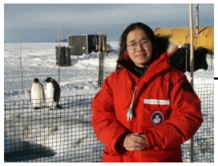
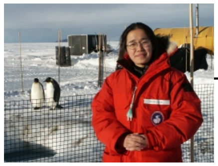


Lecture 39. Target Lidar (4)

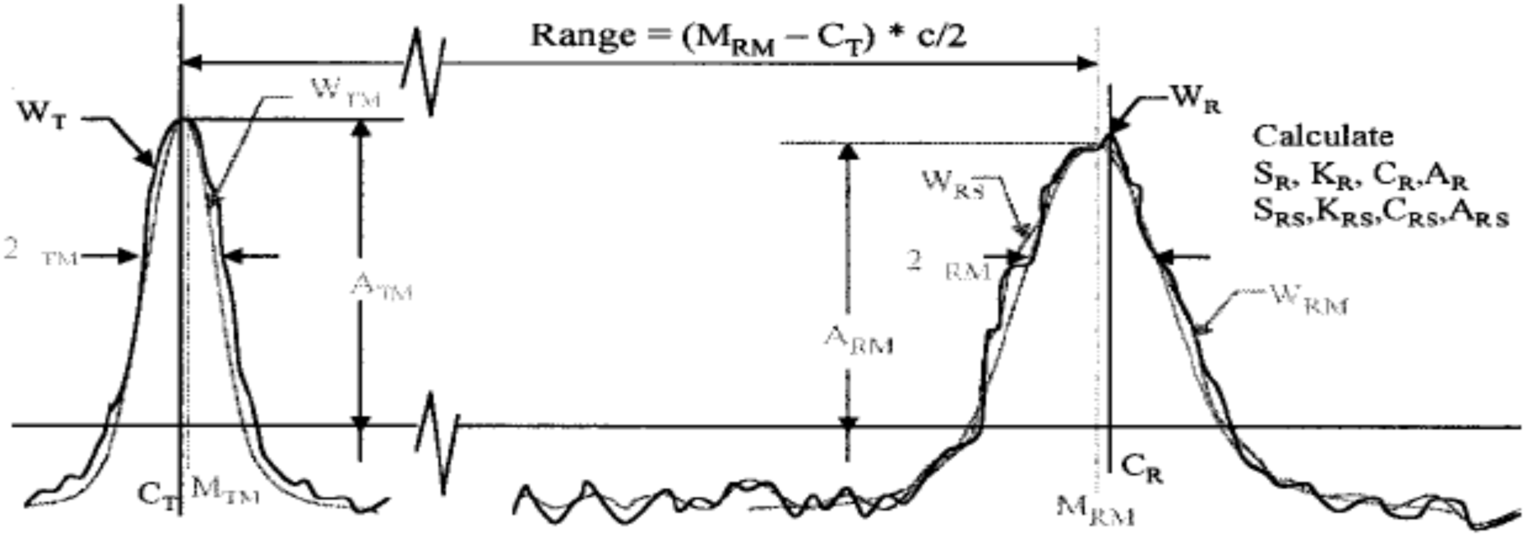
Laser Altimeter

- ☐ Resolution Issues with laser pulse width limitation
  1) In most laser altimeters (satellite-based, airborne)
  2) In bathymetry for shallow water-body ranging
- ☐ Polarizations in Lidar Applications
  1) Polarization applied in bathymetry
  2) Lidar equation modified for polarization lidar calculation
- ☐ Application Examples of Laser Altimeter
  1) Canopy application
  2) Snow depth mapping
  3) National geography mapping



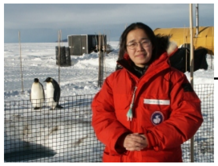
How to Overcome Pulse Width Limit?

- ❑ 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).



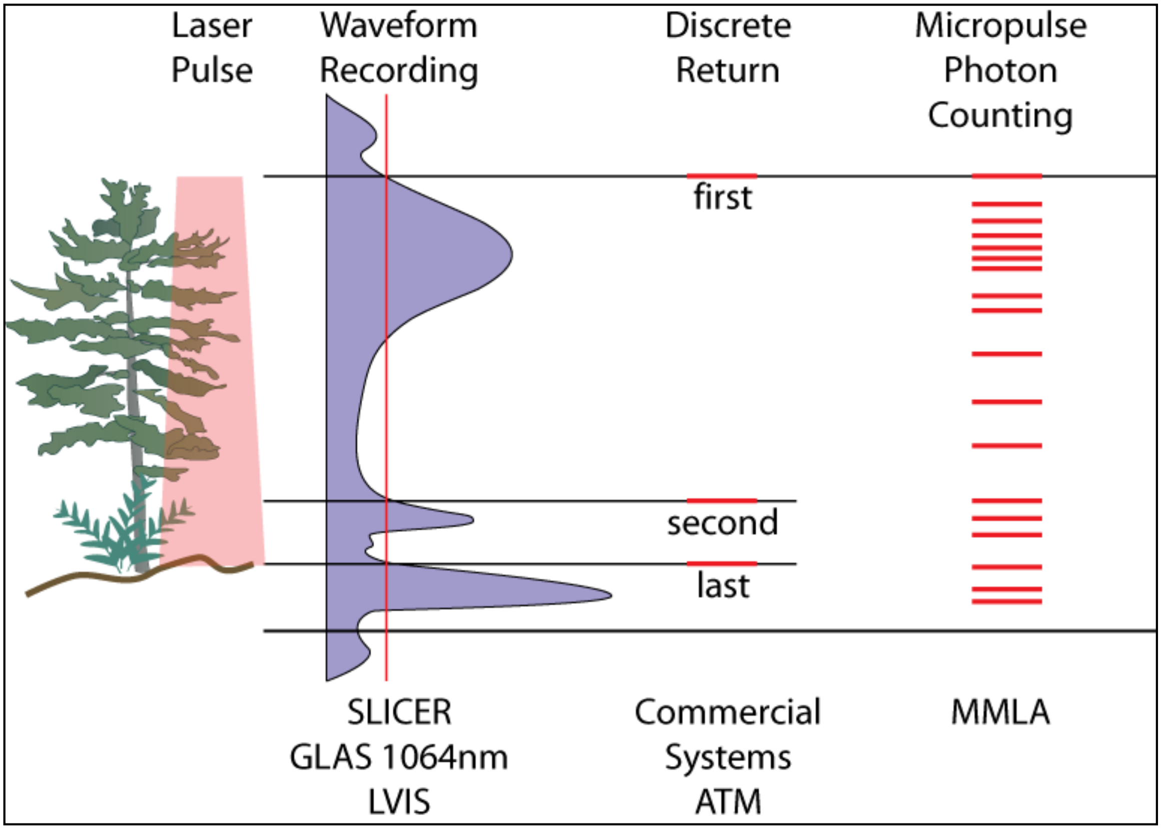
- ❑ When pulse waveforms can be recorded well (with high energy laser pulse), the resolution can be improved by identifying the peak or leading/trailing edge and comparing the transmitted & received pulse waveforms.

