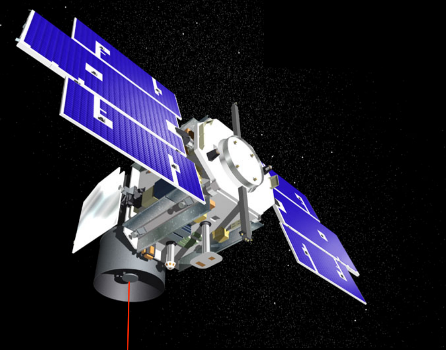
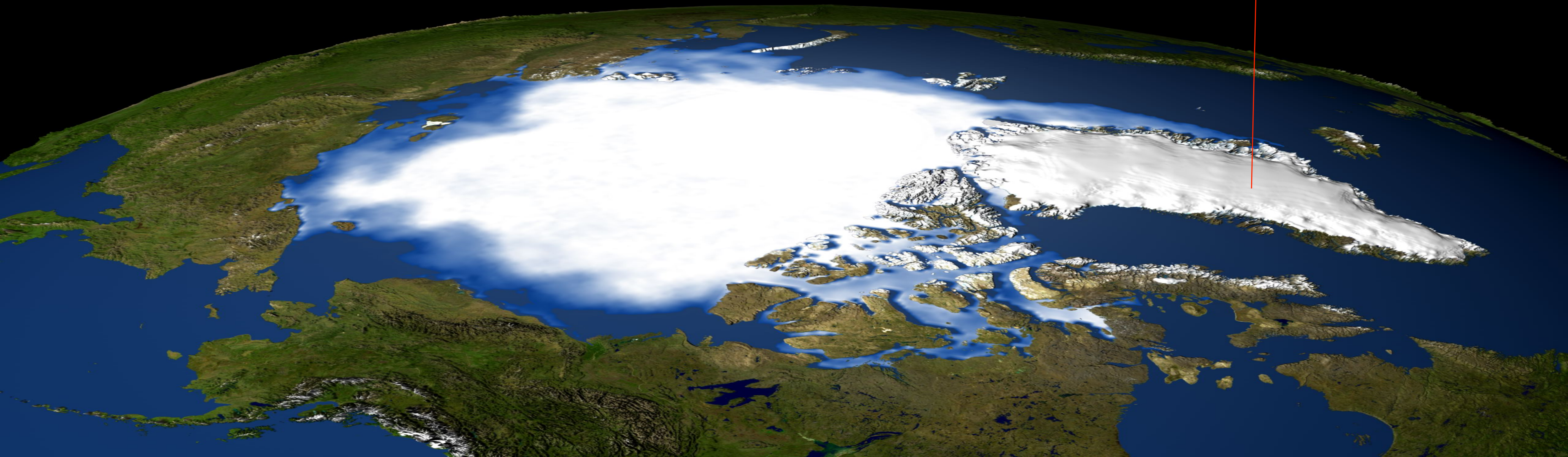
Applications and Implementation of ICESat and ICESat-2

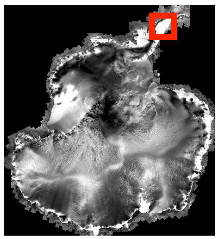


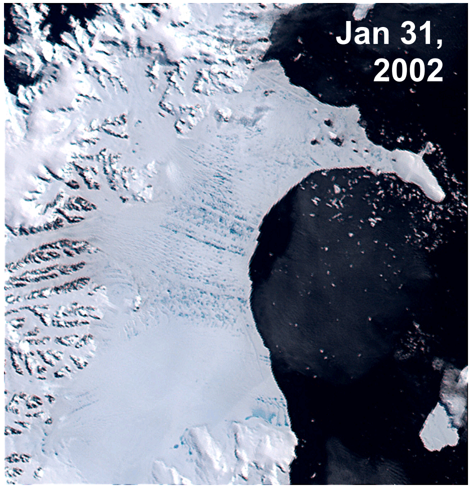
Waleed Abdalati
CIRES

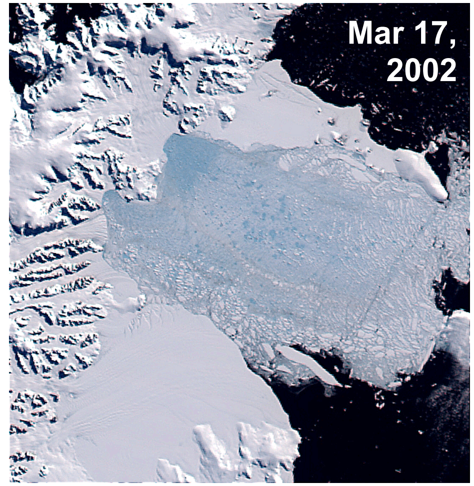


The Earth's Ice is Changing Dramatically With Significant Societal Implications

Antarctica







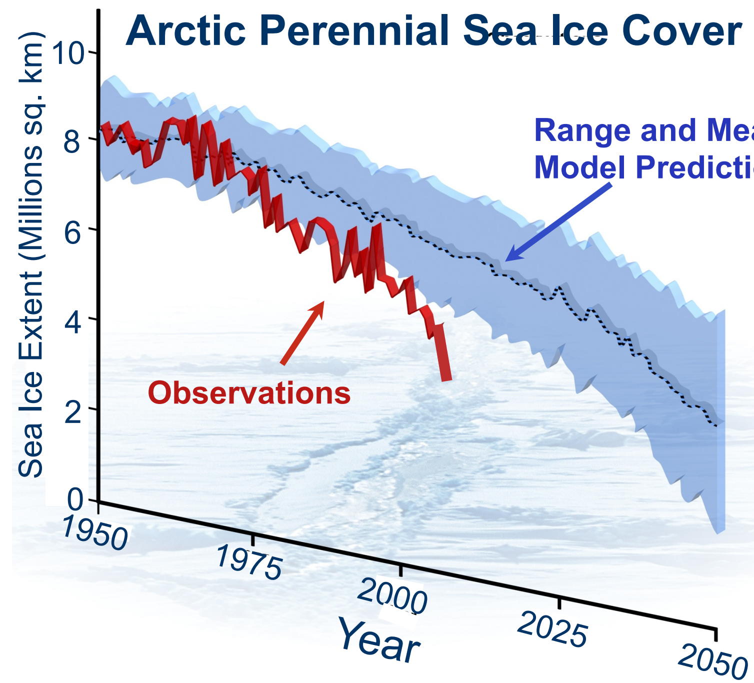
T. Scambos, NSIDC

<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



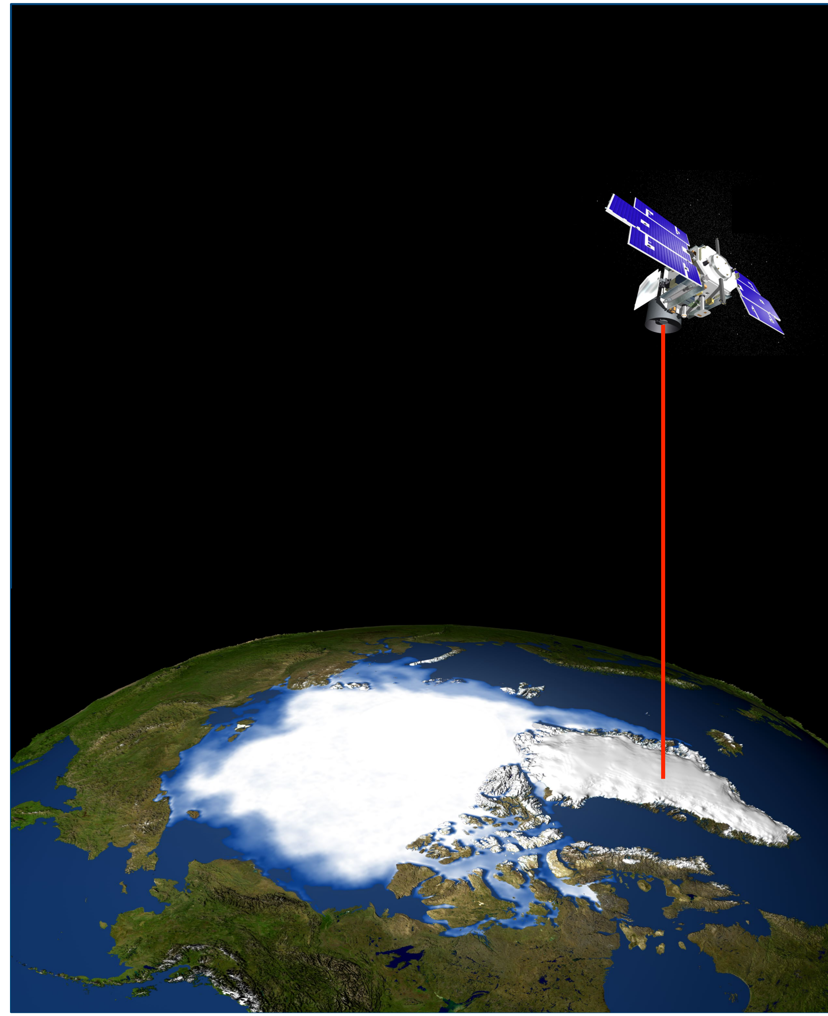
NCAR

LIDAR Applications

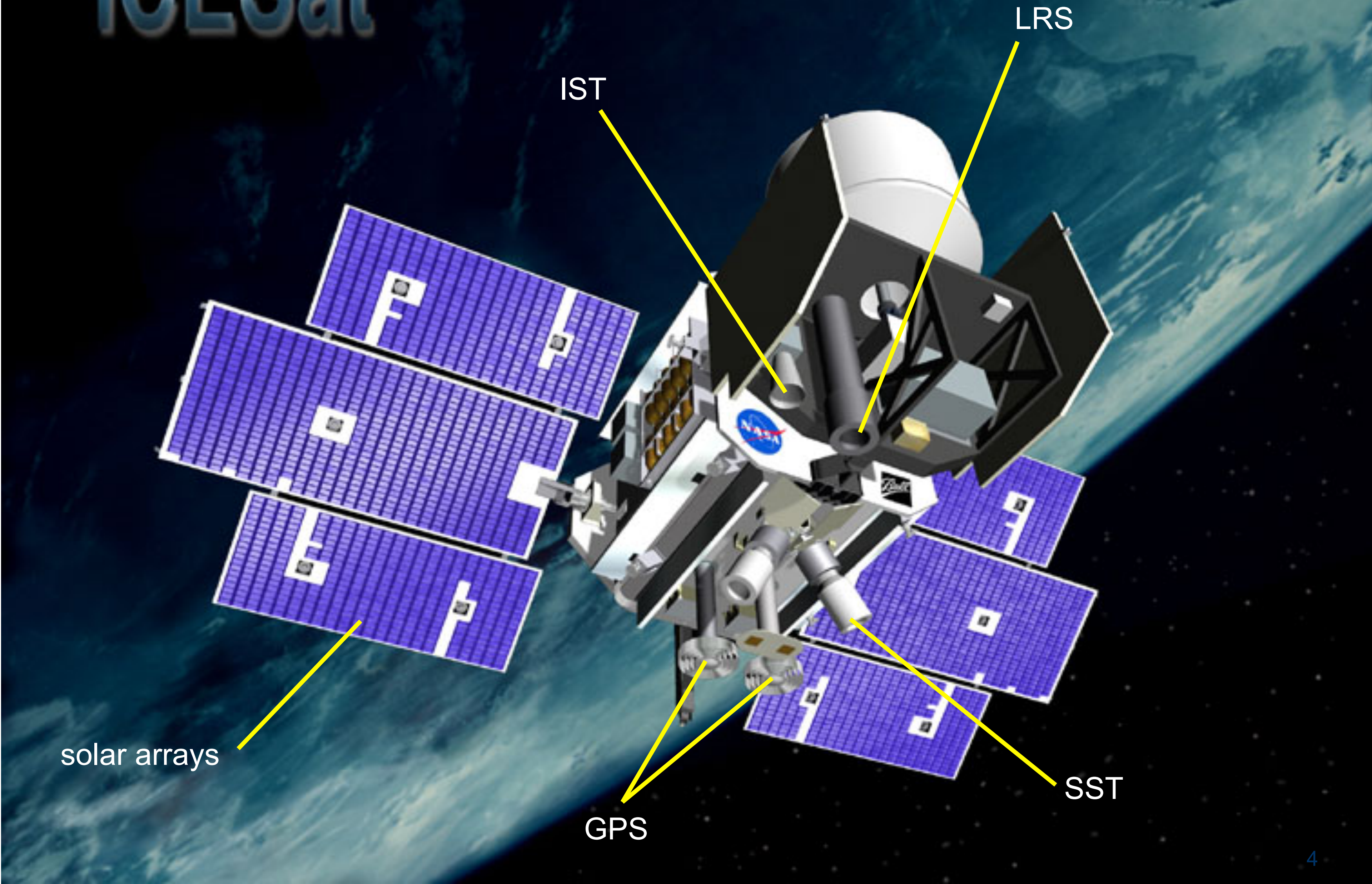
- In 2003 NASA Launched the ICESat mission, to use lasers to measure ice elevation precisely
- Laser ranging from ground stations is used to determine orbits of satellites

- Advantages over radar
  - Small FOV of about 1 mrad (0.2 m on ground from aircraft, 50 m on ground from satellites
  - Range Resolution (~10 cm)
  - No penetration in snow

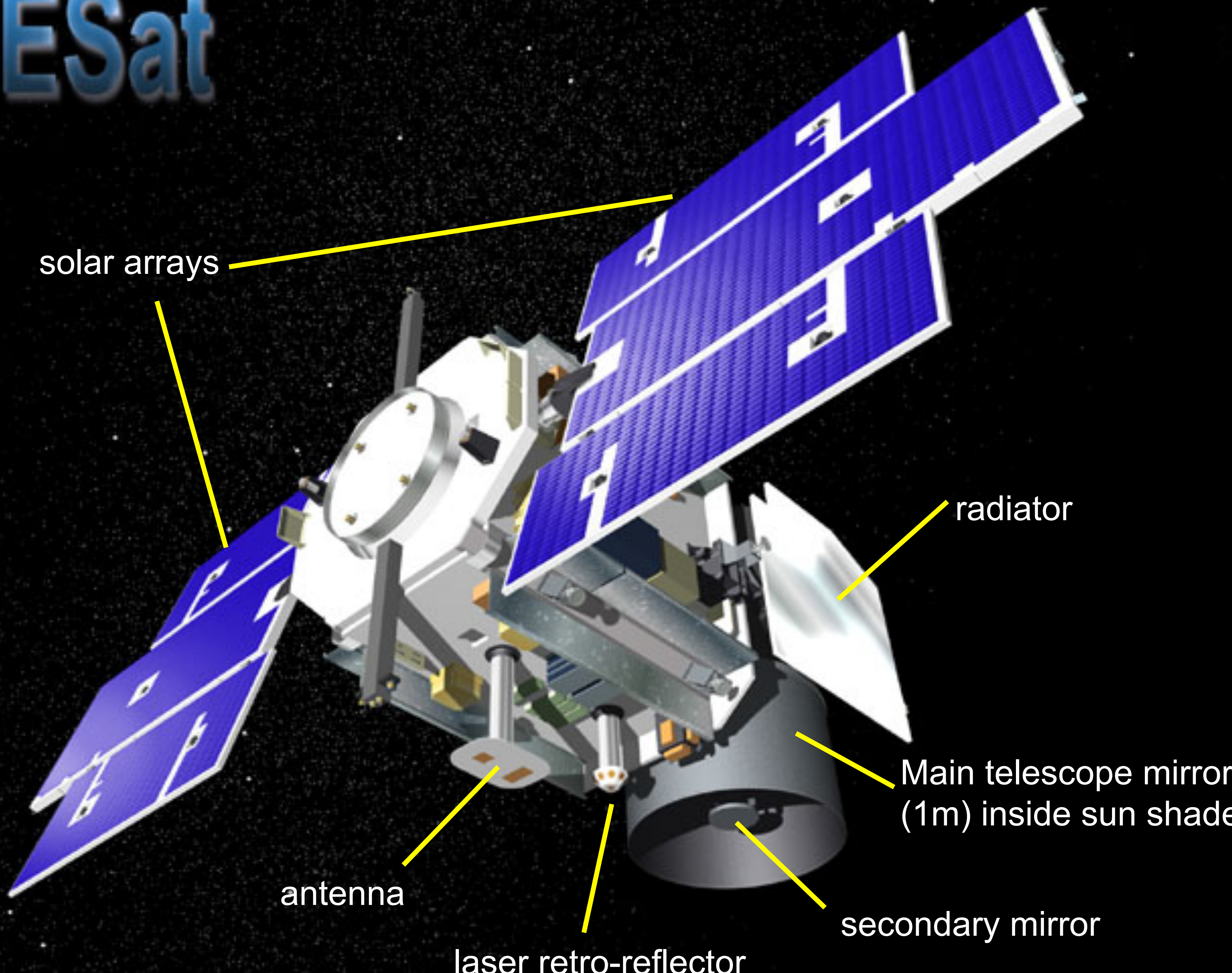
- Disadvantage compared to radar
  - Atmospheric attenuation
  - Path lengthening
  - Heritage



