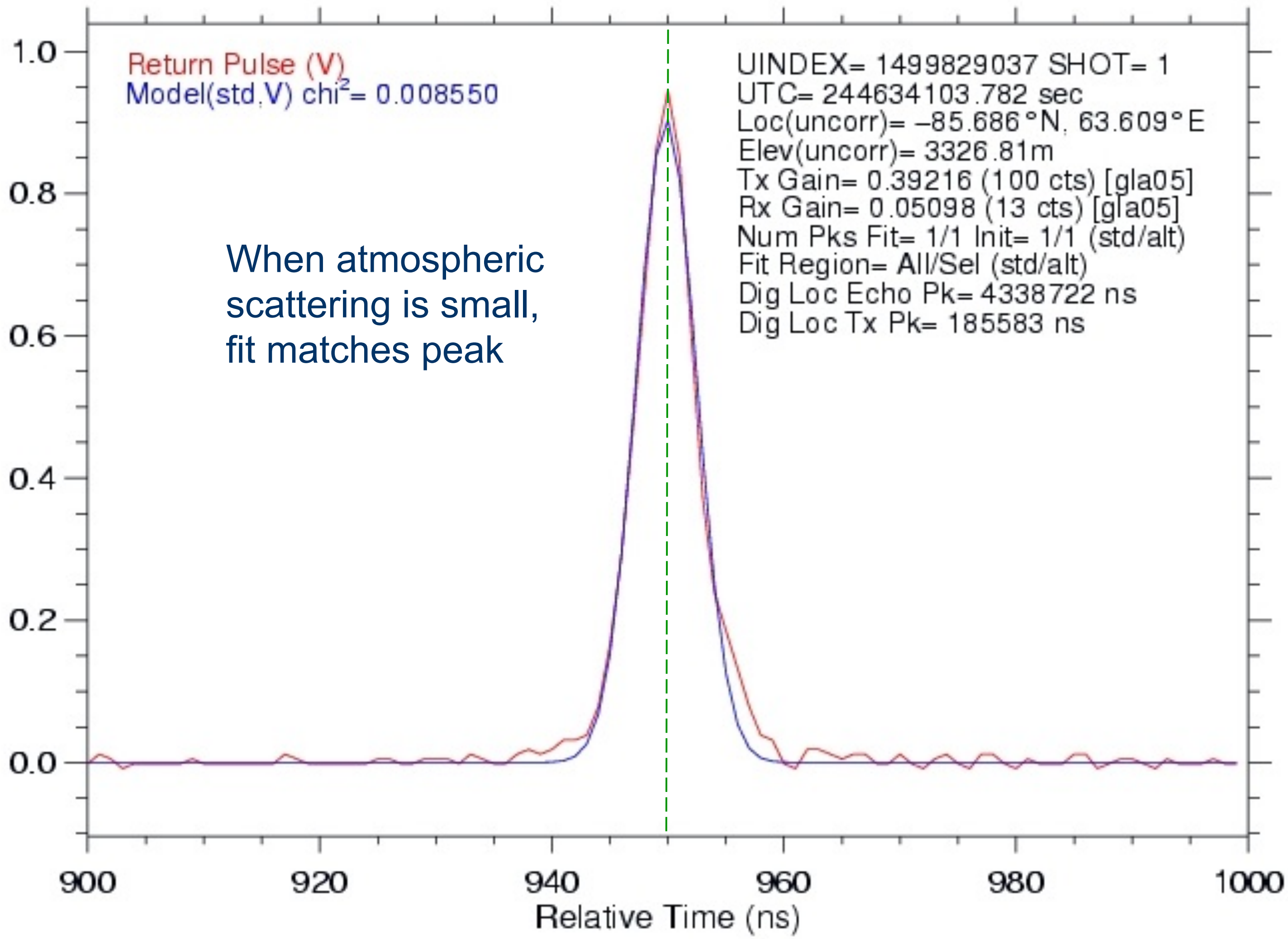
# Calculation of Range: Atmospheric Effects