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

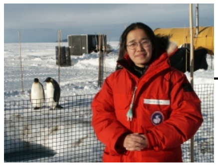


Lidar Ranging Methods

- 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

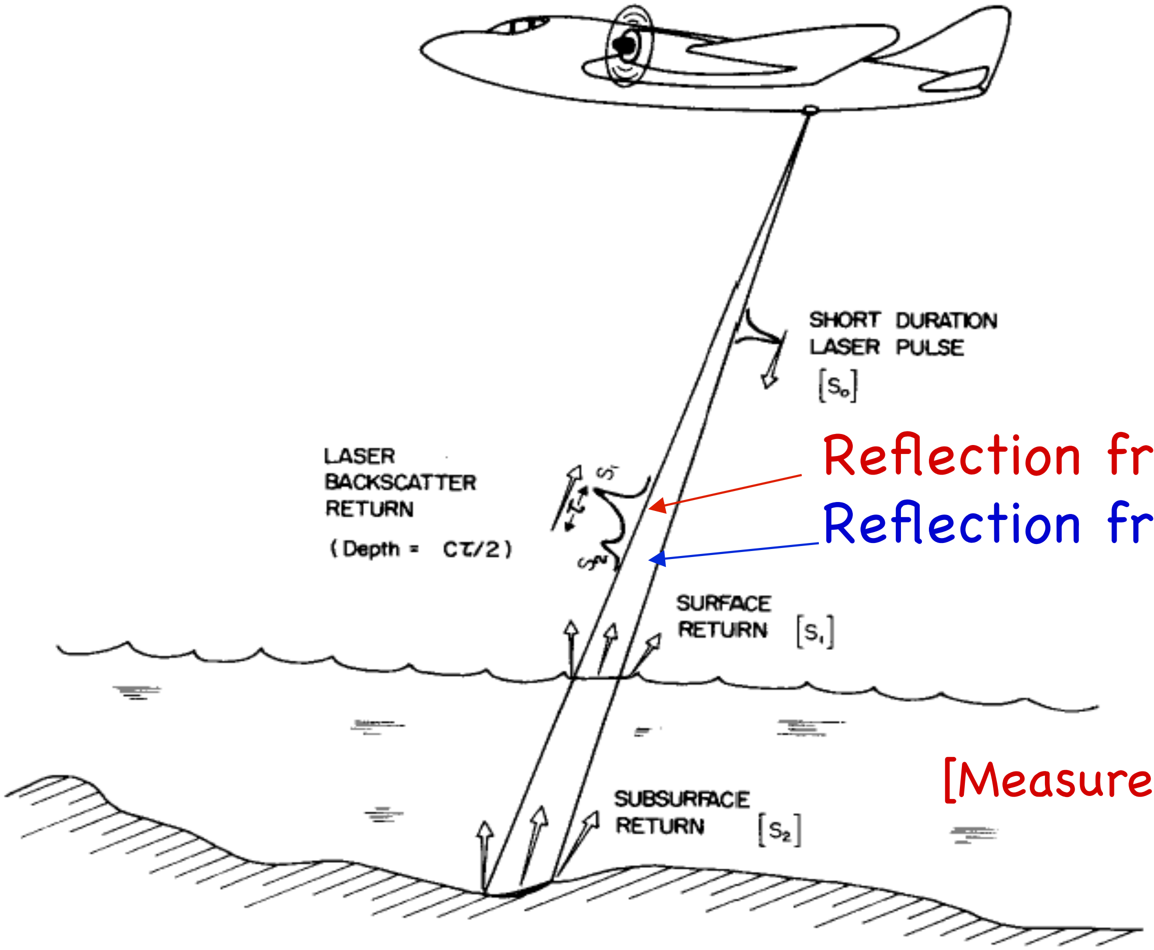


courtesy Dave Harding, NASA/GSFC



Lidar Bathymetry

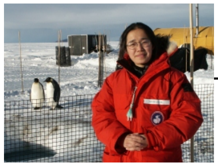
- Lidar bathymetry can face issues different than other laser altimeters: One is the laser penetration of any water body, and another is to deal with shallow water when the water depth is comparable to or smaller than the laser pulse width.



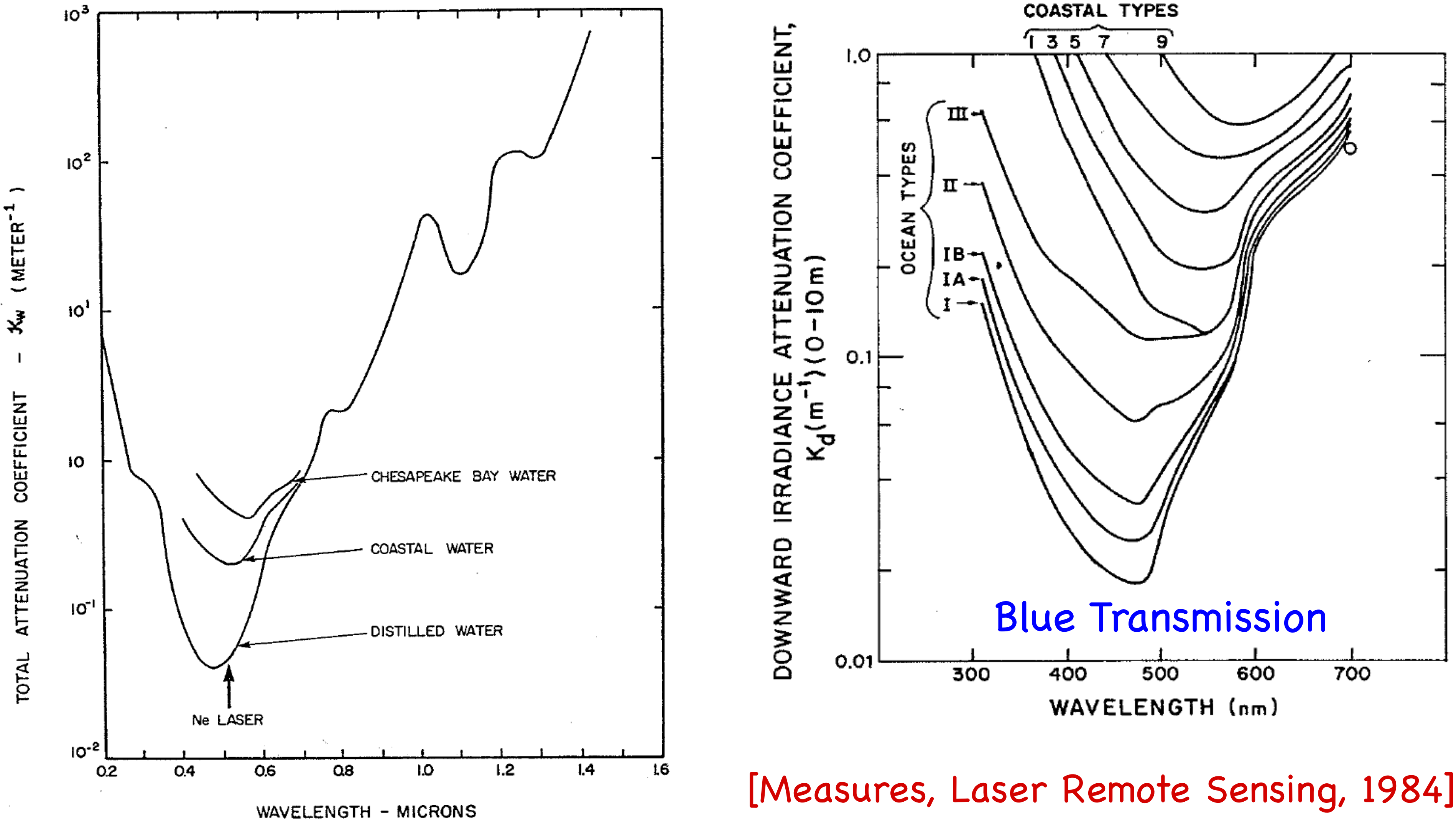
Reflection from water surface

Reflection from river bottom

[Measures, Laser Remote Sensing, 1984]



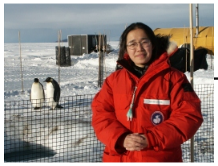
Water Transmission vs. Wavelength



Blue Transmission

[Measures, Laser Remote Sensing, 1984]

Fig. 10.1. (a) Attenuation coefficient of water (adapted from Tyler and Preisendorfer, 1962). (b) Downward irradiance attenuation coefficient measured by Jerlov (1976) in the first 10 m of depth as a function of wavelength for a variety of deep ocean and coastal water types (Northam et al., 1981).



Lidar Bathymetry to Measure Glacial Meltpond

- A major challenge is to obtain resolutions better than the pulse width-limited depth resolution, i.e., the intrapulse ambiguity.

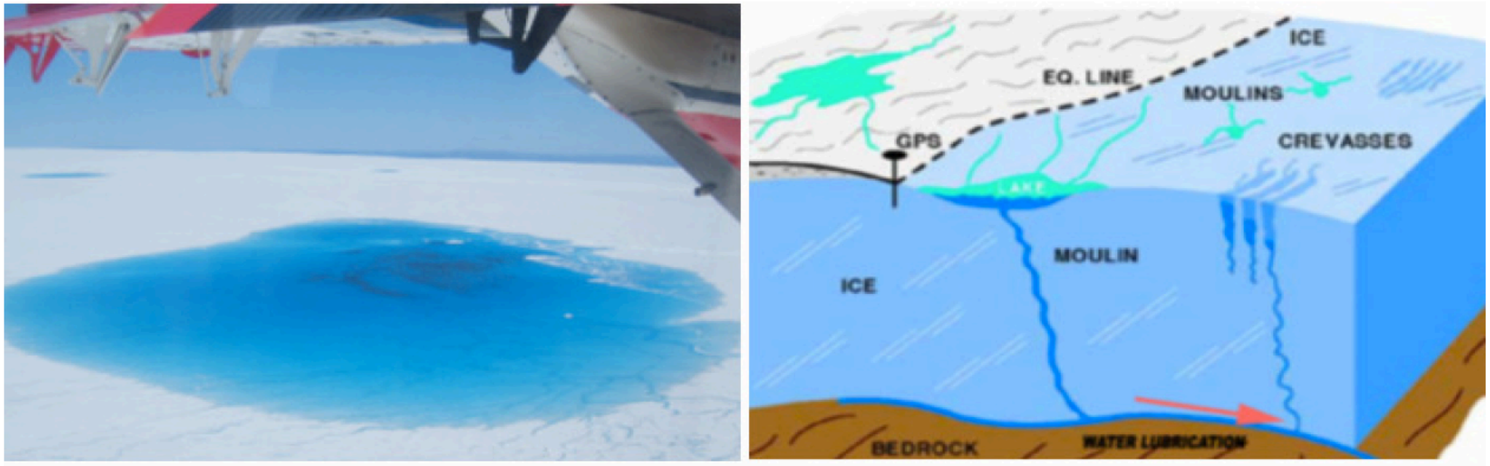
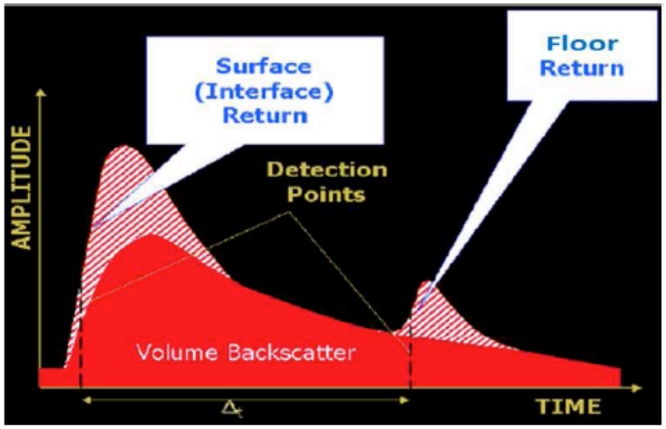
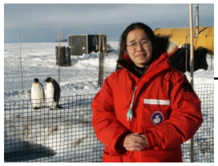


Figure 2.4: Aerial view of a typical glacial meltpond (left) [photo *S. Das*]; illustration of a meltpond and drainage route through a moulin (right) [*Zwally et. al.*, 2002]



[Courtesy of Steve Mitchell]

Figure 1. Scattered optical signals for depth measurement of a semitransparent medium, illustrated here as water [1]. Depth measurement of increasingly shallow water (decreasing Δ) results in intrapulse ambiguities due to overlapping surface and floor returns.