ICESat

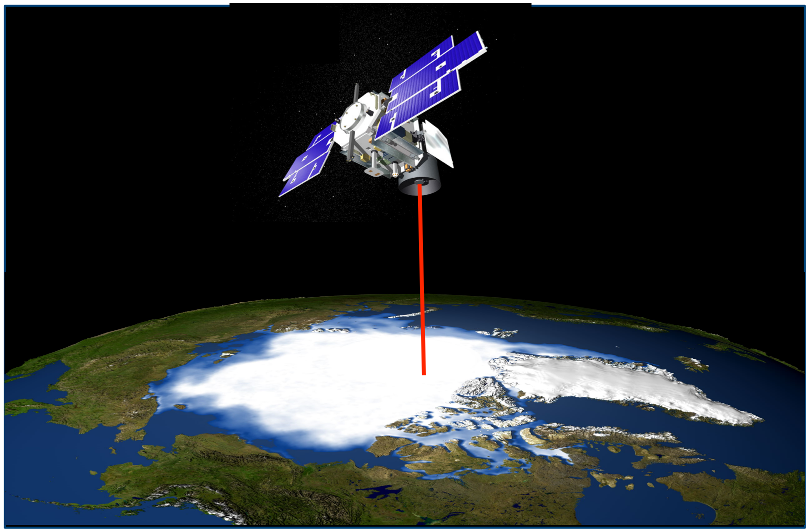


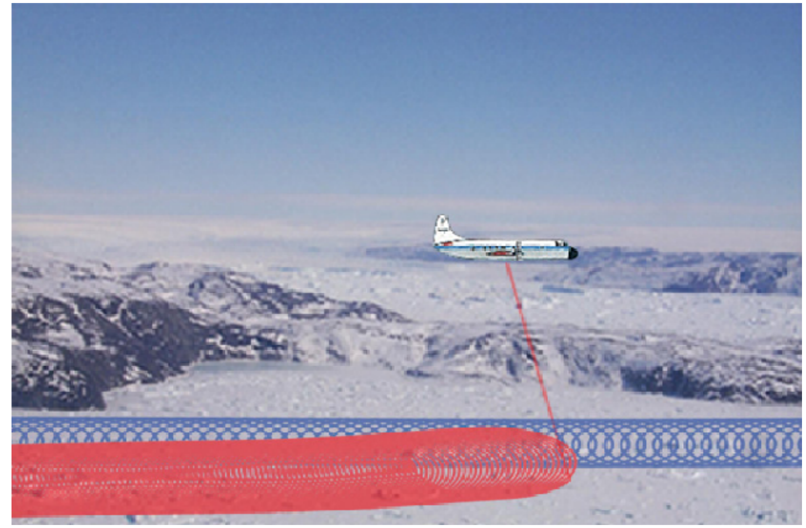
ICESat



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

Elevation Retrieval



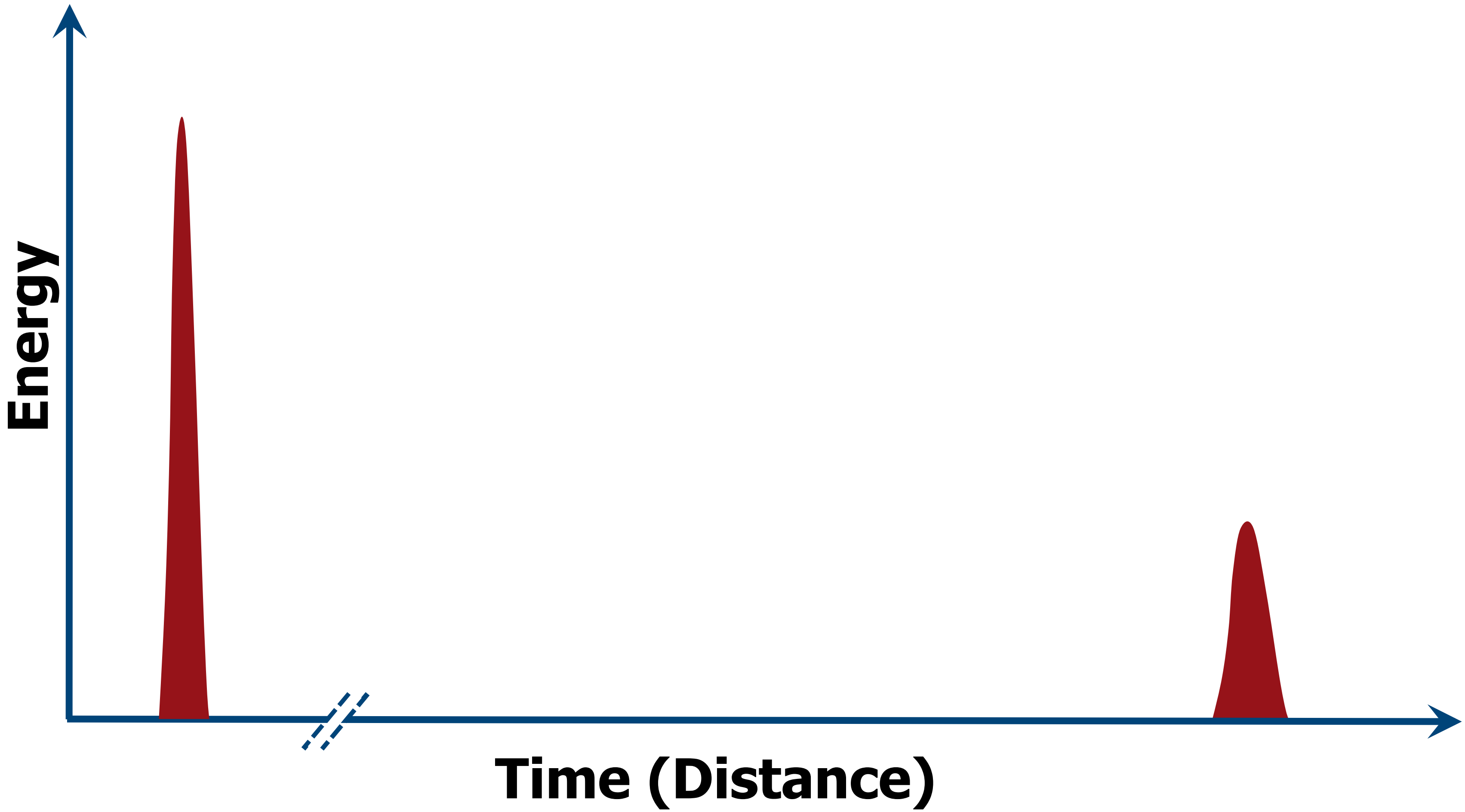


Time-tagged transmit pulse + Timed receive pulse → Range

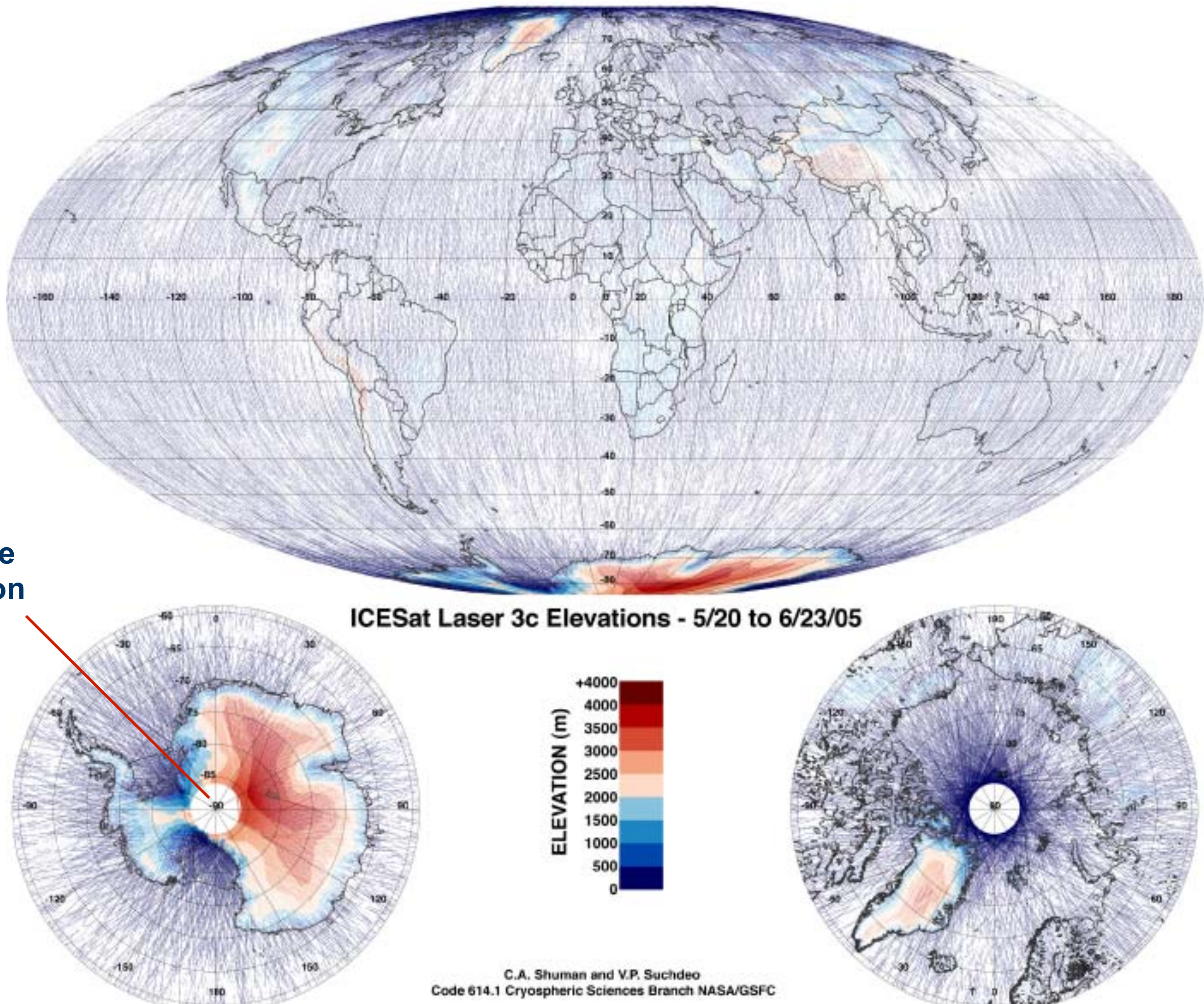
↓

Time-tagged GPS data + Attitude information (start tracker or INS) → Location on the ground and ground elevation

Calculation of Range: Simple Surface



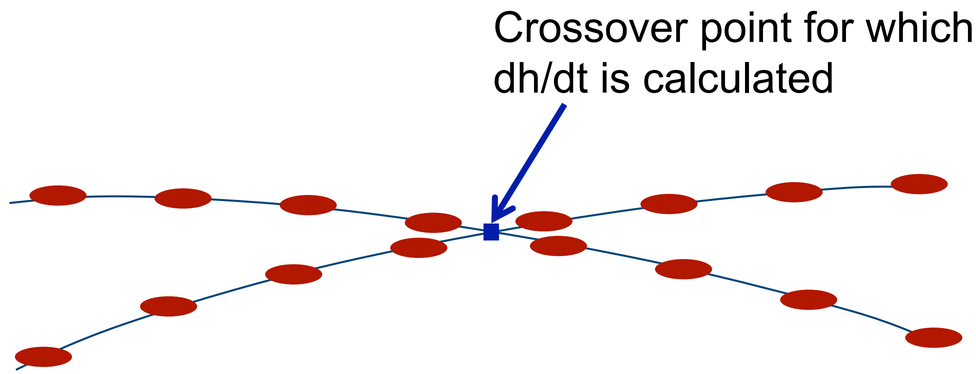
33 Days of ICESat Coverage

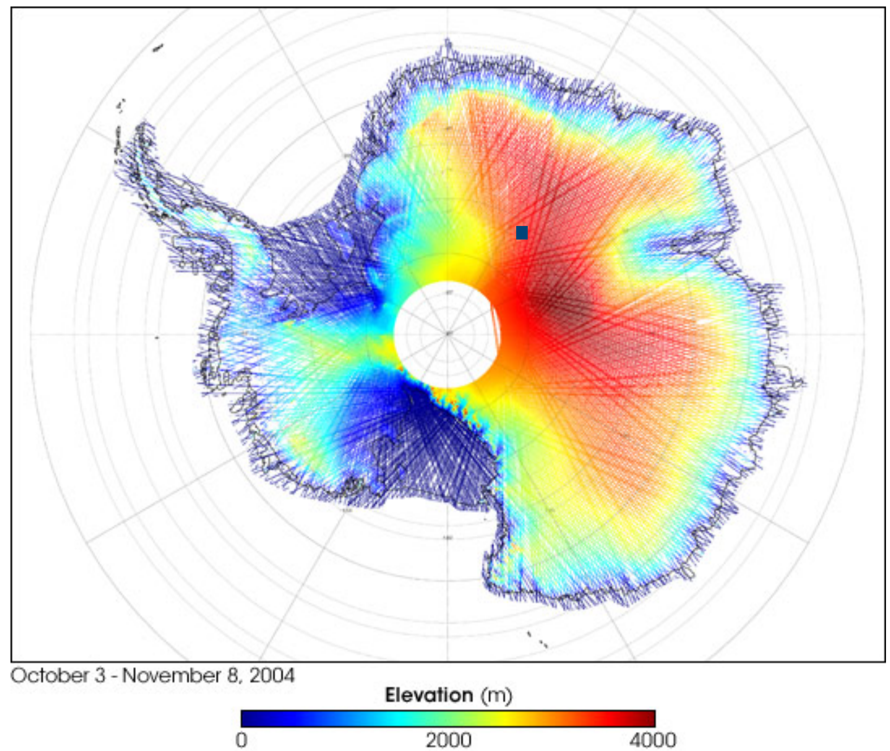


94 degree inclination

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



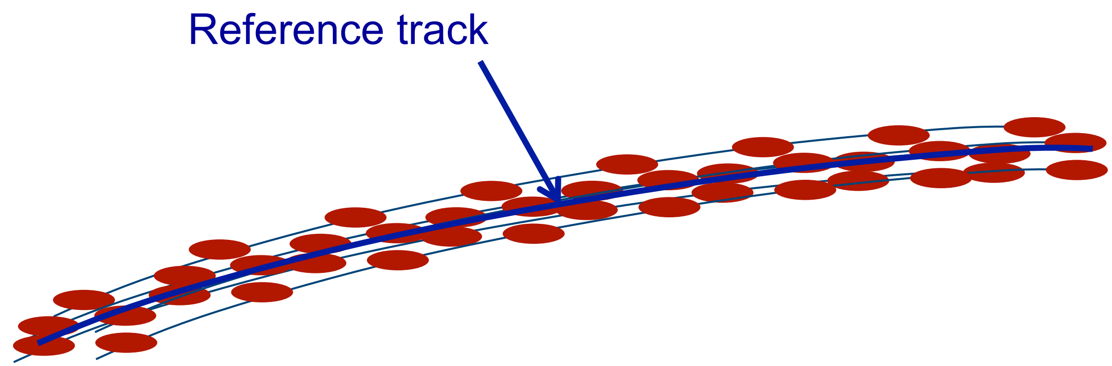


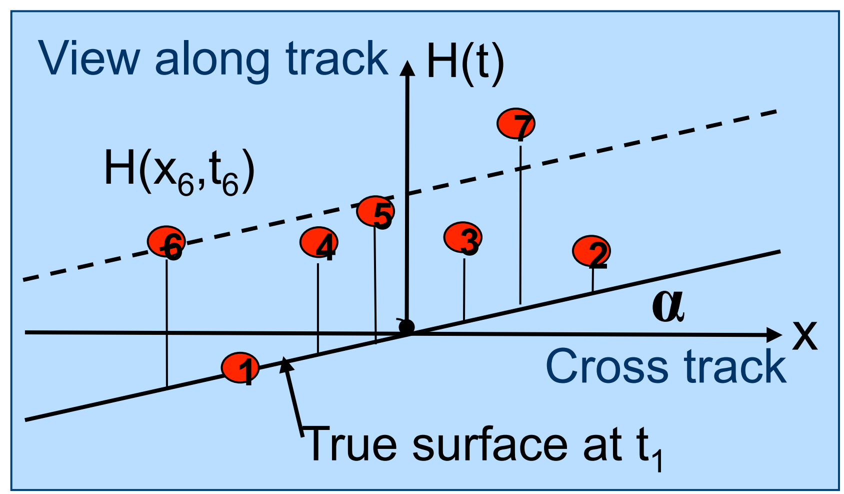
Deriving dh/dt from Repeat-Track Analysis

- 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

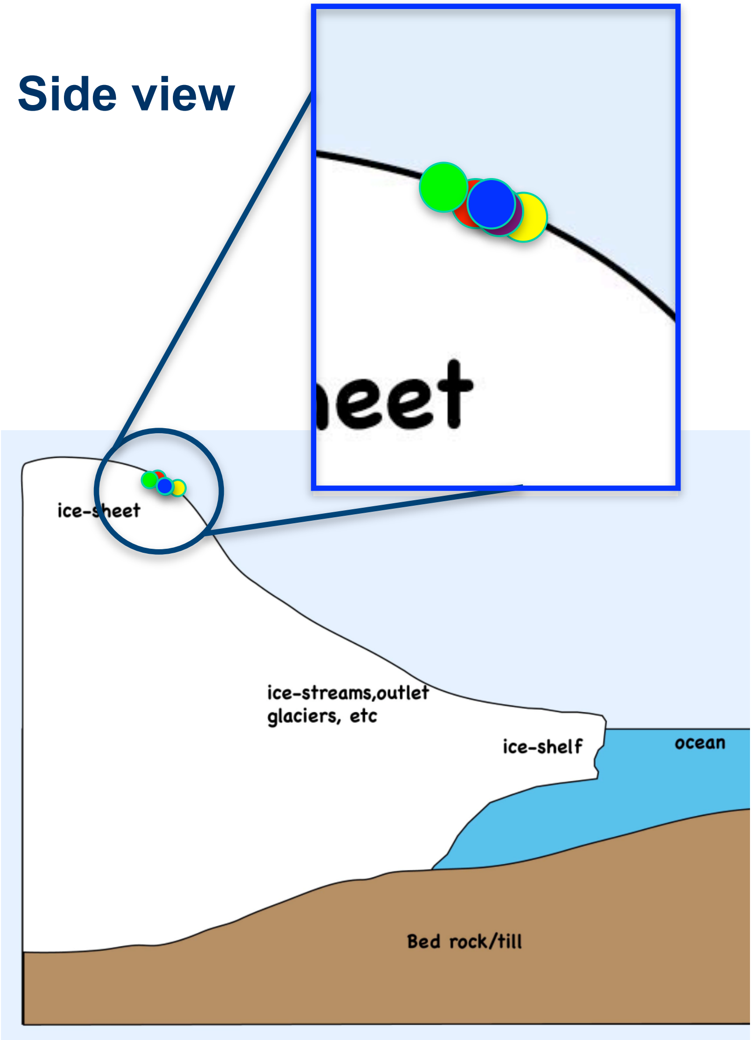




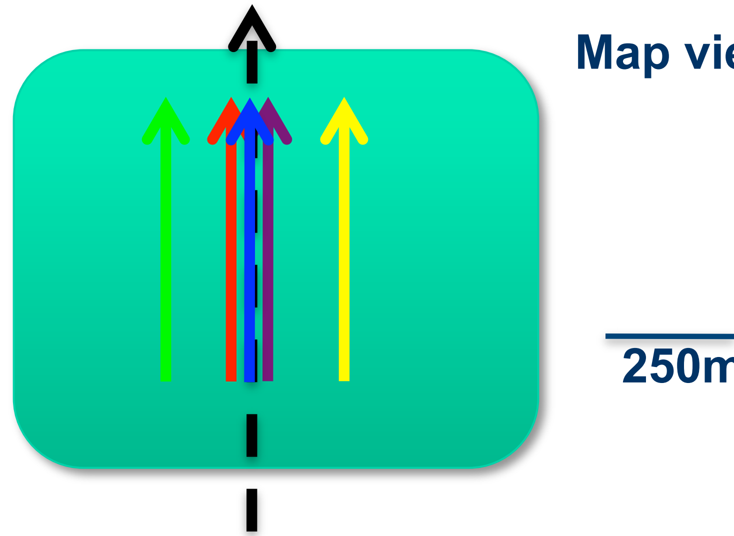
H.J. Zwally, GSFC

Importance of surface slope knowledge

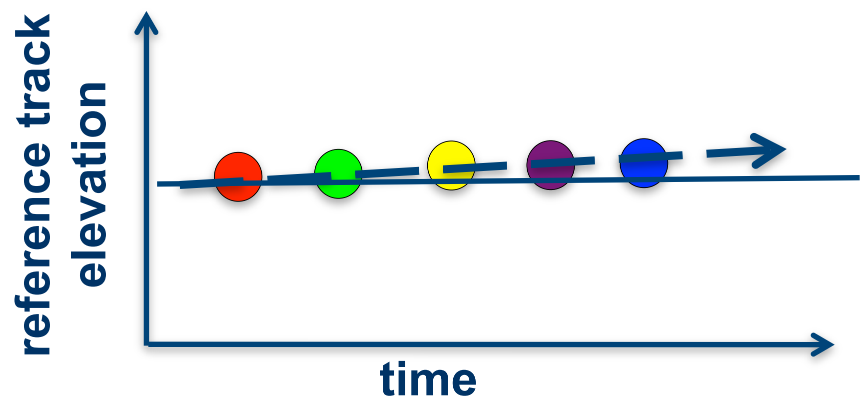
Side view



Map view

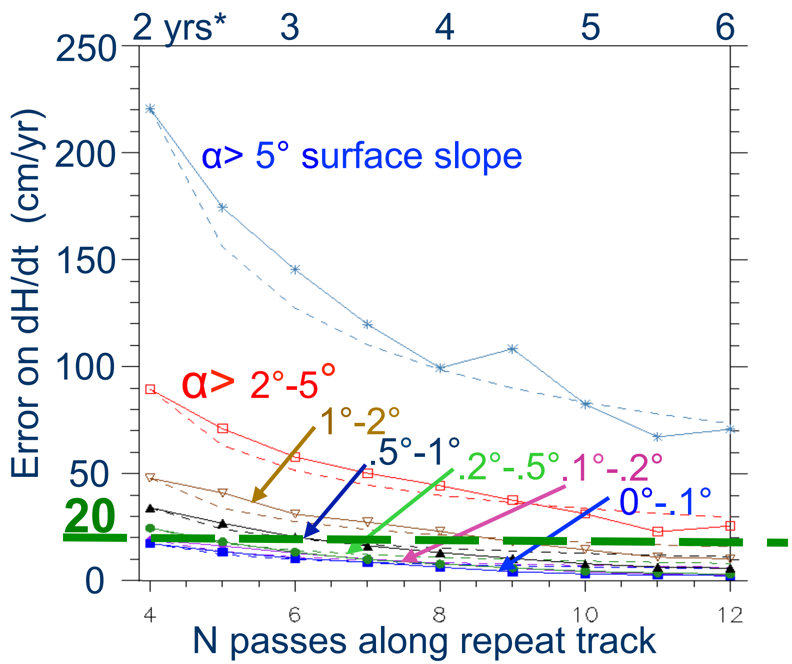


reference ground track

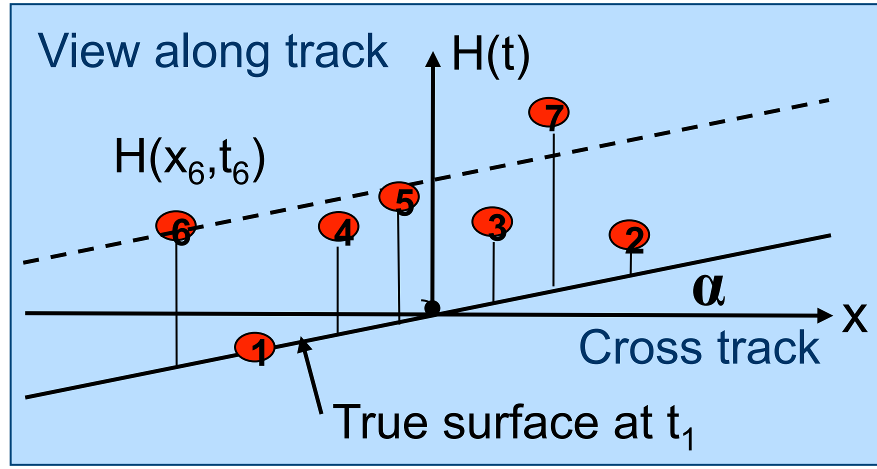


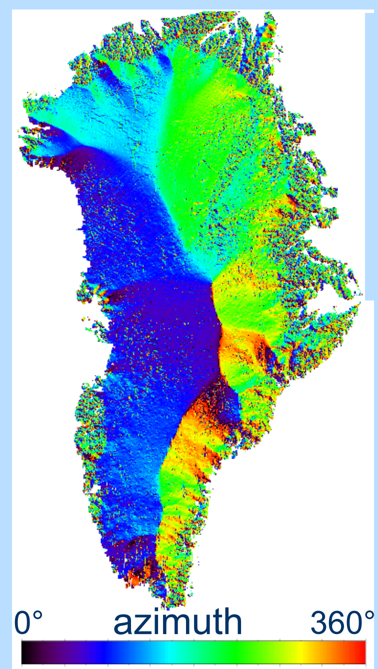
Cross-track slope knowledge necessary for elevation change