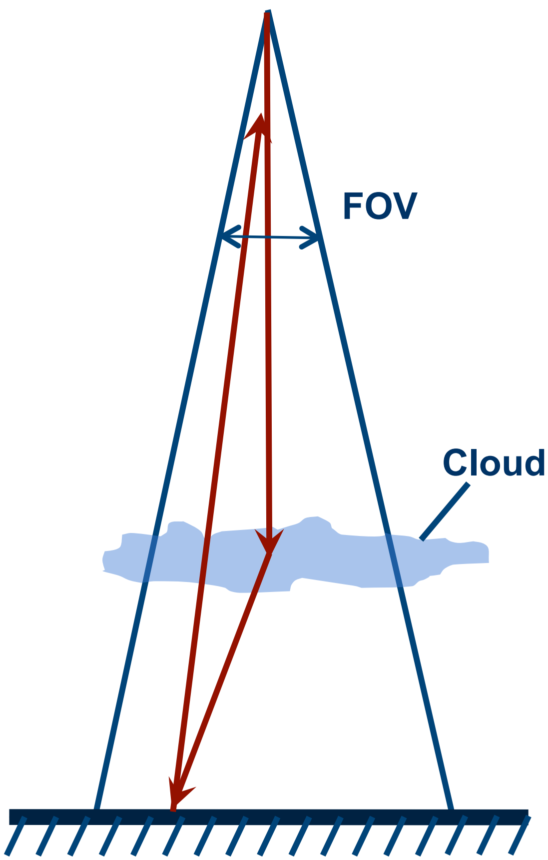
# Sample Return Pulse



# Fitted Return Pulse



# Forward Scattering Effects from Clouds



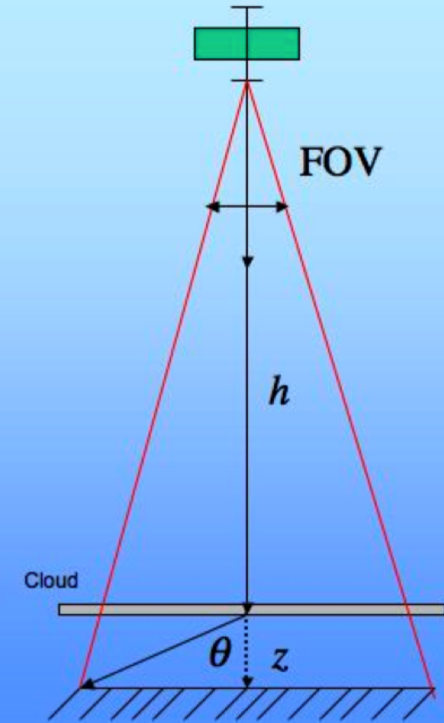

## Simple Analytical Approximation

**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

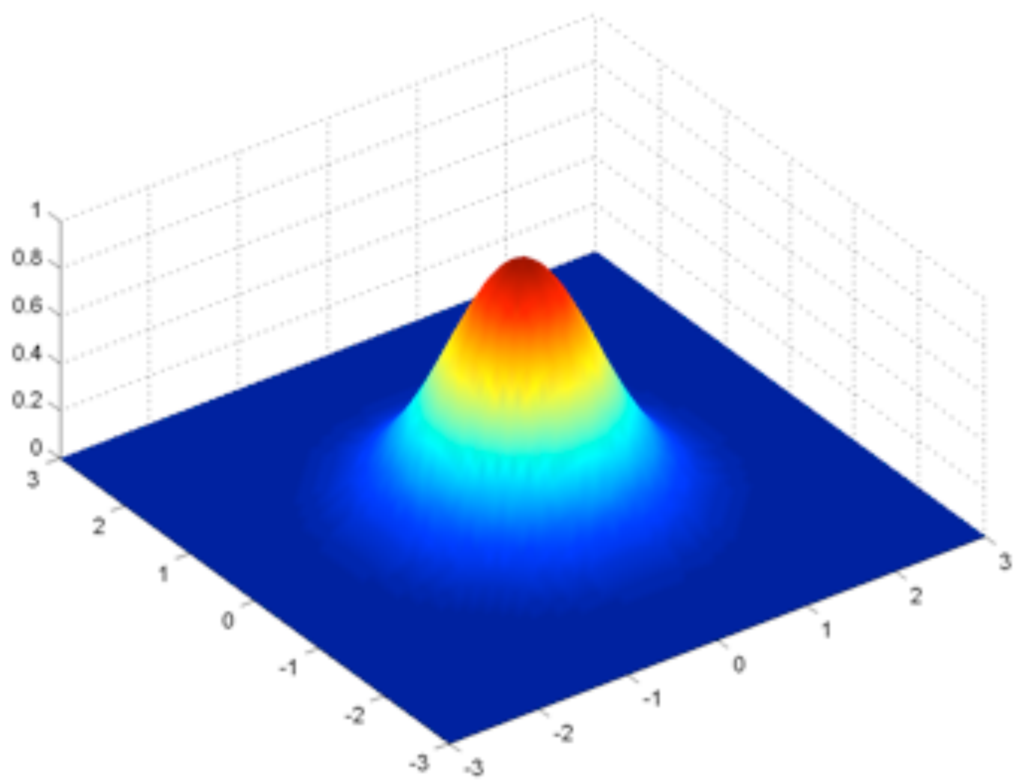
# Key Factors Contributing to Error

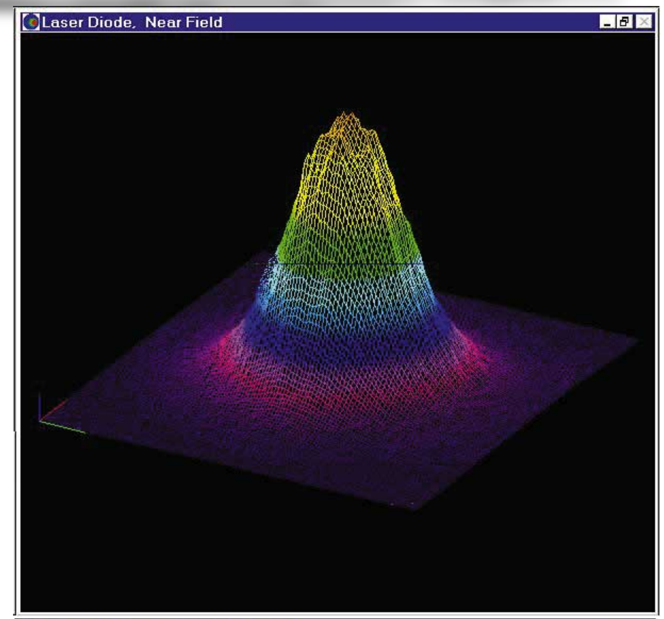
- Pointing knowledge
  - ICESat was designed with state-of-the-art attitude determination system
- Pointing angle
  - Off-nadir pointing possible to 5 degrees to targets of opportunity, but for ice, we try to keep it under a few tenths of a degree
  - Orbit control to within $\pm$1 km of reference track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

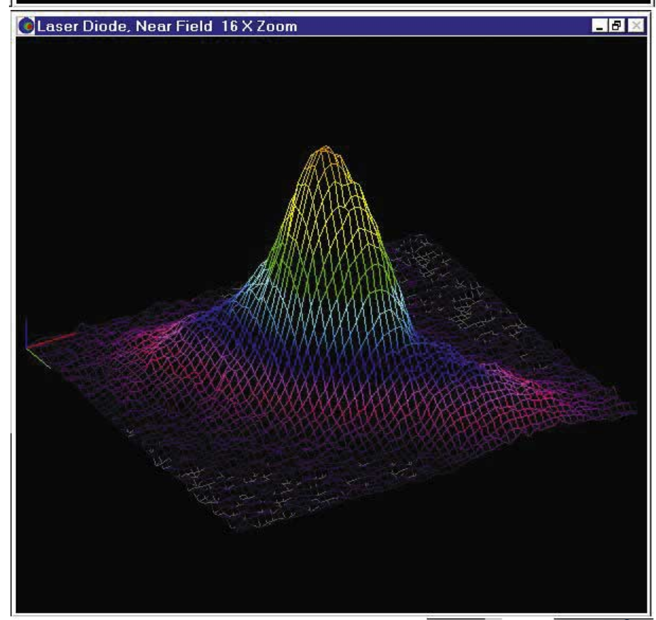
# Key Factors Contributing to Error

- 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

# Laser Energy Distribution



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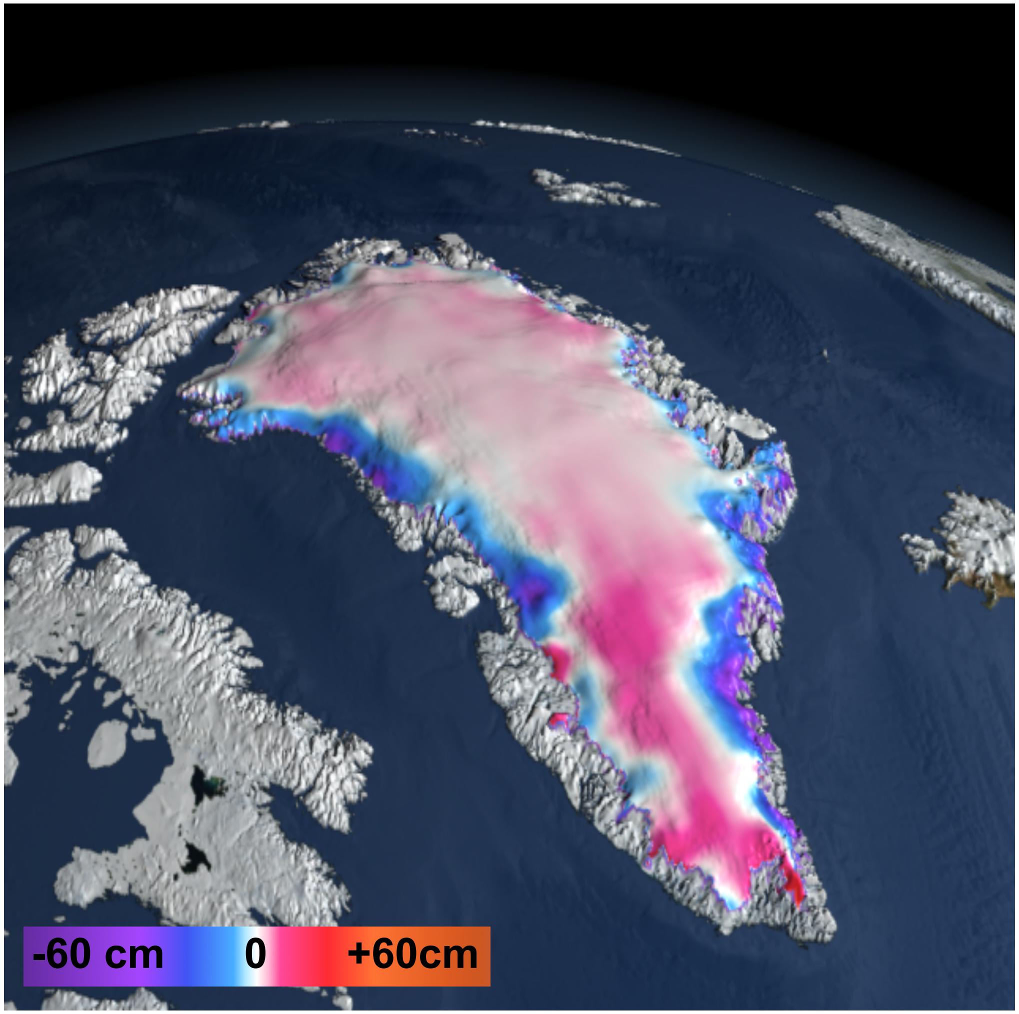
# Elevation Change Observations are The Keys to Understanding Ice Sheet Changes

