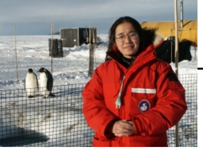


Lecture 36. Laser Altimeter

- TOF: Altitude Determination and Error Budget

- ICESat error analysis as an example

- Resolution Issues with laser pulse width limitation

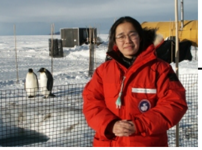
  Waveform recording vs. micropulse photon counting

- Application Examples of Laser Altimeter

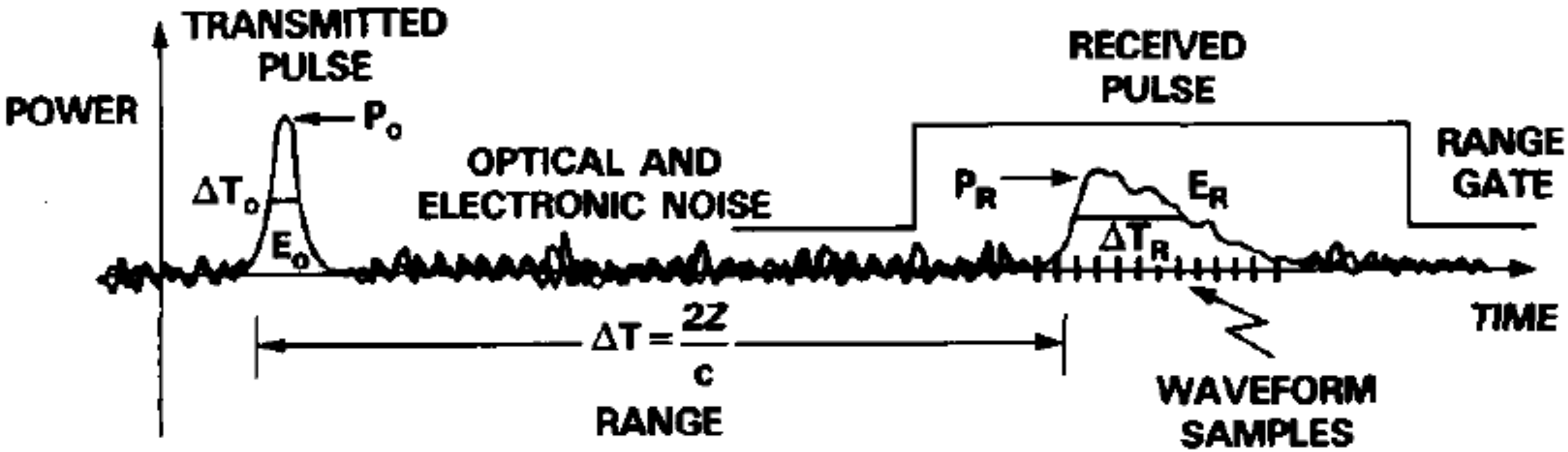
  1) Canopy application

  2) Snow depth mapping

  3) National geography mapping

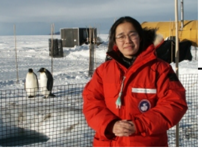


Altitude Determination



- The range resolution is now determined by the resolution of the timer for recording pulses, instead of the pulse duration width. By computing the centroid, the range resolution can be further improved.
- Altitude accuracy will be determined by the range accuracy/resolution and the knowledge of the platforms where the lidar is on.
- In addition, interference from aerosols and clouds can also affect the altitude accuracy.

Altitude = Platform Base Altitude – Range ± Interference of aerosols and clouds



Challenges in Laser Altimeter

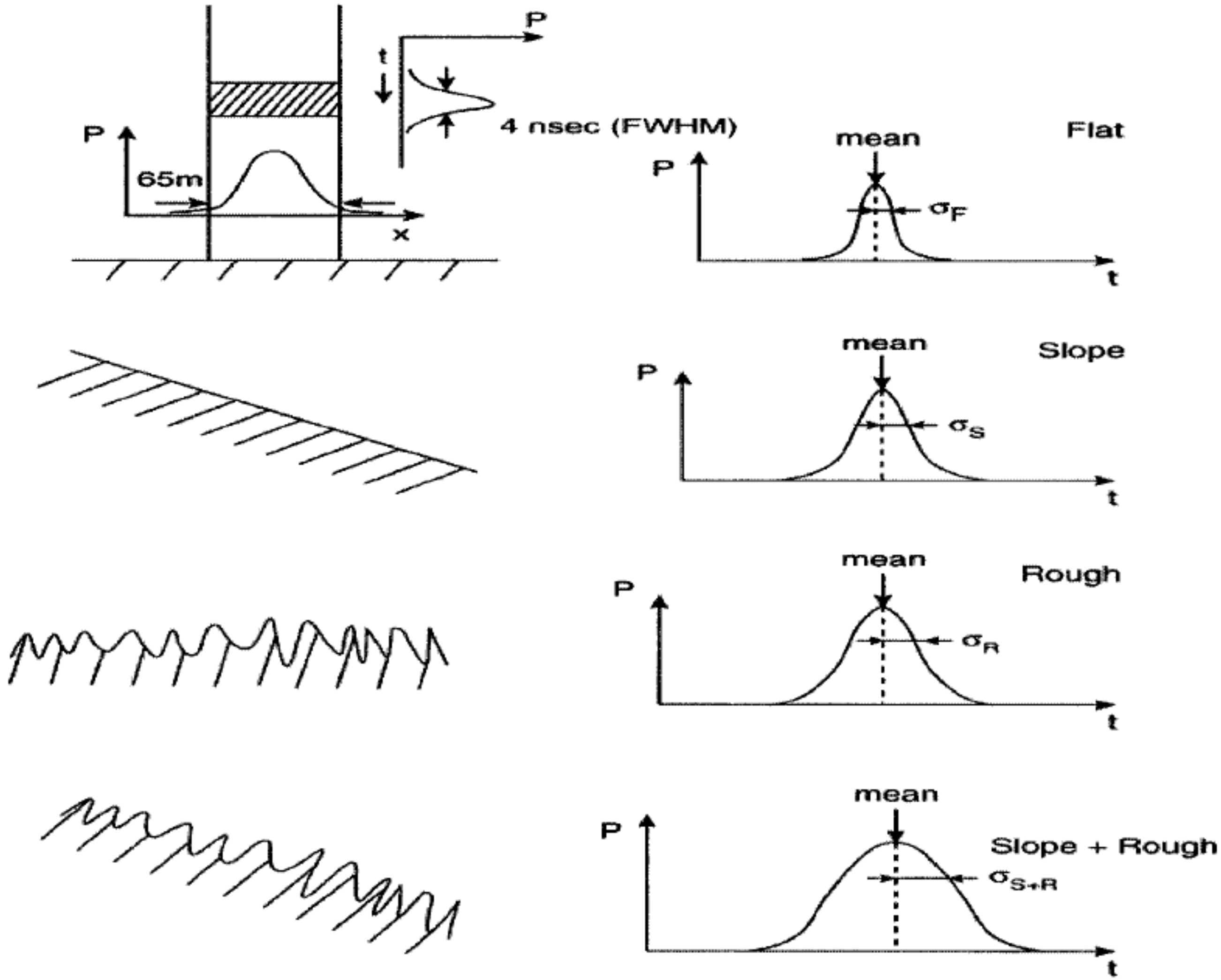
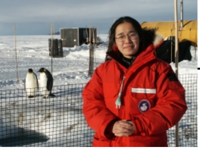
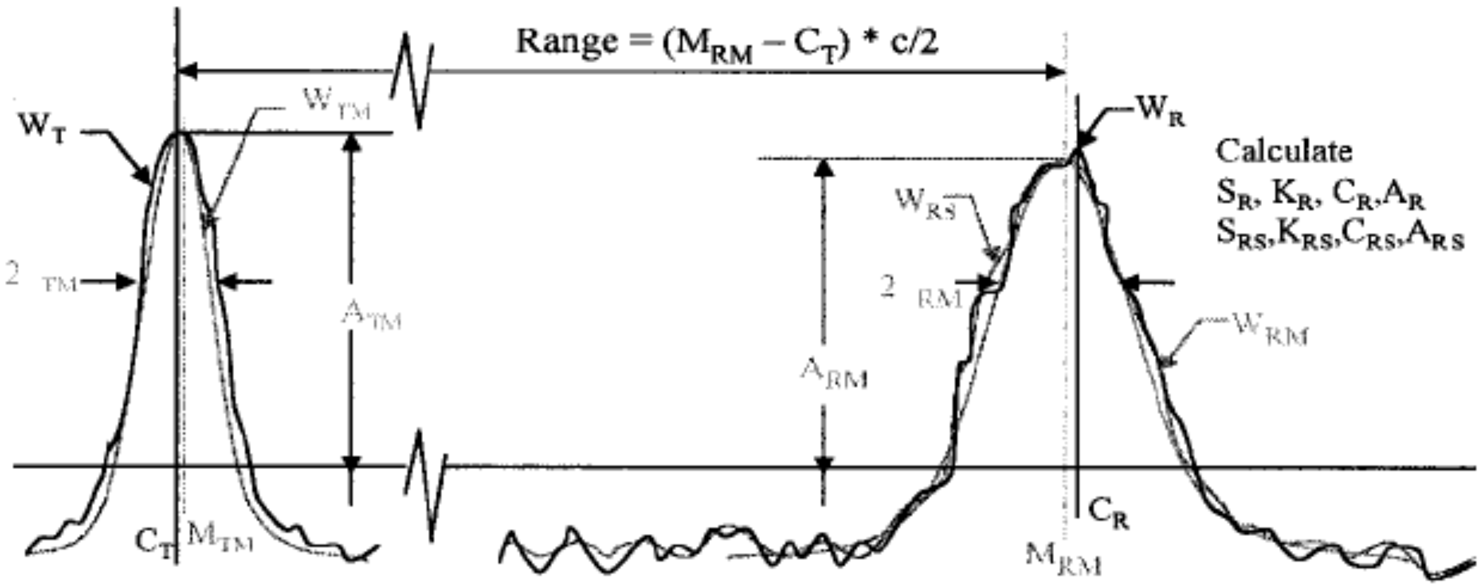


