Lecture 35. Laser Rangefinder

❑ Introduction

   ➢ Different applications facing different challenges

   ➢ Various names: rangefinder, altimeter, ladar, bathymetry, etc.

❑ Rangefinding Techniques and Principles

   ➢ Time of Flight

   ➢ Geometry-based

   ➢ Interferometry / Diffraction ranging

❑ Time of Flight Techniques

   ➢ Pulsed laser rangefinding

   ➢ CW laser amplitude modulation
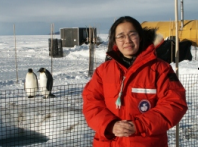
   ➢ CW laser chirp / Chirp pulse compression

Introduction

❑ Lidar remote sensing has two major functions:

➢ One is to measure atmospheric or environmental species, density, temperature, wind, and waves along with their range distributions.

➢ Another major function is to determine range – laser range finder. Laser altimeter is a special laser range finder.

❑ A good reference for laser rangefinding techniques is a paper collection book -- "Selected Papers on Laser Distance Measurements", edited by Brian J. Thompson, SPIE Milestone Series, 1995. Our textbook Chapter 8 "Airborne Lidar Systems" and Chapter 9 "Space-based Lidar" provide references for airborne and spaceborne laser altimeters. Other references could be found through web of science or SPIE related to the new laser altimeter projects.

❑ Laser rangefinders can have various names, like laser altimeter, ladar (scanning laser radar for ranging), bathymetry, etc., depending on their applications. Laser rangefinding faces different challenges for different applications, so demanding different techniques.

Challenges vs. Applications

❑ Laser altimeter: How accurately and precisely can you determine the absolute altitude? How to count in various interference factors, like multiple-scattering-induced time delay, platform absolute altitude uncertainties, etc.? How to improve range resolution / precision?

❑ Long-distance rangefinder and lidar bathymetry: How far can your laser beam penetrate through? Light and EM waves usually experience server attenuation in water.

❑ Laser altimeter and bathymetry: How to achieve high resolution like cm or mm for climate monitoring? How to resolve shallow water depth?

❑ Laser rangefinding: How to resolve tiny motion or range change to µm or smaller?

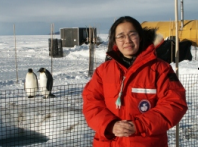❑ Ladar: How to achieve 3-D vision quickly and reliably?

❑ ……

Altitude Determination
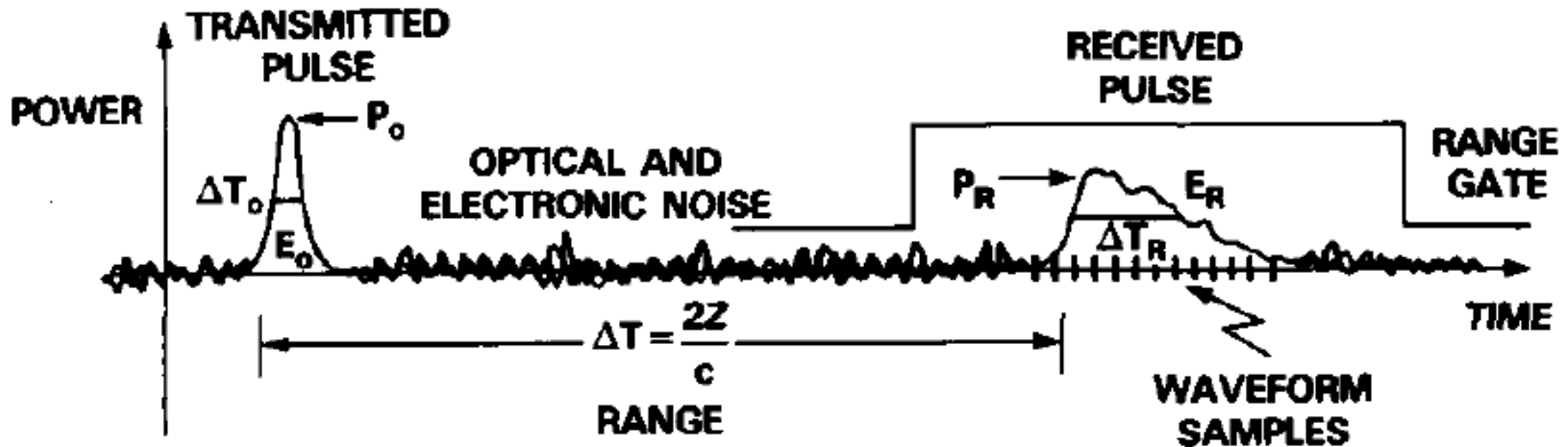
❑ The range resolution is now determined by the resolution of the timer for recording pulses, instead of the pulse duration width. By computing the centroid, the range resolution can be further improved.

❑ Altitude accuracy will be determined by the range accuracy/resolution and the knowledge of the platforms where the lidar is on.

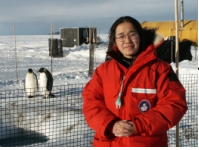❑ In addition, interference from aerosols and clouds can also affect the altitude accuracy.

Altitude = Platform Base Altitude – Range ± Interference of aerosols and clouds
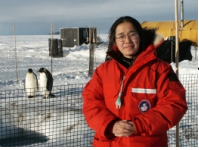
Laser Altimeter (Laser Ranging)

❑ The time-of-flight information from a lidar system can be used for laser altimetry from airborne or spaceborne platforms to measure the heights of surfaces with high resolution and accuracy.