Lidar Bathymetry

❑ To obtain better resolutions in lidar bathymetry (better than the pulse width-limited depth resolution), several methods could be used, including waveform digitizing and signal distinguishing (e.g., depolarization).

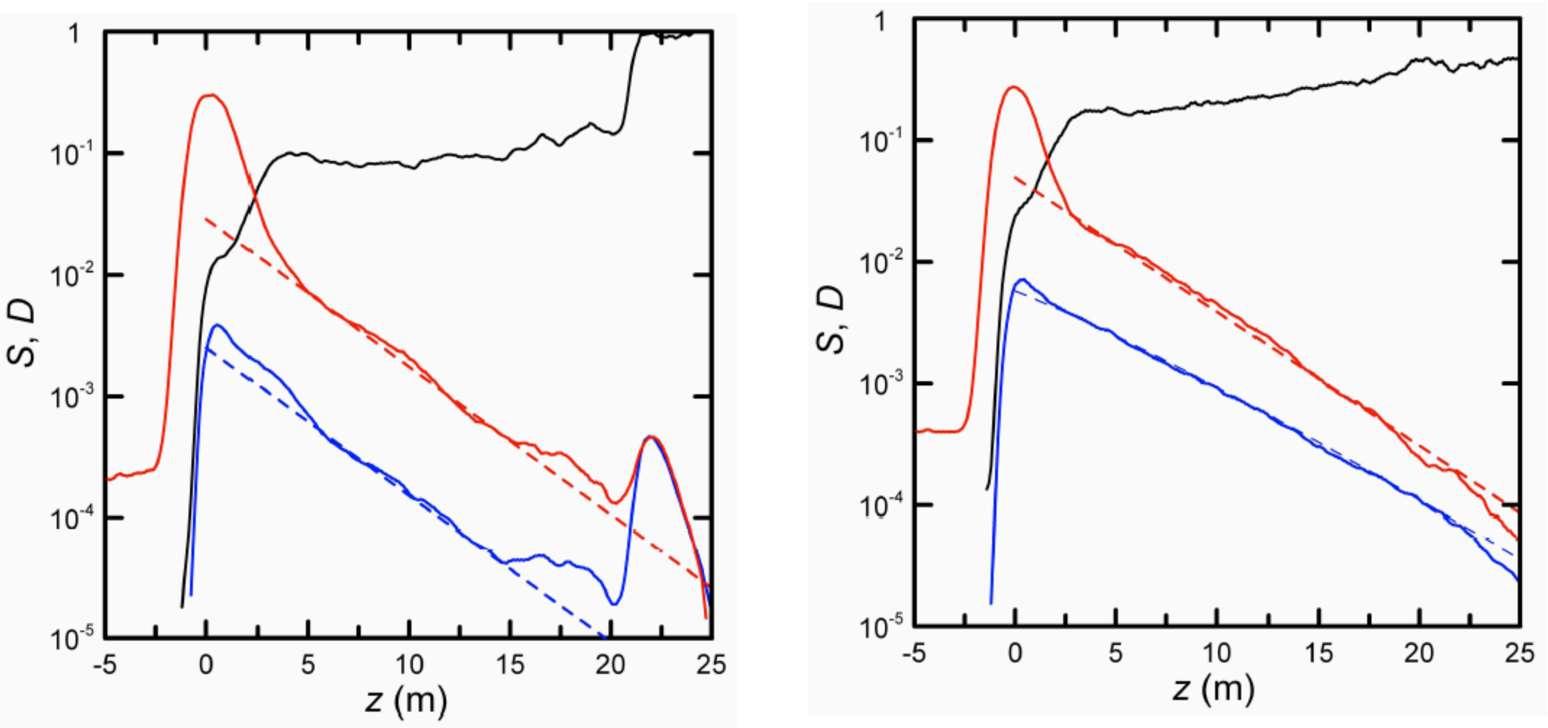
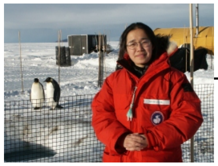


Fig.4. Typical depth profiles of the co-polarized return S_C (red), cross-polarized return S_X (blue), and depolarization D (black). The solid lines are measured values, and the dashed lines are the theoretical profiles from Eq. (8). The left panel is from the near-shore region. The large, unpolarized return at 22 m depth is the bottom of the ocean. The right panel is from the off-shore region.

[Churnside, Polarization effects on ocaneographic lidar, Optics Express, 16, 1196-1207, 2008]



Polarization App in Lidar Bathymetry

[Mitchell et al., Applied Optics, 2010; Mitchell, 2011]