Figure 1 - Characteristics of returned laser pulse as a function of surface type. Presence of surface slope and roughness both broaden the pulse.



Signal Processing in Altimeter

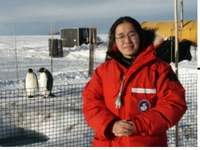


A - Max Amplitude
W - Waveform
M - Gaussian Mean
 - Gaussian 1/e halfwidth
C - Centroid (abscissa value)
S - Skewness
K - Kurtosis

$(\ )_T$ - Transmitted Pulse
$(\ )_{TM}$ - Model of Transmitted pulse
$(\ )_R$ - Return Pulse
$(\ )_{RM}$ - Model of Return Pulse
$(\ )_{RS}$ - Smoothed Return Puls

Figure 3 - Characterization of transmitted and received pulse waveforms

[Brenner et al., GLAS Algorithm Theoretical Basis Document, 2003]



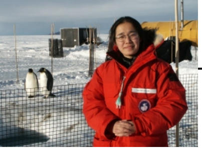
Other Challenges

- Besides waveform distortions caused by surface slope and roughness, other factors that could affect the accuracy of laser altimeter include

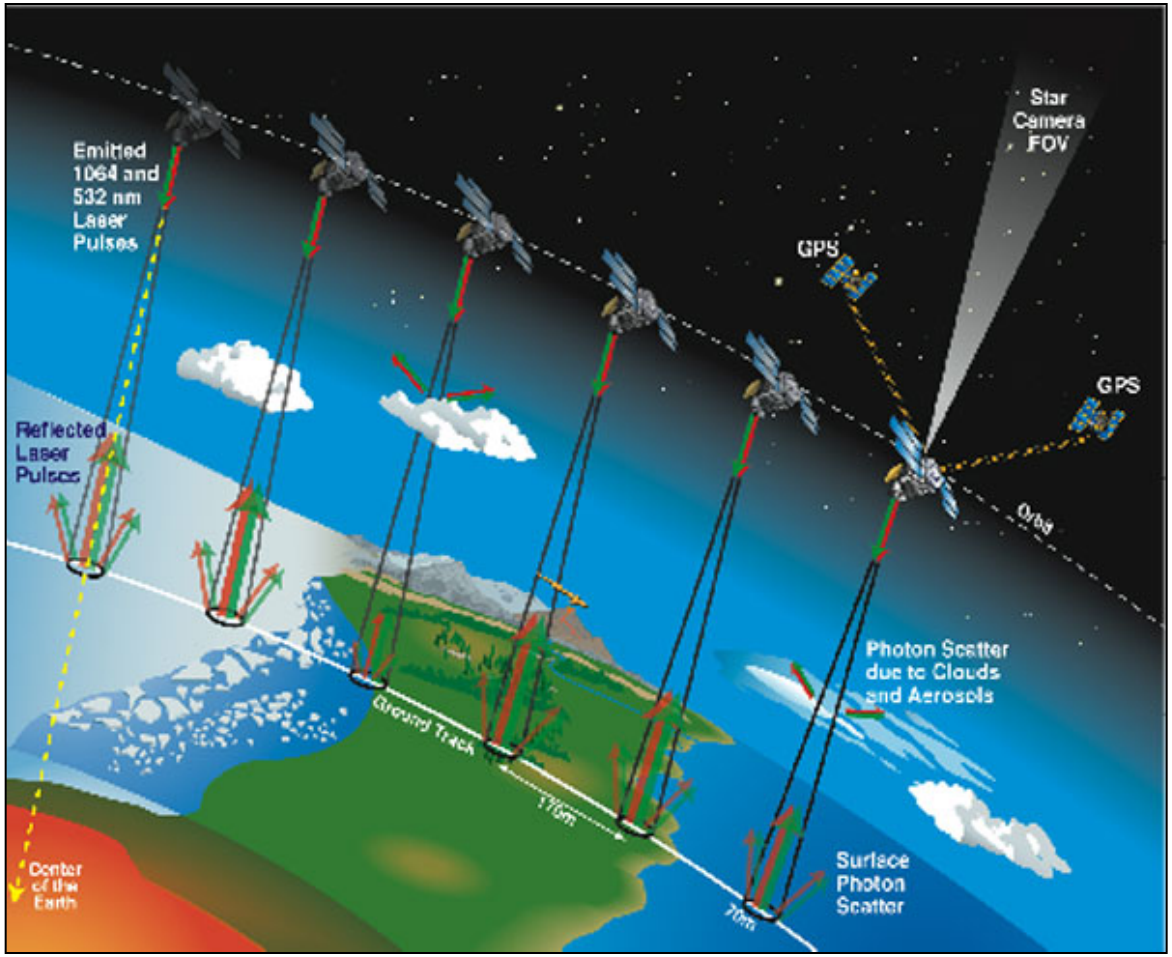
(1) Orbit and attitude calculations for the platforms
(2) Corrections for atmospheric path-length delays
(3) Corrections for changes in the surface elevations due to tidal effects
(4) ……
(5) How will you have enough penetration and get the reflected signals?