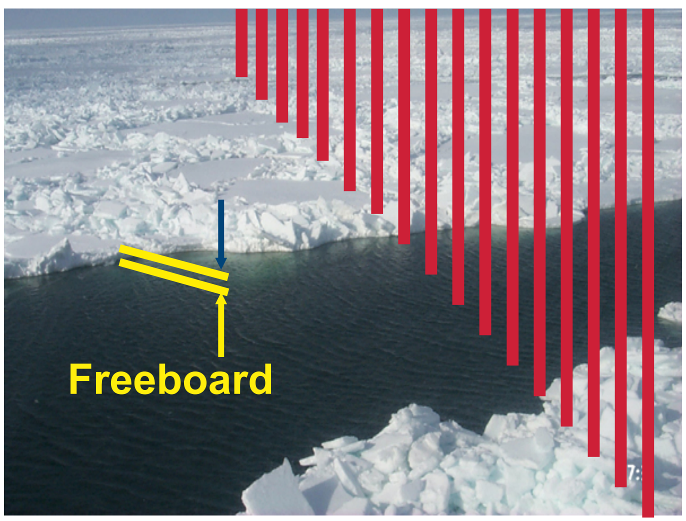


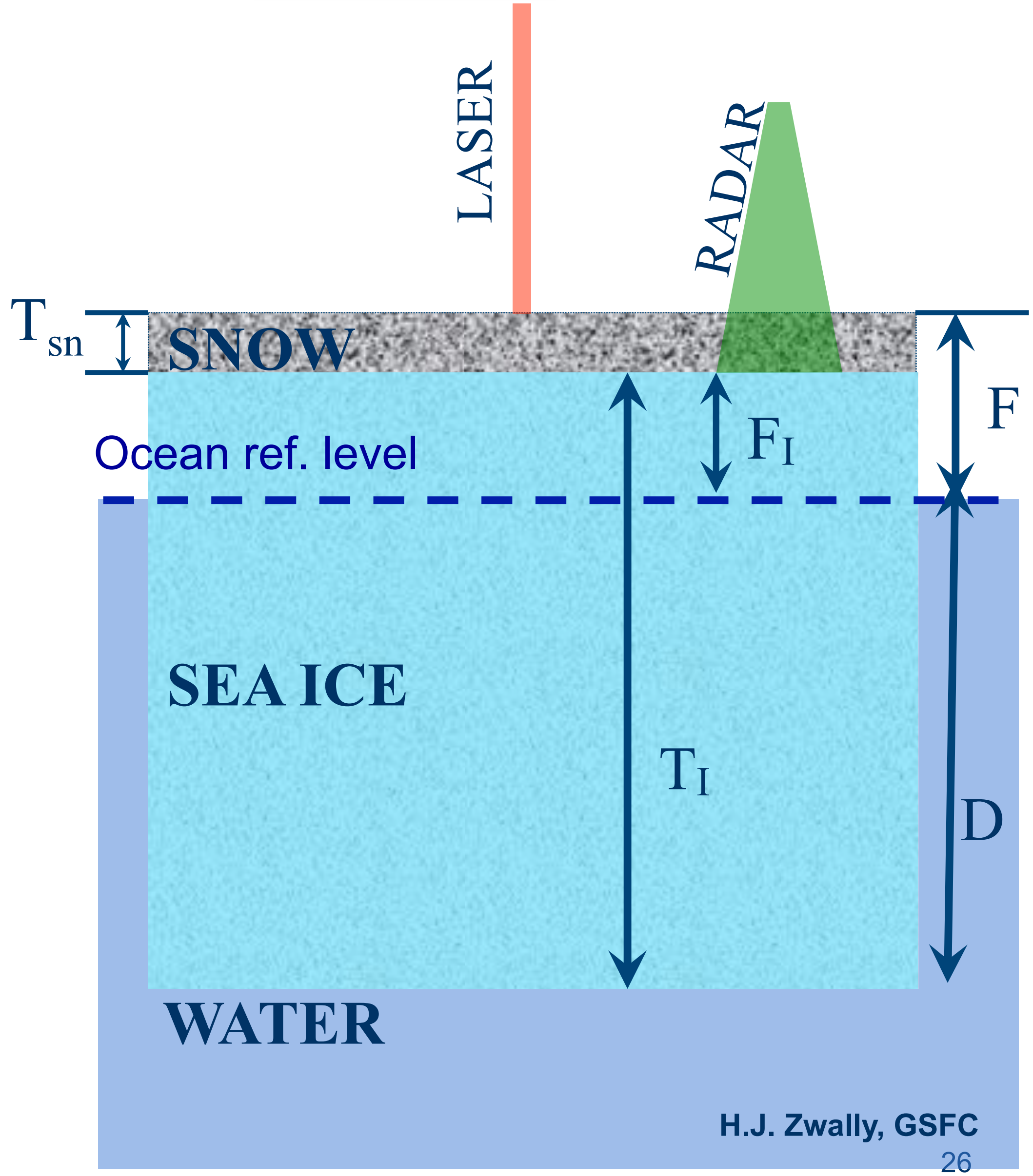

- ICESat is showing dramatic shrinking at the Greenland ice sheet margins and slight growth in the interior.
  - Interior growth over very large areas offsetting some but not all of the losses at the margins
  - Greenland contributing ~160 GT per year (0.35 mm) to sea level
- Antarctica also shows significant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

H.J. Zwally, GSFC

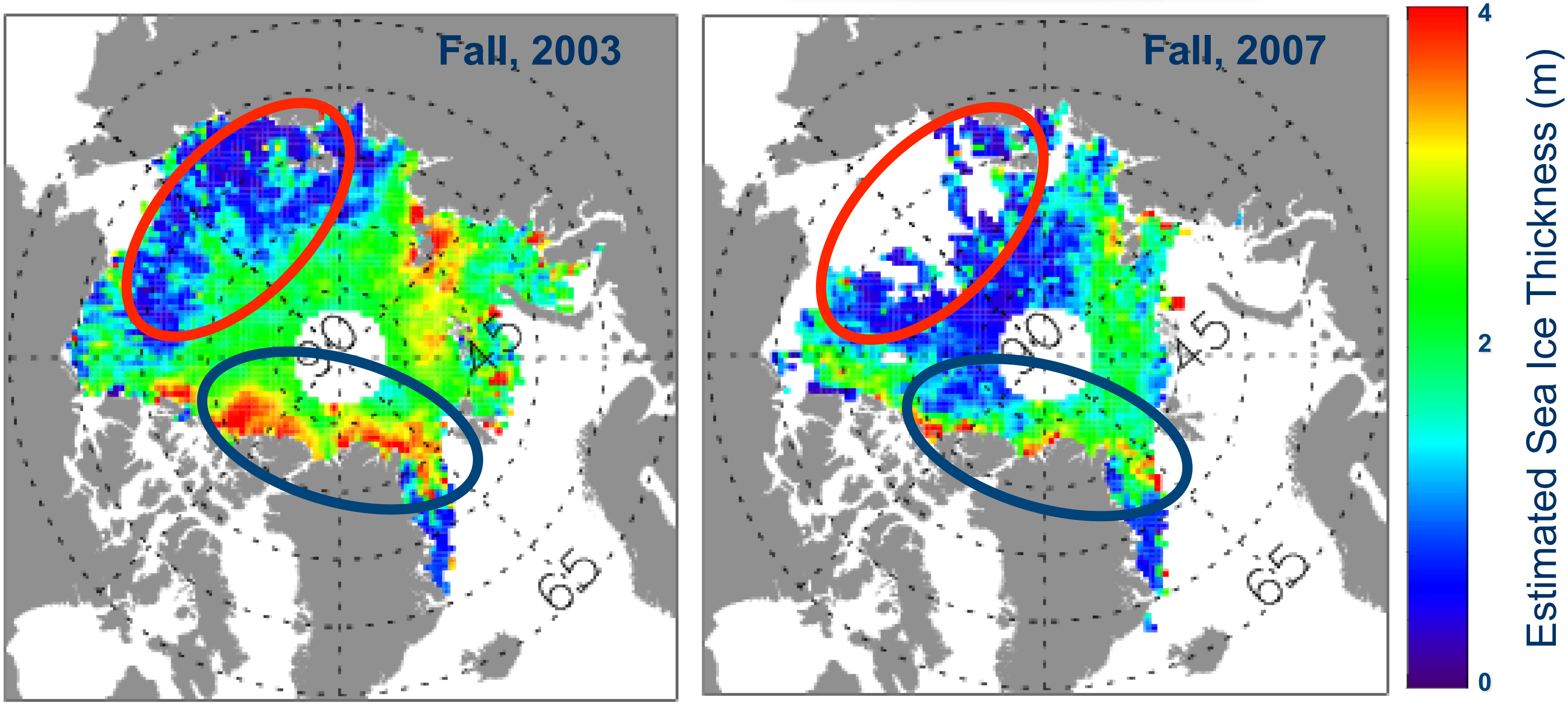
# ICESat Enables Estimates of Sea Ice Thickness