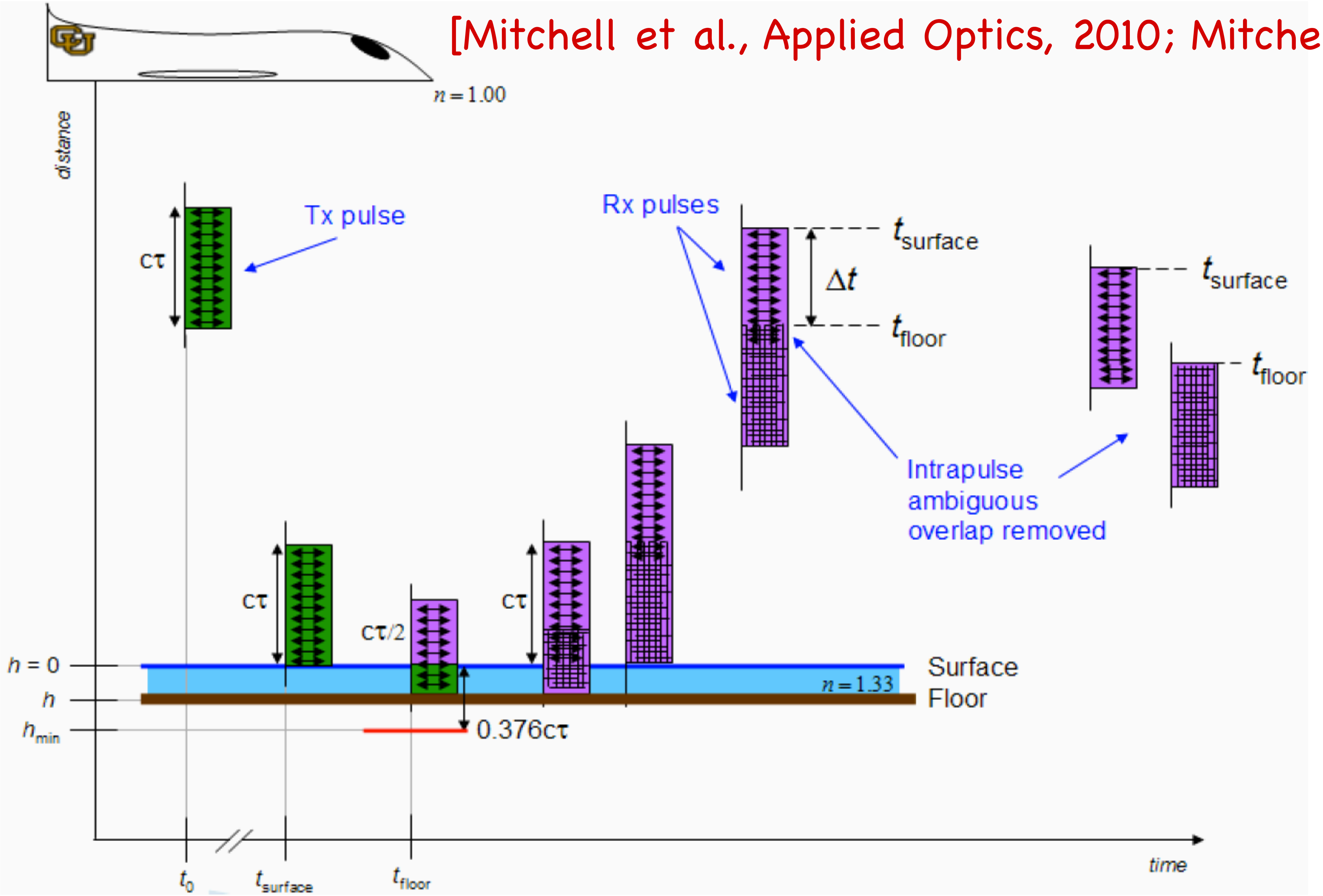
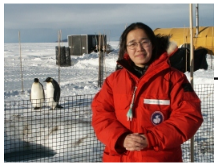
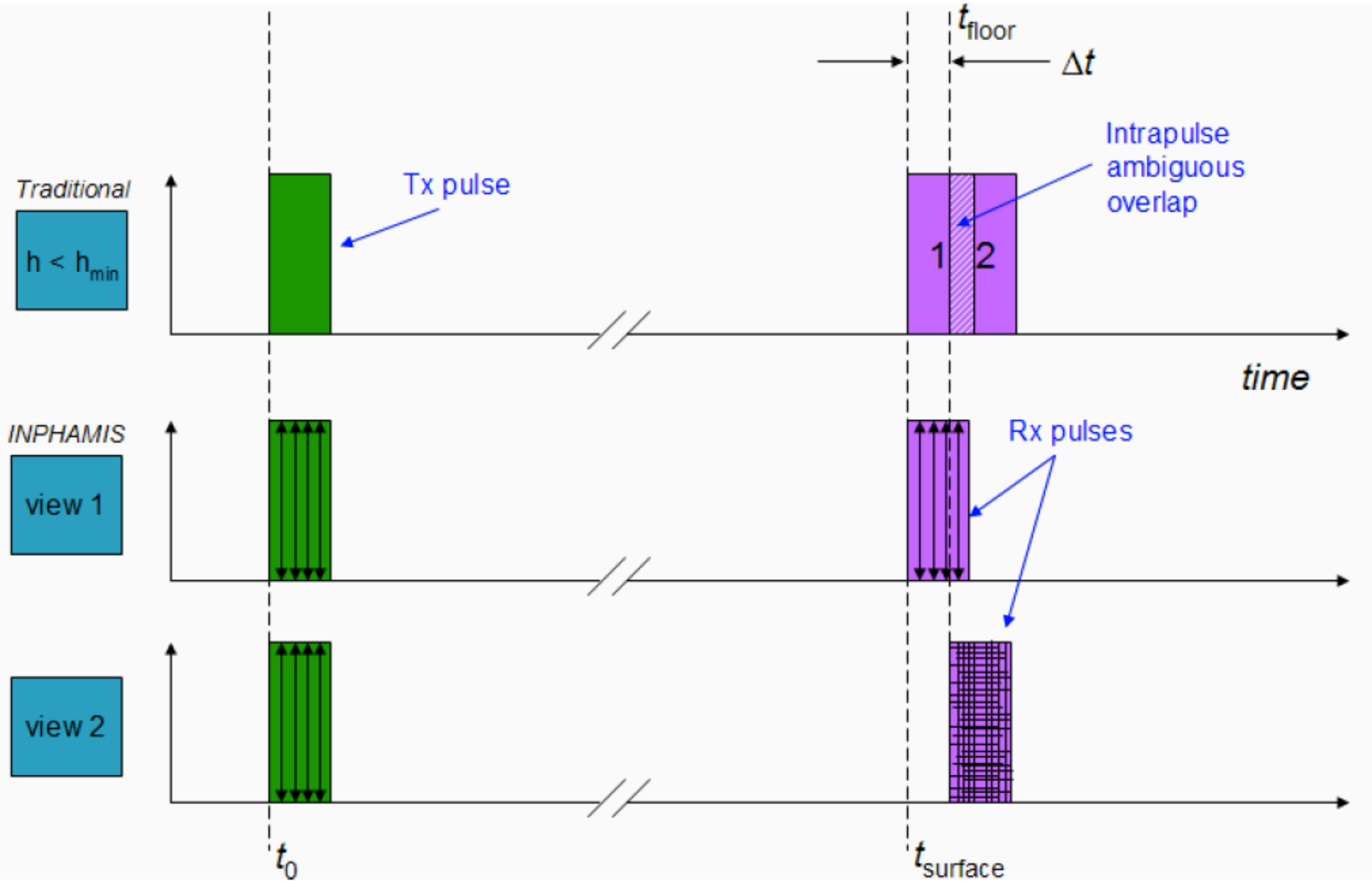


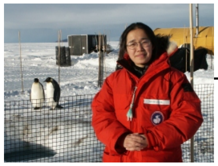
Figure 3.2: Incorporation of polarization discrimination into bathymetry lidar enables the instrument to measure water depths shallower than h_{min}



Comparison between Traditional and Polarization Bathymetry

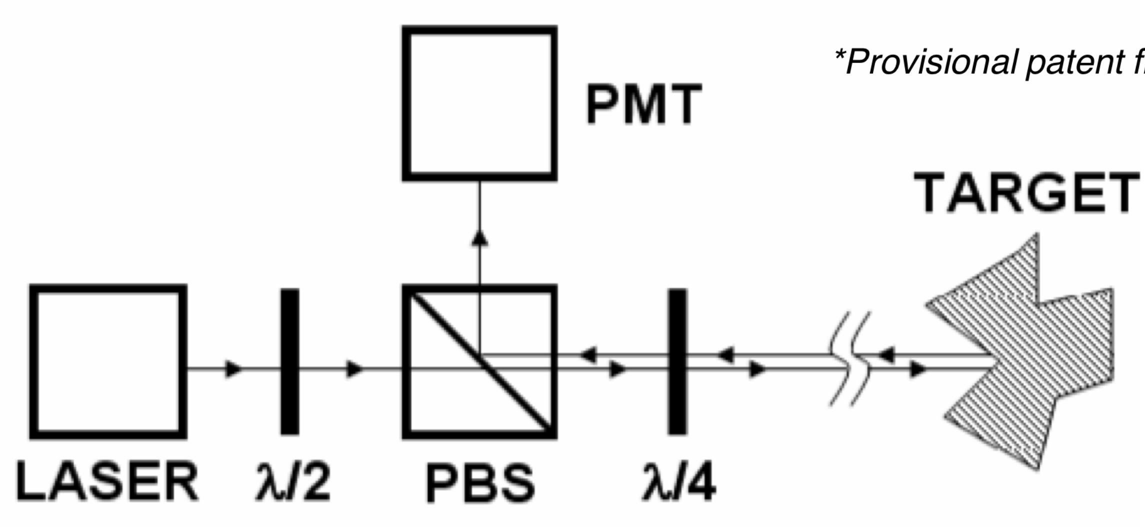


[Mitchell et al., Applied Optics, 2010; Mitchell, 2011]



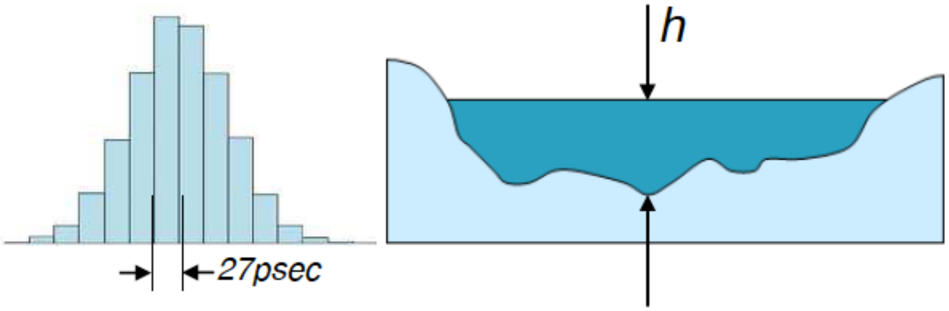
Polarization Lidar Bathymetry

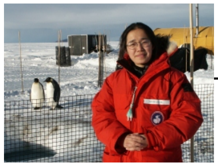
- Foundational setup for intrapulse phase modification induced by scattering [17]



Provisional patent filed April 2010

S. Mitchell, J. P. Thayer, and M. Hayman, "Polarization lidar for shallow water depth measurement," *Applied Optics*, **49** (2010)





More Considerations on Bathymetry

❑ Waveform recoding and digitizing

❑ Polarization applications in bathymetry [Churnside, Optics Express, 2008; Mitchell et al., Applied Optics, 2010]

❑ Besides polarization, other light properties, if they are modified by two surfaces differently, may be used to distinguish the signals returning from the air/water and water/bottom surfaces, so improving the range resolutions.