Accuracy is Sensitive to Number of Observations



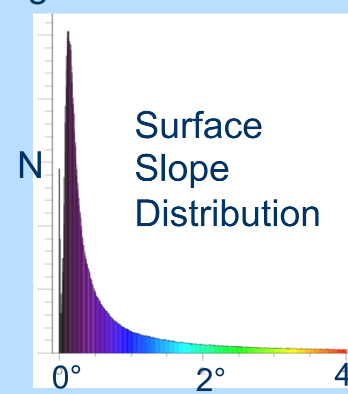
20 cm/yr accuracy achieved after N= 10 passes for slopes < 2° (e.g. 5 yrs* of continuous operation with 50% cloud loss)





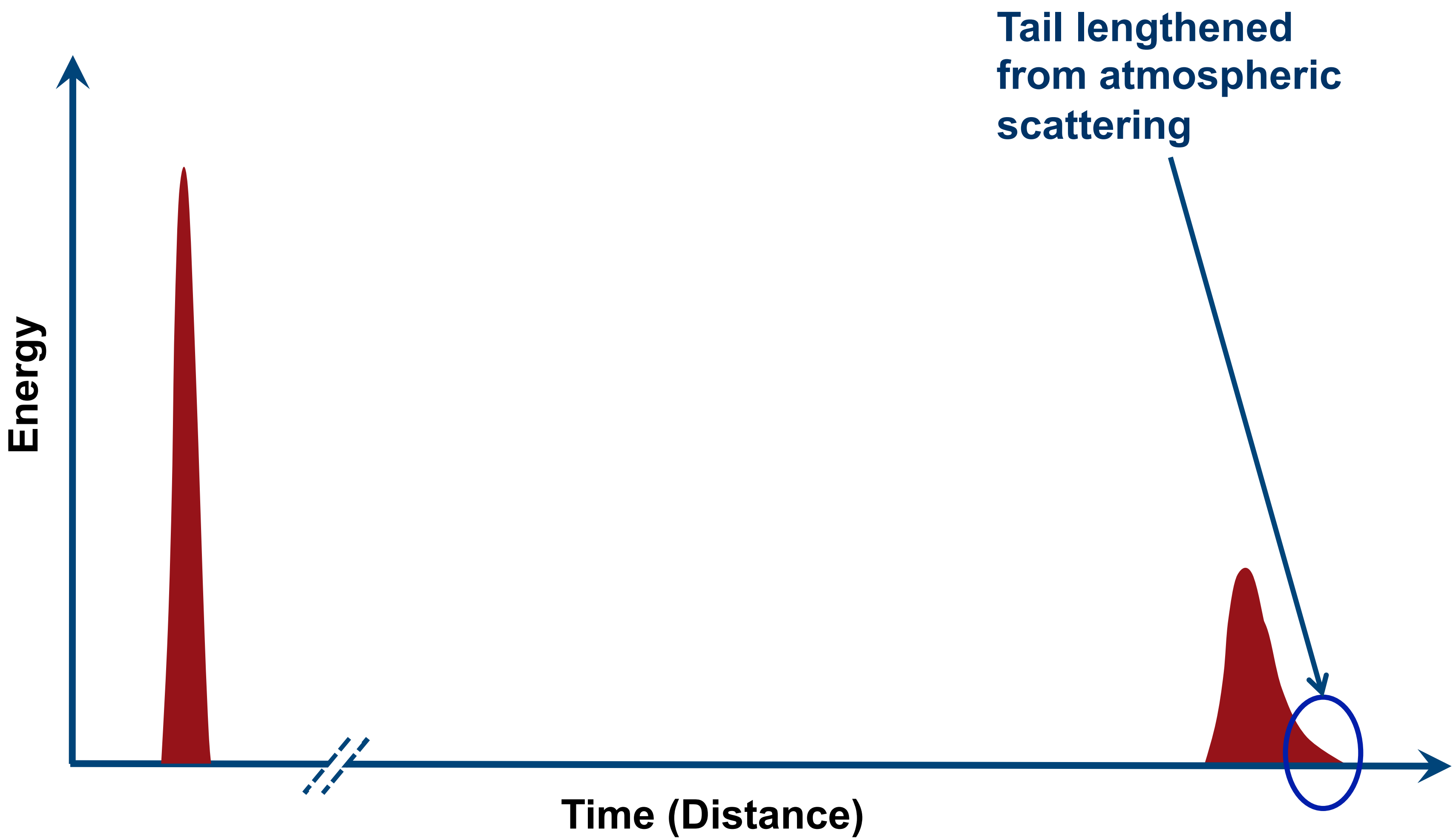
GREENLAND

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

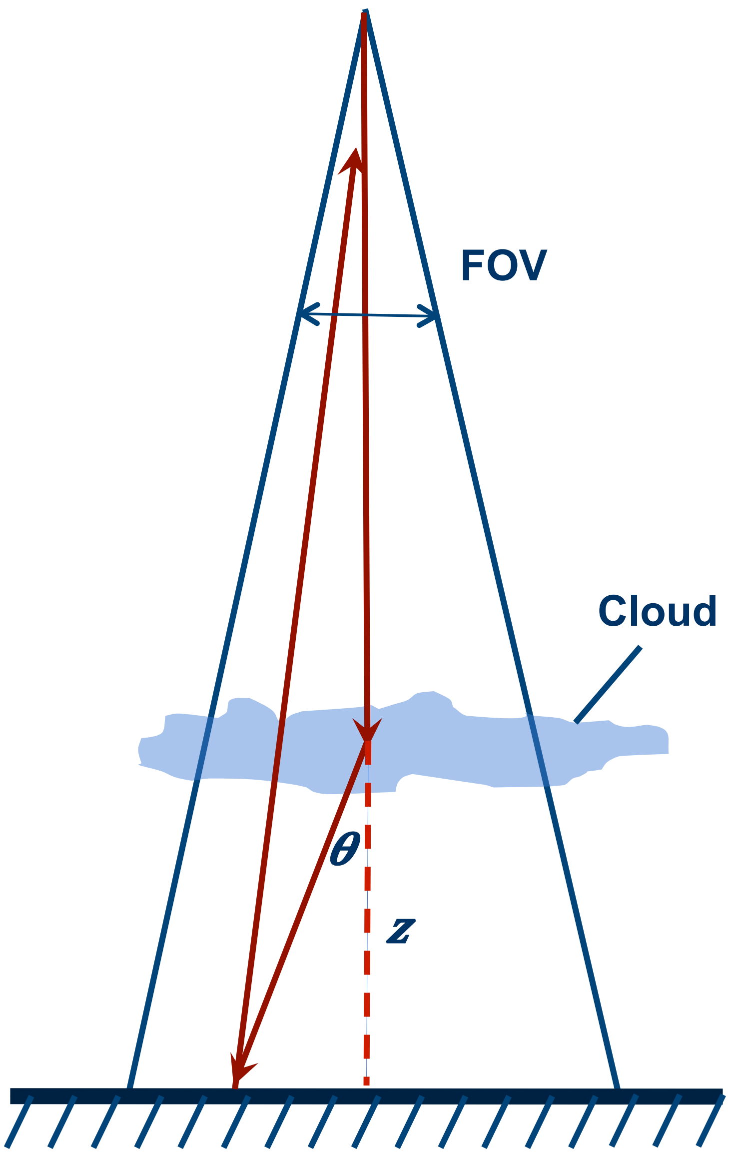


H.J. Zwally, GSFC

Calculation of Range: Atmospheric Effects



Forward Scattering Effects from Clouds

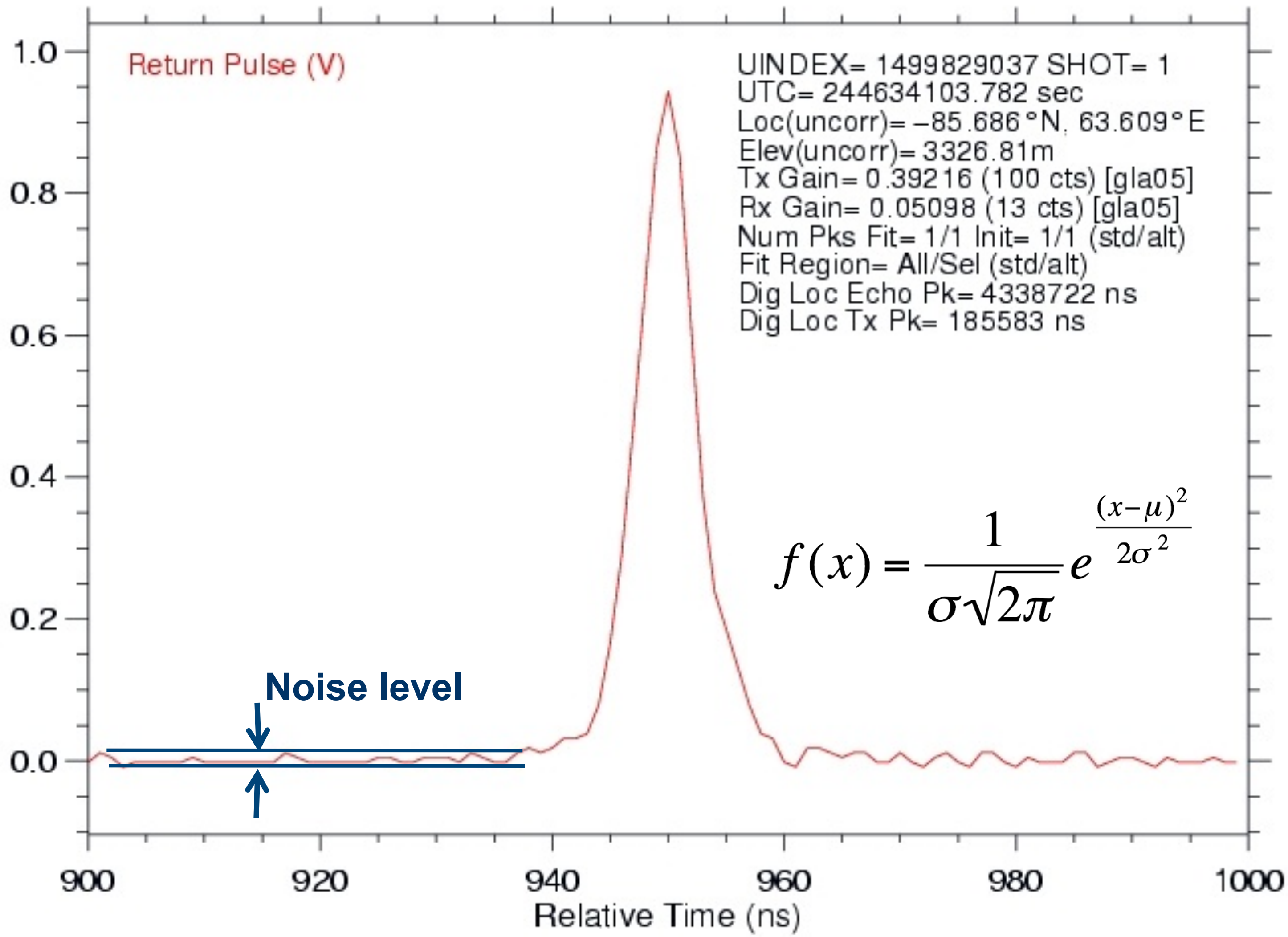


Forward scattering from clouds lengthen path

Delay: $\Delta(z,\theta)=z/\cos\theta - z$

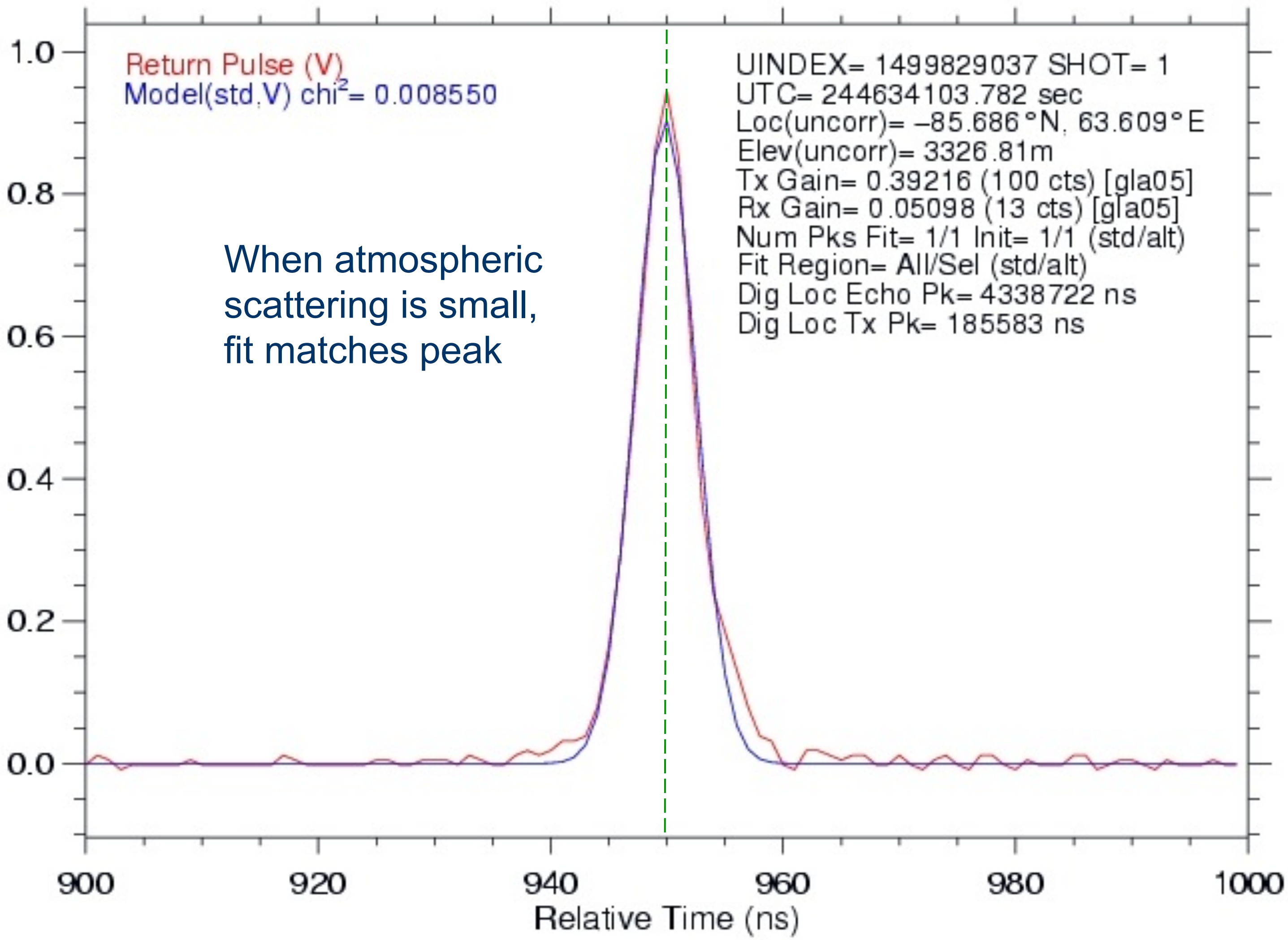
The wider the field of view, the more forward scattered photons will be received.