Table 9.10 Ice Altimetry Error Budget

Source	Error type	Magnitude (cm)
Instrument	Single-shot accuracy (3° surface features)	<10
	Range bias	<5
	Laser beam pointing angle uncertainty (1 arcsec, 2° surface)	18
	Radial orbit uncertainty	5
	Clock synchronization (1 μsec)	1
Spacecraft	Distance uncertainty from S/C POD to GLAS zero reference point	0.5
Environment	Atmospheric error (10-mbar error, 0.23 cm/mbar)	2
	RSS error	0.20

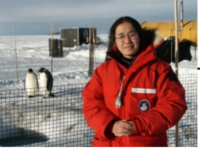


ICESat Laser Altimeter

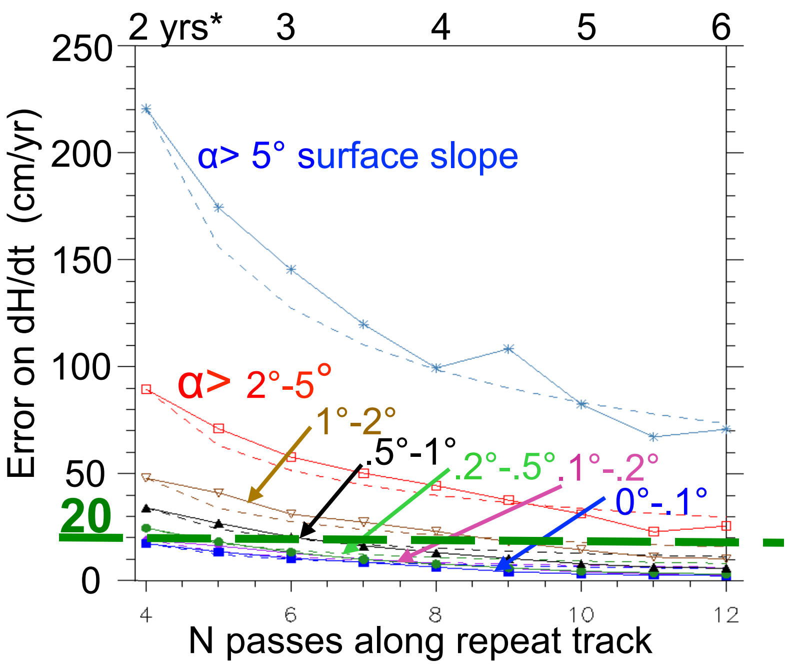


ICESat

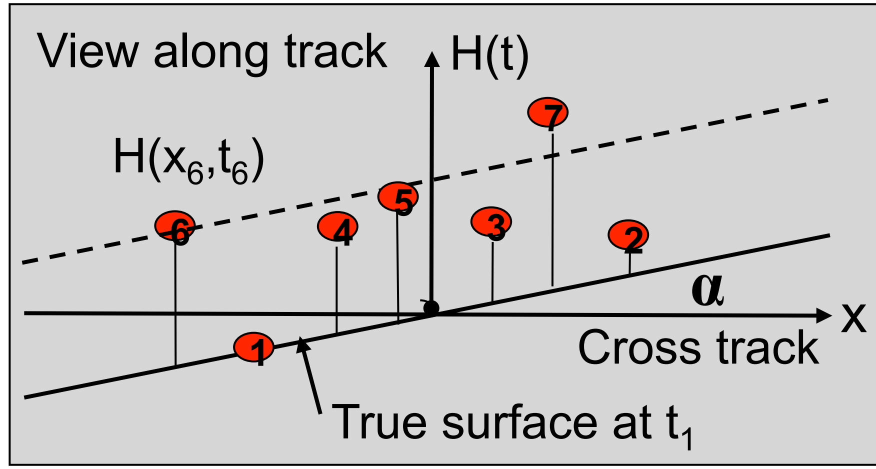
- 532 nm: photon counting atmospheric sounding
- 1064: waveform-recording altimetry
- 70 m laser footprint
- 170 m along-track spacing (due to pulse repetition rate)

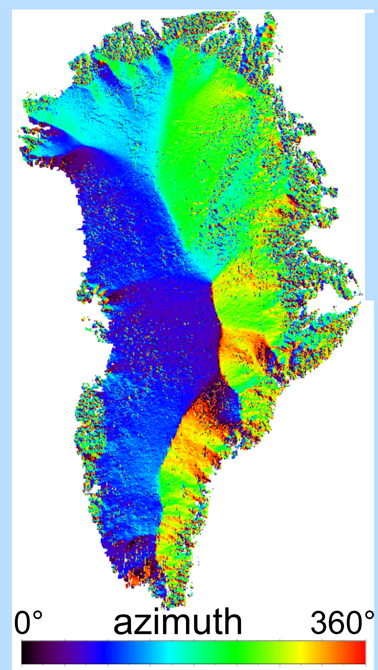


Accuracy is Sensitive to Number of Observations



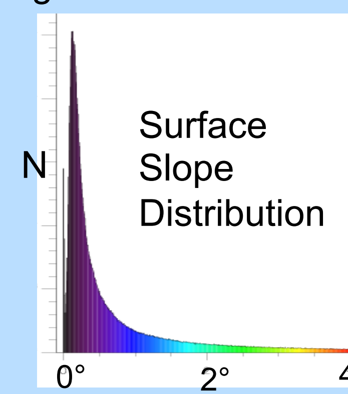
20 cm/yr accuracy achieved after N= 10 passes for slopes < 2° (e.g. 5 yrs* of continuous operation with 50% cloud loss)