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



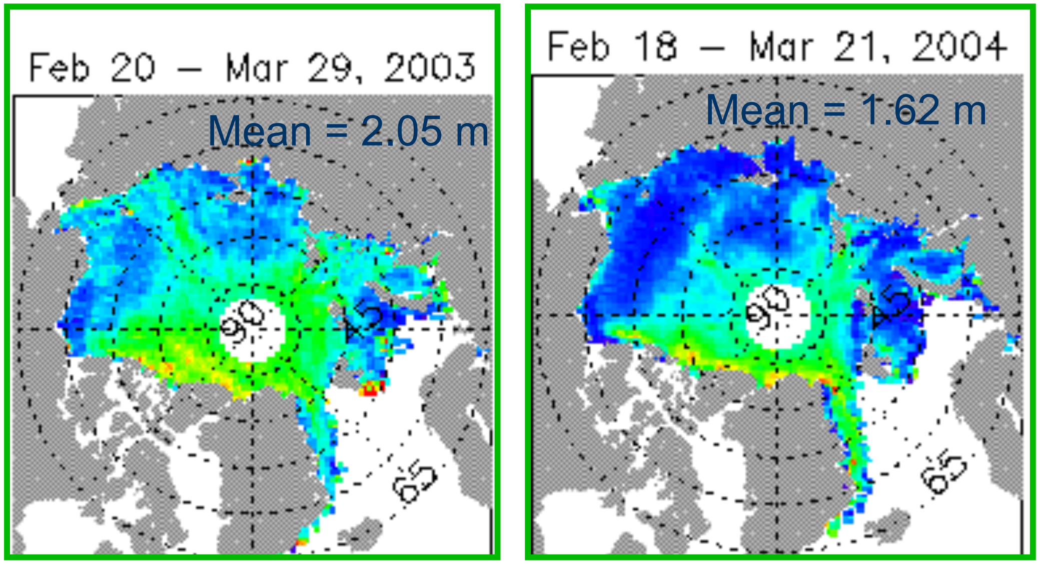
# Thinning of Arctic Sea Ice



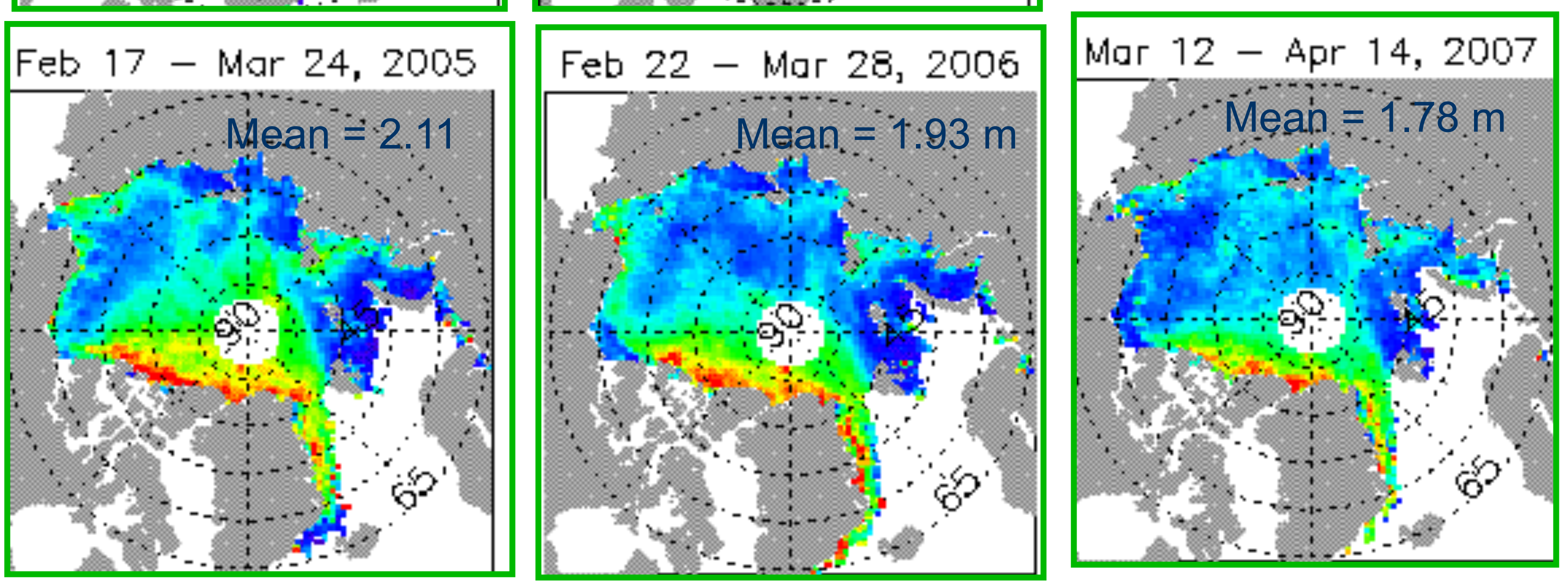

- Arctic Sea ice has thinned substantially since the launch of ICESat making it more vulnerable for rapid loss
  - 1-to-2 m thick ice thinned to <1m between 2003 and 2007 (Red Ovals)
  - Most thick 3-to-4 m ice near Greenland is gone (Black Ovals)