Sample Return Pulse



$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-\mu)^2}{2\sigma^2}}$$

Fitted Return Pulse



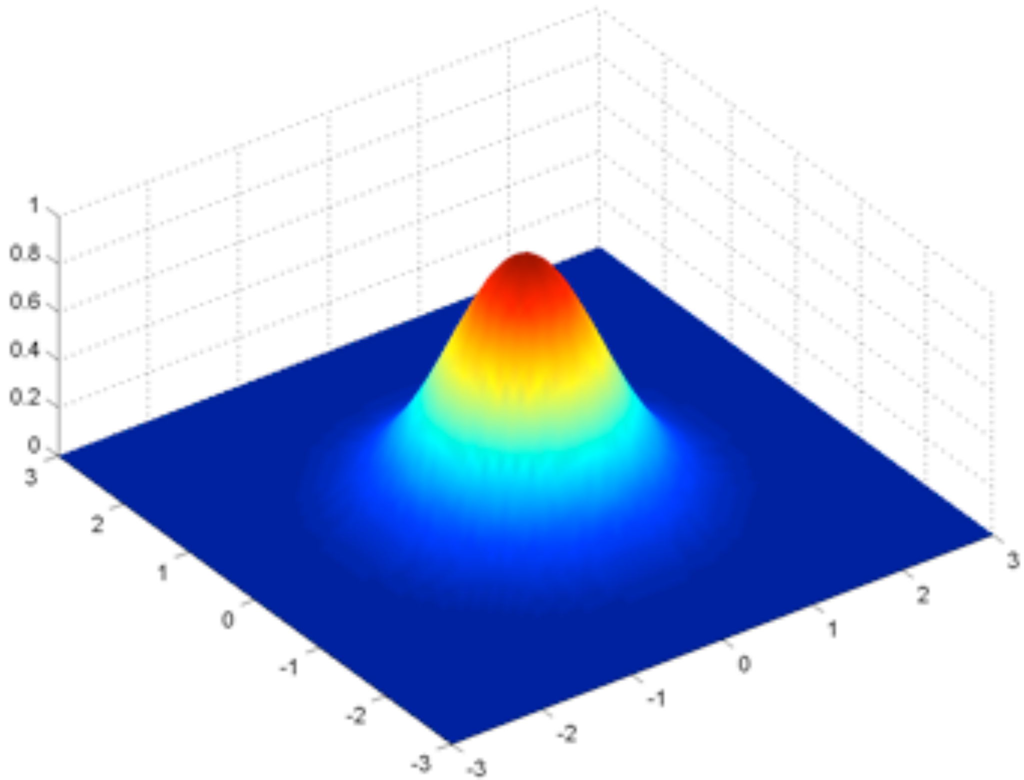
Key Factors Contributing to Uncertainty

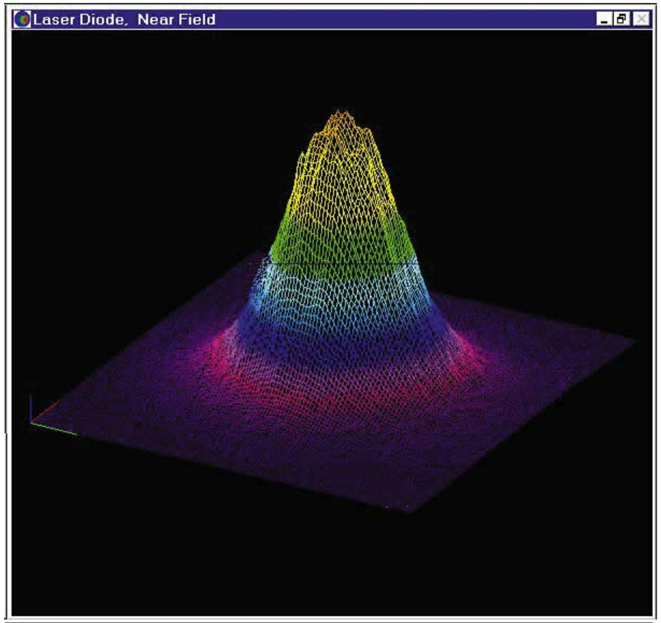
- Pointing knowledge
  - ICESat was designed with state-of-the-art attitude determination system
- Pointing angle
  - Off-nadir pointing possible to 5 degrees to targets of opportunity, but for ice, we try to keep it under a few tenths of a degree
  - Orbit control to within $\pm$1 km of reference track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

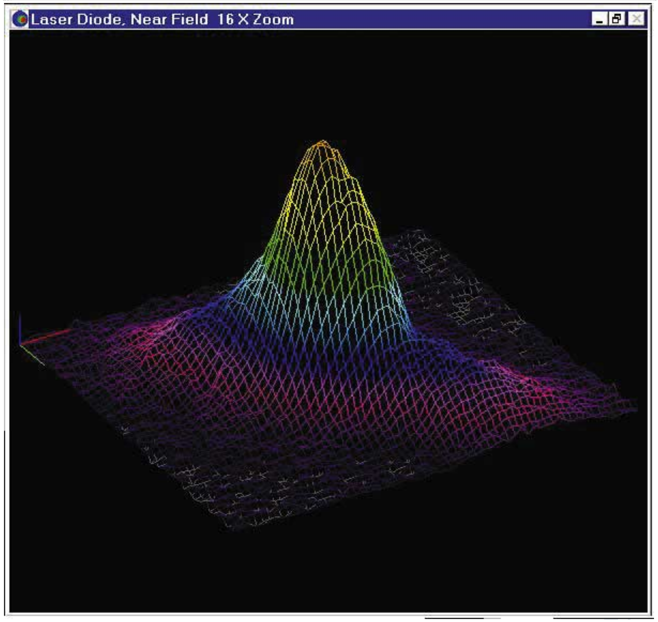
Key Factors Contributing to Uncertainty

- 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

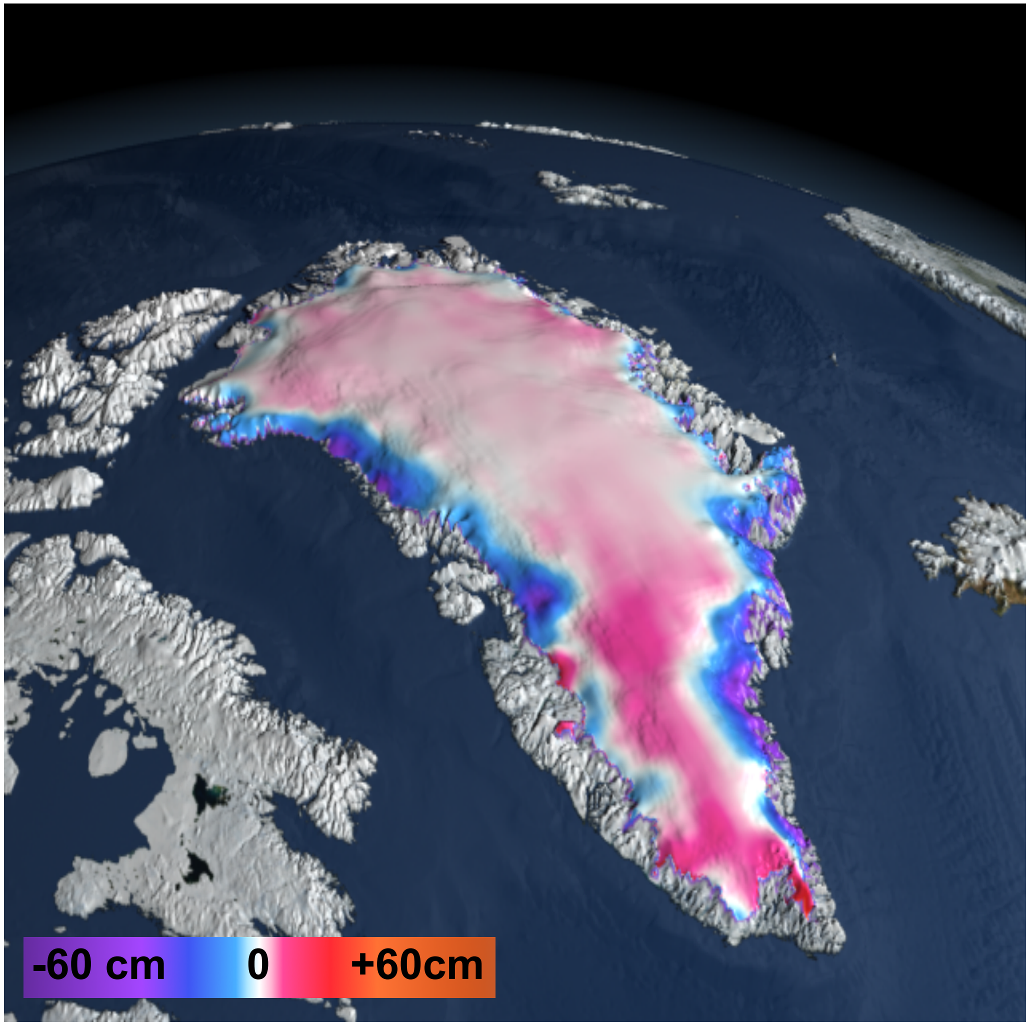
Laser Energy Distribution







Elevation Change Observations are The Keys to Understanding Ice Sheet Changes



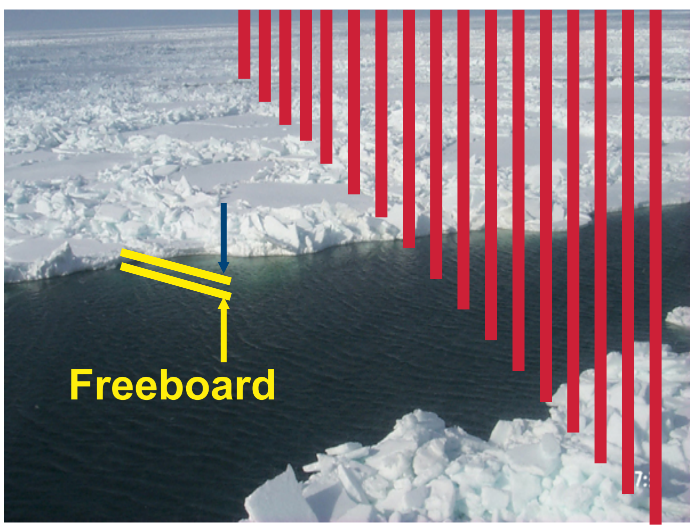
- ICESat is showing dramatic shrinking at the Greenland ice sheet margins and slight growth in the interior.
  - Interior growth over very large areas offsetting some but not all of the losses at the margins
  - Greenland contributing ~160 GT per year (0.35 mm) to sea level
- Antarctica also shows significant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

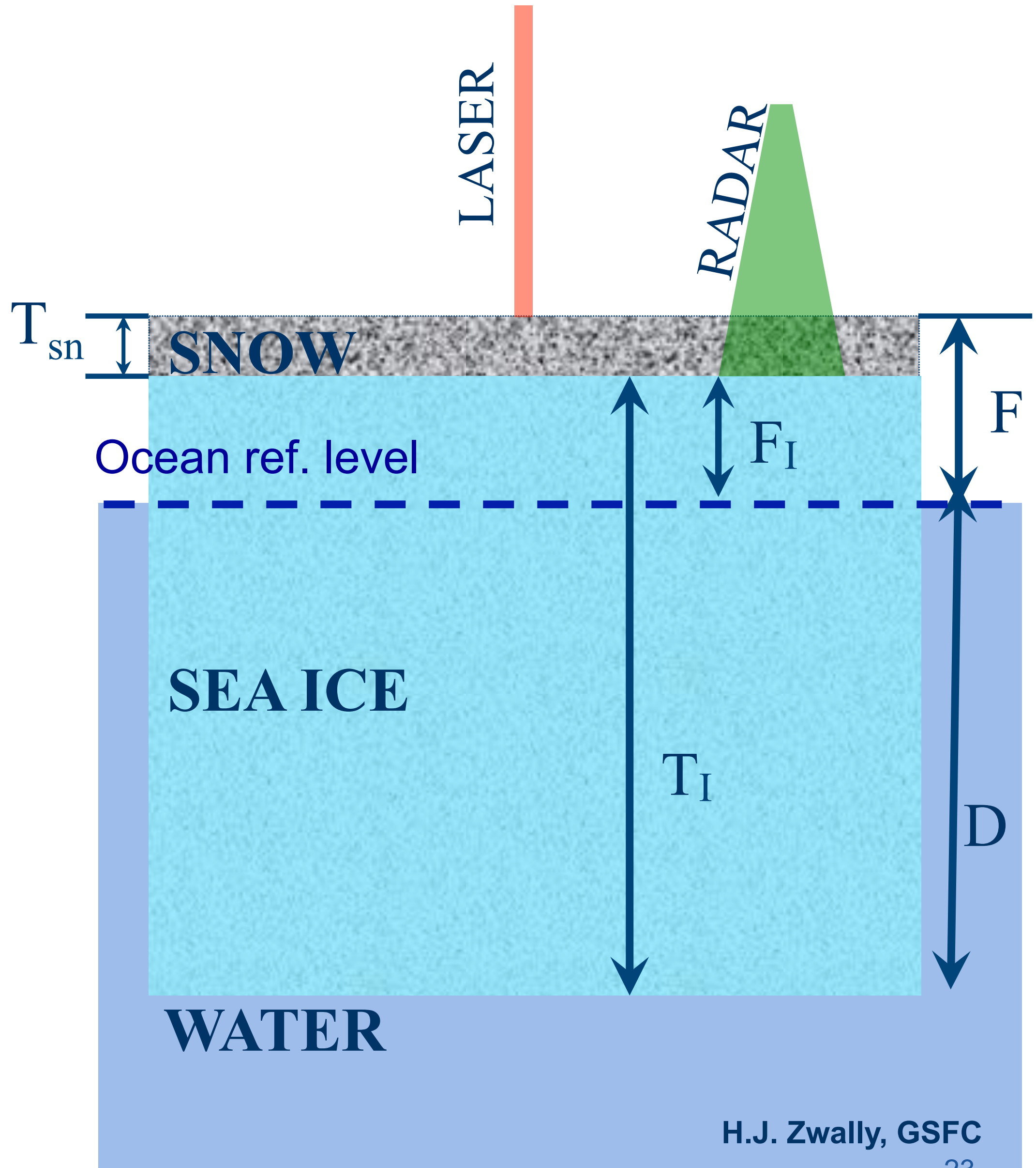
H.J. Zwally, GSFC

ICESat Enables Estimates of Sea Ice Thickness

- ICESat's precision allows measurement of difference between water and sea ice surface heights

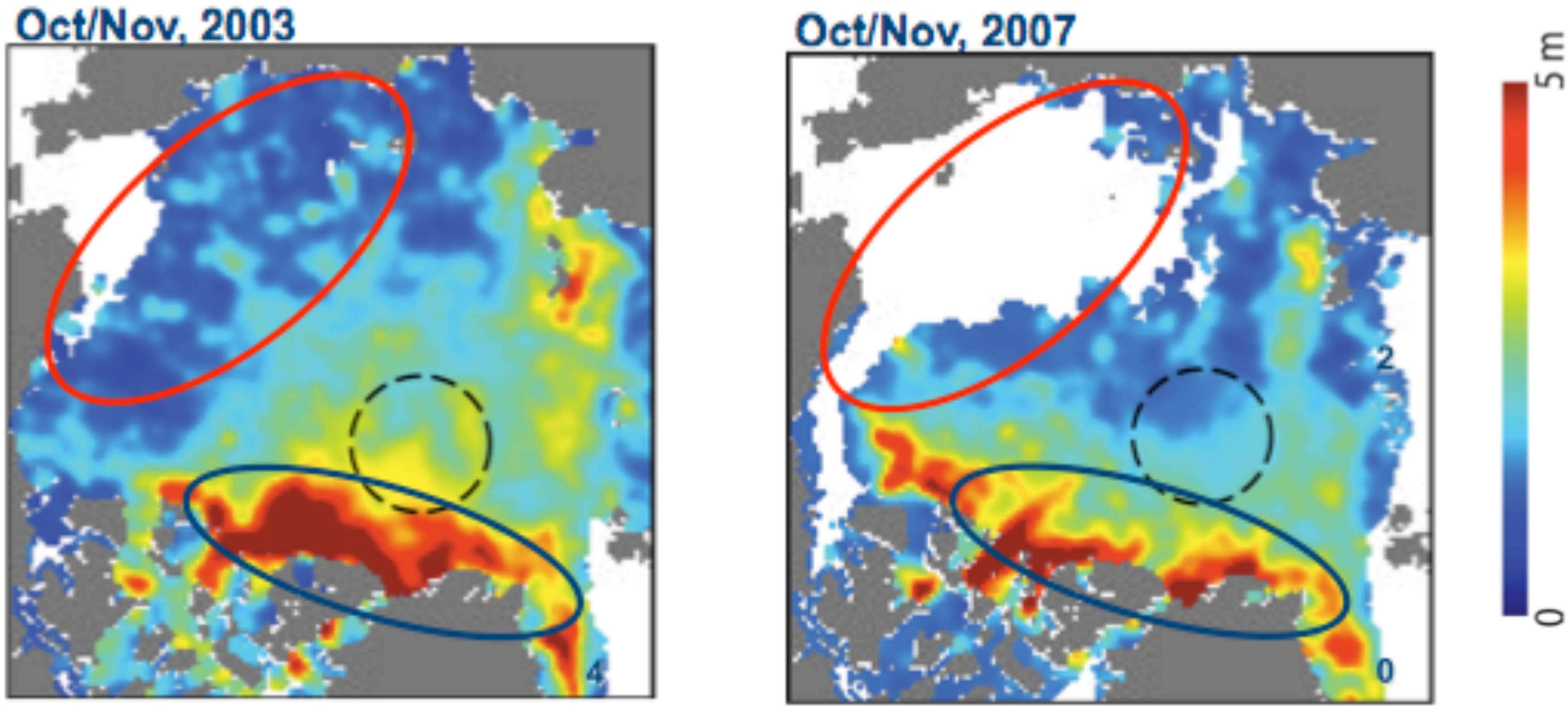
- Adjusting for snow depth and buoyancy yields ice thickness estimates





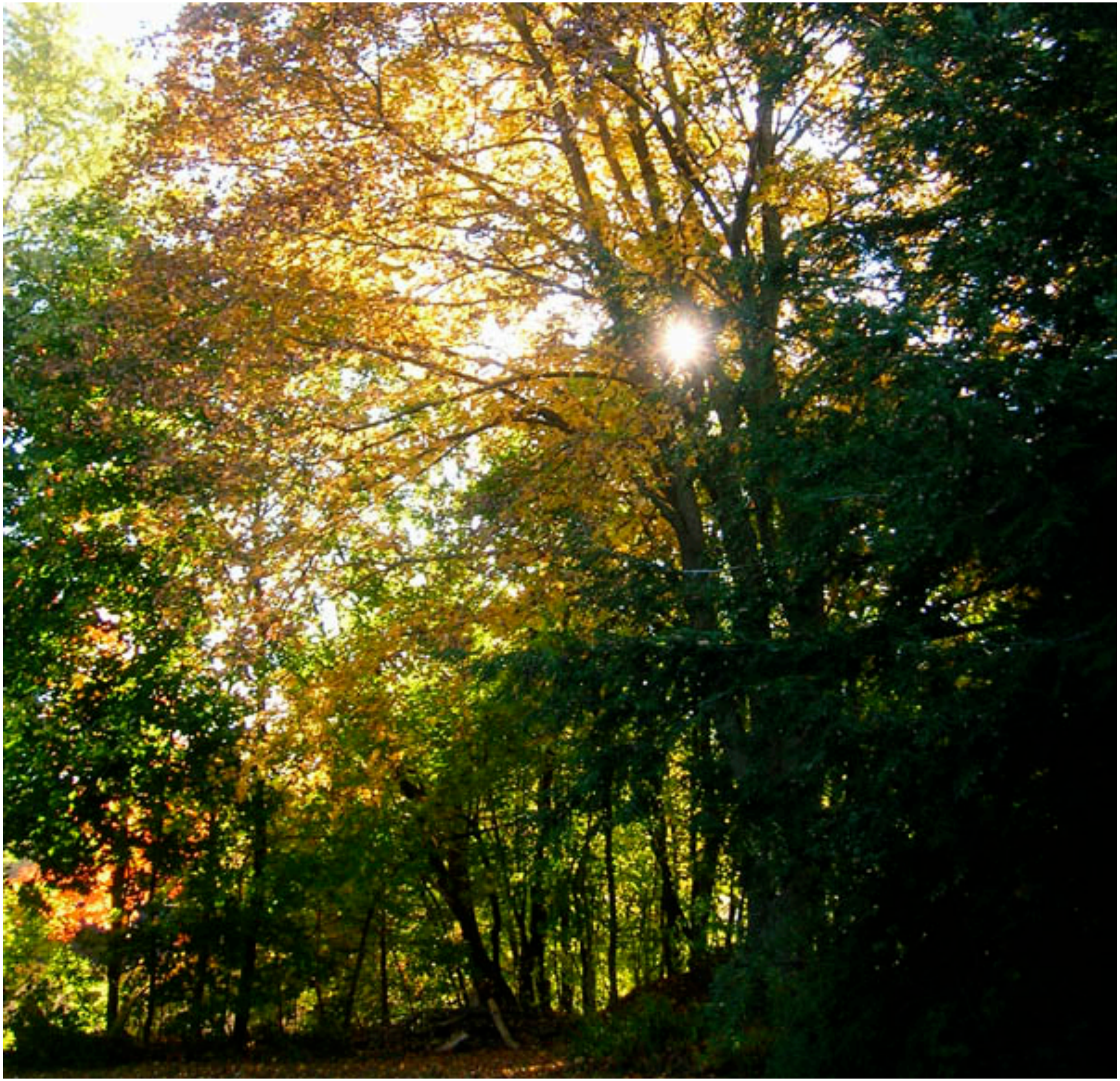
H.J. Zwally, GSFC

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)