❑ Both methods mentioned above are ultimately limited by the receiver bandwidth and pulse width …

❑ Potential improvement: combination of polarization detection with CW laser chirp technique

Polarization Lidar Equation

Stokes Vector Lidar Equation (SVLE)

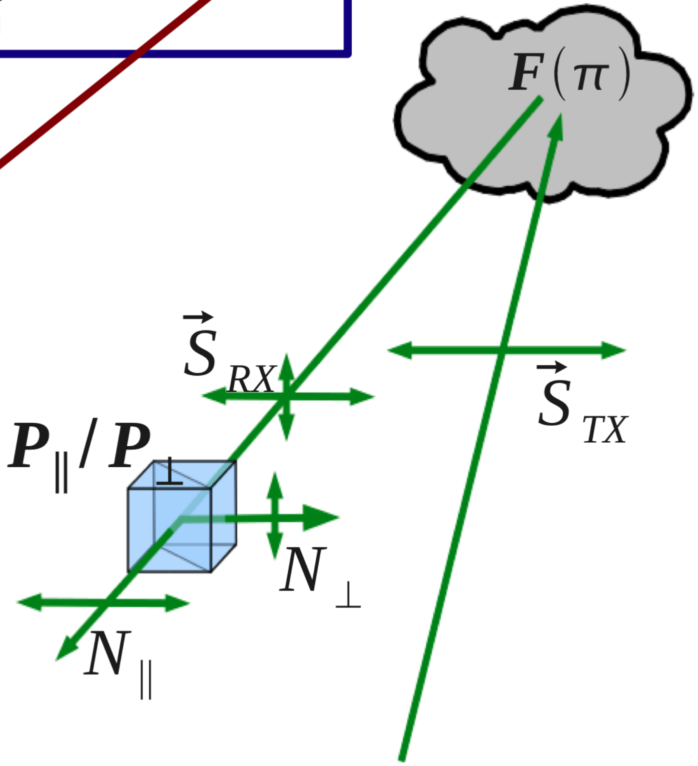
[Matt Hayman, PhD dissertation, 2011]

$$\vec{S}_{RX}(z)=\boldsymbol{M}_{RX}\left[\left(G(z)\,\Delta z\,\frac{A}{z^2}\right)\boldsymbol{T}_{atm}(z)\,\boldsymbol{F}(\vec{k}_i,\vec{k}_s,z)\,\boldsymbol{T}_{atm}(z)\,\boldsymbol{M}_{TX}\vec{S}_{TX}+\vec{S}_B\right]$$

Scatterer

Transmission

Optical System

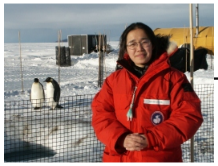


Measured Intensity/Photon Counts

$$N_m(z)=\vec{o}\,\boldsymbol{P}_m\vec{S}_{RX}(z)$$

$$\vec{o}=\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}$$

All matrices are Mueller matrices that can be analyzed using Lu-Chipman Decomposition



Polarization Lidar Considerations

❑ Polarization lidar should be described in terms of Stokes vectors and Mueller matrices. The so-called Stokes Vector Lidar Equation is to do the matrix calculation, writing the equation in an opposite sequence of the more general lidar equation. But all obey the same physics picture of lidar remote sensing.

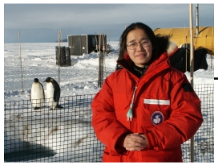
➢ Results should be reported in terms of scattering matrix parameters

➢ Mueller matrix descriptions of the instrument descriptions offer better solutions for system error in polarization measurements.

❑ Polarization can be used to study a number of particle properties relating to shape, index of refraction and size.

❑ Detection of linear diattenuation provides a means of identifying horizontally oriented ice crystals while providing backscatter signals in the same dynamic range as other clouds and aerosols.

[Refer to a guest lecture (34) by Matt Hayman in the Lidar Class 2011]
http://cires.colorado.edu/science/groups/chu/classes/Lidar2011/



Light Polarization Characterized by Stokes Vectors

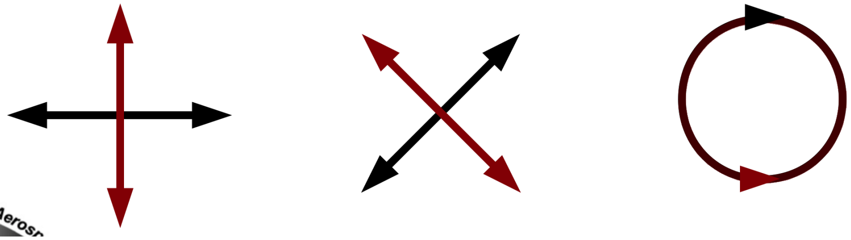
$$\vec{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

Total Intensity $|\vec{E}|^2$

Horizontal (+1) and Vertical (-1) Intensity

+45º (+1) and -45º (-1) Intensity

Left Hand Circular (+1) and Right Hand Circular (-1) Intensity

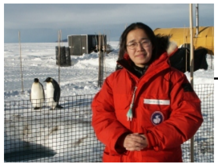


Degree of Polarization (DOP)

$$DOP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} \leq 1$$

Unpolarized Light

$$\vec{S}_{unpol} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



Optics Described by Mueller Matrices

Mueller Matrices

4x4 Matrix that describes polarization optics

Three types of Polarization Matrices

Diattenuator – Polarization dependent efficiency

i.e. Horizontal Polarizer

Horizontal Polarized Input

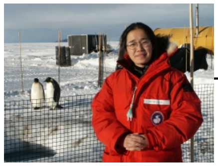
$$\begin{bmatrix}1\\1\\0\\0\end{bmatrix}=\begin{bmatrix}0.5 & 0.5 & 0 & 0\\0.5 & 0.5 & 0 & 0\\0 & 0 & 0 & 0\\0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}1\\1\\0\\0\end{bmatrix}$$

Vertical Polarized Input

$$\begin{bmatrix}0\\0\\0\\0\end{bmatrix}=\begin{bmatrix}0.5 & 0.5 & 0 & 0\\0.5 & 0.5 & 0 & 0\\0 & 0 & 0 & 0\\0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}1\\-1\\0\\0\end{bmatrix}$$

Unpolarized Input

$$\begin{bmatrix}0.5\\0.5\\0\\0\end{bmatrix}=\begin{bmatrix}0.5 & 0.5 & 0 & 0\\0.5 & 0.5 & 0 & 0\\0 & 0 & 0 & 0\\0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$$



Optics Described by Mueller Matrices

Mueller Matrices

Three types of Polarization Matrices
Retarder – Polarization dependent phase shift

i.e. Horizontal Quarter Wave Plate

Horizontal Polarized Input

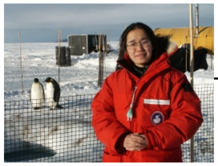
$$\begin{bmatrix}1\\1\\0\\0\end{bmatrix}=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&-1&0\end{bmatrix}\begin{bmatrix}1\\1\\0\\0\end{bmatrix}$$

45° Polarized Input

$$\begin{bmatrix}1\\0\\0\\-1\end{bmatrix}=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&-1&0\end{bmatrix}\begin{bmatrix}1\\0\\1\\0\end{bmatrix}$$

Unpolarized Input

$$\begin{bmatrix}1\\0\\0\\0\end{bmatrix}=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&-1&0\end{bmatrix}\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$$



Optics Described by Mueller Matrices

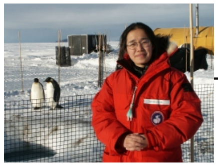
Mueller Matrices

Three types of Polarization Matrices
Depolarizer – reduces DOP

i.e. Total Depolarizer

Horizontal Polarized Input

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$



Application of Stokes Vector and Mueller Matrix in Polarization Lidar

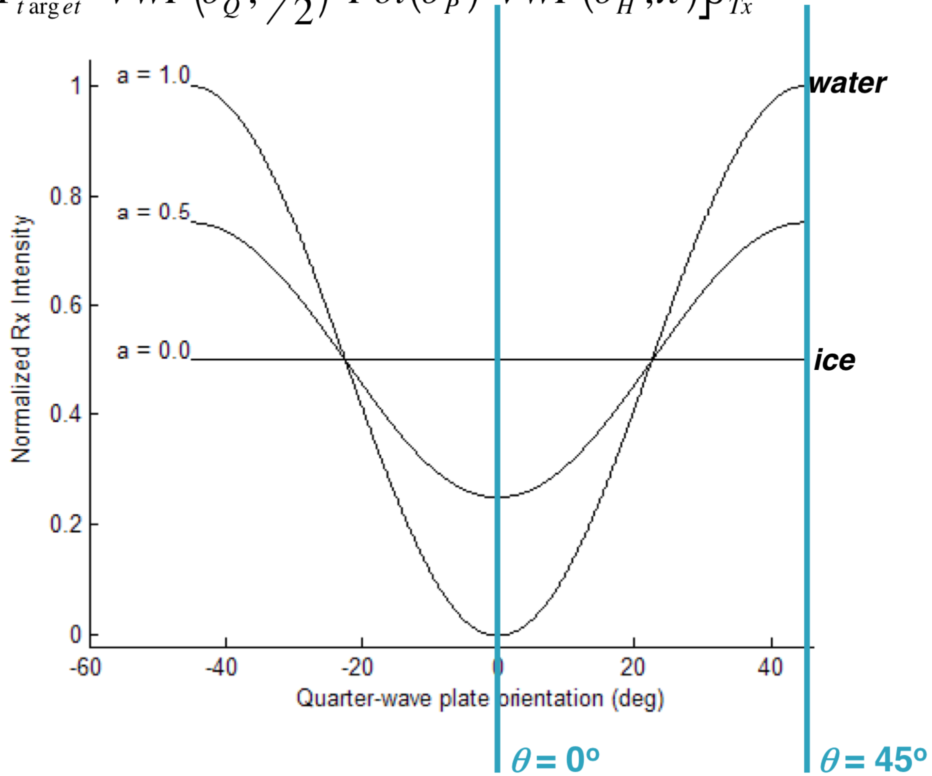
- Evaluate the received Stokes vector

$$\vec{S}_{Rx} = \left[Pol(\theta_P + 90)\cdot VWP\left(-\theta_Q, \pi/2\right)\cdot M_{target}\cdot VWP\left(\theta_Q, \pi/2\right)\cdot Pol(\theta_P)\cdot VWP(\theta_H, \pi)\right]\vec{S}_{Tx}$$