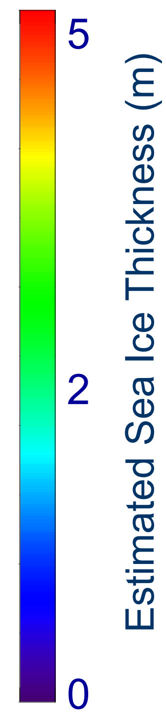
H.J. Zwally, GSFC

# 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

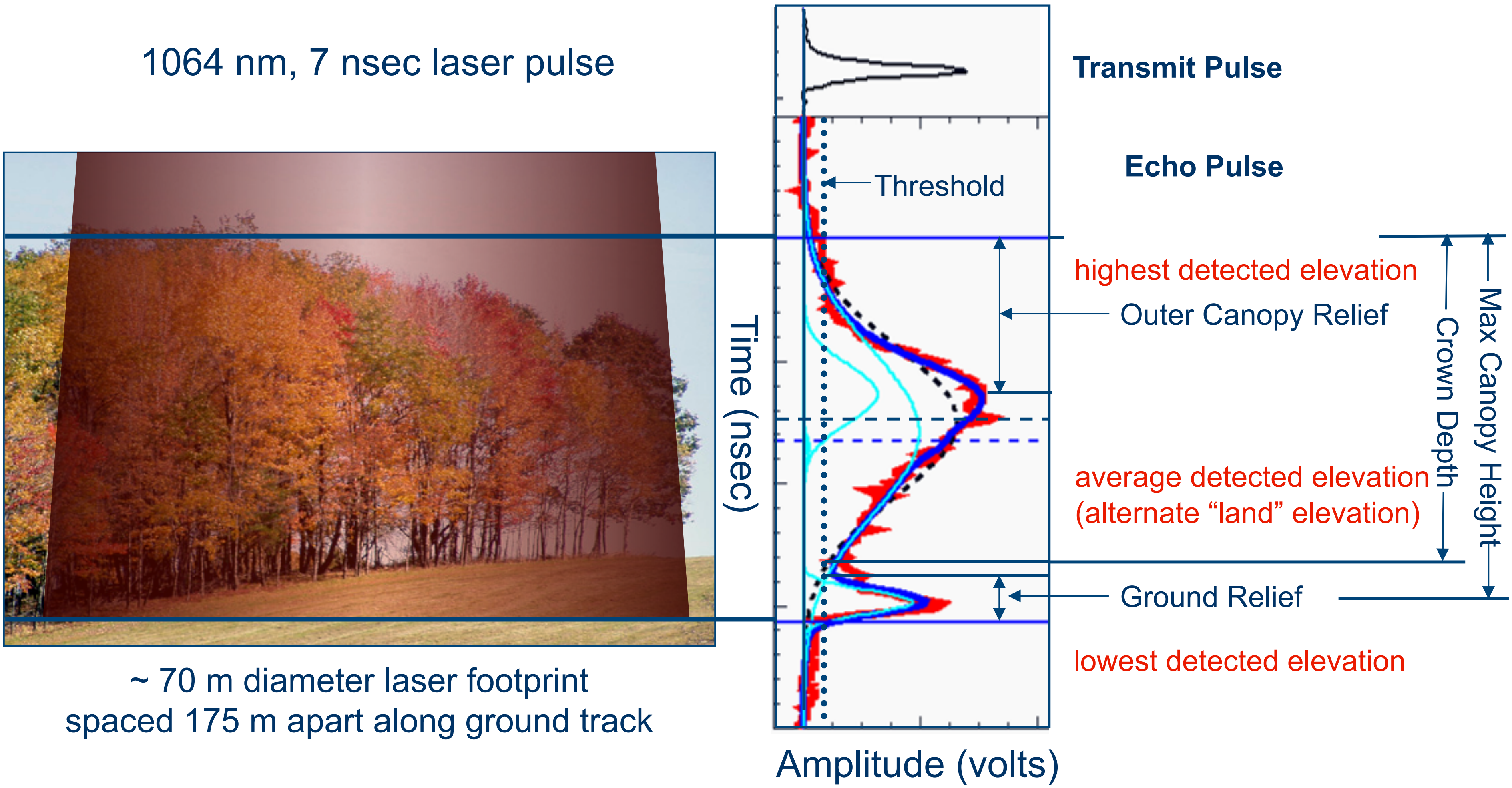



H.J. Zwally, GSFC

# GLAS Measurement of Echo pulse from Trees

1064 nm, 7 nsec laser pulse

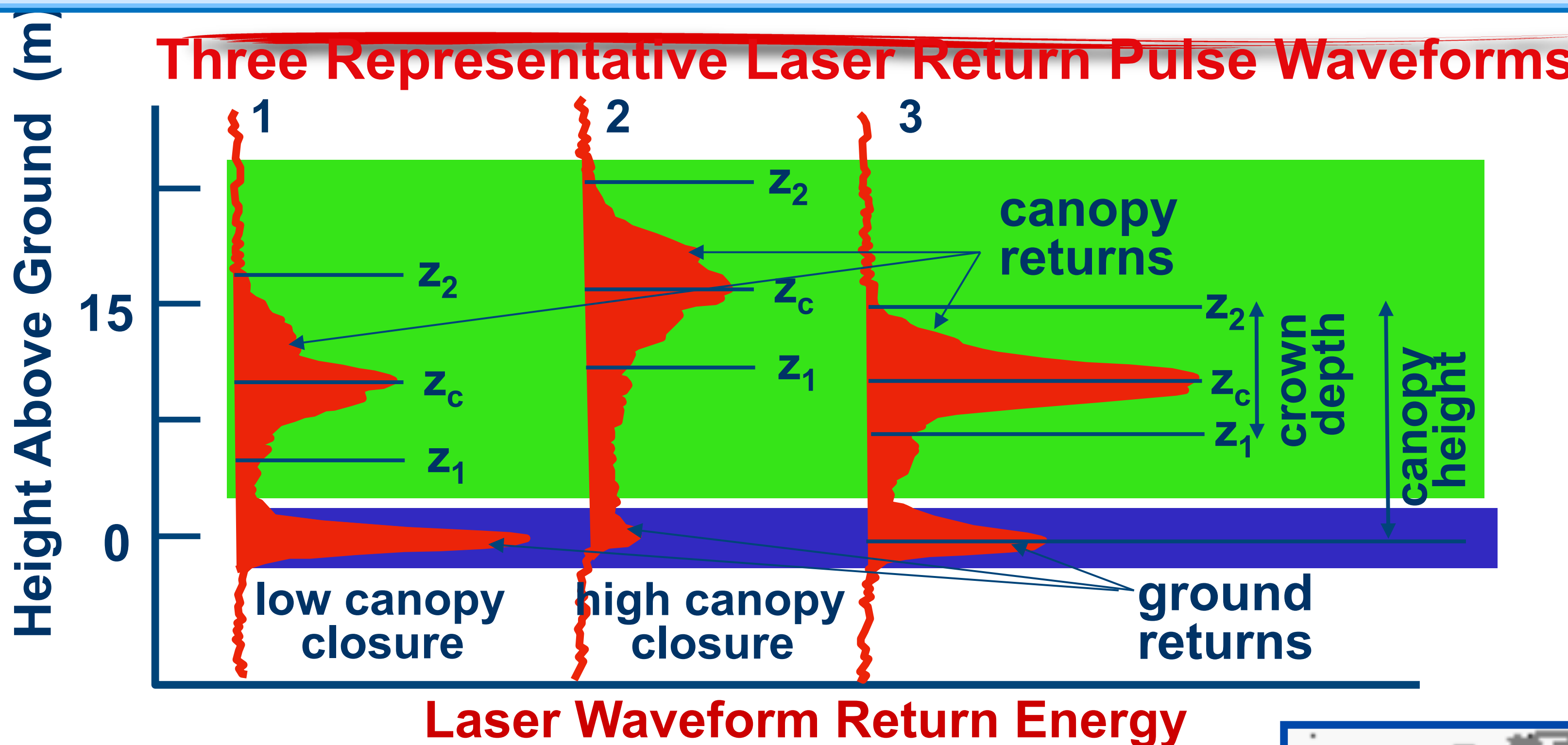


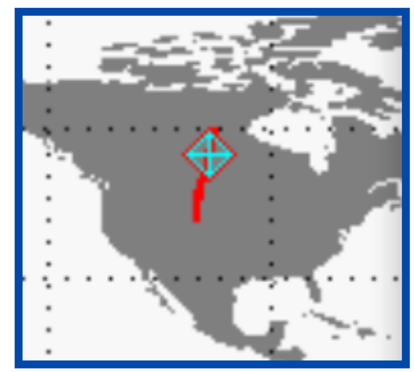

~ 70 m diameter laser footprint
spaced 175 m apart along ground track

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, $z_2$

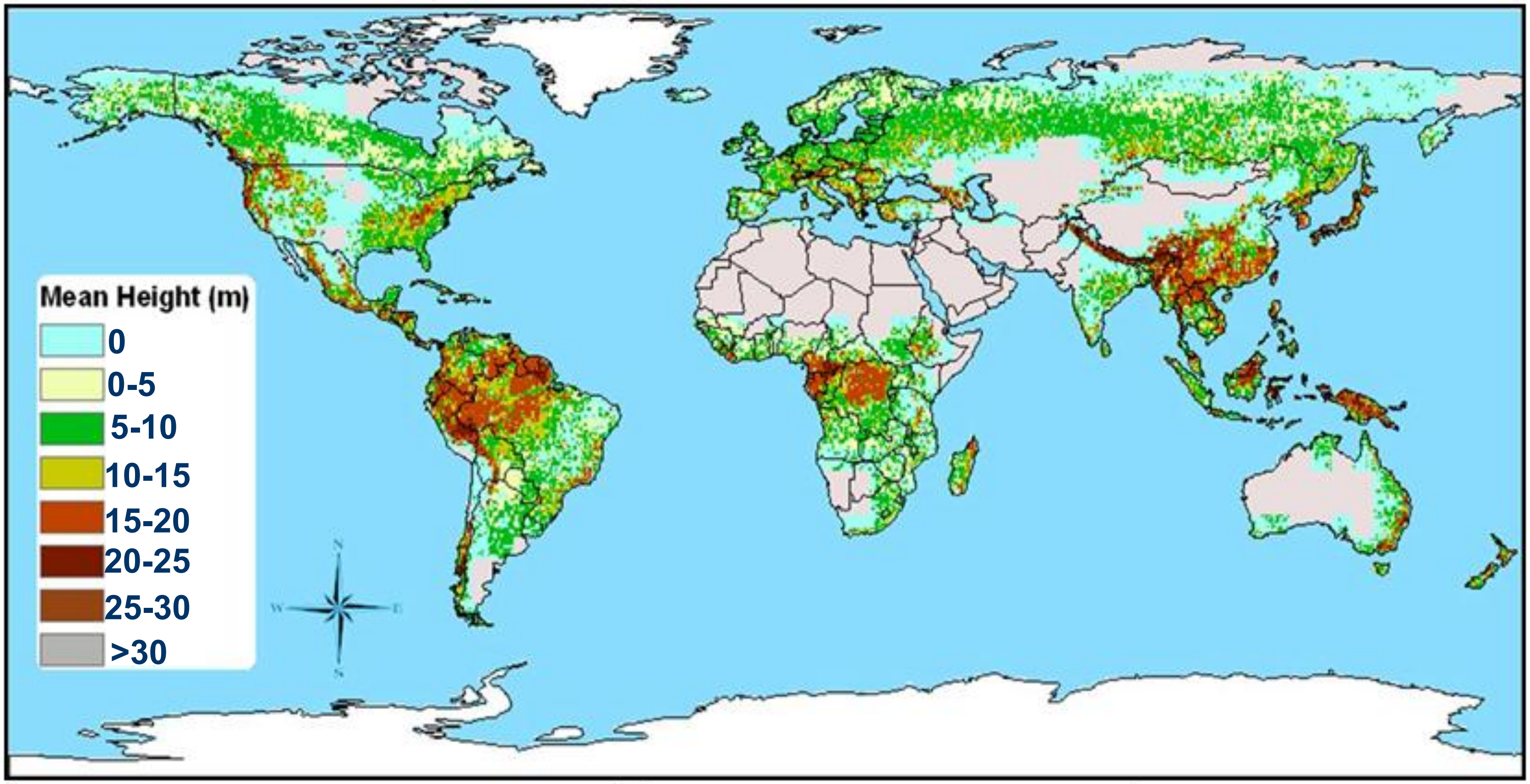
**Crown Depth** = Width of Upper Part of Canopy Return, $z_2 - z_1$