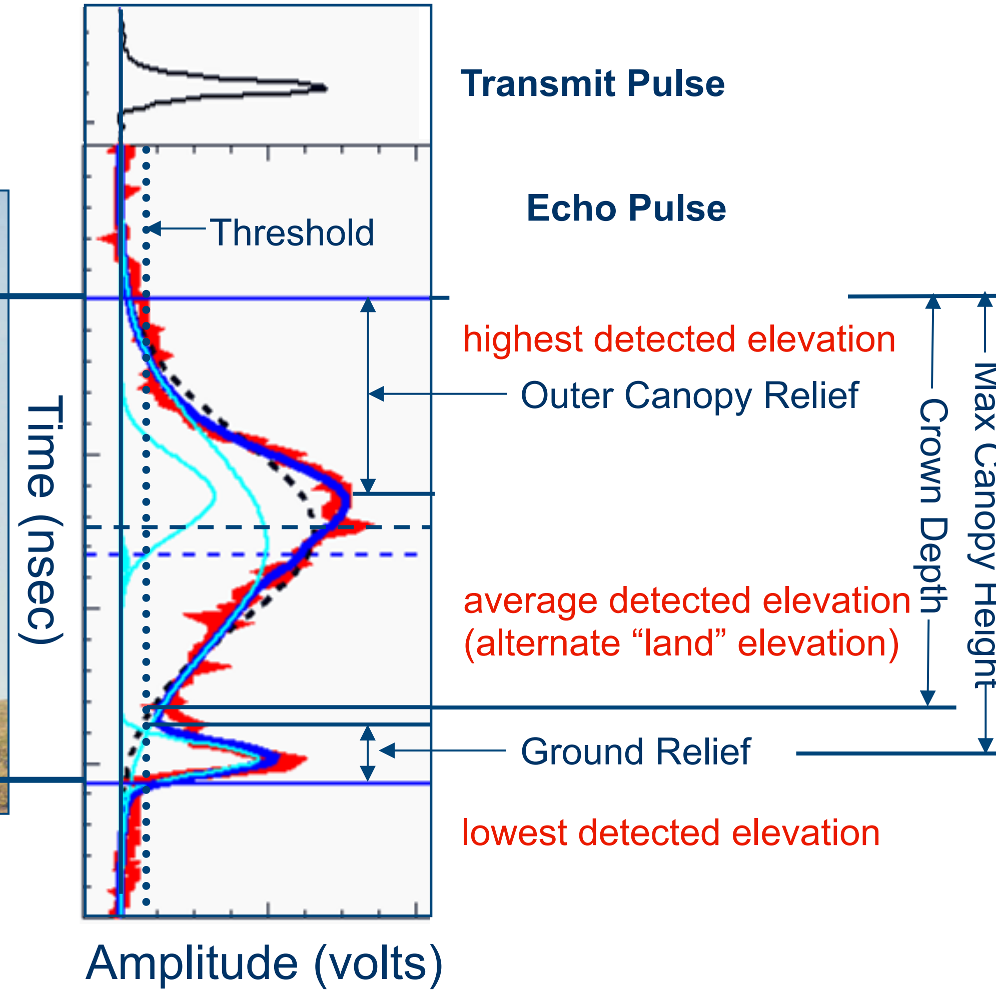
H.J. Zwally, GSFC



GLAS Measurement of Echo pulse from Trees

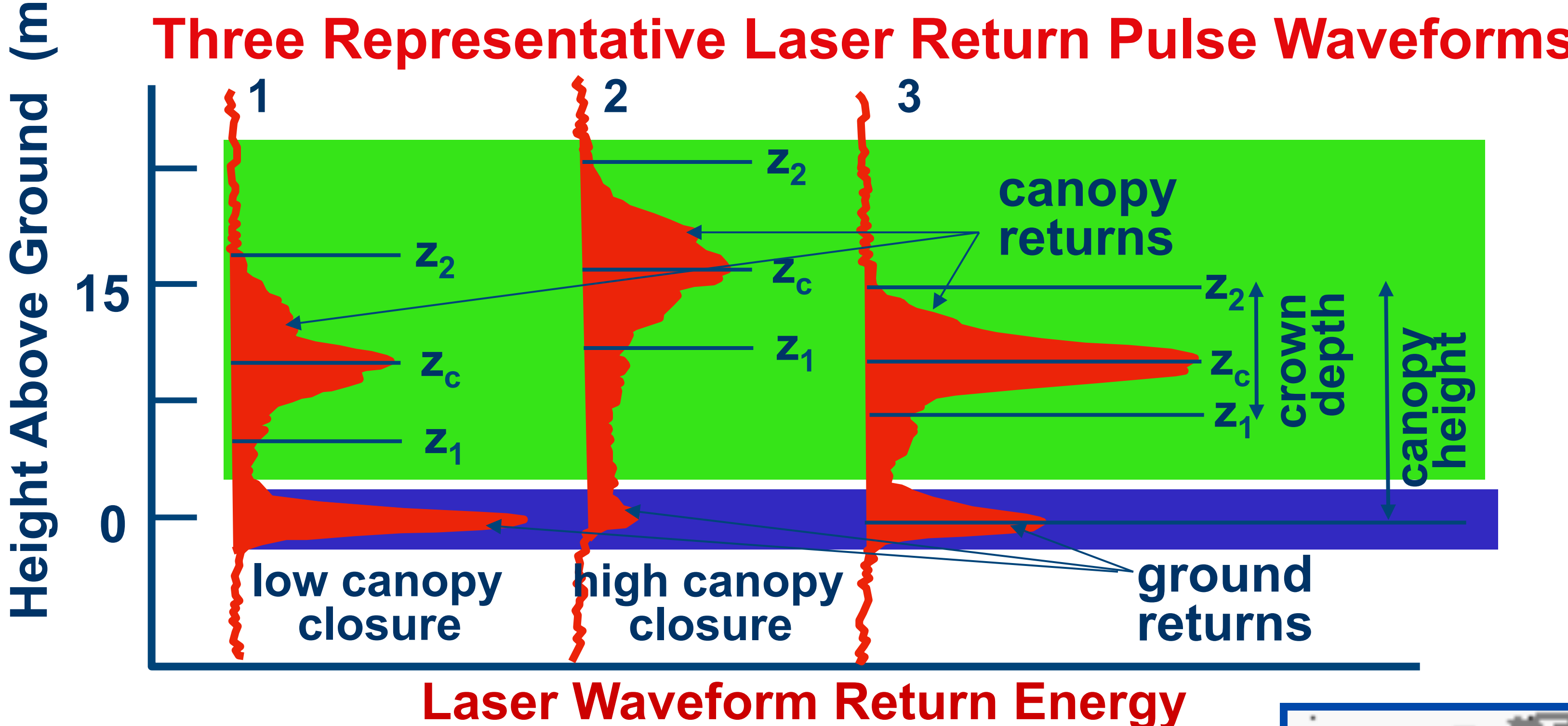
1064 nm, 7 nsec laser pulse

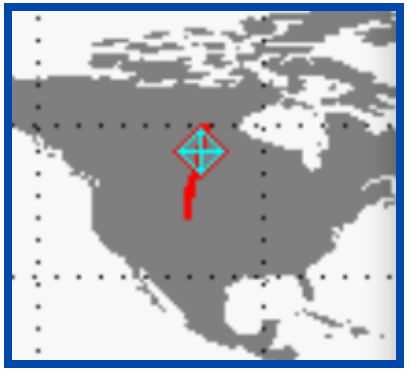
~ 70 m diameter laser footprint
spaced 175 m apart along ground track



Height Distribution of Reflected Laser power with 15 cm Vertical Sampling

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

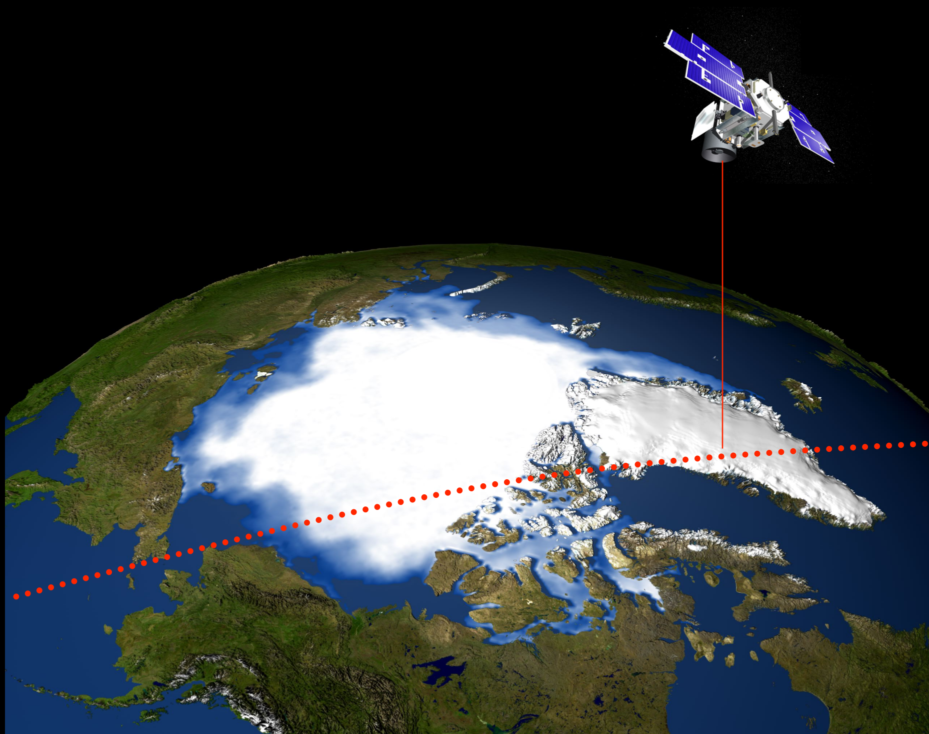
$$\text{Canopy Closure} \sim \frac{\text{Ground Return Energy}}{\text{Total Return Energy}}$$

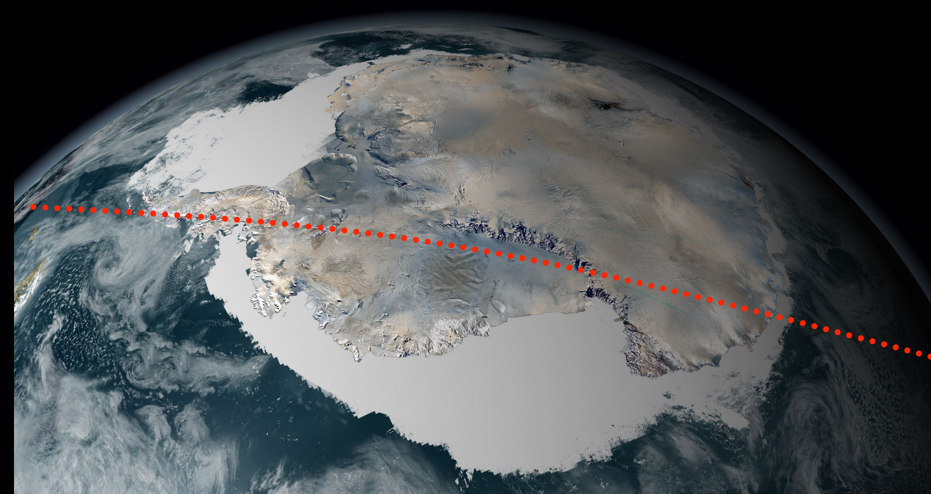
D. Harding et al., NASA GSFC

Summary: ICESat

- 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
- ICESat has applications for other science disciplines as well
  - Atmospheric science, hydrology, etc.

Ice Cloud and Land Elevation Satellite – 2
ICESat-2





Elevation Changes from Repeat-Track Analysis

- Simultaneous solutions for cross-track slope and elevation change

- For ICESat, 10 or more repeat pass are required to solve for both cross-track slopes and linear change rates (dH/dt) with acceptable accuracies.

- Limited in areas with changing slopes

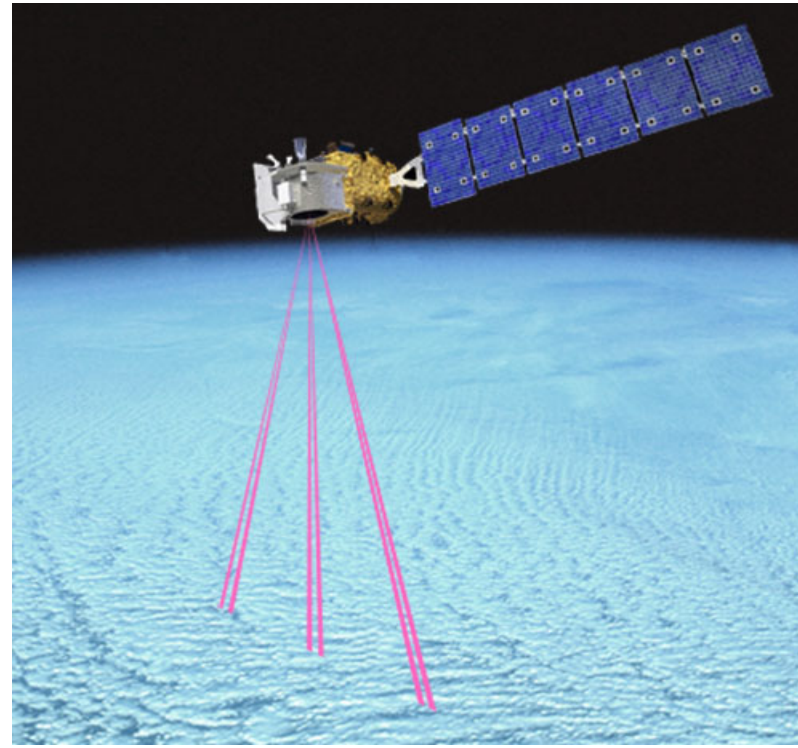
- Little information about seasonal changes.

- Interannual variability limited to post-processed results at end of mission.

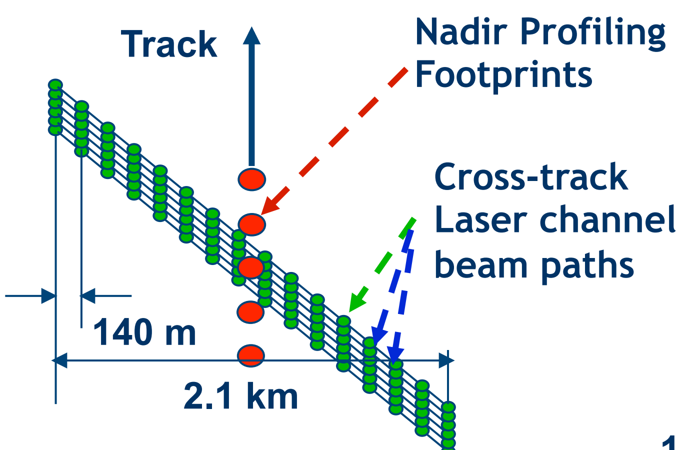
ICESat solutions are limited by lack of knowledge of cross track slopes in vicinity of reference track (X).

ICESat-2 Mission Concept

In contrast to ICESat design, ICESat-2 will incorporate a multi-beam laser system using micro-pulse multi-beam photon counting approach