❑ The reflected pulses from the solid surface (earth ground, ice sheet, etc) dominant the return signals, which allow a determination of the time-of-flight to much higher resolution than the pulse duration time.
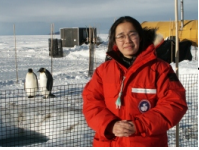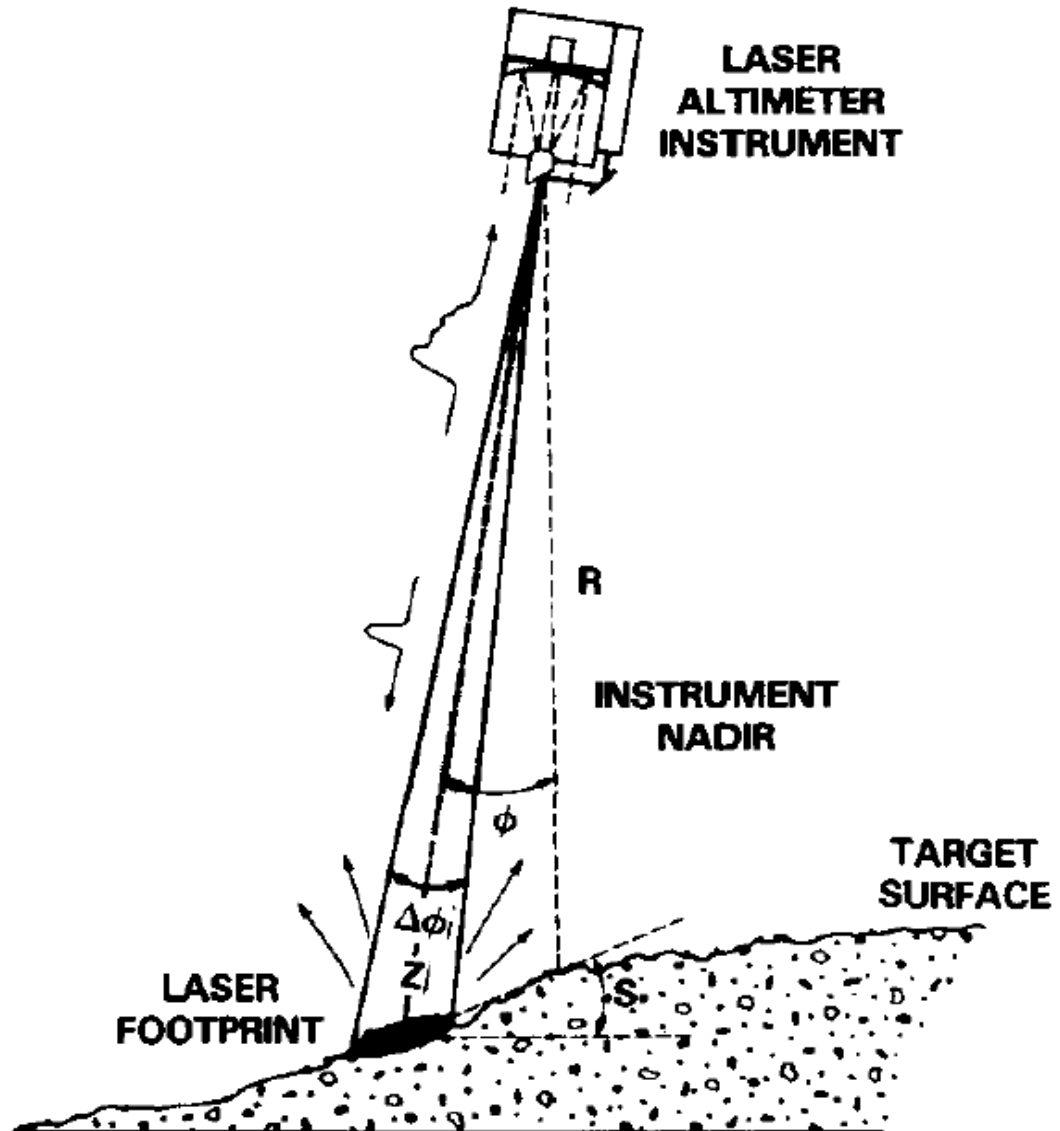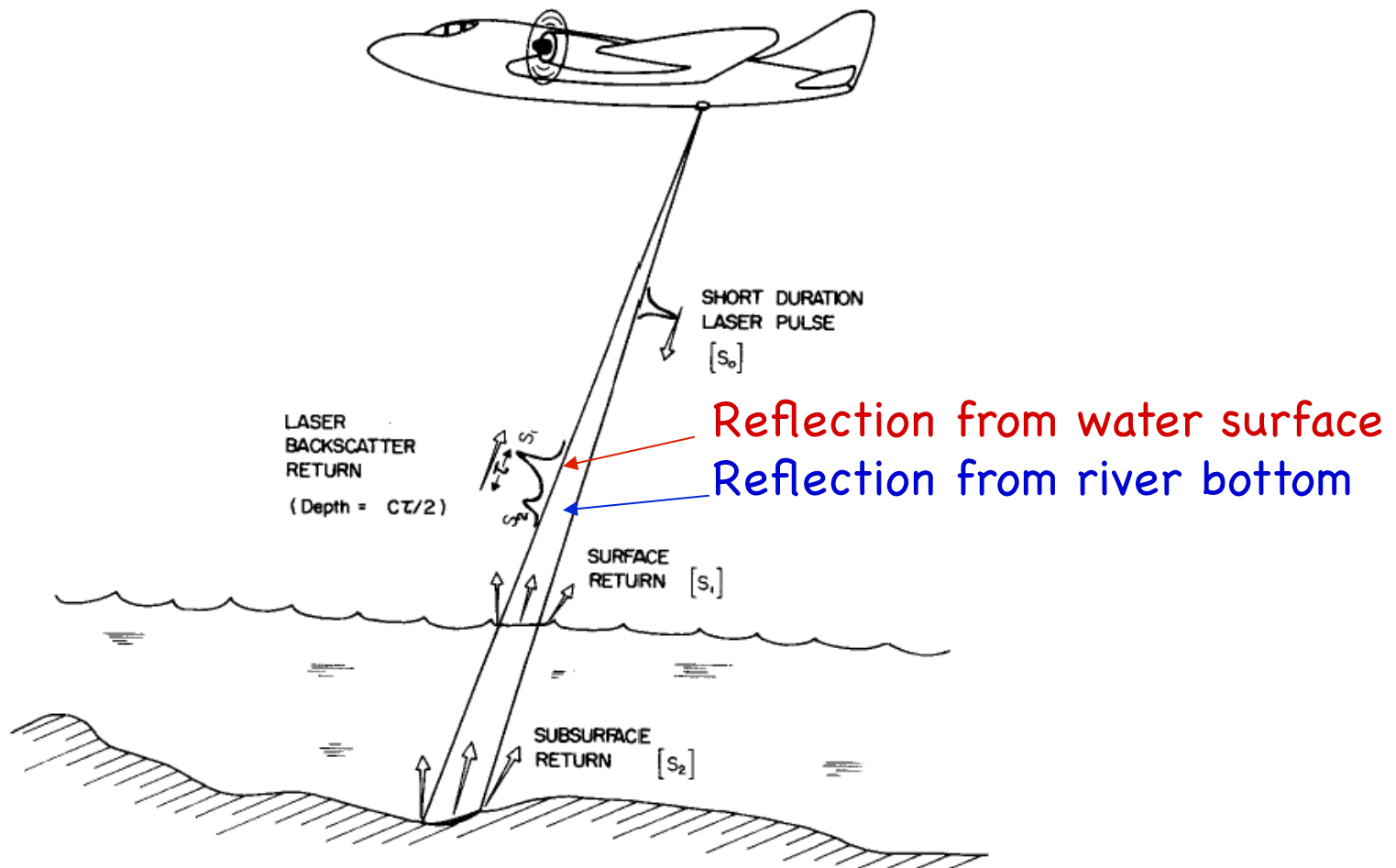
Principles and Applications