**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

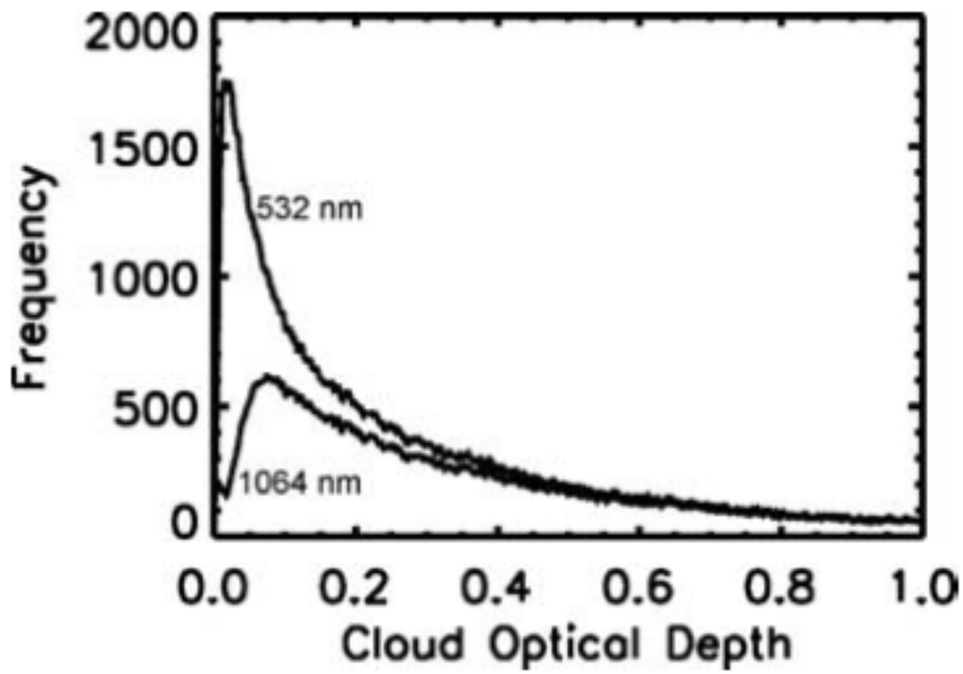
# Vegetation Height Measurements




- 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

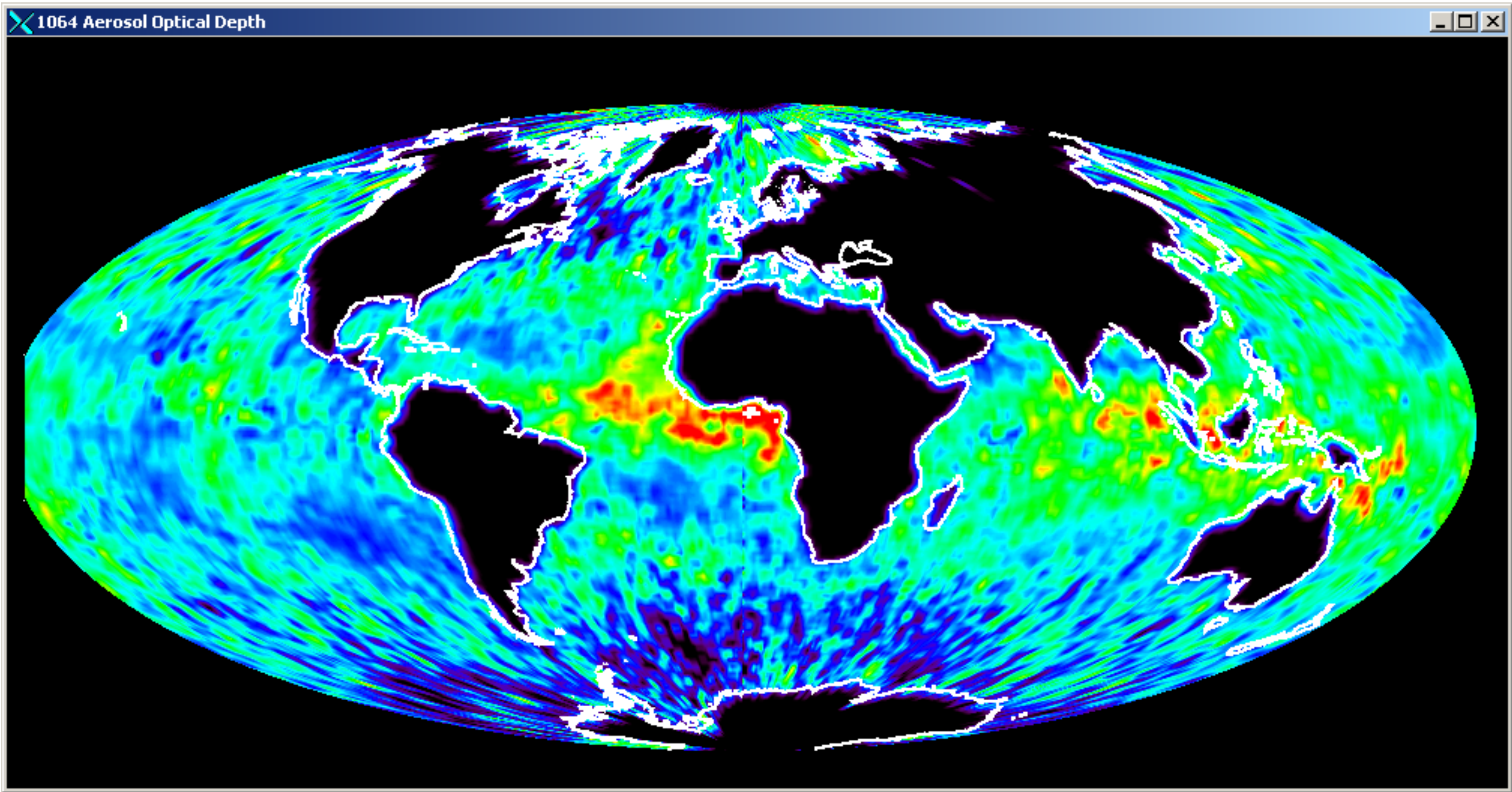



**Spinhirne et al., Cloud and Aerosol Measurements from GLAS GRL, 2005**

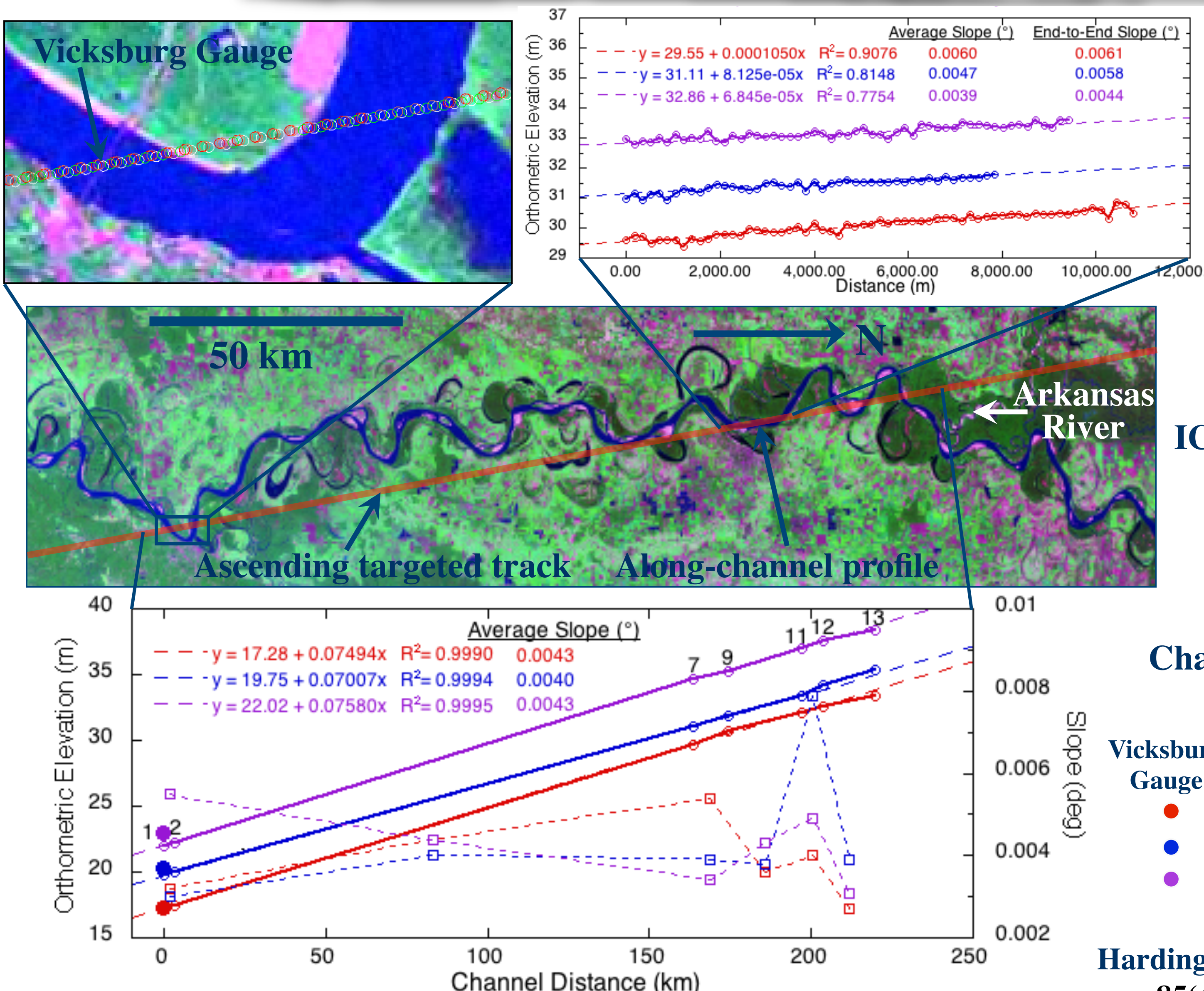
**Figure 4.** The relative frequency of cloud optical depth retrieval from GLAS for clouds above 4 km altitude from the 532 nm channel for all global observations in October 2003. The lower line indicates the relative frequency clouds are also flagged as detected in analysis of the 1064 nm channel alone. 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)