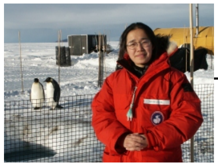
$$I_{Rx} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}\vec{S}_{Rx}$$

- Normalized depol matrix[18]

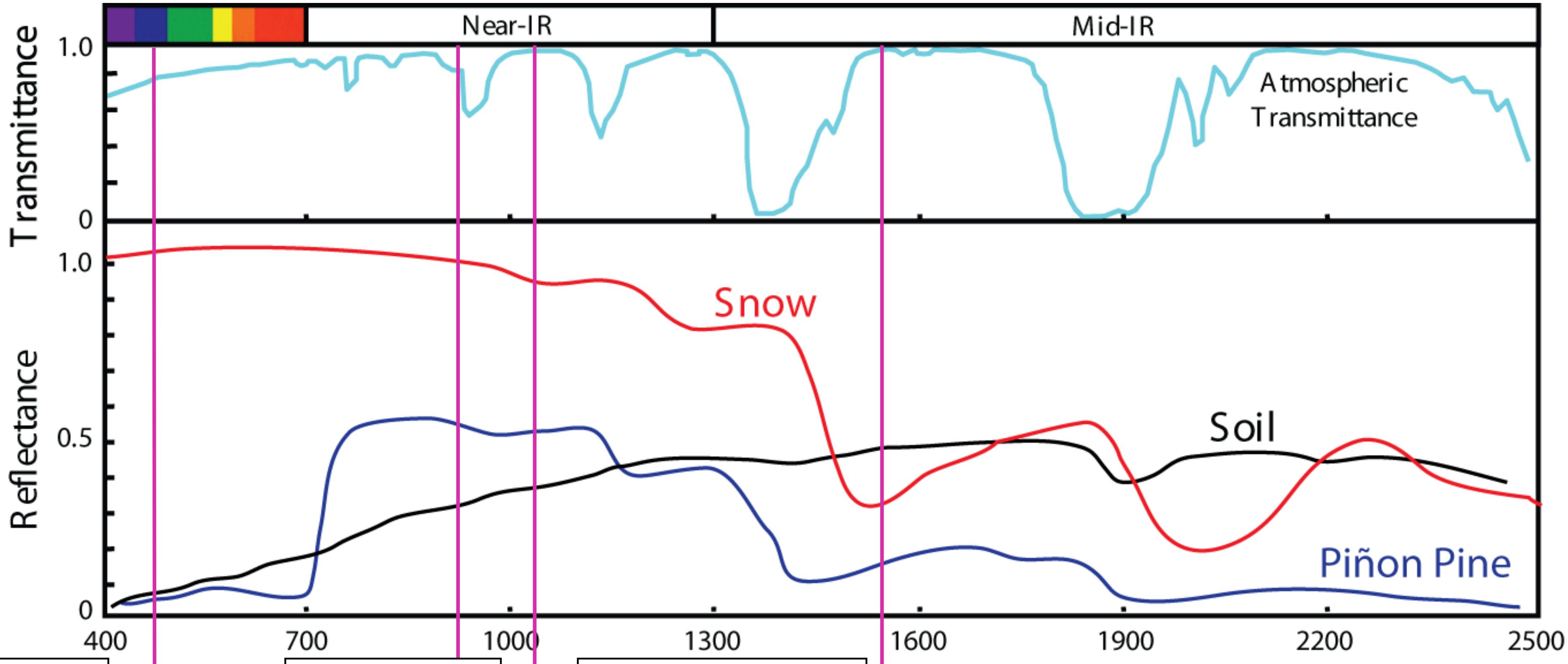
$$M_{target} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & a & 0 & 0 \\ 0 & 0 & b & 0 \\ 0 & 0 & 0 & c \end{bmatrix}$$



[Steve Mitchell, Guest Lecture 35, 2011]