❑ The basic principle of active noncontact rangefinding systems is to project a wave (radio, ultrasonic, or optical) onto an object and process the reflected signal to determine its range.

❑ If a high-resolution rangefinder (especially spatial resolution) is needed, an optical source must be chosen because radio and ultrasonic waves cannot be focused adequately.

❑ Mainly there are three types of rangefinding techniques:
(1) Time of flight techniques: this is for the majority of laser rangefinder;
(2) Geometric-based technique: the classical triangulation by projection of a light beam onto a target;
(3) Optical interference rangefinding: Interferometry -- using interferometry principle to measure distance to high accuracy; Diffraction range measurement techniques: like speckle tech. and diffraction imaging.

❑ The main applications of laser rangefinding techniques, in addition to distance measurements, are bathymetry, obstacle detection for autonomous robots or car safety, nondestructive testing, level control, profilometry, displacement measurements, 3-D vision, and so on.

Time of Flight Rangefinding

❑ Time of flight technique: this is for the majority of laser range finders;

SHORT DURATION
LASER PULSE
$[s_o]$

LASER
BACKSCATTER
RETURN

(Depth = $C\tau/2$)

SURFACE
RETURN $[s_1]$

SUBSURFACE
RETURN $[s_2]$

Reflection from water surface
Reflection from river bottom

Rangefinding Techniques

❑ There are several different approaches to determine range, including the triangulation method with a very long history. We introduce three (or four) major rangefinding techniques.

(1) Time of flight techniques: these are for the majority of laser range finders and laser altimeters. Time of flight (TOF) is also used in all other atmosphere lidars to determine the range where scattering signals come from.

$$R = c \cdot \Delta t / 2$$

(2) Geometric–based technique: the classical triangulation by projection of a light beam onto a target.
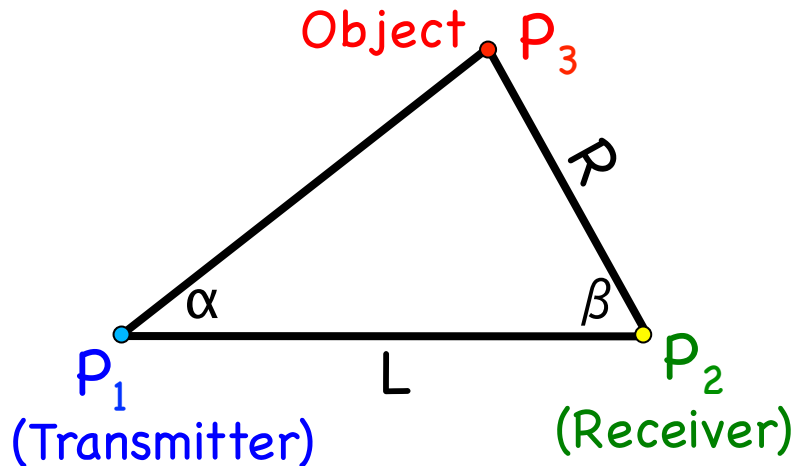
(3) Interferometry: using interferometry principle to measure distance to high accuracy; Diffraction range measurement techniques, like speckle tech. and diffraction imaging.

Geometric-Based Rangefinding

❑ Geometric–based rangefinding technique is a generalization of the classical triangulation method. By projection of a light beam onto a target, the range can be calculated from known geometry.

❑ Triangulation rangefinders all use the principles illustrated below:

Object P_3

R

α β

P_1 L P_2

(Transmitter)

(Receiver)

From the law of sines, we have

$$\frac{R}{\sin\alpha} = \frac{L}{\sin\left[180° - (\alpha + \beta)\right]} = \frac{L}{\sin(\alpha + \beta)}$$