# River & Lake Heights - Profiles of Mississippi River




**ICESat Footprint Elevations along Straight Reach and Derived Slopes**

**Orange: ICESat Targeted Profile on Landsat Image**

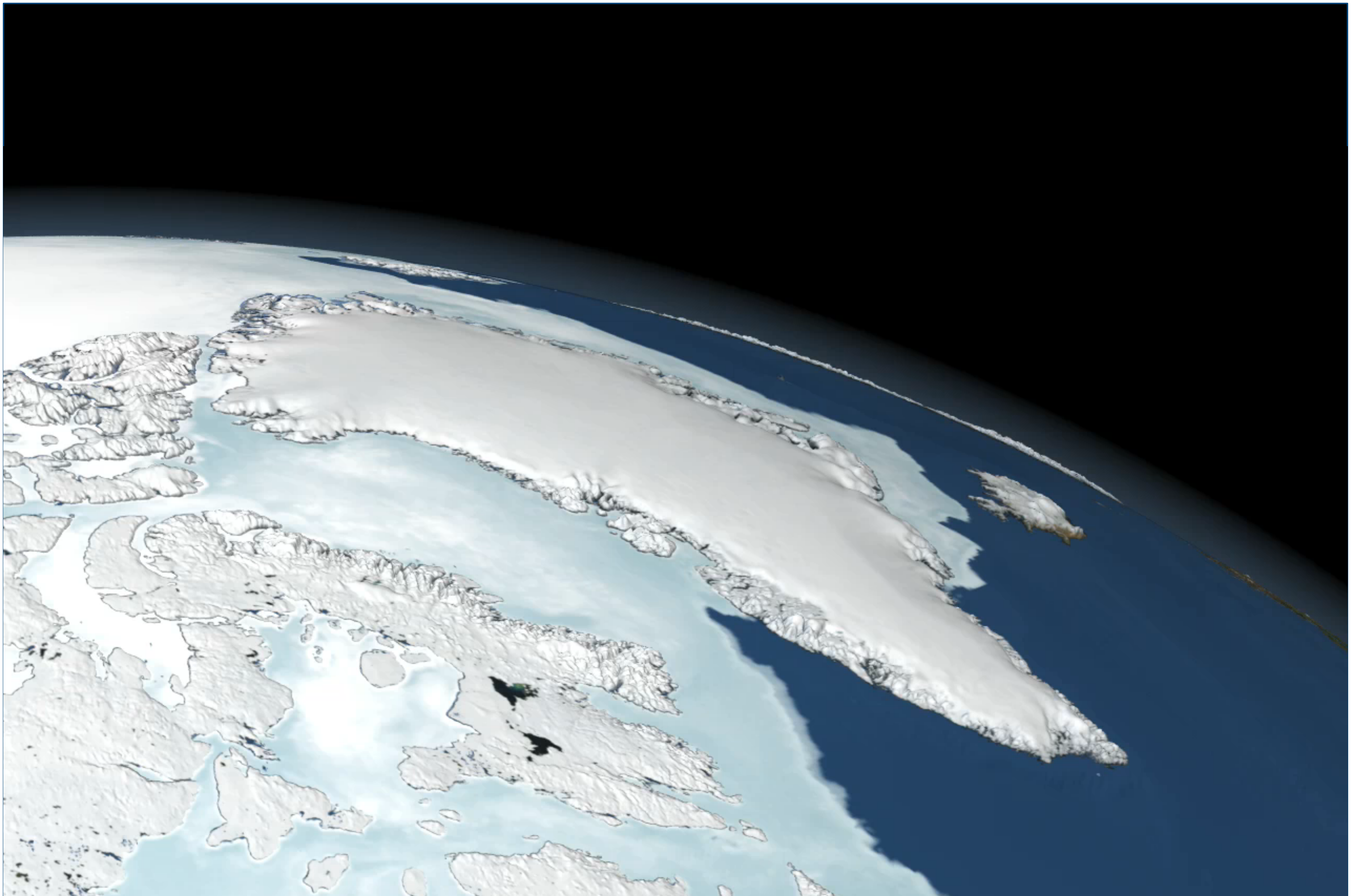
**River Stage at Channel Crossings and Derived Slopes**

| 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



# Back-up

# NRC Decadal Survey Call for ICESat-II

- "Sustained measurements are needed to distinguish short-term variability in the Earth system from long-term trends."

- "Trends in all of the measurements are needed to calibrate climate models that predict future changes in sea level and in other climate variables."

- "As climate change continues, ongoing, continuous measurements of both land ice and sea ice volume will be needed to observe trends, update assessments and test climate models."

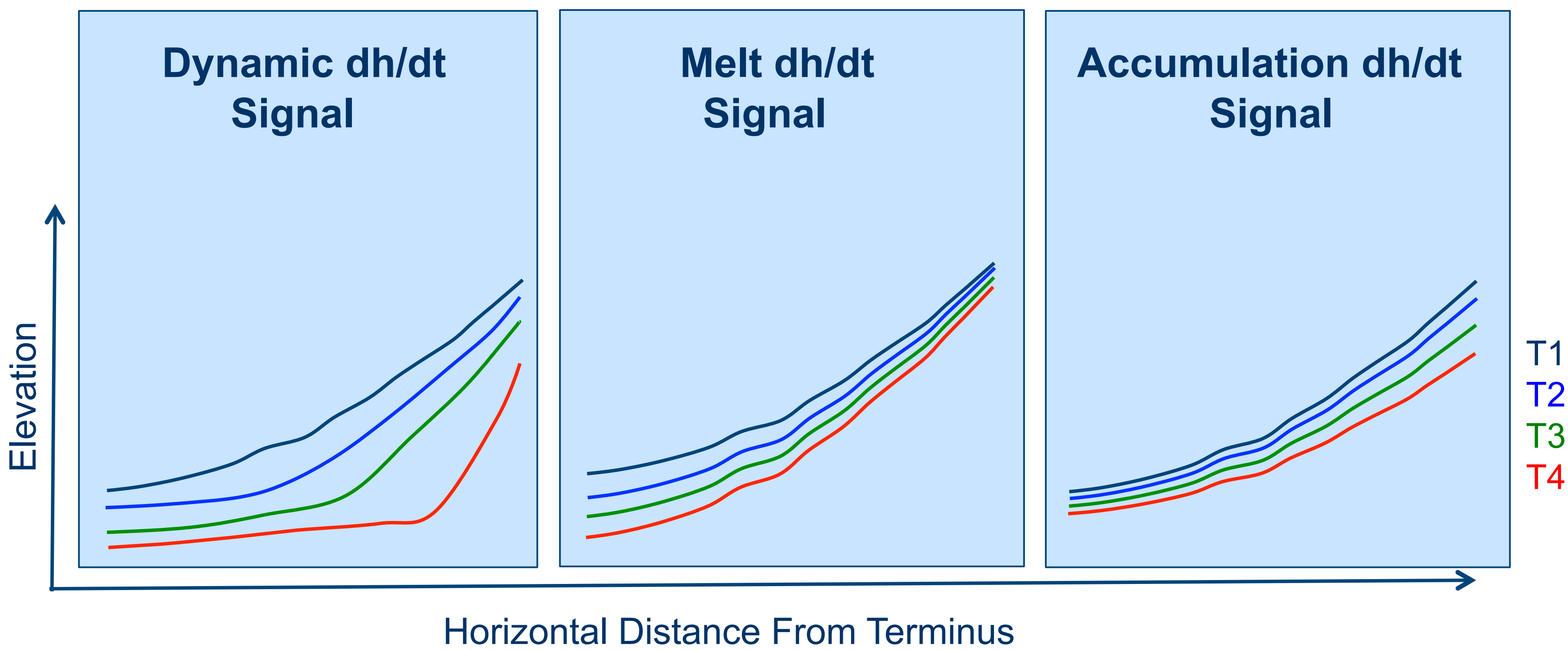
- "sea ice areas and extents have been well observed from space since the 1970s and have been shown to have significant trends, but sea ice thicknesses do not have such a record."