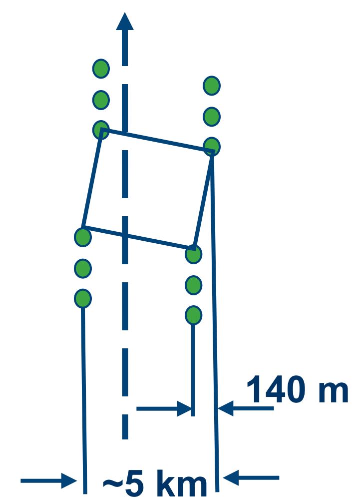


Cross-track coverage can be achieved through various approaches



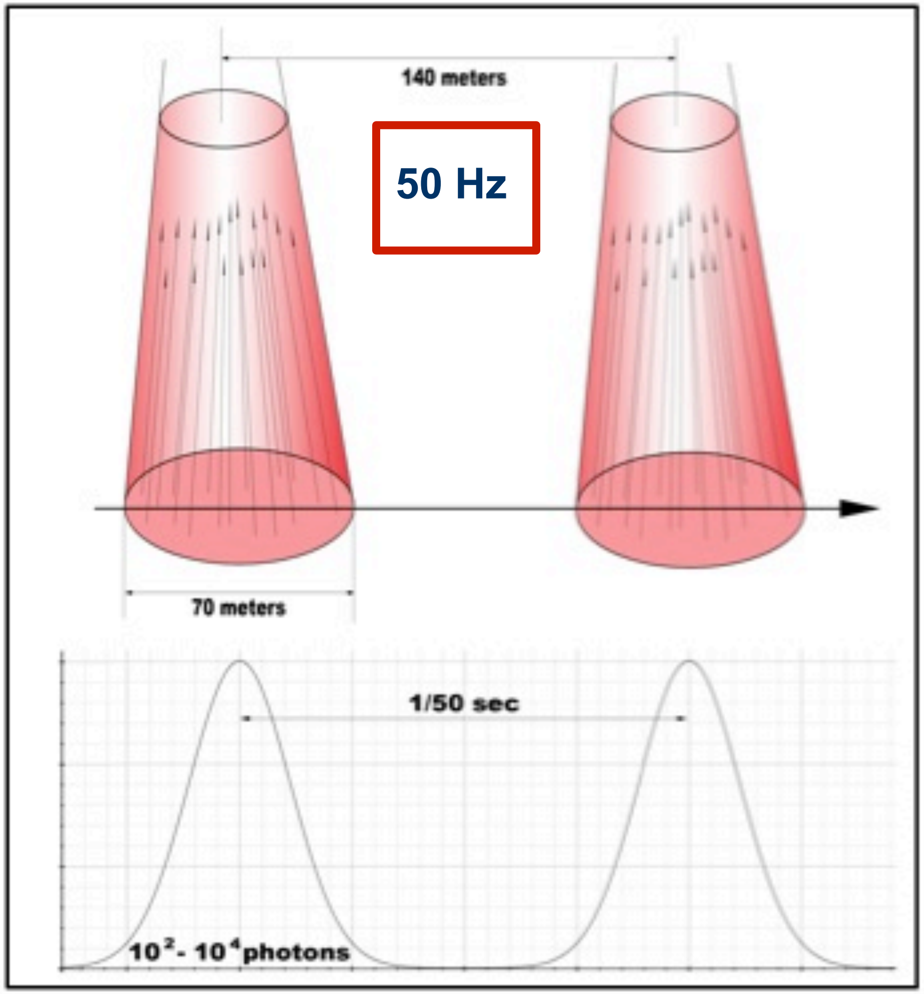
Photon counting

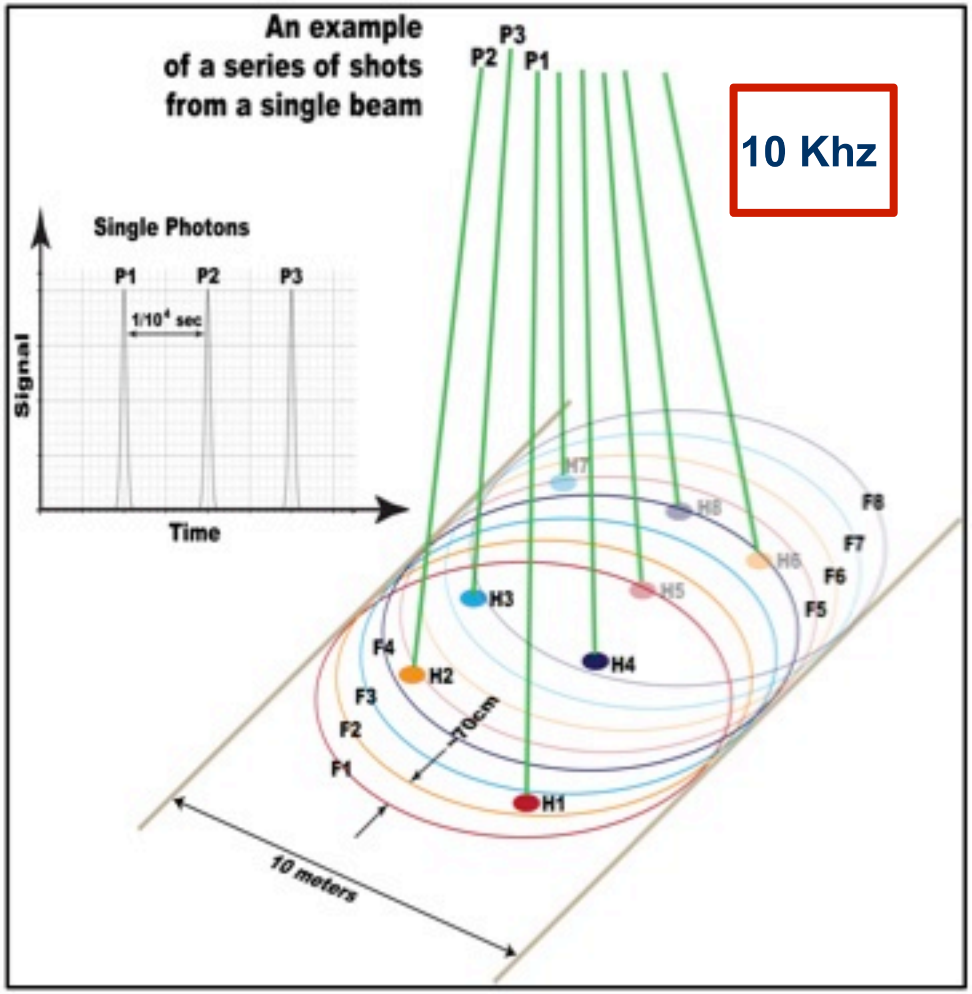
2 beams from 2 lasers or w/ a DOE



4 Beams w/ a DOE

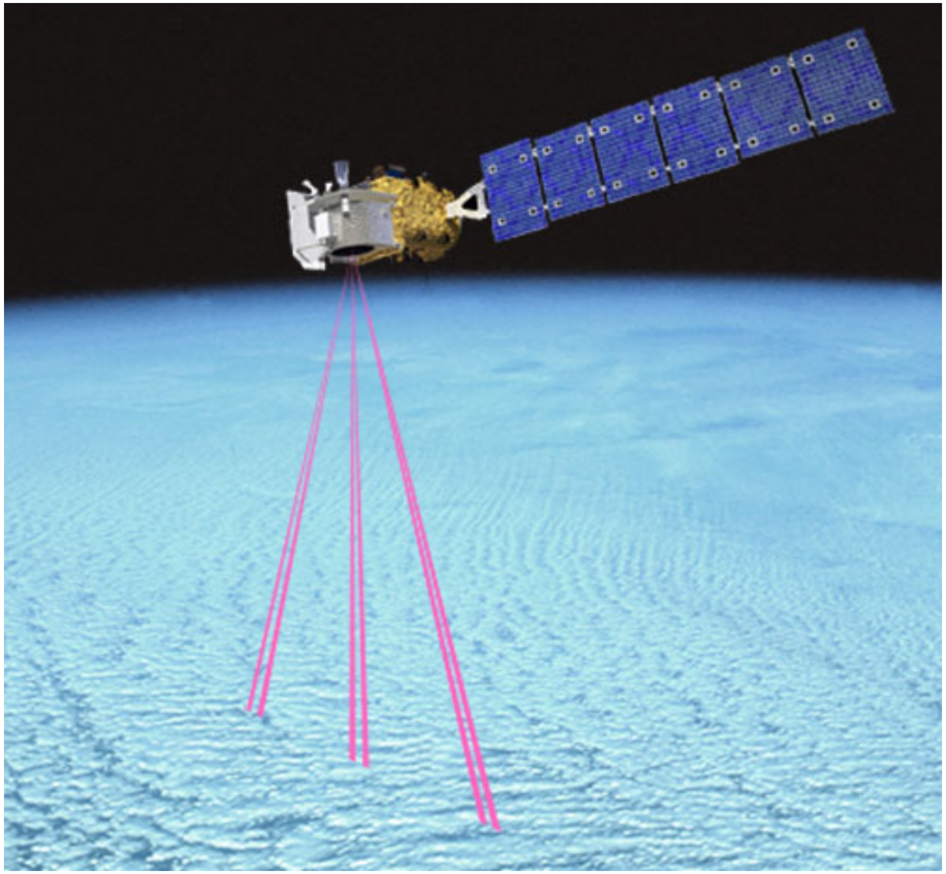
Pulse Laser vs. Micropulse





ICESat-2 Mission Concept

Multi-beam micro-pulse multi-beam photon counting approach provides



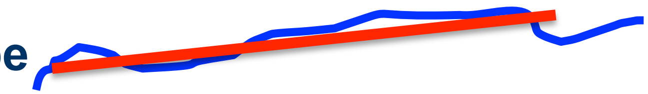
- **Dense cross-track sampling to resolve surface slope on an orbit basis**
- **High repetition rate (10 kHz) generates dense along-track sampling (~70 cm).**

Advantages:

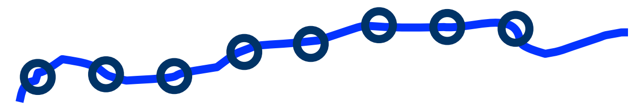
- **Improved elevation estimates over high slope areas and very rough (e.g. crevassed) areas**
- **Flexibility in beam configuration**
- **Improved lead detection for sea ice freeboard with denser smaller multi-beam footprints**

What Drives the Instrument Requirements?

measurement requirement for surface slope



drives the requirement for
multiple cross-track beams



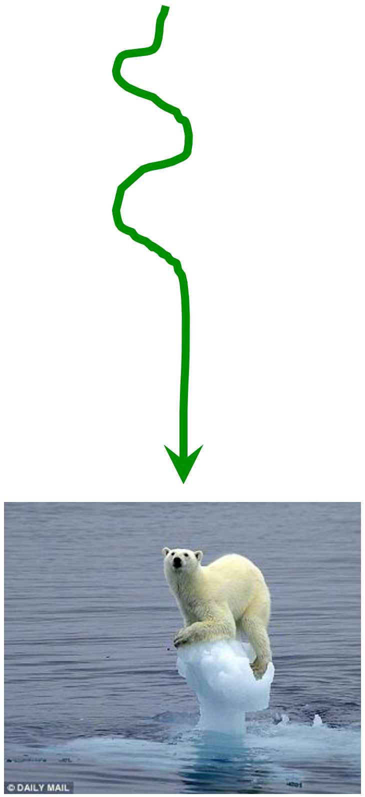
drives the requirement for
laser pulse energy and repetition rate

drives the requirement for
single photon sensitivity

drives the requirement for
narrow field of view

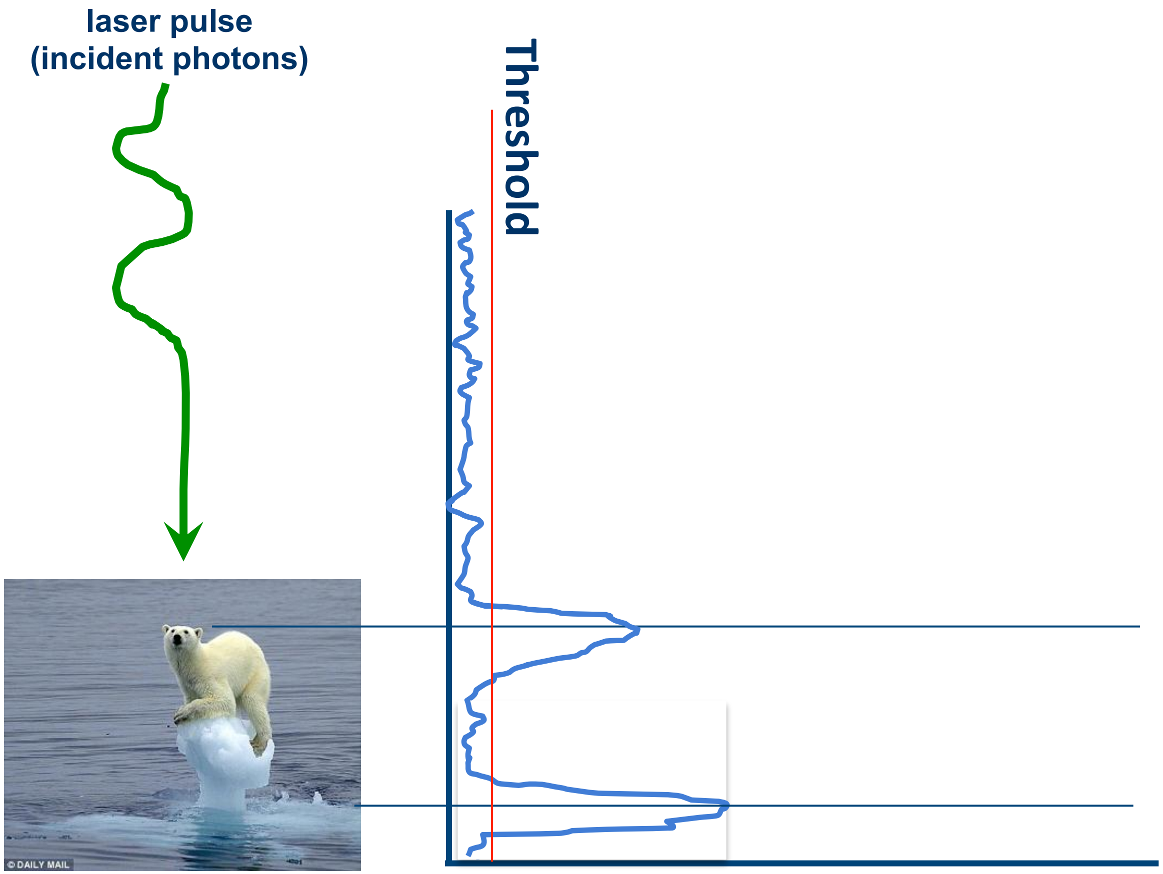
Analog –vs- Photon-counting

laser pulse
(incident photons)



Analog approach
(digitized waveform)

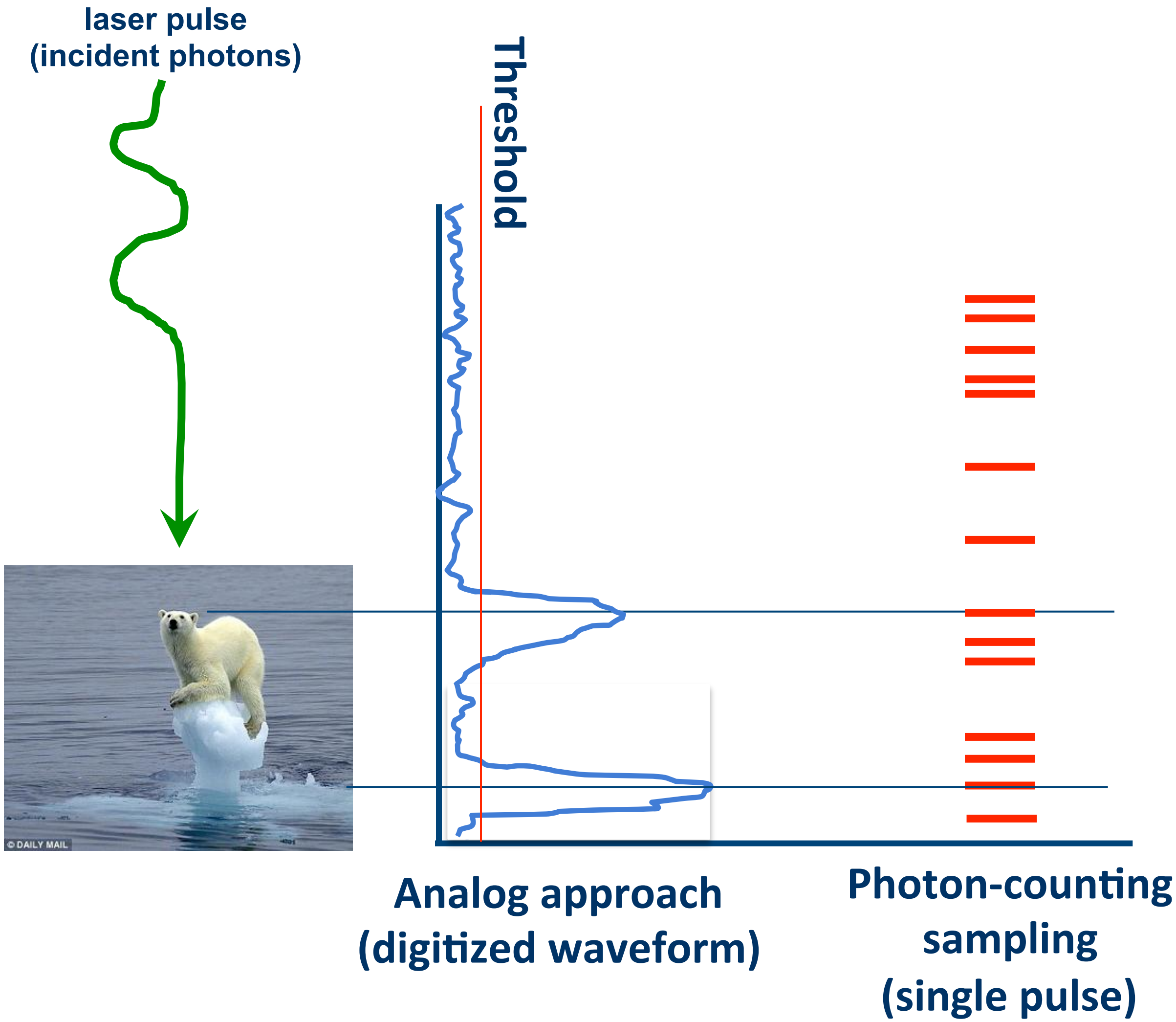
Analog –vs- Photon-counting



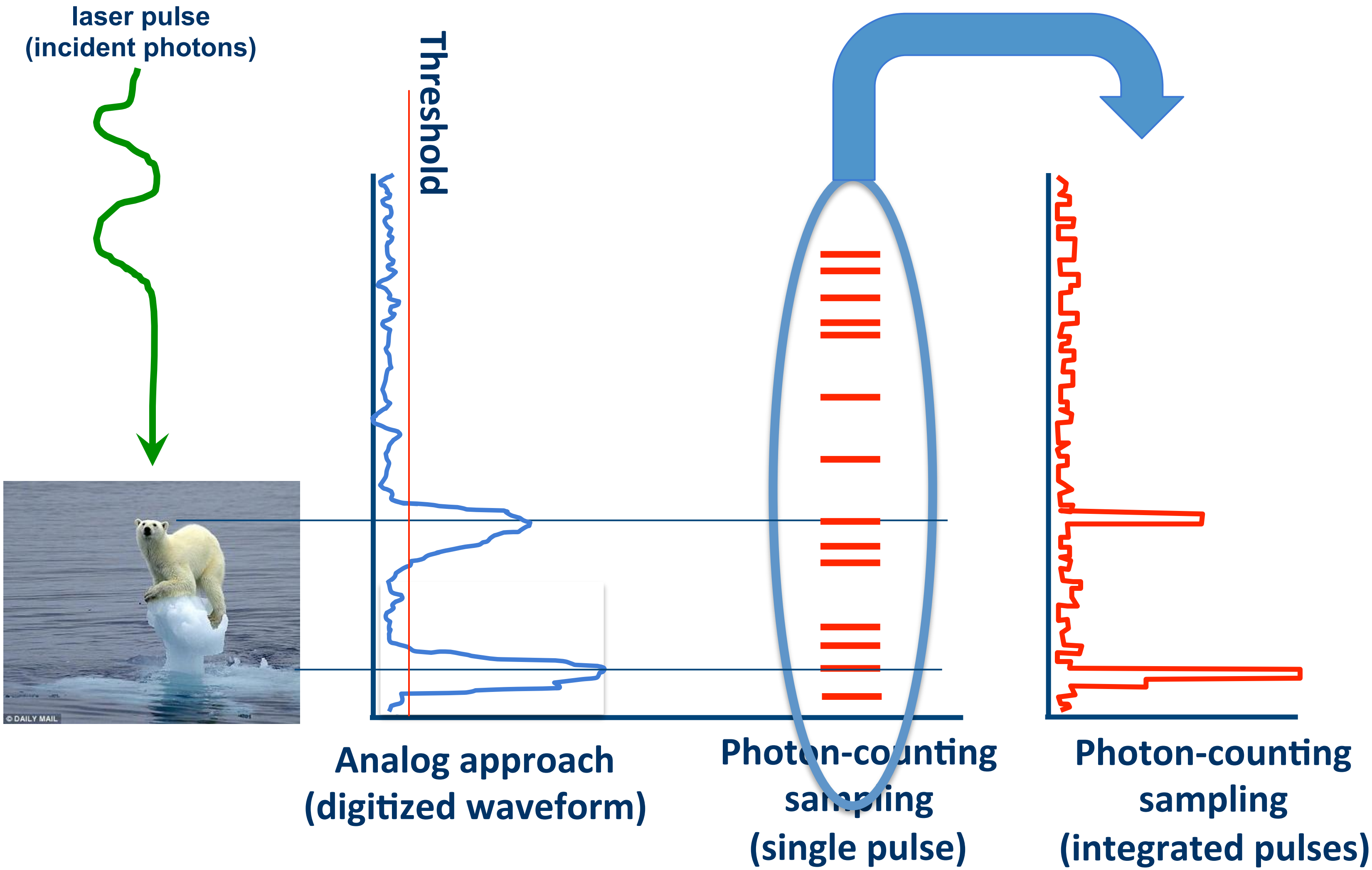
Analog approach
(digitized waveform)

Apply arbitrary threshold;
anything above the threshold is something,
everything below the threshold is nothing.

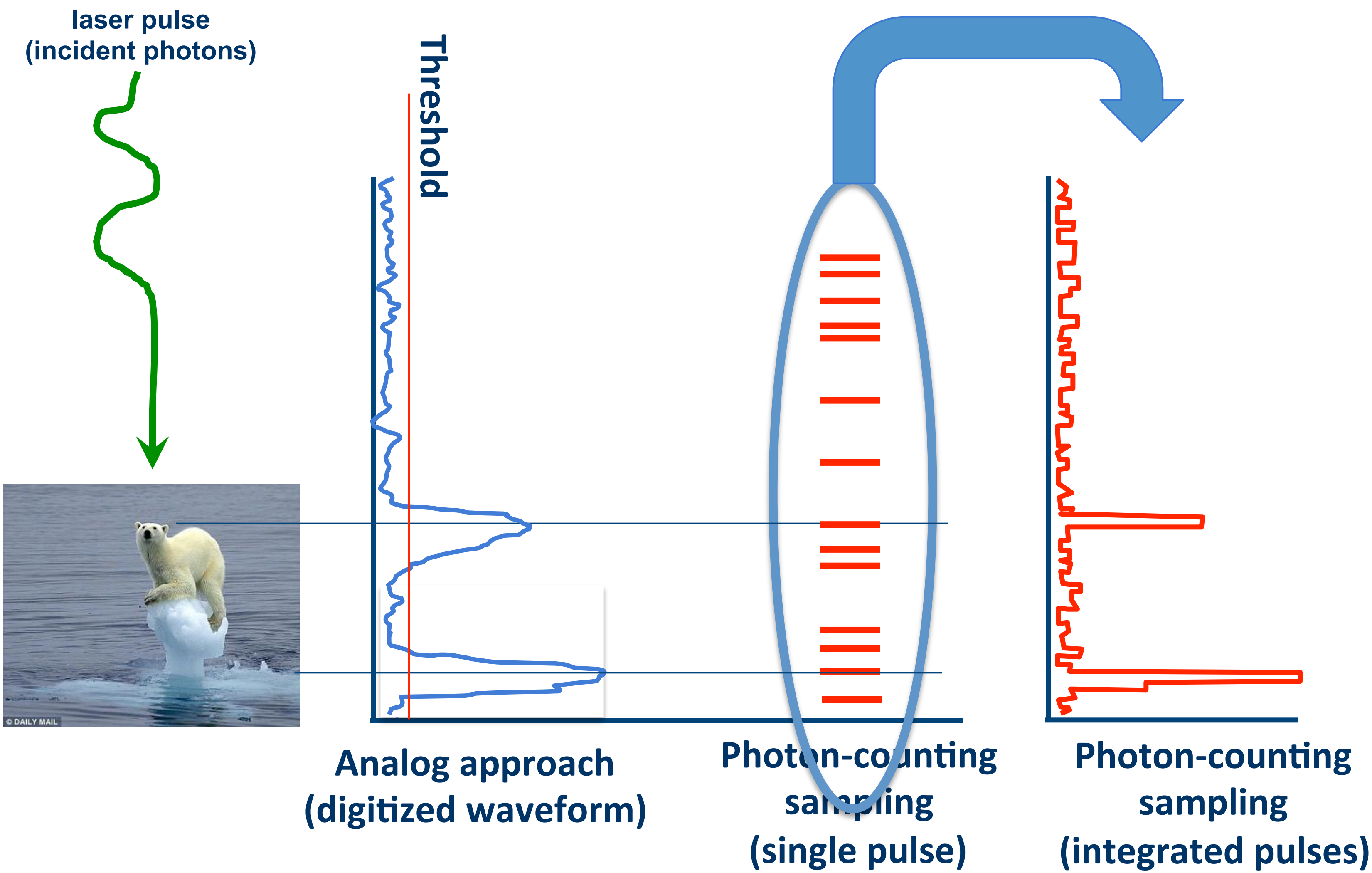
Analog –vs- Photon-counting



Analog –vs- Photon-counting



Analog –vs- Photon-counting



IMPORTANT: the integrated photon-counting sample ("histogram") *looks* like the analog waveform, but *it is not* – the information content is different, and the method of analyzing the data is different.