The range R is given by the range formula
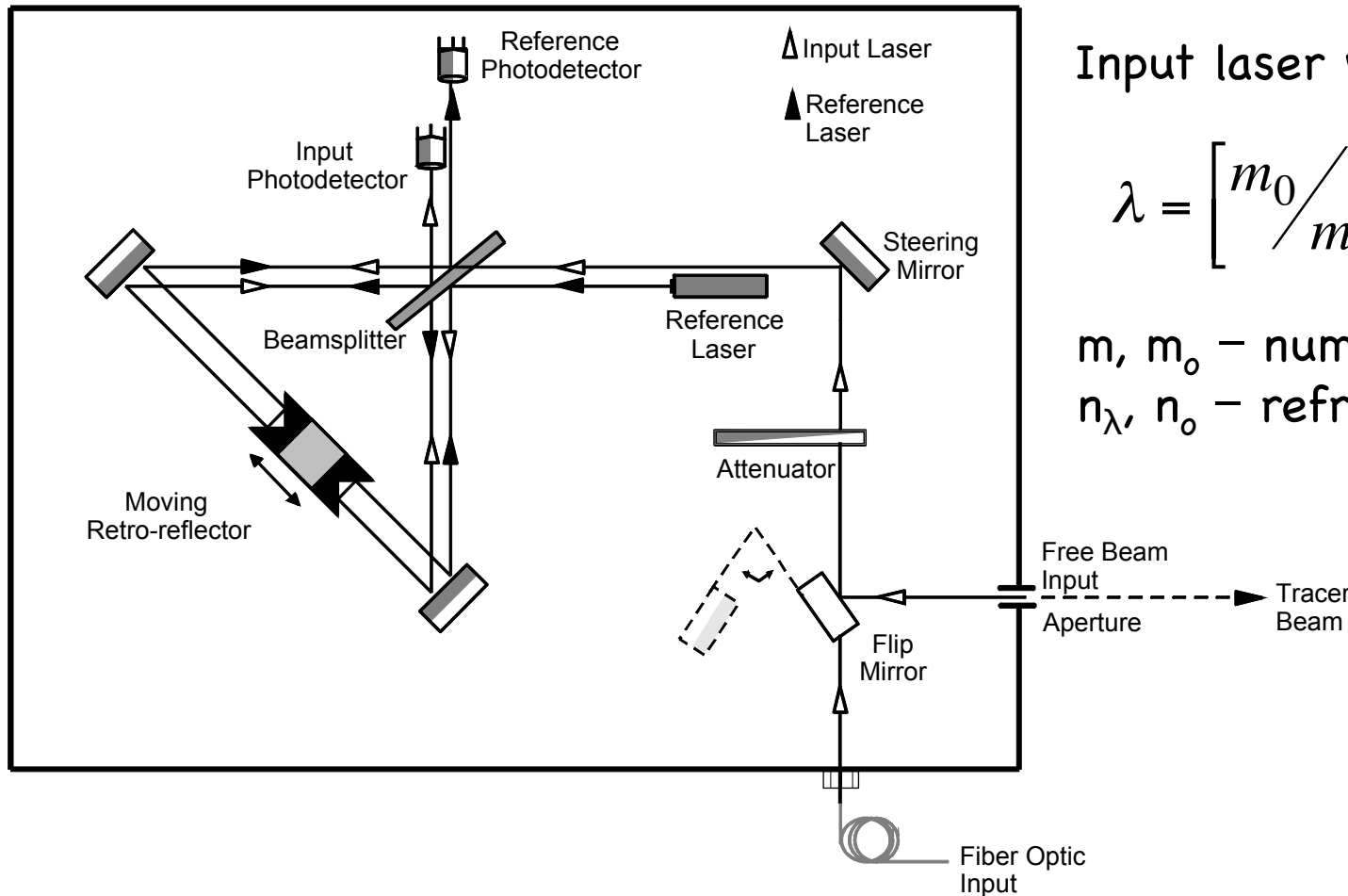
$$R = \frac{L\sin\alpha}{\sin(\alpha + \beta)}$$

The range error formula is

$$\Delta R \approx \frac{R^2}{L\sin(\beta)}(\Delta\alpha + \Delta\beta)$$

[Pipitone and Marshall, J. Robotics Res., 1983]

Interferometry Rangefinding

❑ Interferometry: using interferometry principle to measure distance to high accuracy, e.g., using Michelson interferometer

Input laser wavelength λ

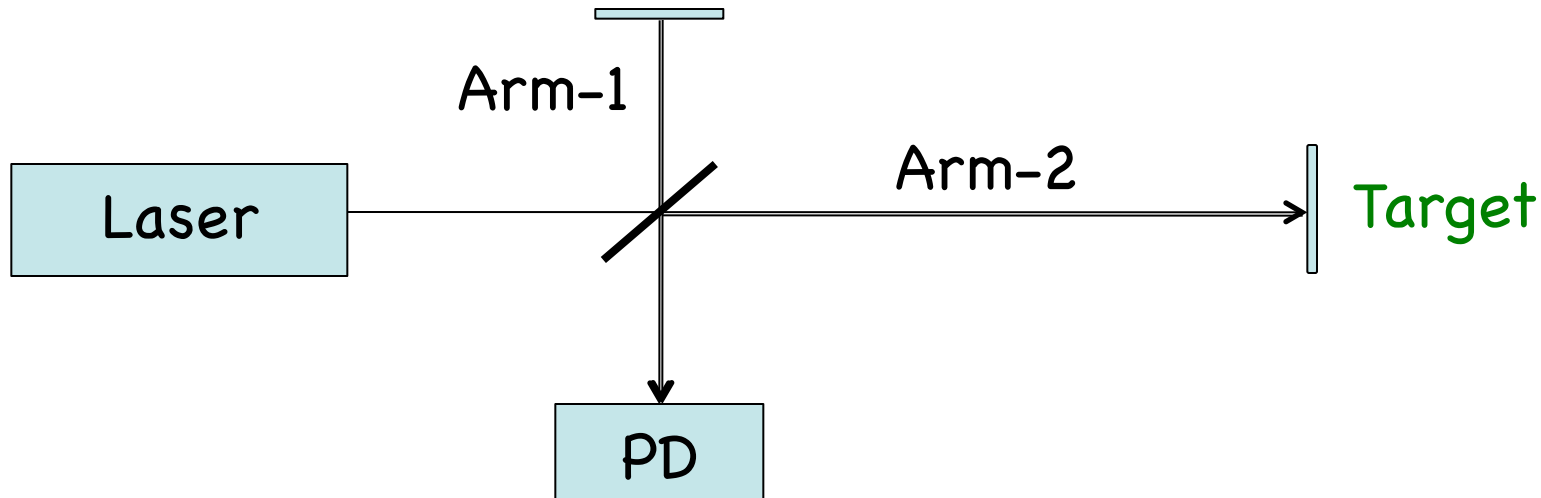$$\lambda = \left[\frac{m_0}{m}\right]\left[\frac{n_\lambda}{n_0}\right]\lambda_0$$