**From Decadal Survey Executive Summary (Question #1)**
*Will there be catastrophic collapse of the major ice sheets, including Greenland and West Antarctic and, if so, how rapidly will this occur? What will be the time patterns of sea level rise as a result?*

# ICESat-II Science Traceability

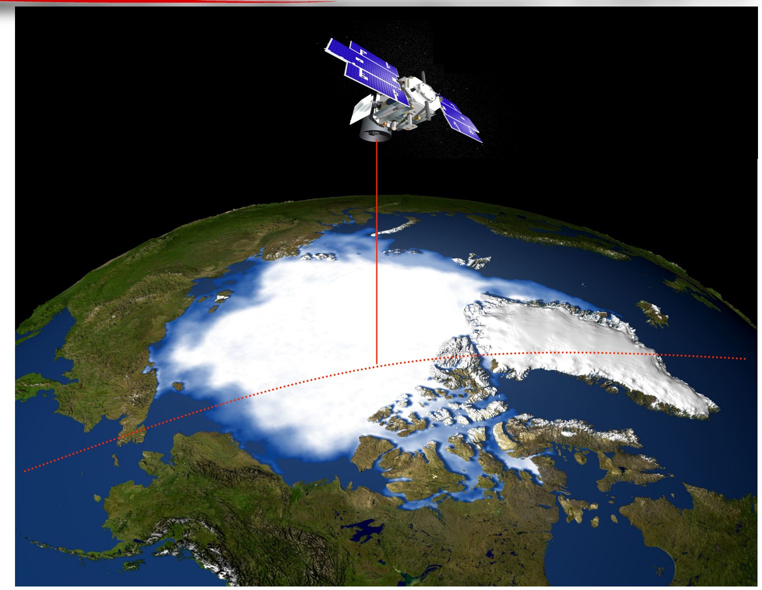
| Science Goals | Science Requirements | Measurement Requirements | Instrument Functional Requirements | Mission Functional Requirements |
|---|---|---|---|---|
| Ice Sheets<br>**Quantify polar ice sheet mass balance to determine contributions to current and recent sea level change and impacts on ocean circulation**<br>**Determine seasonal cycle of ice sheet changes**<br>**Determine topographic character of ice sheet changes to assess mechanisms driving that change and constrain ice sheet models** | **Annual elevation change of 0.2 cm/yr over entire ice sheet**<br>**Surface elevation change of 25 cm/yr annually in 100 $km^2$ areas**<br>**Resolve winter and summer ice sheet elevation change to 2.5 cm over 10,000 $km^2$ areas**<br>**Continuous observations through at least one climate cycle**<br>**Direct comparability to ICESat-I measurements for 15-year dh/dt** | **140 m ground track spacing**<br>**Ability to penetrate optically thin clouds**<br>**Precise repeatability of ground tracks**<br>**Repeat sampling 4x per year, uniformly spaced in time**<br>**Slope information in the cross-track direction**<br>**Continuous measurements for no less than 5 years** | **50-70 m spot size for each laser pulse**<br>**>50 mJ transmit energy per pulse**<br>**4.5 m pointing knowledge**<br>**5 years continuous operation with 7-year goal**<br>**Measurement capability in the cross-track direction (to be specified by the aSDT)**<br>**Surface reflectivity capability of 5% to enable characterization of snow conditions for gain and range corrections**<br>**Telescope FOV of 100 m to minimize atmospheric forward-scattering effects**<br>**Atmospheric vertical resolution of 75 km to enable atmospheric corrections plus studies of clouds** | **Orbit parameters that match ICESat (600 km altitude; 94 deg. incl., 91-day repeat).**<br>**10 arcsec (30-m) pointing control**<br>**2 cm radial orbit accuracy requirement**<br>**5 year continuous operation with 7-year goal**<br>**1.5 arcsec (4.5-m) pointing knowledge**<br>**91 day repeat orbit to capture seasonal effects and maximize comparability to ICESat for trend detection** |
| Sea Ice<br>**Estimate sea ice thickness to examine ice/ocean/ atmosphere exchanges of energy, mass and moisture** | **Discriminate freeboard from surrounding ocean level to within 3 cm along a 25 km segment of ground track**<br>**Capture seasonal evolution of sea ice cover on 25 x 25 km scales** | **Shot-to-shot precision of <2cm**<br>**Monthly near-repeat coverage of Arctic and Southern Oceans at 25 x 25 km scales**<br>**Coverage up to at least 86 deg. latitude** | | |

# Topographic Expressions of Different Ice Sheet Change Mechanisms

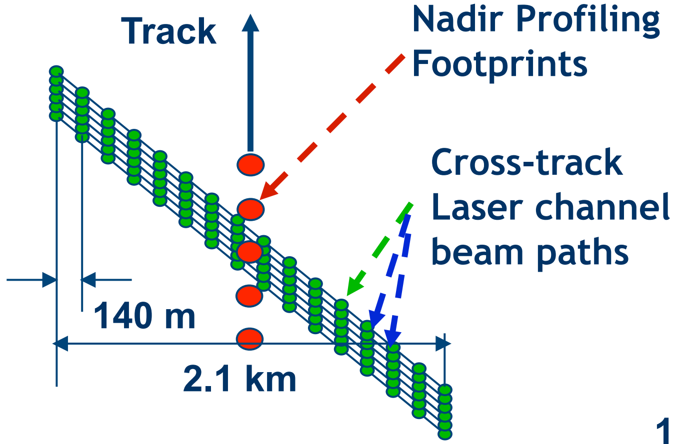


# Strong Interest in Cross Track Channel for ICESat-II

- Ice sheet cross-track slope information for improved elevation change accuracy.
- Significantly increased sea ice sampling
- Increased coverage of ice sheets with higher resolution of dynamic outlet glaciers.
- Improves monitoring of changes of small glaciers globally.
- Improved elevation mapping of land surfaces for solid-earth interests.
- Increased information on vegetation canopy structure.

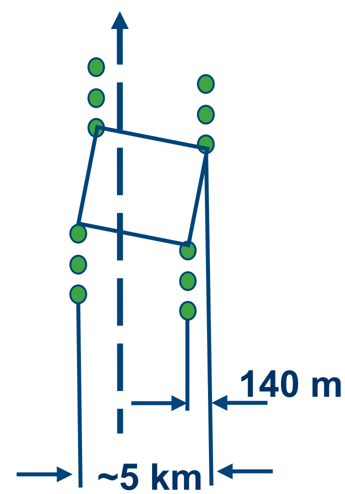


**Cross-track coverage can be achieved through various approaches**



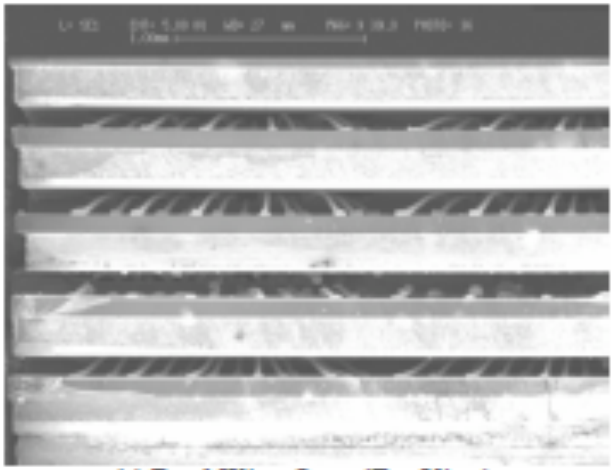

Photon counting


2 beams from 2 lasers or w/ a DOE

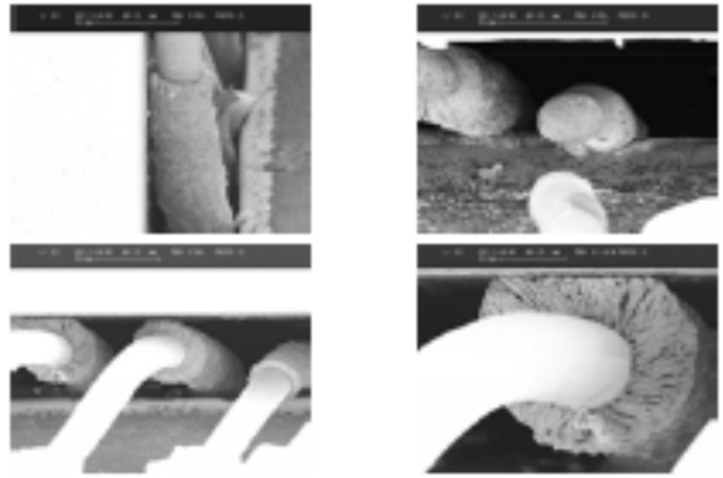



4 Beams w/ a DOE

# Recent SEMs of Flight Laser 3 Amplifier Array Wire Bond Open Failure Show Indide Growth on Gold Wires

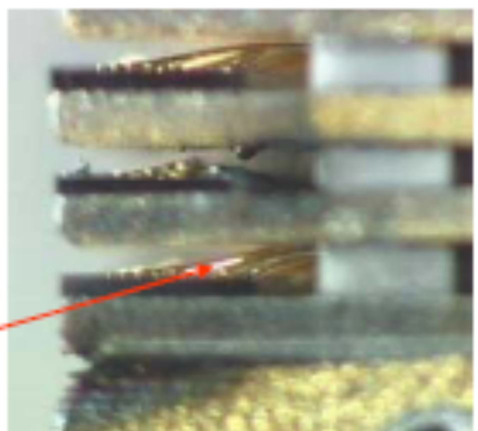


(a) Bond Wires Open (Top View)



(b)

(c)




Bond Wires Open (Edge View)

·Far left top photo (a) is a view from the top, looking down into the diode array.

–It shows "healthy" bond wires on the top two and bottom rows.

–It shows that all the bond wires on the second-from-bottom row are damaged, and interrupted.

▪Some have a melted mid-section, with melt-balls visible on top and bottom stubs.

▪Others are fractured at their base.

▪And some are evaporated away – evidence of arcing.

·Outer Gold-Indium intermetallic material detail in lower right photo (c) is brittle indide, where inner gold conductor is not brittle.

·Stub in upper right photograph (b) is indicative of a possible wire fatigue fracture.