GREENLAND

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



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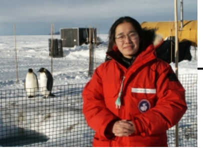
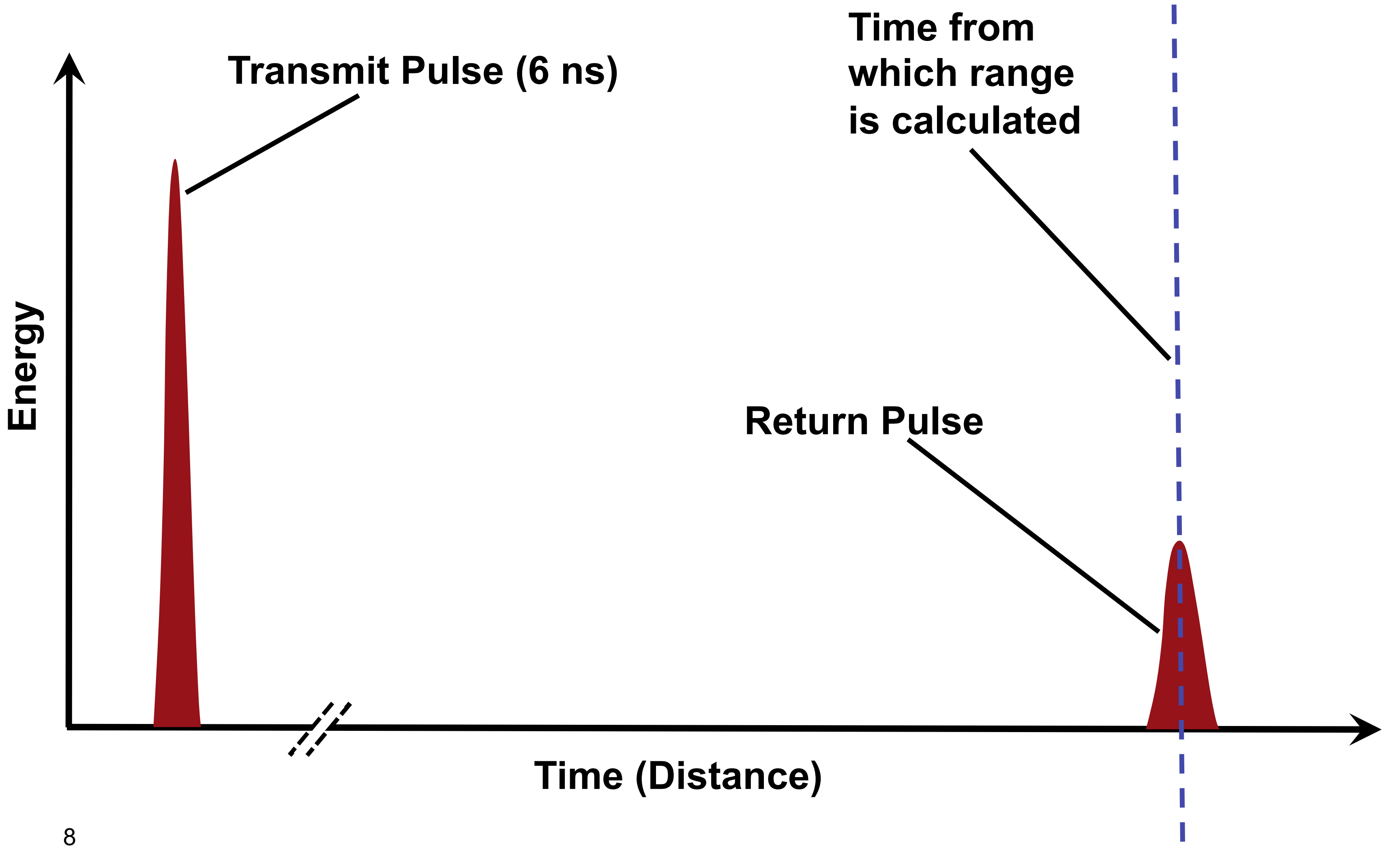
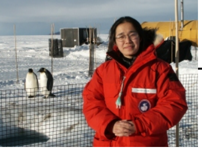
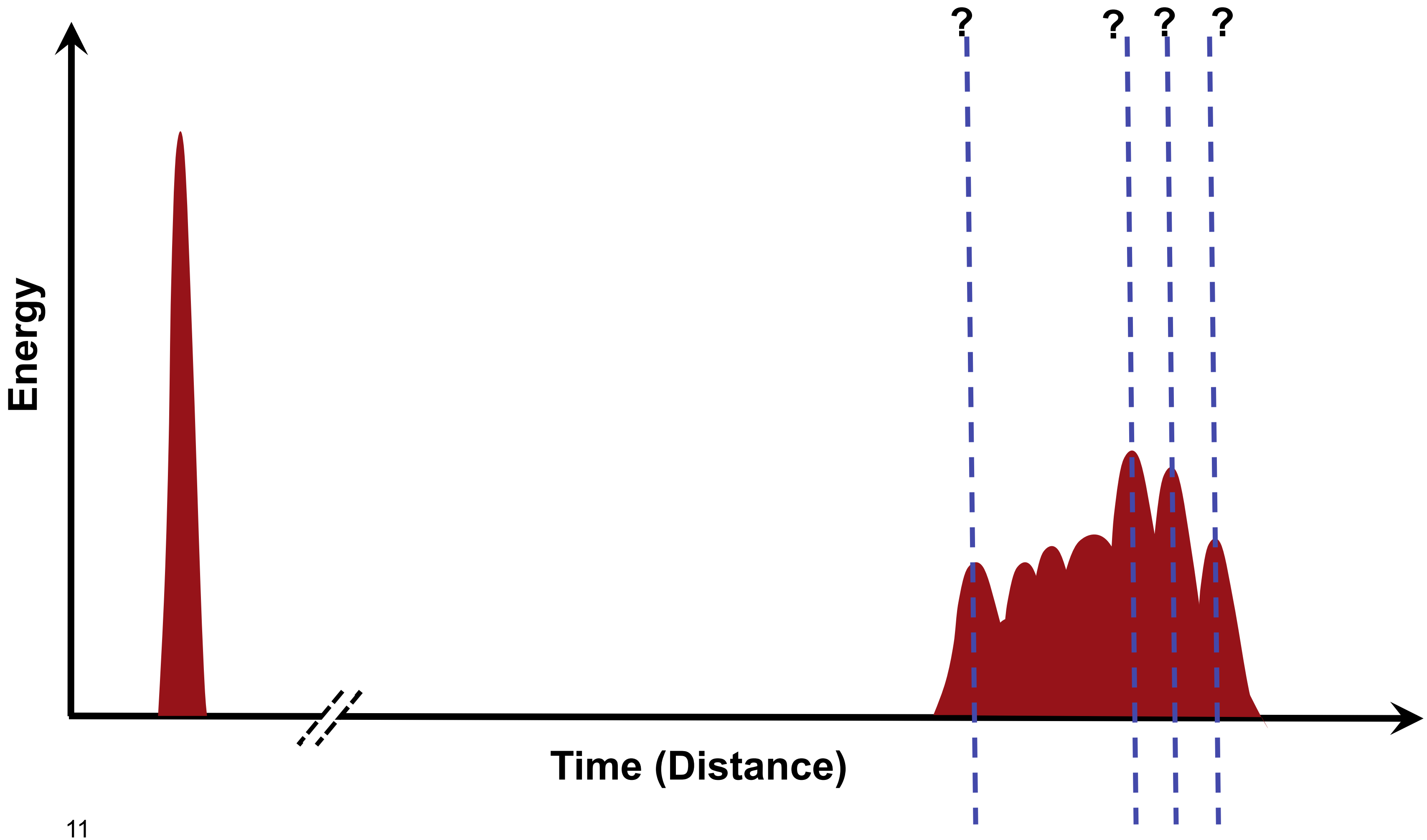