m, m_o − number of fringes
n_λ, n_o − refractive index

Michelson interferometer for cw laser wavelength measurements

Interferometry Rangefinding

❑ Michelson interferometer for laser rangefinding

Arm–1

Laser

Arm–2

Target

PD

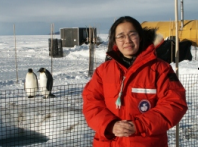Single wavelength: phase difference between two arms

$$\phi = \frac{2\pi}{\lambda} 2nL$$

$$L = m(\lambda/2) + \varepsilon$$

Pre-known range   Range change

Multiple wavelengths $\Delta\phi = 2nL(\frac{2\pi}{\lambda_2} - \frac{2\pi}{\lambda_1}) = 2nL \cdot \frac{2\pi}{\lambda_1\lambda_2/(\lambda_2 - \lambda_1)}$
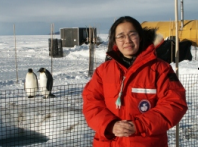
Interferometry Rangefinding

❑ Both interferometry and diffraction techniques utilize the multiple beam interference principles to generate interference fringes or diffraction patterns. By counting the phase difference caused by path difference, small range or range change can be determined to very precise degree. However, if only single wavelength is used, range ambiguity will occur beyond half of the laser wavelength (λ/2) range.

❑ To increase the range of detection or say to remove the range ambiguity, multiple wavelengths are used to generate various longer wavelength, called synthetic wavelength. For example, using two wavelengths λ_1 and λ_2, the synthetic wavelength is given by
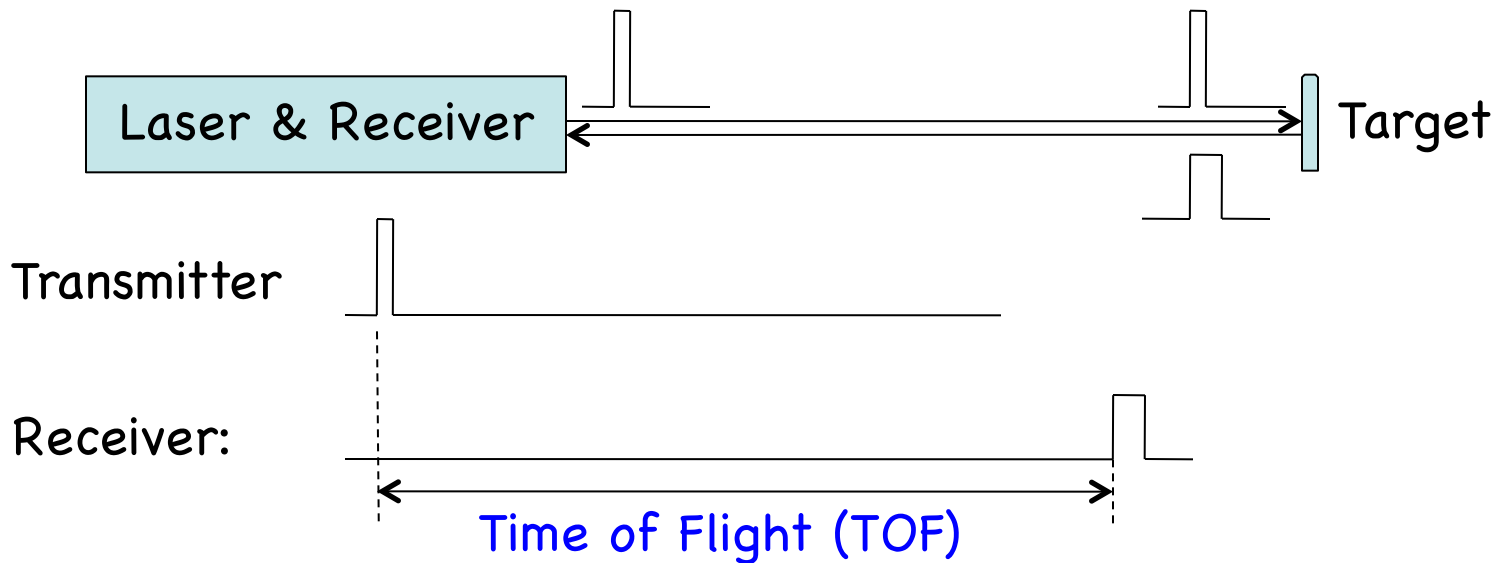
$$\lambda = \frac{\lambda_1 \lambda_2}{(\lambda_2 - \lambda_1)}$$

❑ By adjusting λ_1 and λ_2 values, the synthetic wavelength λ can be much larger than the original two wavelengths. Thus, the range to be determined without ambiguity can be enlarged to λ/2.