Some Lidar Sensor Wavelengths



532 nm
NASA ATM
GLAS
MMLA

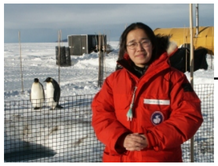
900 nm
FLI-MAP I/II

1064 nm
Optech ALTM
Leica ALS50
GLAS
SLICER

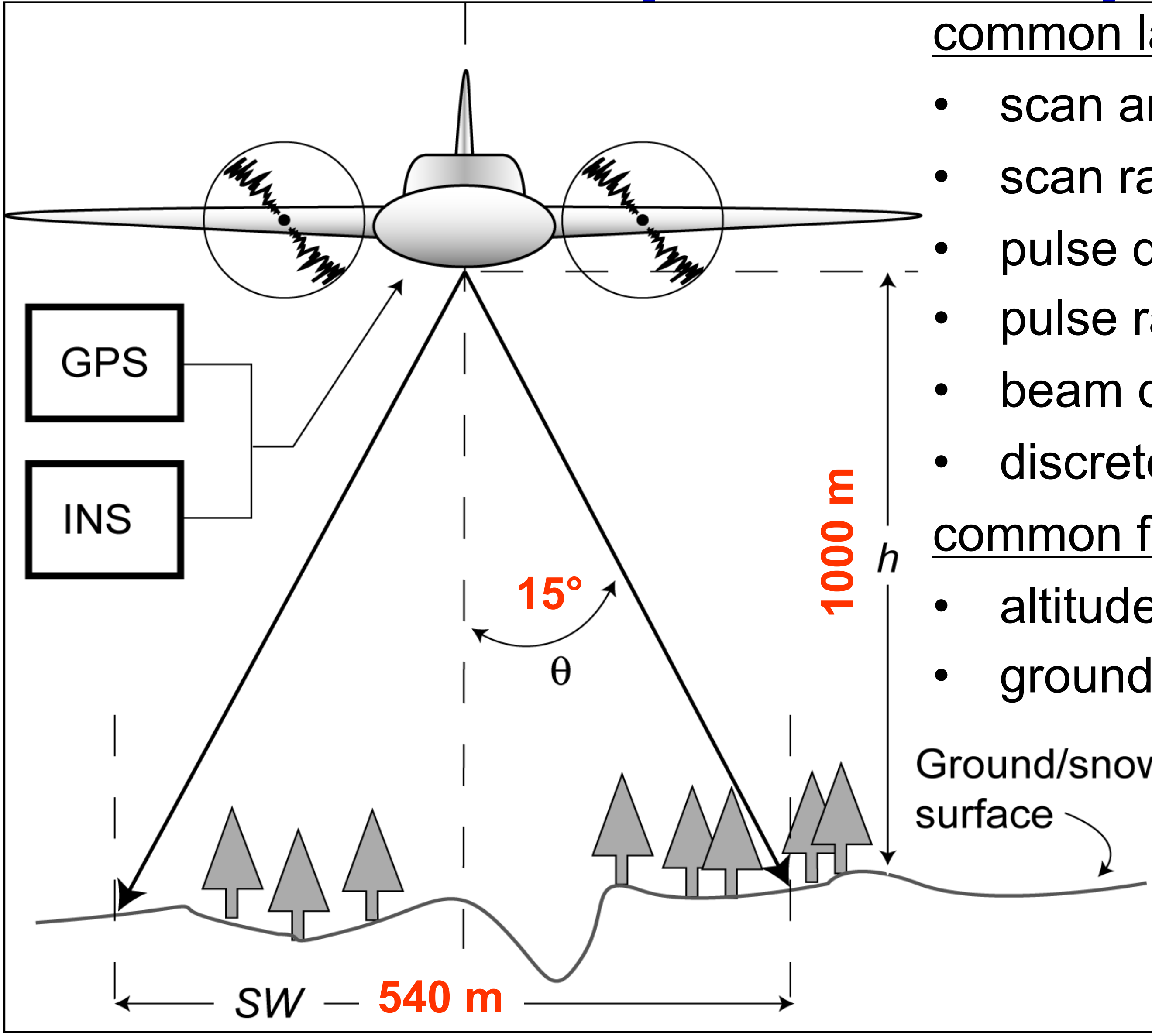
1540 nm
TopoSys I/II

532 & 1064 nm
LADS / SHOALS/Hawkeye
Bathymetric Systems

image courtesy Michael Lefsky, CSU



Commercial Airborne Lidar System Components

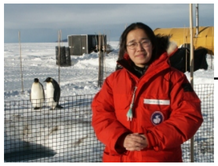


common laser parameters

- 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

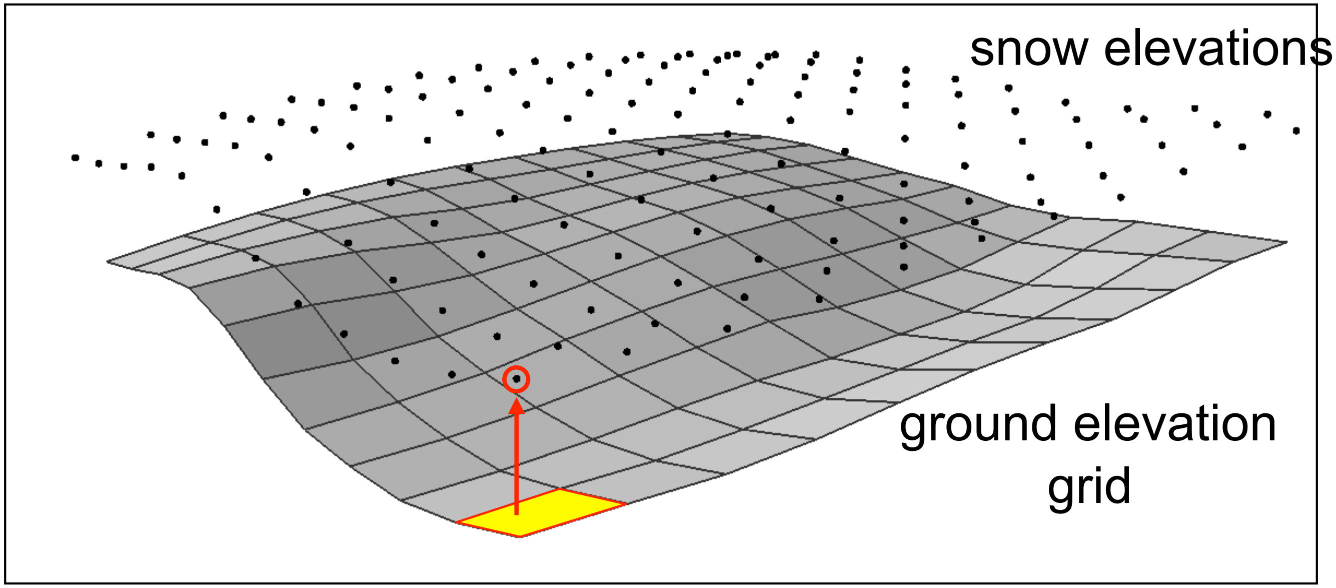
common flight parameters

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

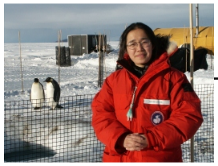


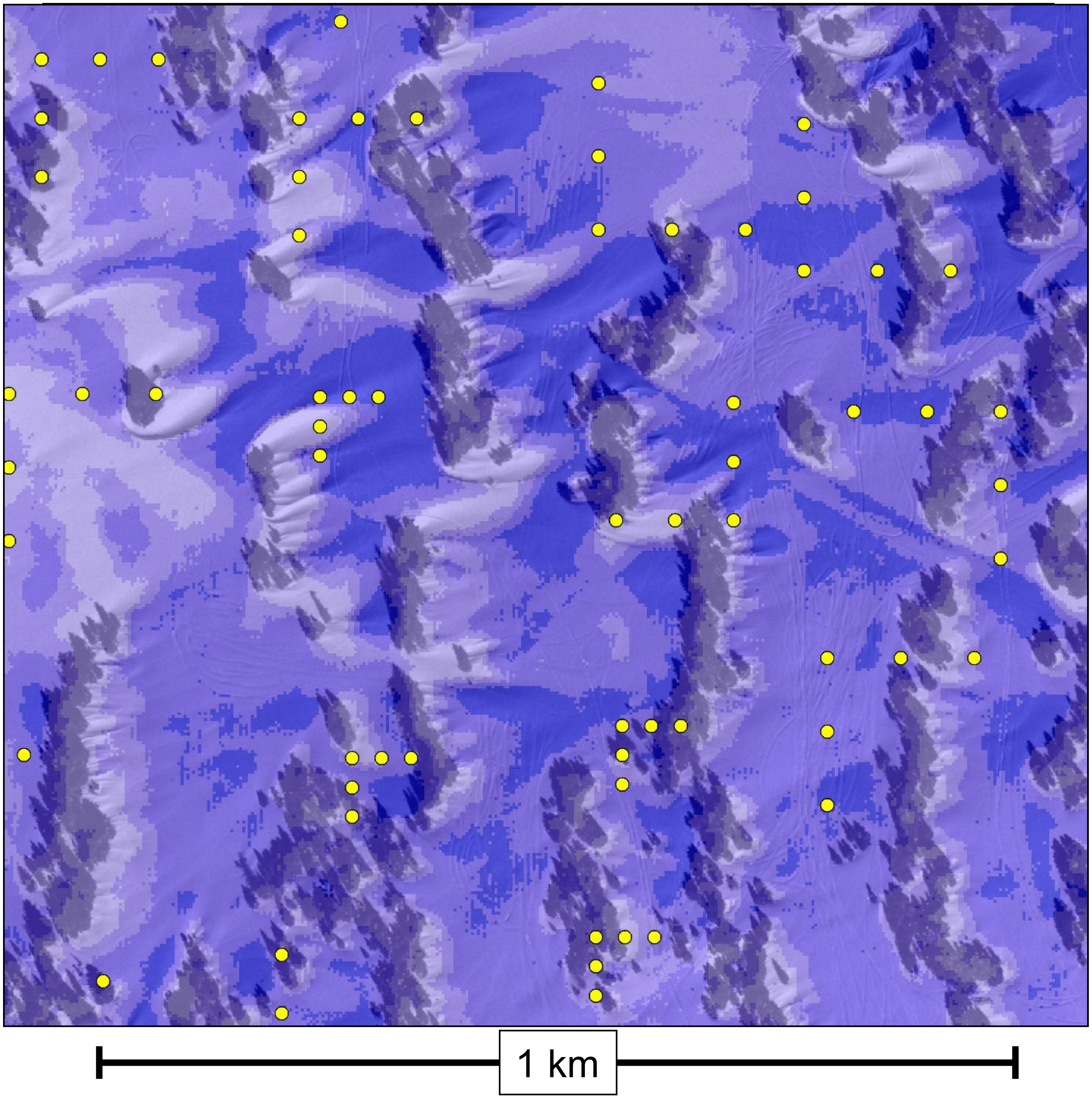
Lidar Snow Depth Mapping

- 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

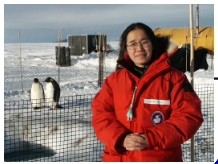




CLPX Buffalo Pass ISA

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

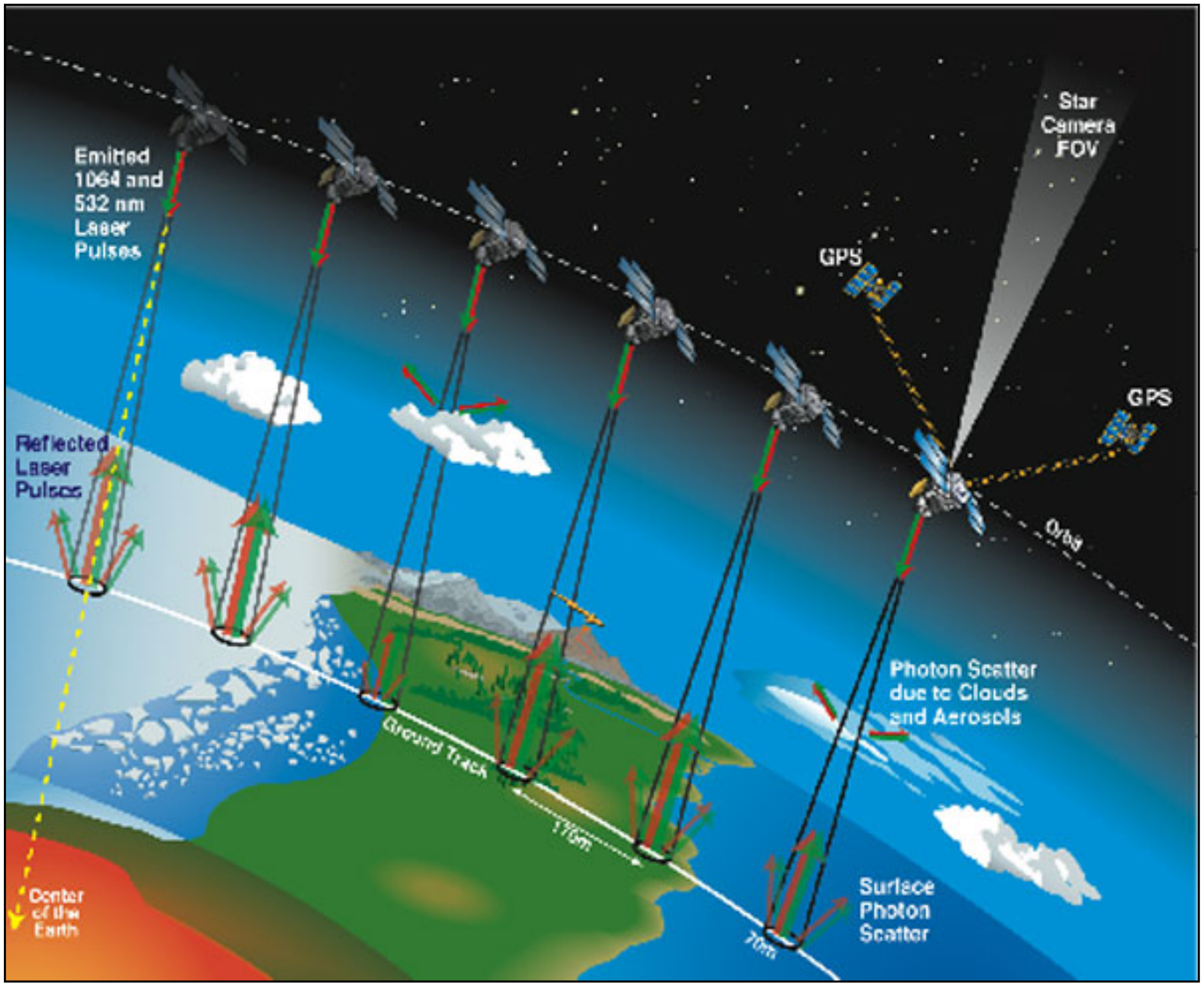
Courtesy of Jeff Deems, CSU



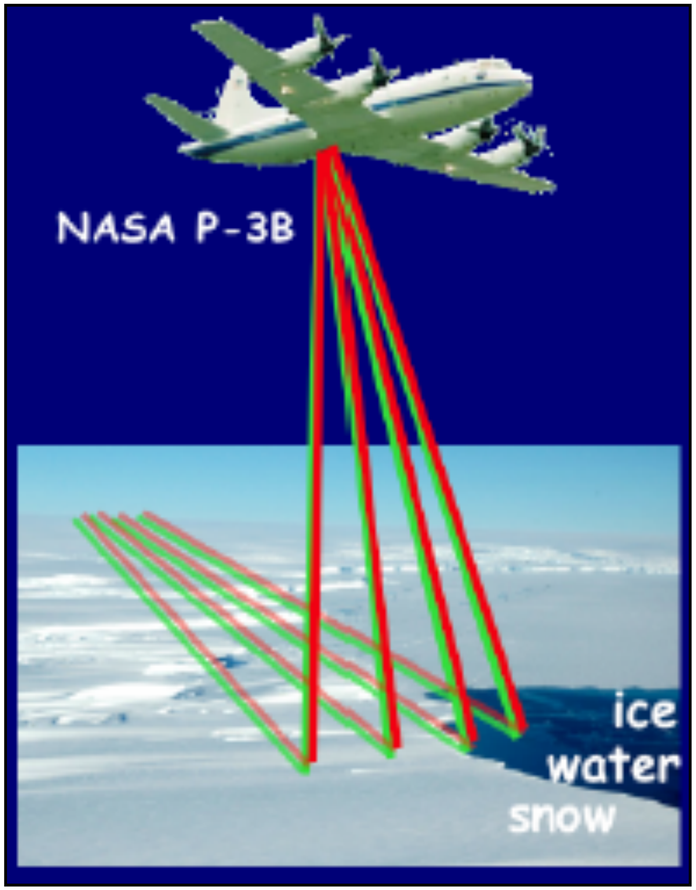
Current Laser Altimeter: ICESat

<u>ICESat</u>

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



Future Laser Altimeter



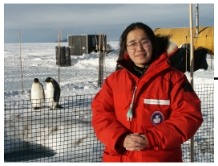
courtesy Dave Harding, NASA/GSFC

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

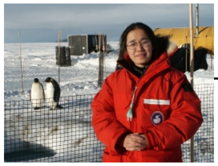


National Lidar Mapping Initiative Concept

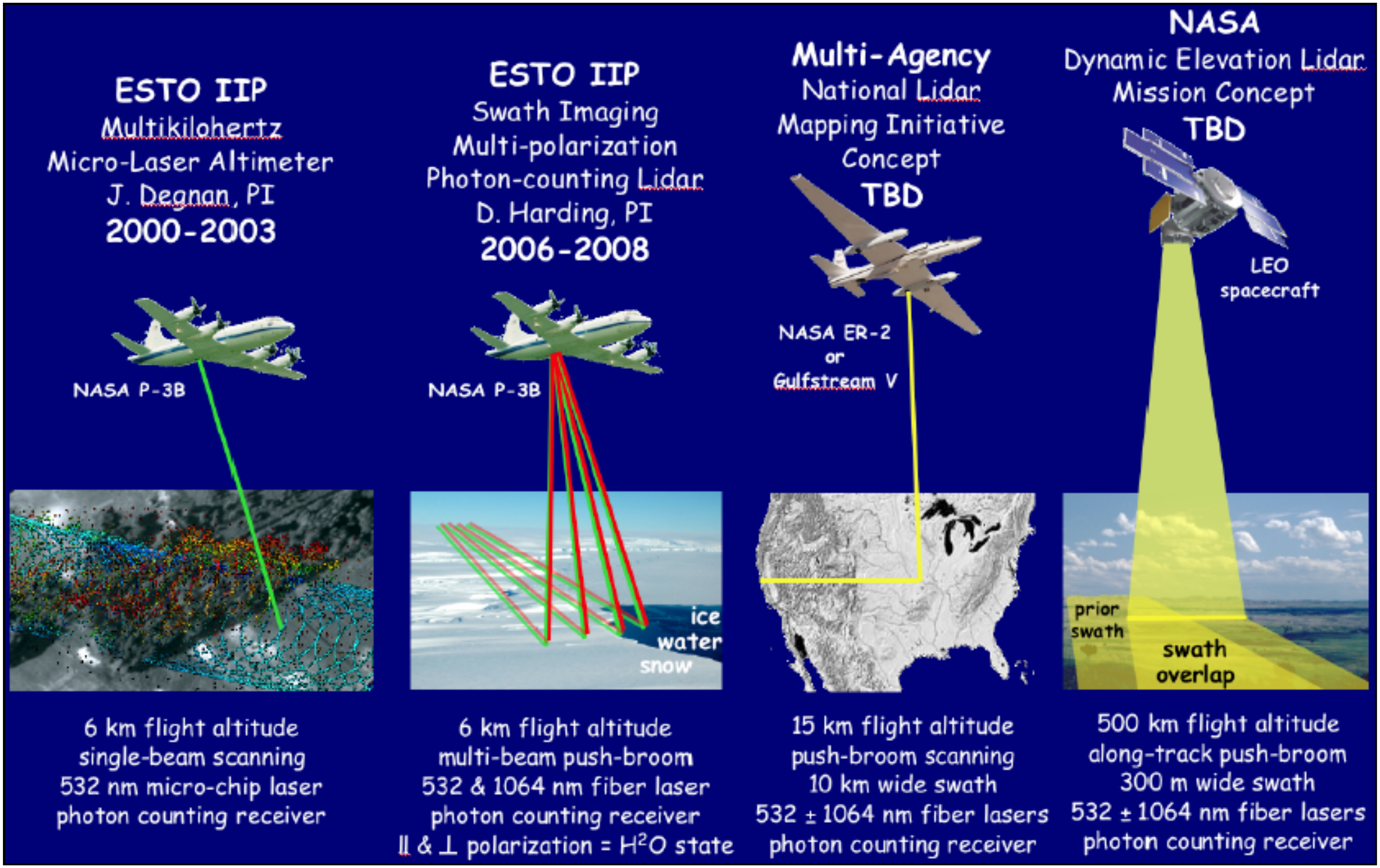
- long-duration, long-range aircraft (e.g., ER-2)
  - high altitude enables wide swath (~10 km)
- cross-track scanned push-broom laser altimeter
  - nationally uniform data collection method
  - photon-counting, dual-polarized
- potential for complementary instrumentation
  - MSI/HIS