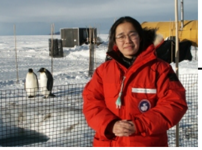
Calculation of Range: Simple Surface



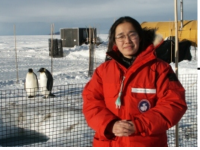


Calculation of Range: Complex Surface

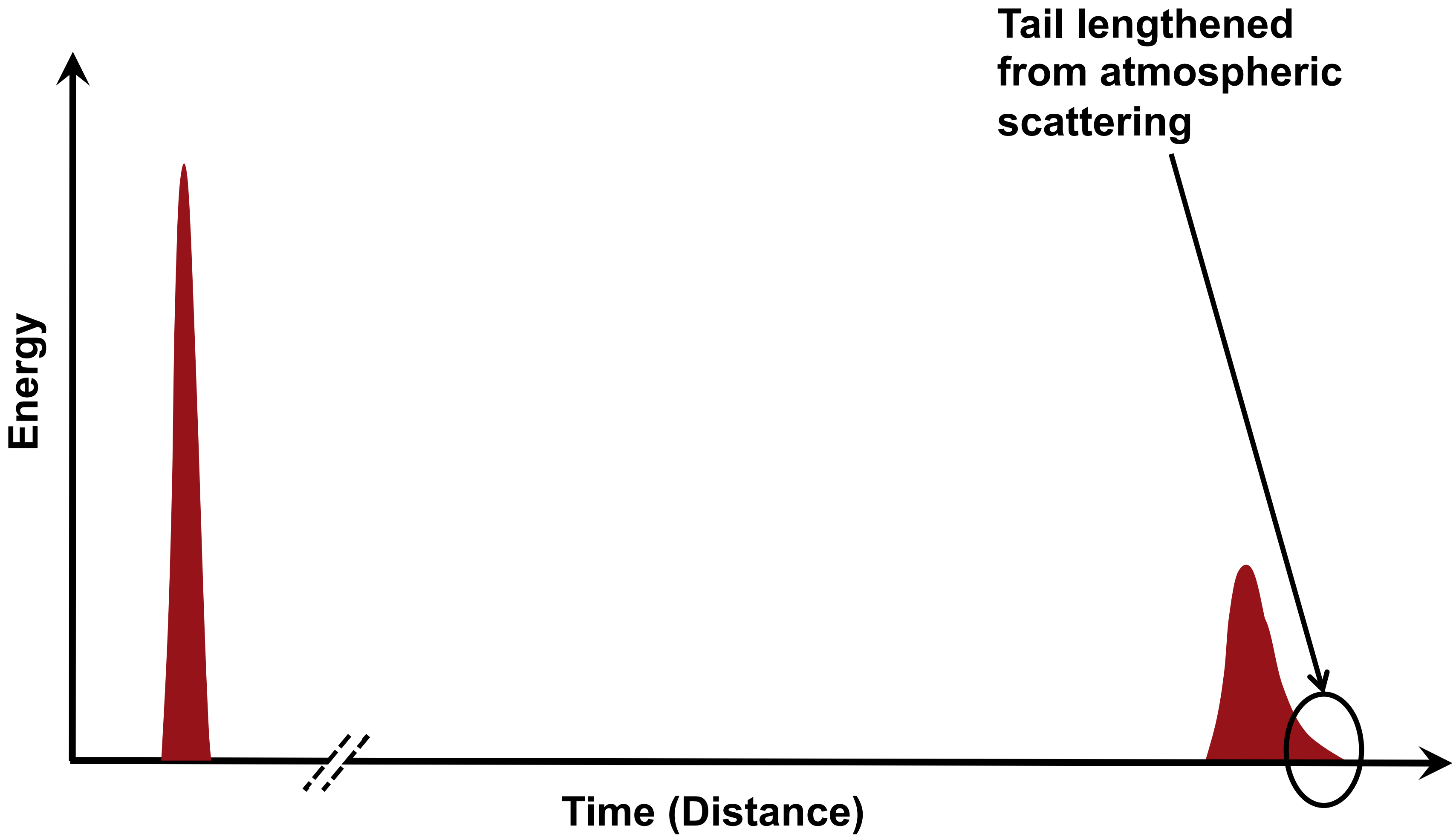


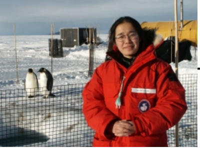


Calculation of Range: Simple Surface

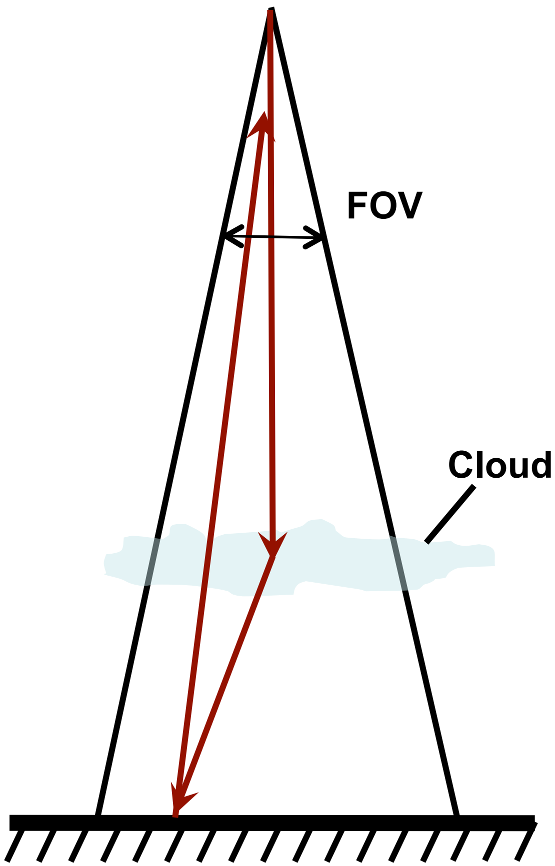


Calculation of Range: Atmospheric Effects





Forward Scattering Effects from Clouds



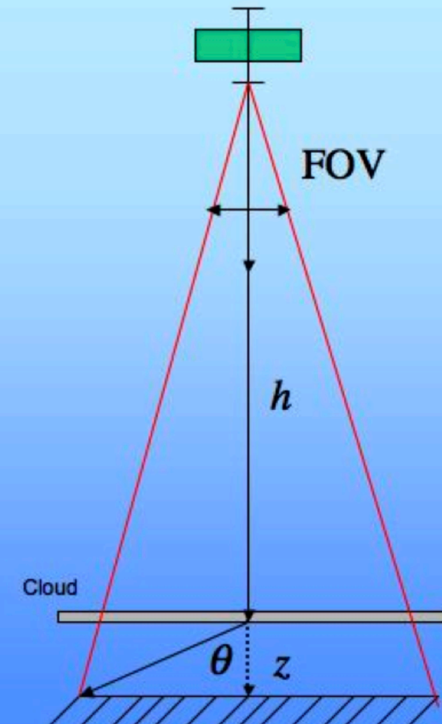
Simple Analytical Approximation

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

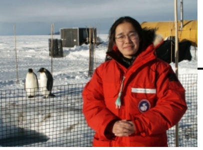
FOV: $\mathrm{FOV}(\theta) = \frac{2z}{h}\tan(\theta)$

Total Delay

$$\frac{\tau \int_{z_{base}}^{z_{top}} \int_0^{\theta} \Delta(z,\theta') P(\theta') \sin\theta' d\theta' dz}{1 + \tau \int_0^{\theta} P(\theta') \sin\theta' d\theta'}$$

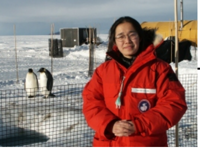


A. Marshak, GSFC



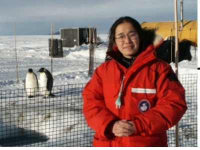
Key Factors Contributing to Error

- 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 ±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



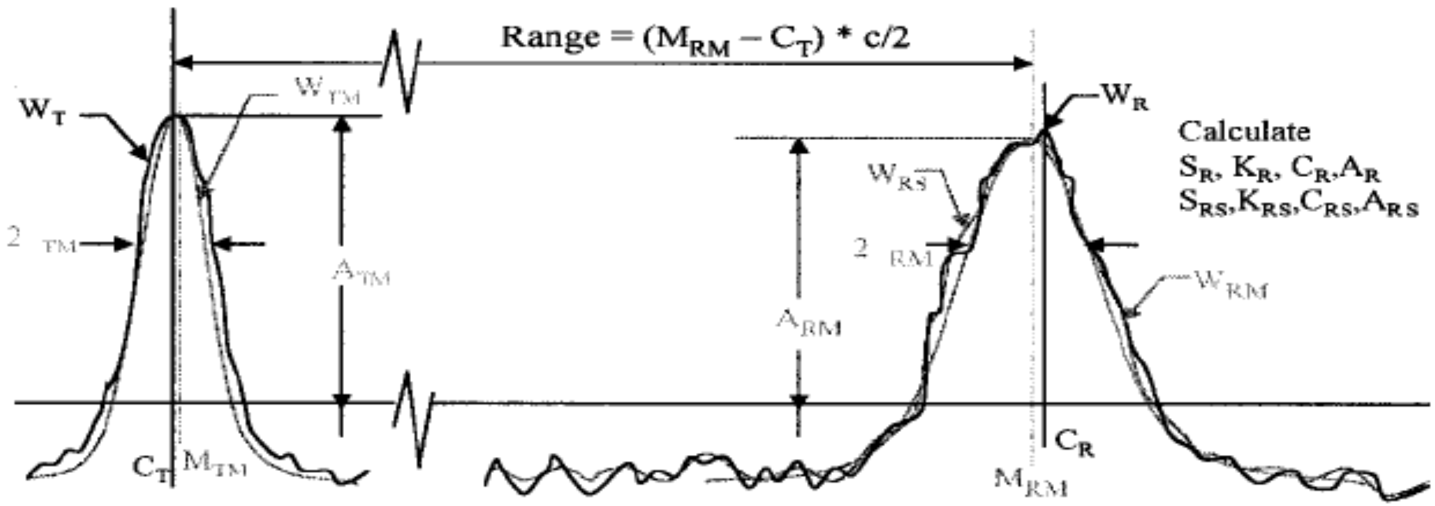
Key Factors Contributing to Error

- 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



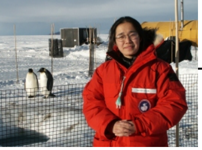
How to Overcome Pulse Width Limit?

❑ In most laser altimeter applications, there is sufficient (longer than the laser pulse width) time separation between the transmitted and received pulses, but users like to determine the time of flight better than the pulse duration time (pulse width).