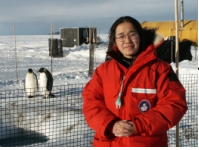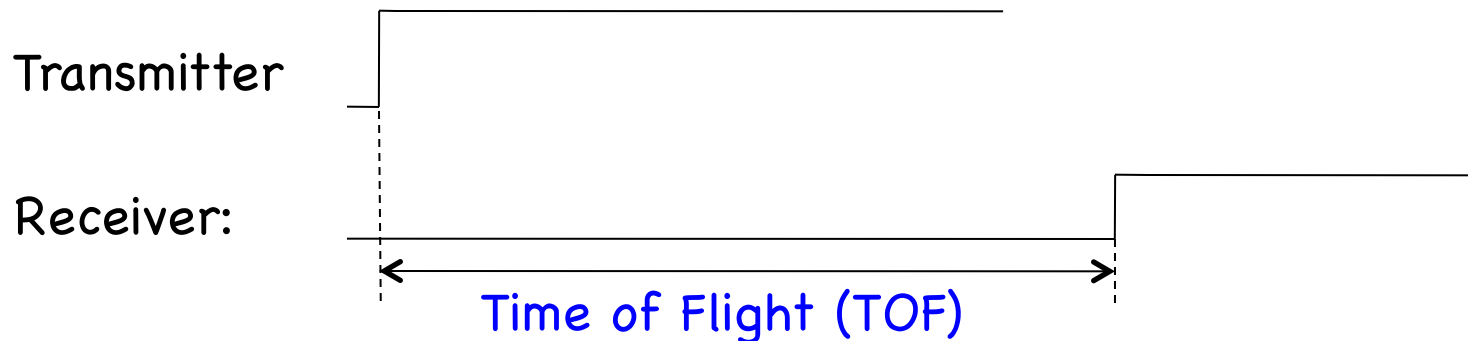# Time Of Flight (TOF) Rangefinding

➢ Pulsed laser TOF rangefinding:

Laser & Receiver   Target

Transmitter

Receiver:

Time of Flight (TOF)

How about if the laser is a very long pulse?

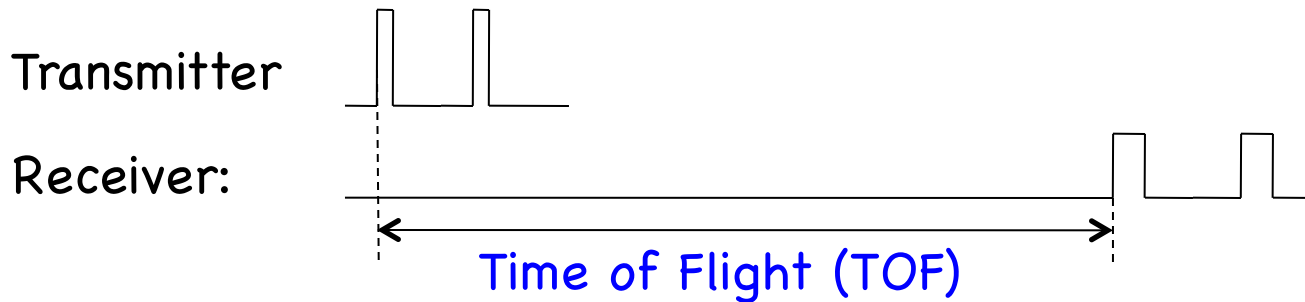Transmitter

Receiver:

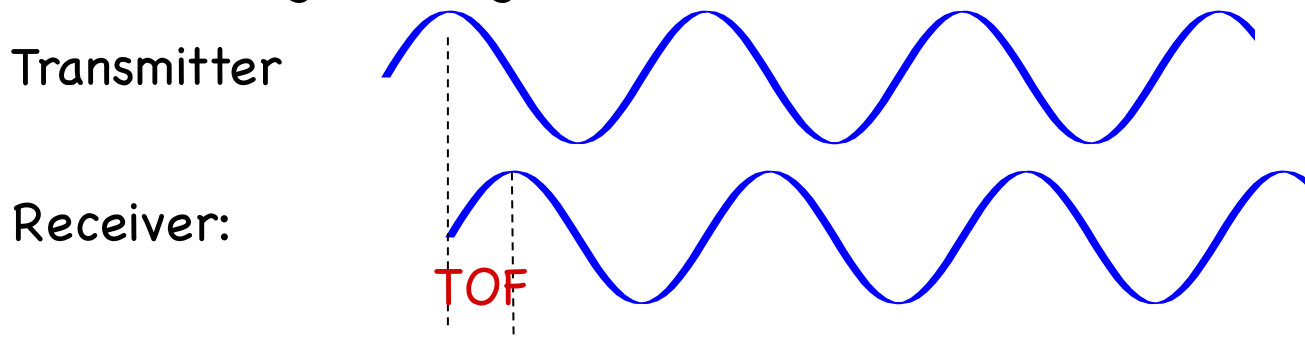Time of Flight (TOF)

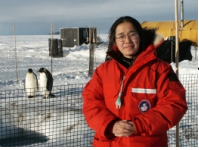# Time Of Flight (TOF) Rangefinding

➢ **Phase-shifting rangefinding technique:** CW amplitude modulation

How about if you are given a cw laser, not pulsed?

Solution 1: Chop the cw laser beam to a pulsed laser beam

Transmitter

Receiver:

Time of Flight (TOF)

Solution 2: Modulate continuous wave amplitude, and then shift the received signals in time to maximize the correlation between the transmitted and received light. Random coding can help remove ambiguity when the range is longer than half of the modulation frequency/λ.

Transmitter

Receiver:

TOF

Time Of Flight (TOF) Rangefinding

➢ CW laser chirp: linear variation of frequency with time, and then take the beat frequency to determine TOF
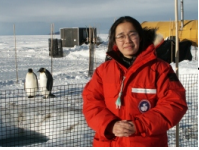