  - SAR interferometry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



ESTO IIP
Multikilohertz
Micro-Laser Altimeter
J. Degnan, PI
2000-2003

6 km flight altitude
single-beam scanning
532 nm micro-chip laser
photon counting receiver

ESTO IIP
Swath Imaging
Multi-polarization
Photon-counting Lidar
D. Harding, PI
2006-2008

6 km flight altitude
multi-beam push-broom
532 & 1064 nm fiber laser
photon counting receiver
∥ & ⊥ polarization = H^2O state

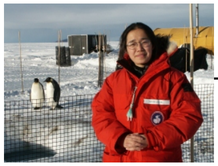
Multi-Agency
National Lidar
Mapping Initiative
Concept
TBD

15 km flight altitude
push-broom scanning
10 km wide swath
532 ± 1064 nm fiber lasers
photon counting receiver

NASA
Dynamic Elevation Lidar
Mission Concept
TBD

500 km flight altitude
along-track push-broom
300 m wide swath
532 ± 1064 nm fiber lasers
photon counting receiver

courtesy Dave Harding, NASA/GSFC



Summary of Target Lidar

- Target lidars, including fluorescence lidar, laser altimeter, hydrosphere lidar, ladar, fish lidar, etc, are an variant of atmospheric lidars. They share some of the same techniques used in atmospheric lidars.
- Laser altimeter and ladar use time-of-flight to determine the range of objects or surface. Many factors are involved.
- Fluorescence is used to measure species, organic materials, plants.
- Raman scattering by water is used to normalize the lidar returns.
- Target lidars face some different challenges and difficulties than atmospheric lidars. These challenges and difficulties also determines the growing points in this field.
- Target lidars have been deployed on different platforms for various applications. More efficient and compact target lidars on platforms like UAV, promise more applications.