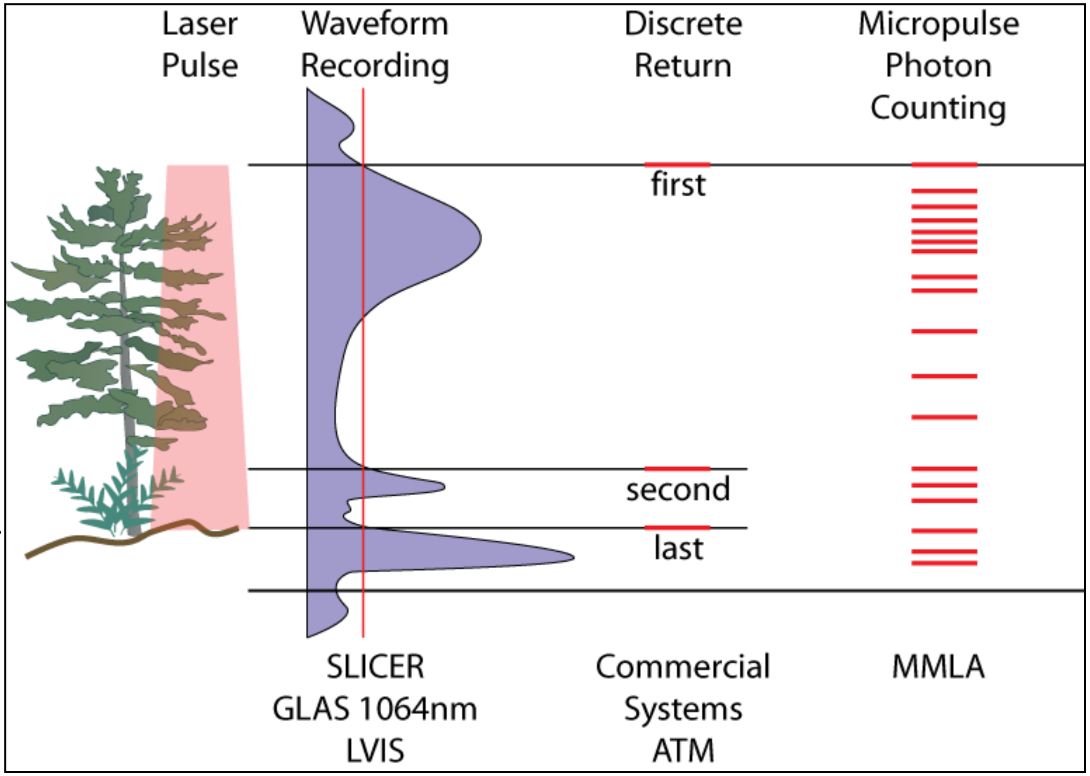
❑ When pulse waveforms can be recorded well (with high energy laser pulse), the resolution can be improved by identifying the peak or leading/trailing edge and comparing the transmitted & received pulse waveforms.

❑ In the micropulse case, many micro pulses form a statistical profile, and better-than-pulse-width resolution can be determined from this profile.

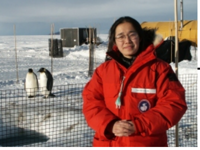


Lidar Ranging Methods

- Discrete return
  - logs time when return intensity exceeds threshold
  - commercial airborne systems
- Waveform recording
  - records entire return intensity profile
  - vegetation, atmospheric applications
- Photon counting
  - digital recording of individual photon returns
  - low power requirements
  - good cloud penetration
- Profiling or scanning
  - scan patterns



courtesy Dave Harding, NASA/GSFC



Some Lidar Sensor Wavelengths

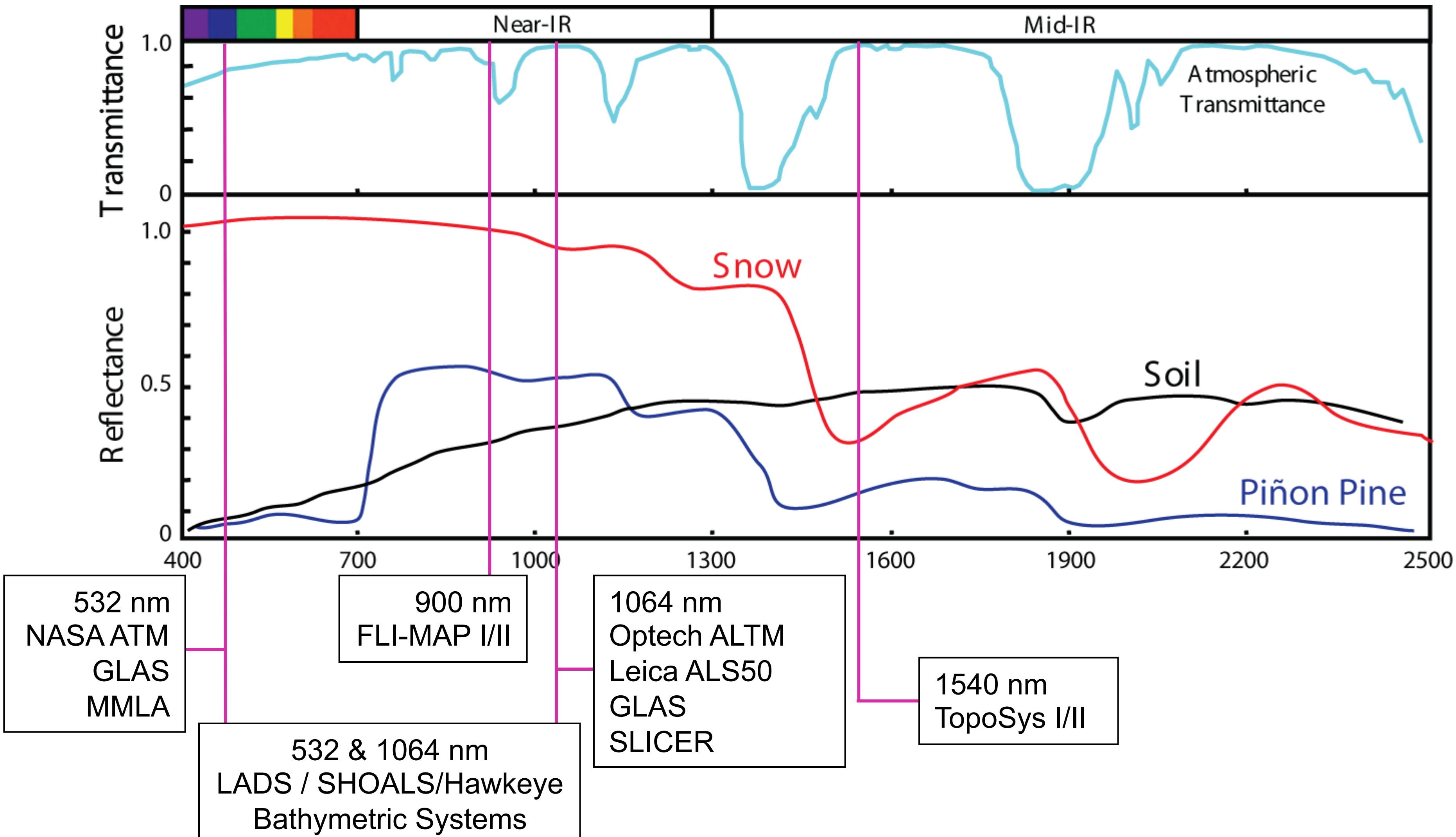
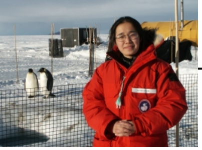
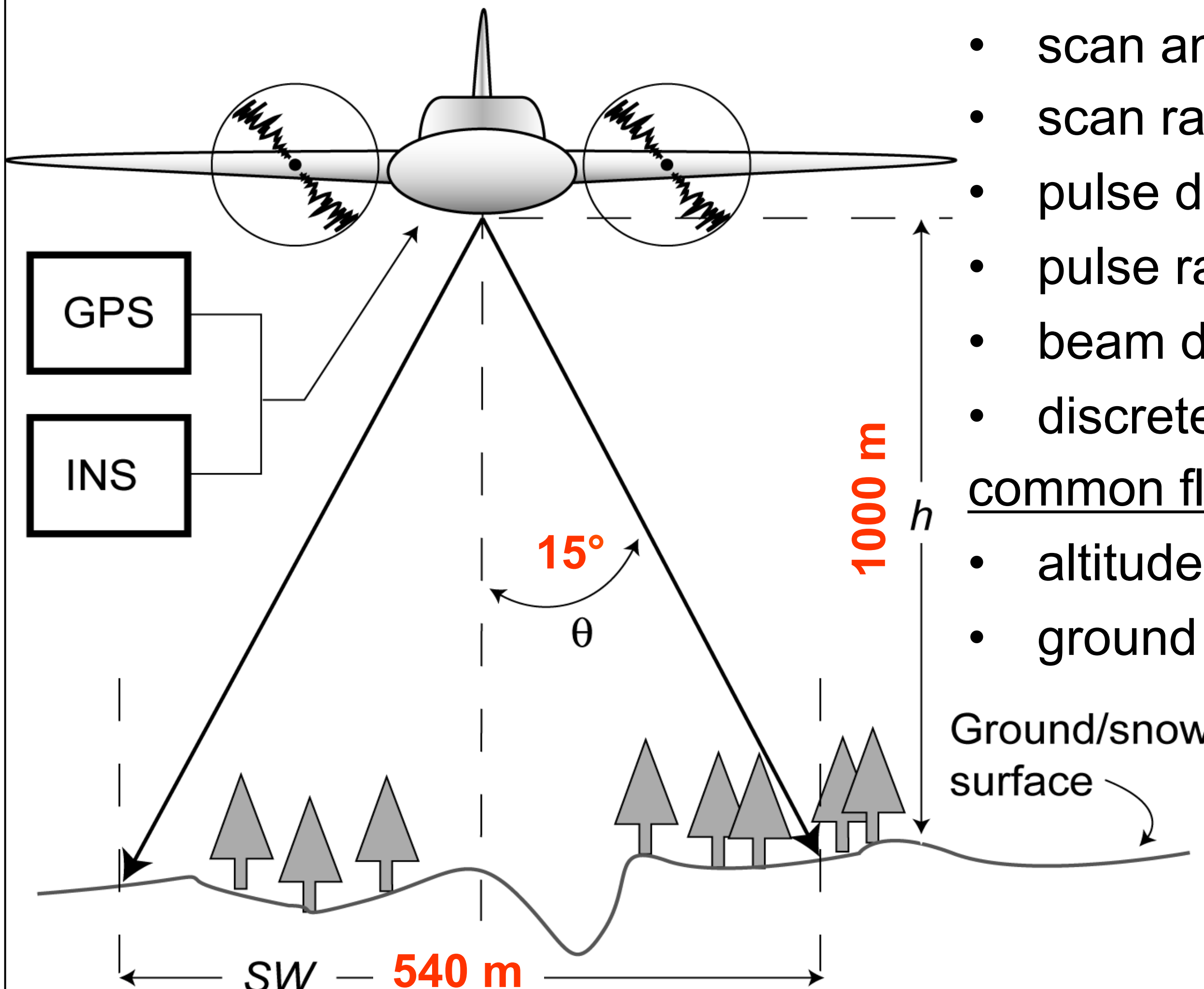