$f_{return} = f_0 + K\,t$
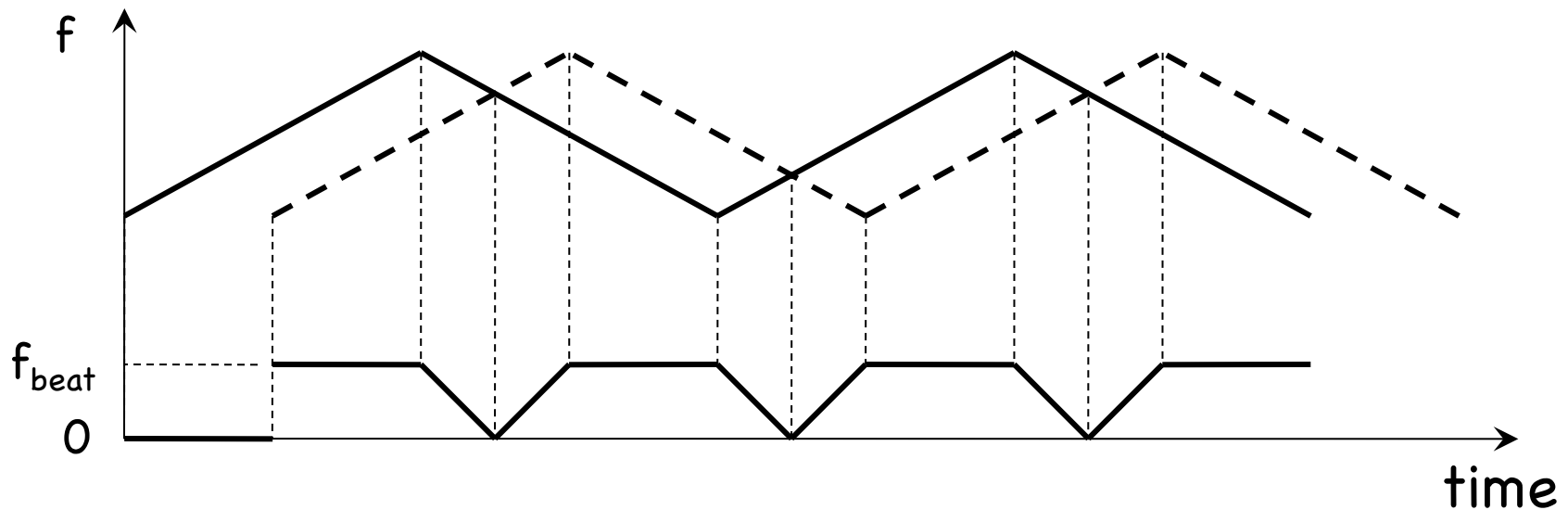
$f_{transmitter} = f_0 + K\,(t + \Delta t)$

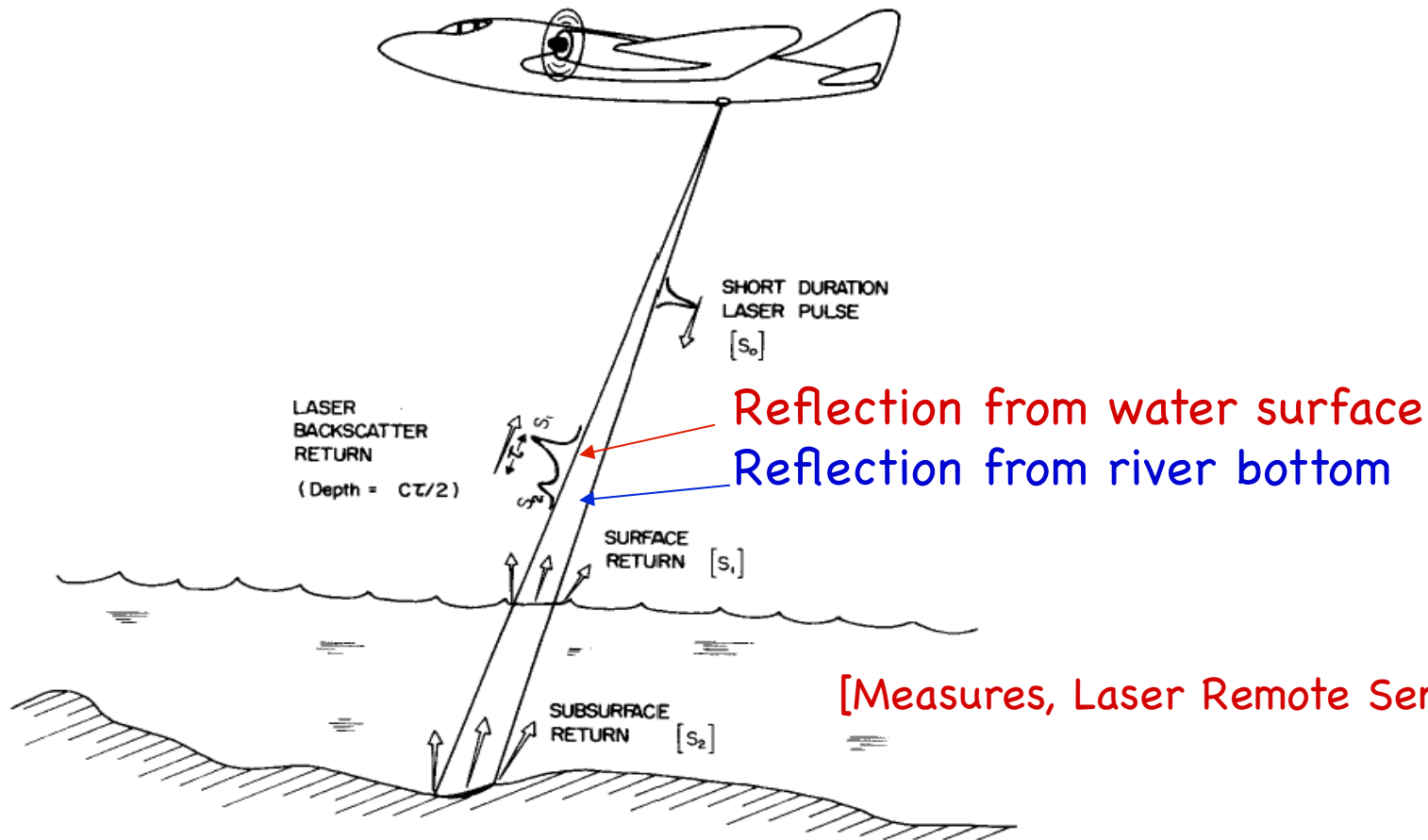$\Longrightarrow$ $f_{beat} = f_{transmitter} - f_{return} = K\,\Delta t$