Probability of Detection

- In order for sufficient statistics to be accumulated. There has to be an good probability of photon detection (P_{ph})

$$P_{ph} = f(E, \tau, \alpha, D_s)$$

Where:

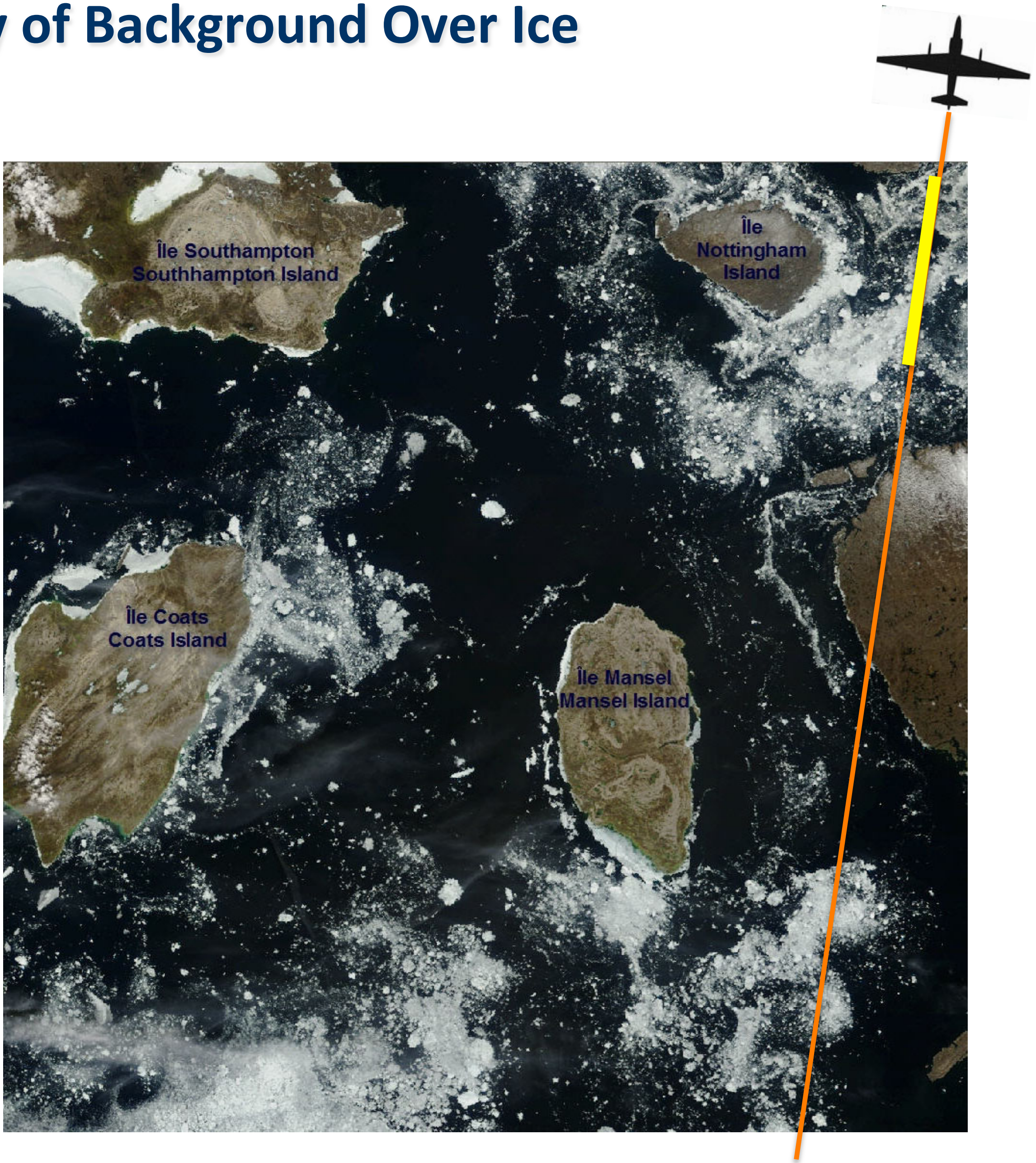
E = beam energy

τ = atmospheric optical thickness

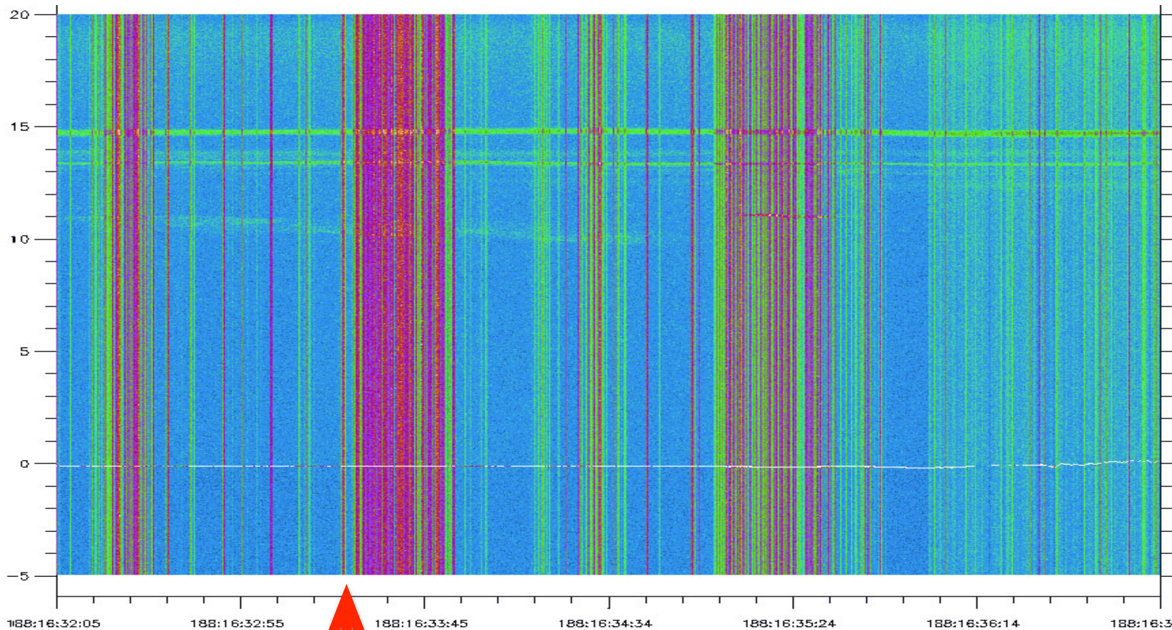
α = surface albedo

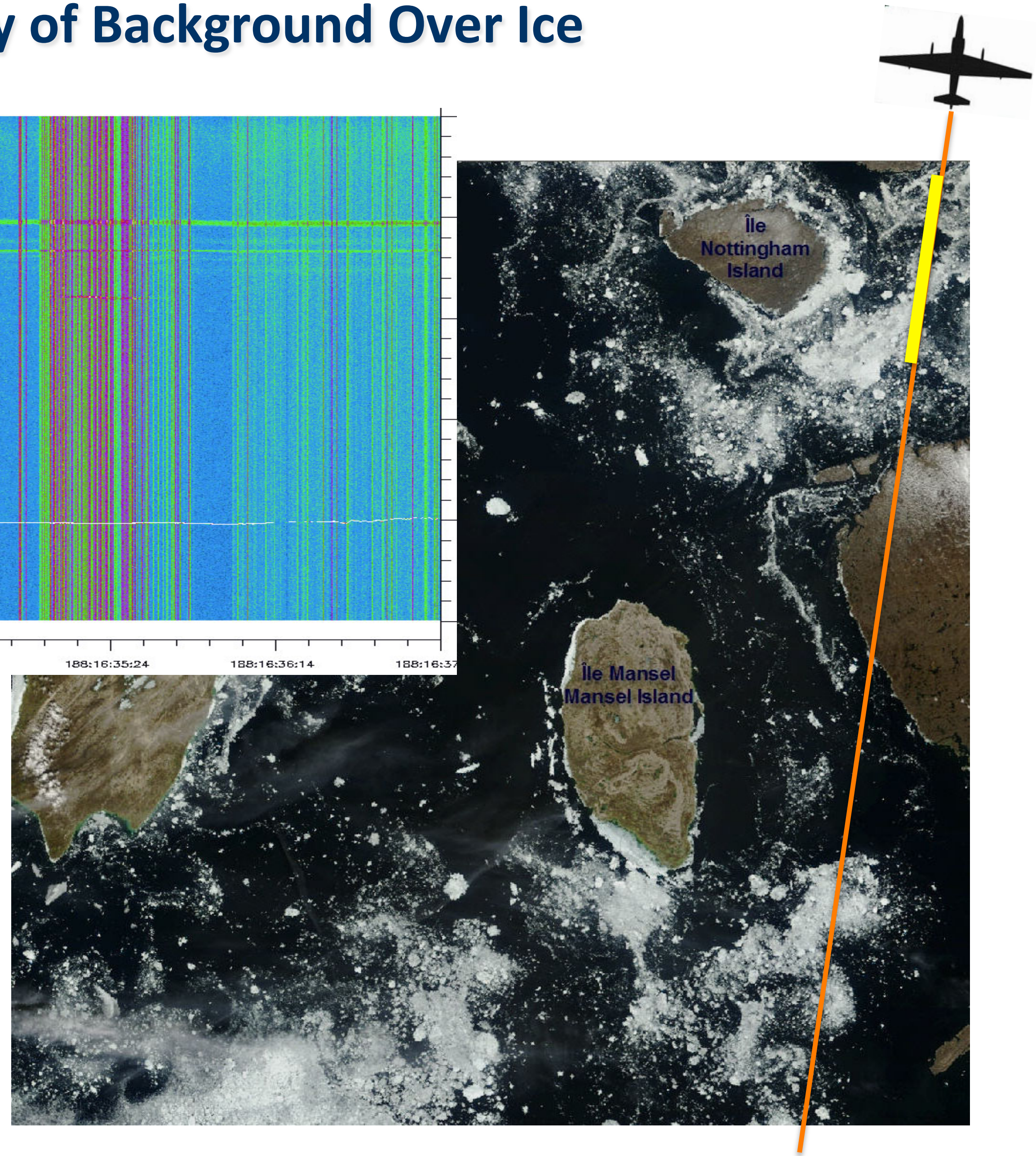
D_s = Detector sensitivity

Variability of Background Over Ice



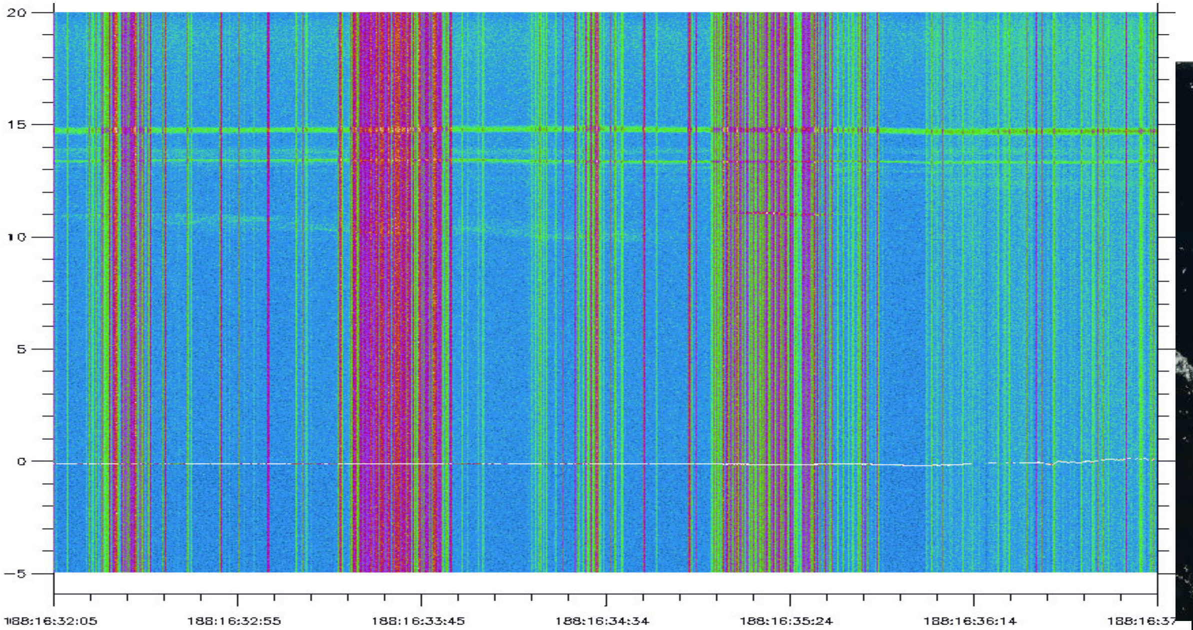
Variability of Background Over Ice

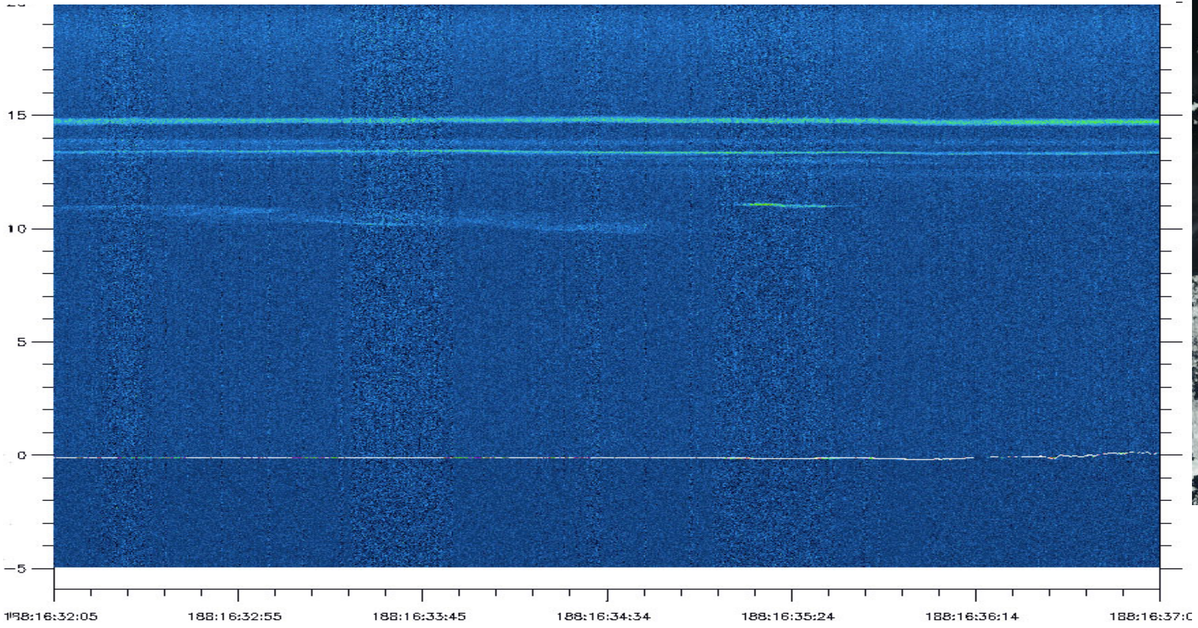


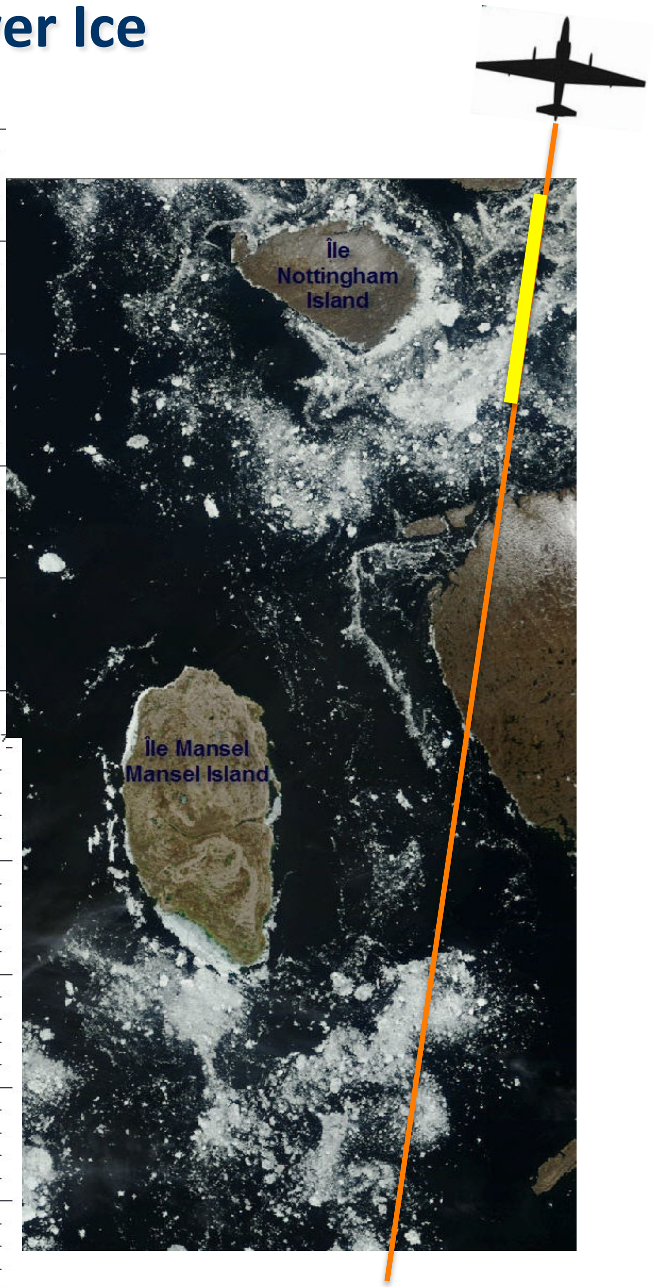


Raw data exhibits high-frequency variability (i.e., “stripes”) due to changes in background radiance along the flight track.