image courtesy Michael Lefsky, CSU



Commercial Airborne Lidar System Components

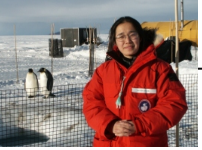


common laser parameters

- scan angle: 0-45°
- scan rate: 0-70 Hz
- pulse duration: 6-12 ns
- pulse rate: 4-100 kHz
- beam divergence: 0.25-1mrad
- discrete returns/pulse 4-5

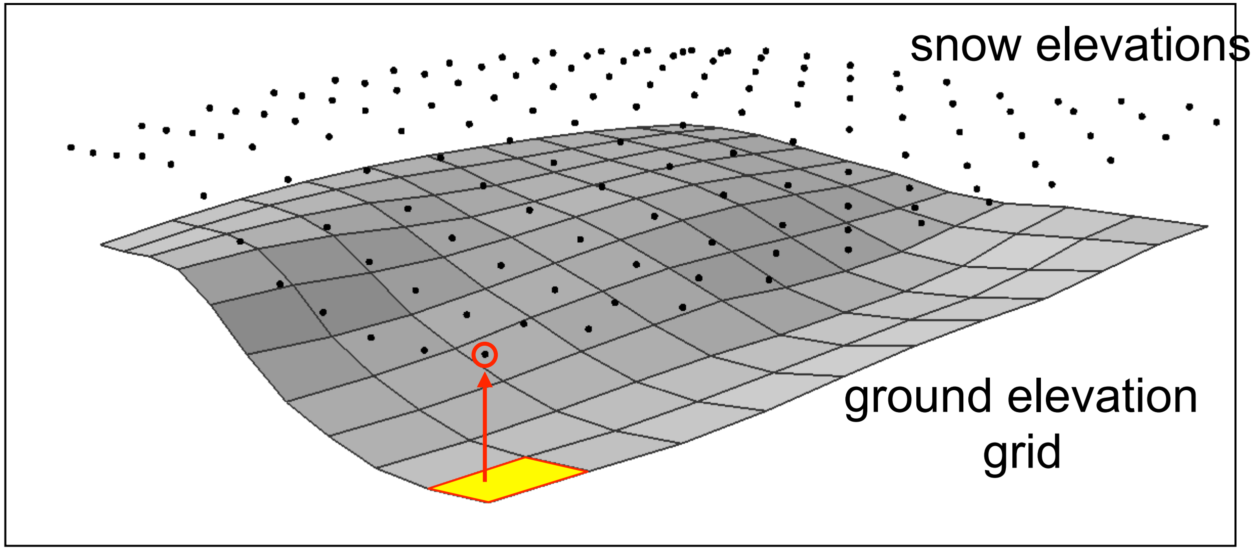
common flight parameters

- altitude AGL 1000-1500 m
- ground speed 230 km/h

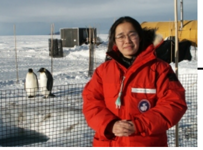


Lidar Snow Depth Mapping

- 2 data collections required
  - snow free & snow covered
- Filter to remove 'not-ground' (vegetation) points
- Convert ground (snow-free) point elevations to grid
- Extract grid values to snow elevation points
- Subtract elevations



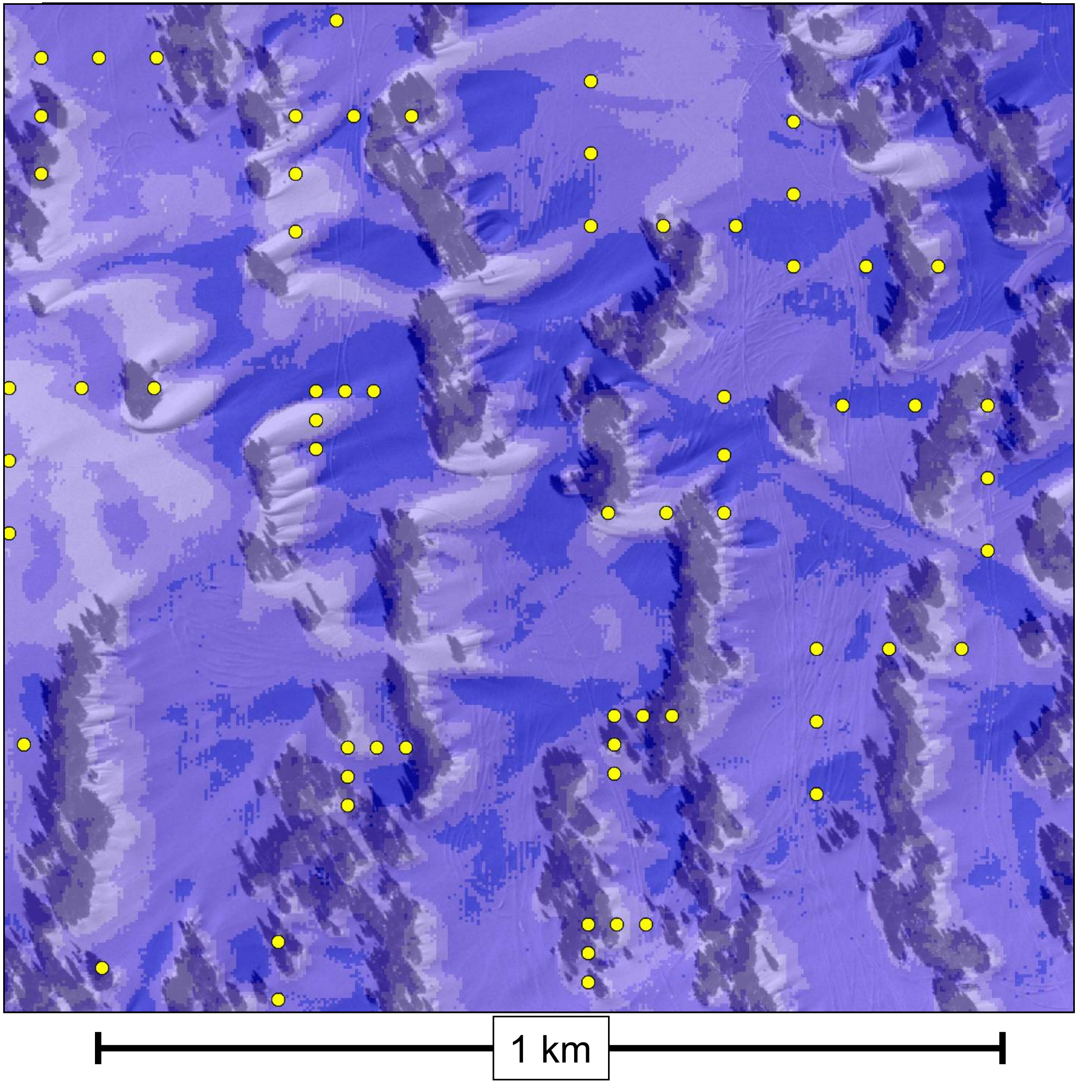
Courtesy of Jeff Deems, CSU

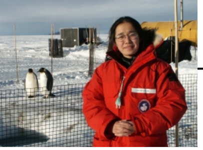


CLPX Buffalo Pass ISA

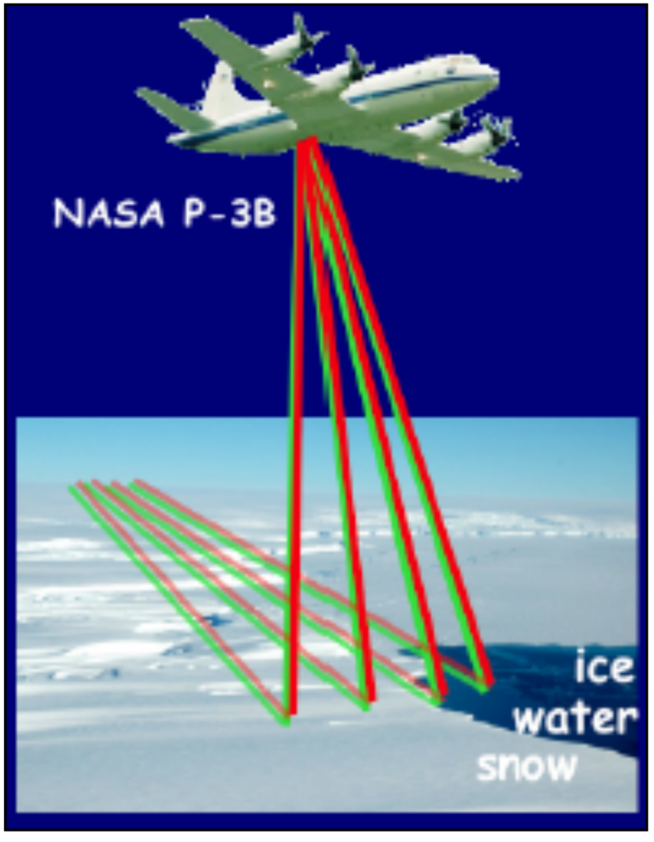
- 9 April 2003
- discrete-return 1064 nm airborne scanning system
- 1.5 m point spacing
- 0.15 m vertical accuracy
- 600k data points

Courtesy of Jeff Deems, CSU





Future Laser Altimeter



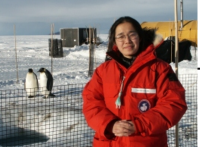
courtesy Dave Harding, NASA/GSFC

Swath-Imaging Multi-polarization Photon-counting Lidar (SIMPL)

NASA/ESTO IIP

D. Harding, PI 2006-2008

- 532 & 1064 nm micropulse lasers
- 1-beam profile in 2007
- 4-beam pushbroom in 2008 photon-counting
- parallel and perpendicular polarizations
- spaceflight instrument & mission development

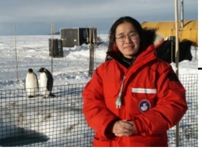


National Lidar Mapping Initiative Concept

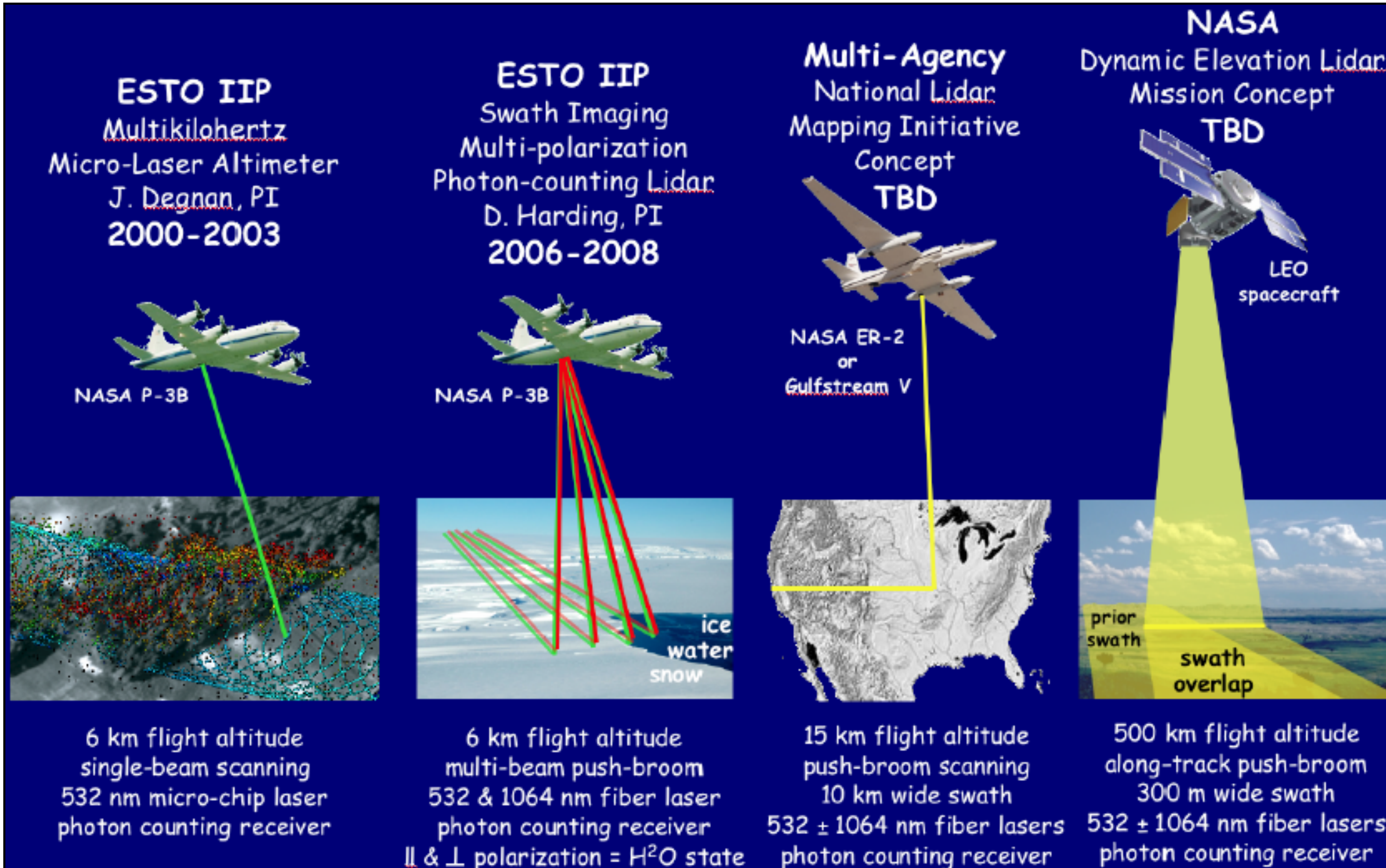
- long-duration, long-range aircraft (e.g., ER-2)
  - high altitude enables wide swath (~10 km)
- cross-track scanned push-broom laser altimeter
  - nationally uniform data collection method
  - photon-counting, dual-polarized
- potential for complementary instrumentation
  - MSI/HIS
  - SAR interferometry
- 7-year implementation timeline
  - 4-year refresh interval

- base map for extending snow depth mapping to other basins/regions

courtesy Dave Harding, NASA/GSFC



NASA/GSFC
Lidar Swath Mapping Development



courtesy Dave Harding, NASA/GSFC