Variability of Background Over Ice

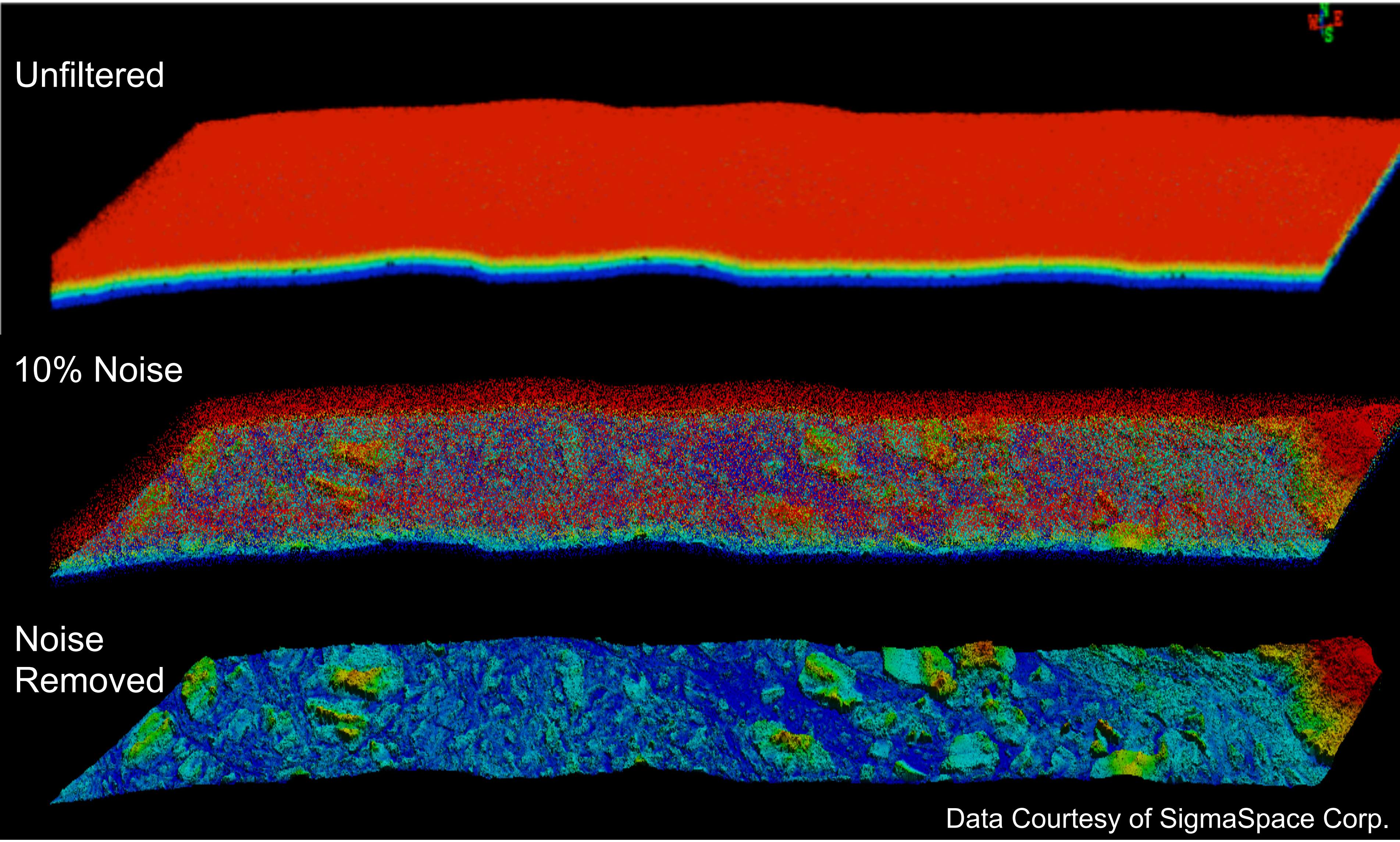






Airborne Observations of Ice in the Jakobshavn Fjord

Area is 6.5 km long and 750 m wide, color-coded by elevation (red high, blue low)



http://www.nasa.gov/feature/goddard/lasers-path-through-icesat-2

ICESat-II Science Traceability

<table>
<tr><th>Science Goals</th><th>Science Requirements</th><th>Measurement Requirements</th><th>Instrument Functional Requirements</th><th>Mission Functional Requirements</th></tr>
<tr>
<td><u>Ice Sheets</u>

Quantify polar ice sheet mass balance to determine contributions to current and recent sea level change and impacts on ocean circulation

Determine seasonal cycle of ice sheet changes

Determine topographic character of ice sheet changes to assess mechanisms driving that change and constrain ice sheet models</td>
<td>Annual elevation change of 0.2 cm/yr over entire ice sheet

Surface elevation change of 25 cm/yr annually in 100 km^2 areas

Resolve winter and summer ice sheet elevation change to 2.5 cm over 10,000 km^2 areas

Continuous observations through at least one climate cycle

Direct comparability to ICESat-I measurements for 15-year dh/dt</td>
<td>140 m ground track spacing

Ability to penetrate optically thin clouds

Precise repeatability of ground tracks

Repeat sampling 4x per year, uniformly spaced in time

Slope information in the cross-track direction

Continuous measurements for no less than 5 years</td>
<td rowspan="2">50-70 m spot size for each laser pulse

>50 mJ transmit energy per pulse

4.5 m pointing knowledge

5 years continuous operation with 7-year goal

Measurement capability in the cross-track direction (to be specified by the aSDT)

Surface reflectivity capability of 5% to enable characterization of snow conditions for gain and range corrections

Telescope FOV of 100 m to minimize atmospheric forward-scattering effects

Atmospheric vertical resolution of 75 km to enable atmospheric corrections plus studies of clouds</td>
<td rowspan="2">Orbit parameters that match ICESat (600 km altitude; 94 deg. incl., 91-day repeat).

10 arcsec (30-m) pointing control

2 cm radial orbit accuracy requirement

5 year continuous operation with 7-year goal

1.5 arcsec (4.5-m) pointing knowledge

91 day repeat orbit to capture seasonal effects and maximize comparability to ICESat for trend detection</td>
</tr>
<tr>
<td><u>Sea Ice</u>

Estimate sea ice thickness to examine ice/ocean/ atmosphere exchanges of energy, mass and moisture</td>
<td>Discriminate freeboard from surrounding ocean level to within 3 cm along a 25 km segment of ground track

Capture seasonal evolution of sea ice cover on 25 x 25 km scales</td>
<td>Shot-to-shot precision of <2cm

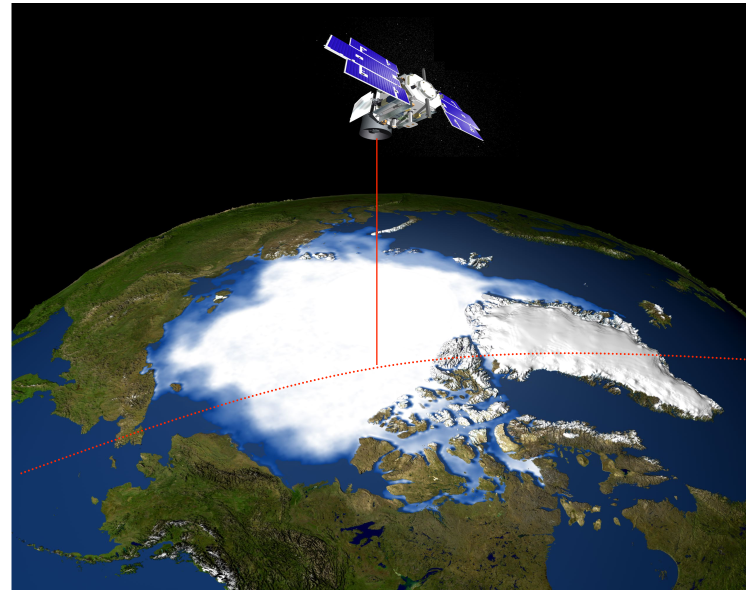
Monthly near-repeat coverage of Arctic and Southern Oceans at 25 x 25 km scales

Coverage up to at least 86 deg. latitude</td>
</tr>
</table>

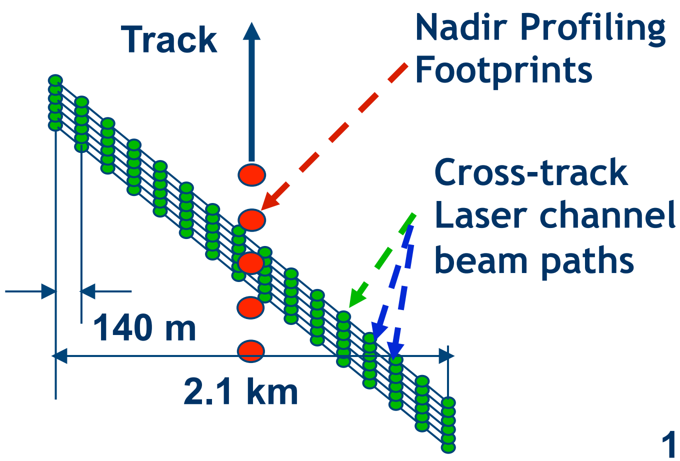
Back-up

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.

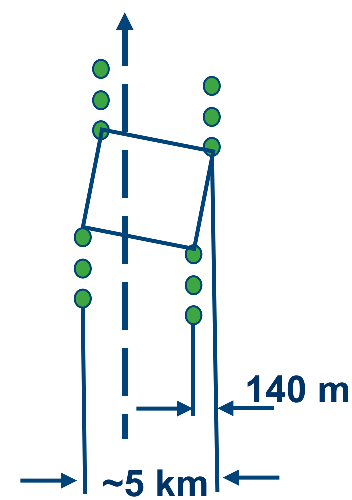


Cross-track coverage can be achieved through various approaches

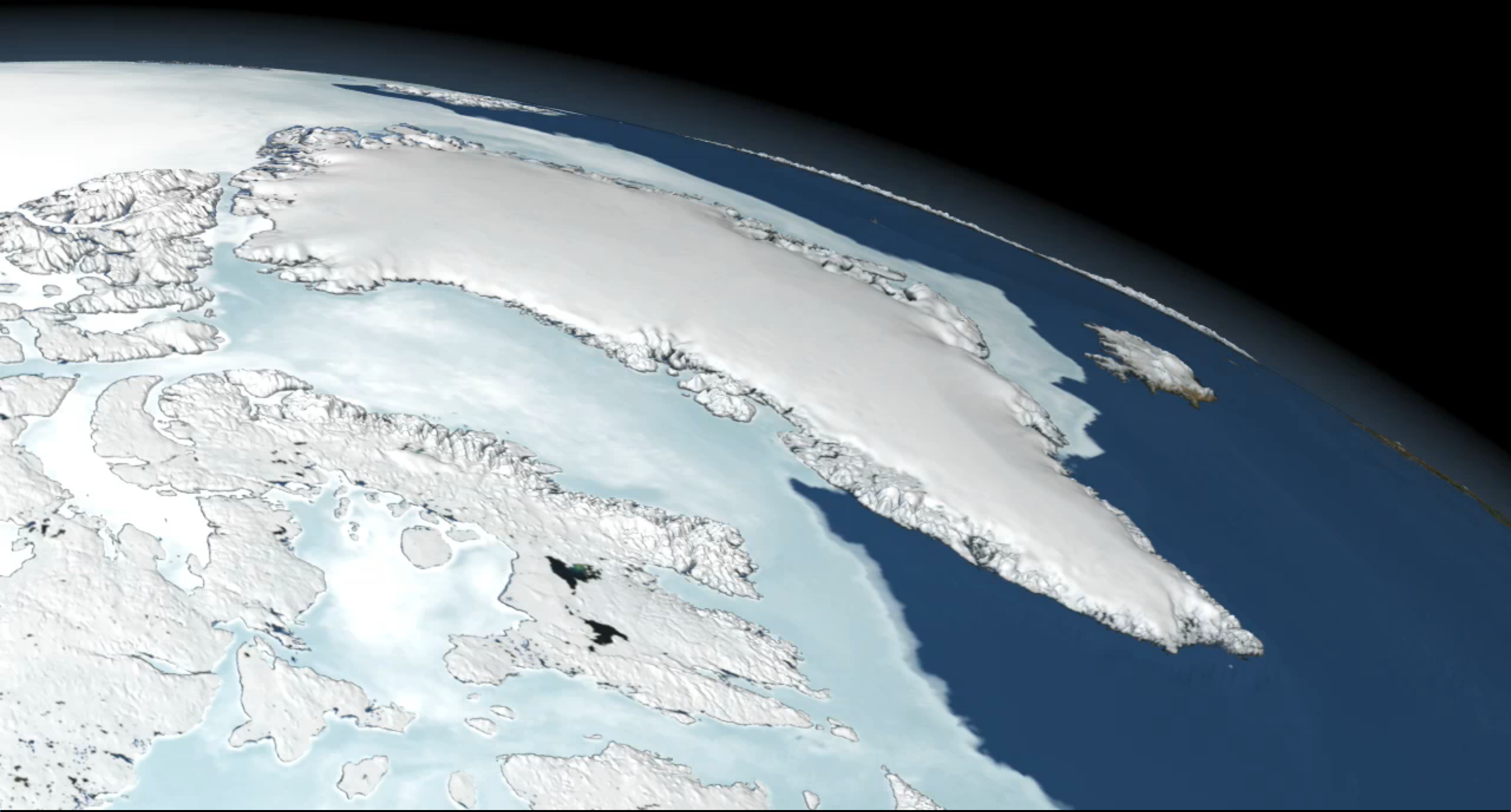


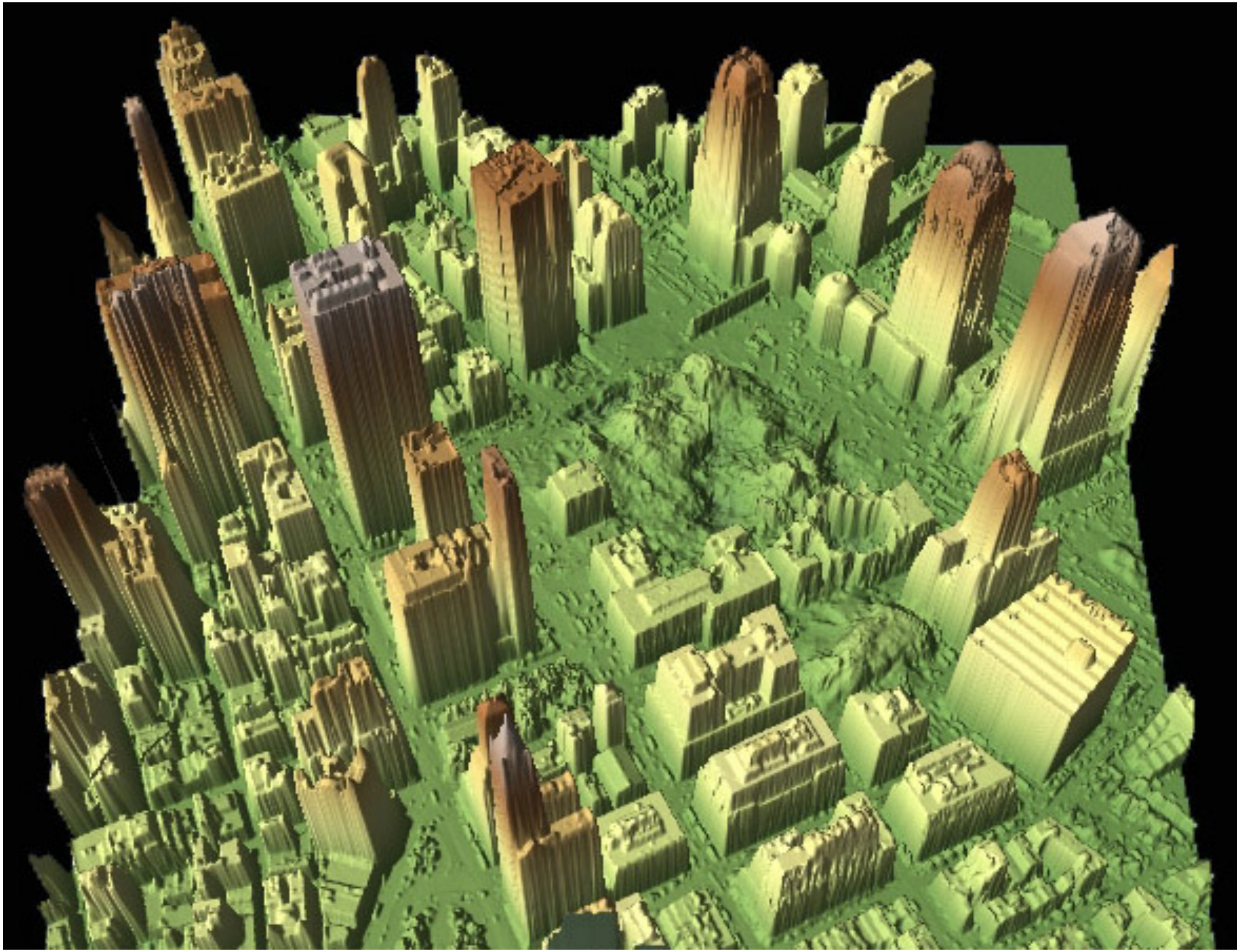
Photon counting

2 beams from 2 lasers or w/ a DOE



4 Beams w/ a DOE





NRC Decadal Survey Call for ICESat-II

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

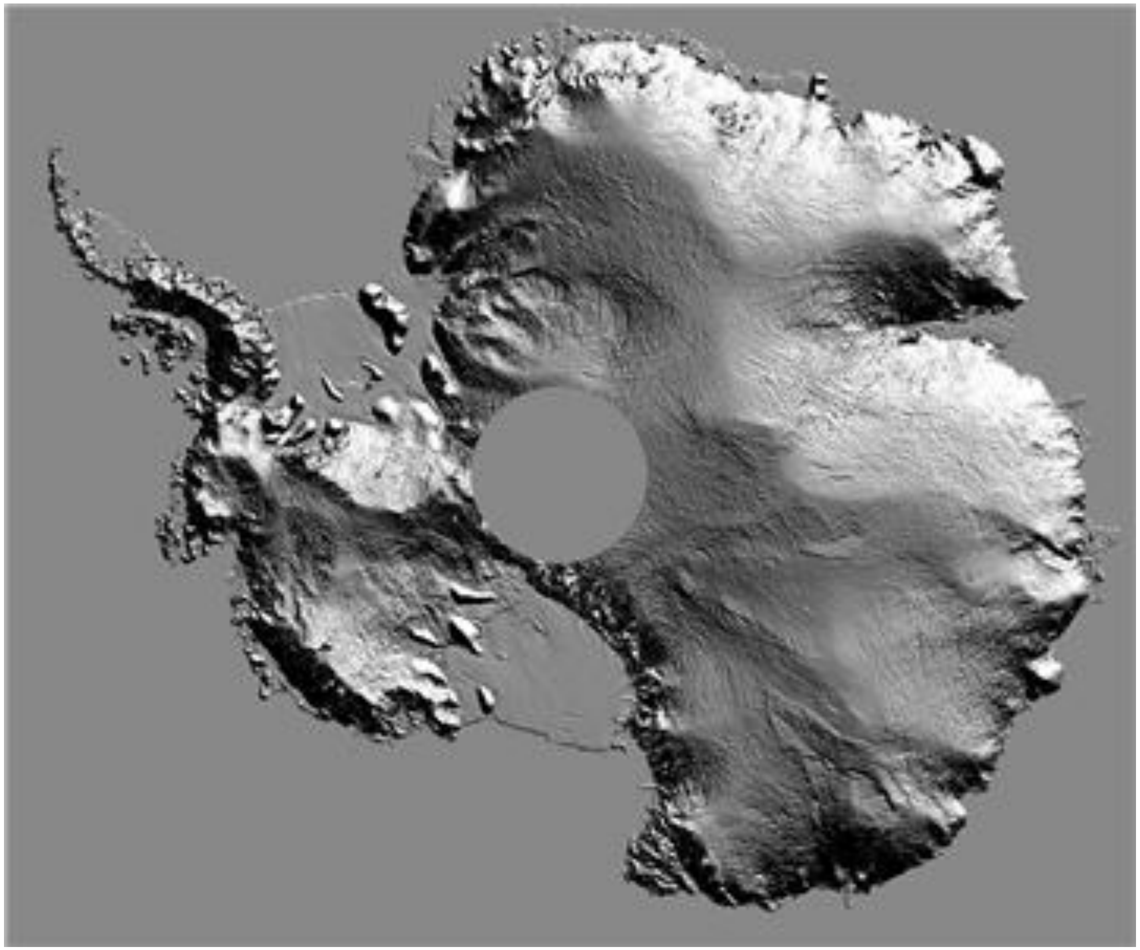
- "Trends in all of the measurements are needed to calibrate climate models that predict future changes in sea level and in other climate variables."

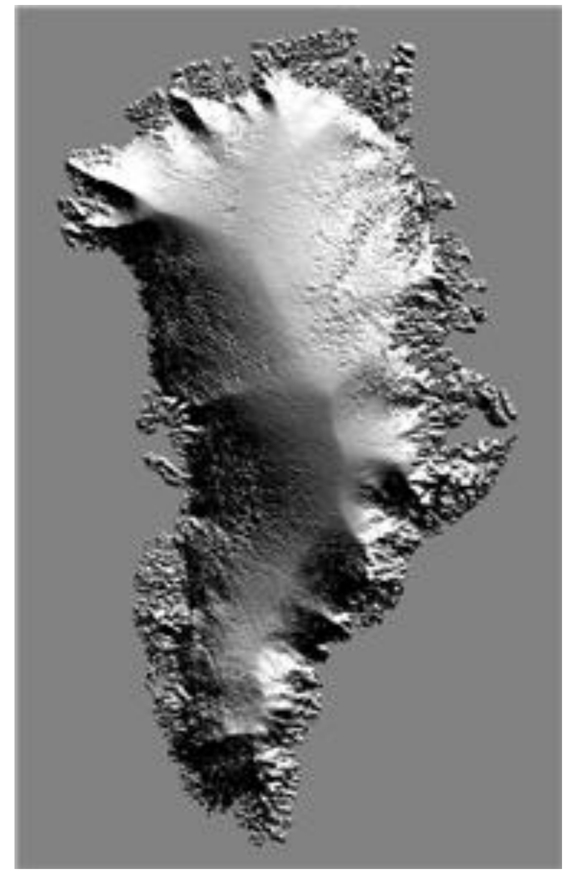
- "As climate change continues, ongoing, continuous measurements of both land ice and sea ice volume will be needed to observe trends, update assessments and test climate models."

- "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?

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





Calculation of Range: Complex Surface