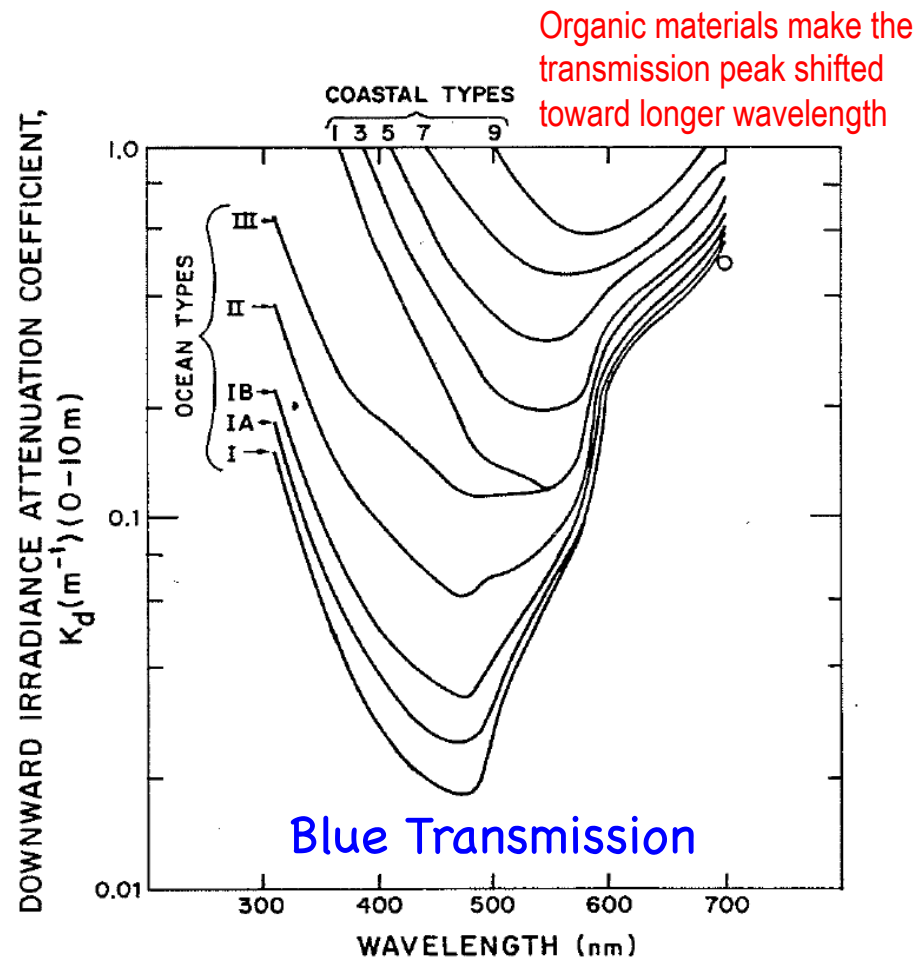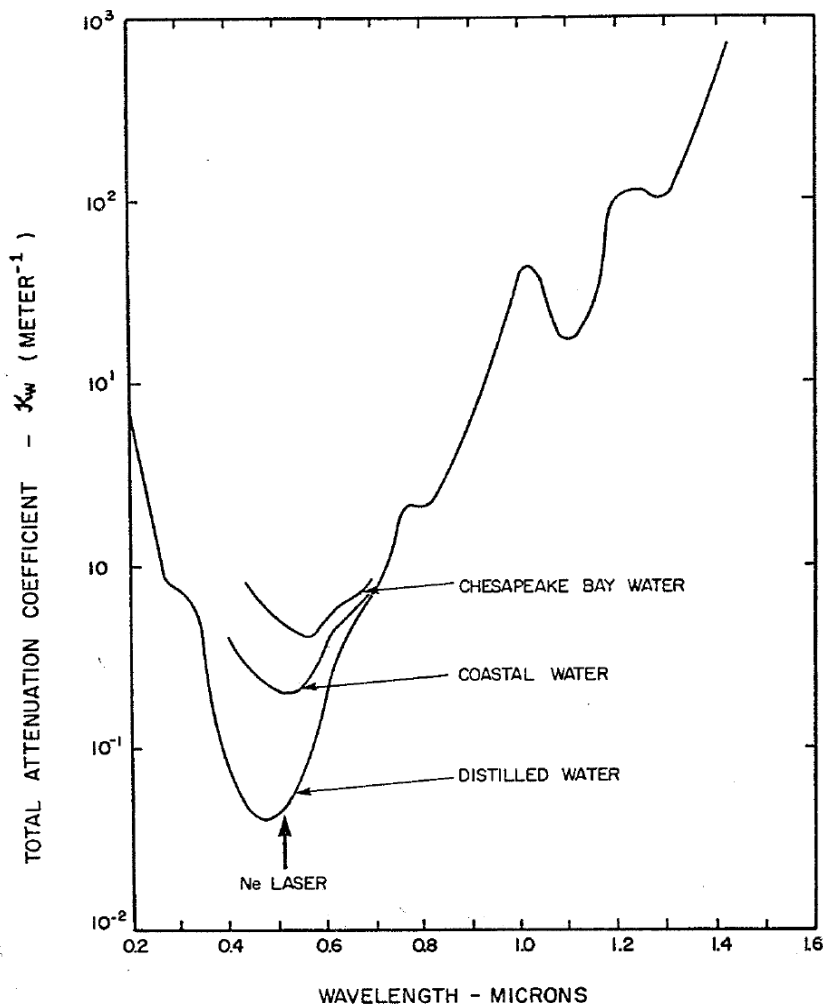$\Longrightarrow$ $\Delta t = f_{beat}\,/\,K$

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.

SHORT DURATION
LASER PULSE
$[S_0]$

Reflection from water surface
Reflection from river bottom

LASER
BACKSCATTER
RETURN

(Depth = $C\tau/2$)

S_i

SURFACE
RETURN $[S_1]$

SUBSURFACE
RETURN $[S_2]$

[Measures, Laser Remote Sensing, 1984]

Water Transmission vs. Wavelength

Organic materials make the transmission peak shifted toward longer 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.
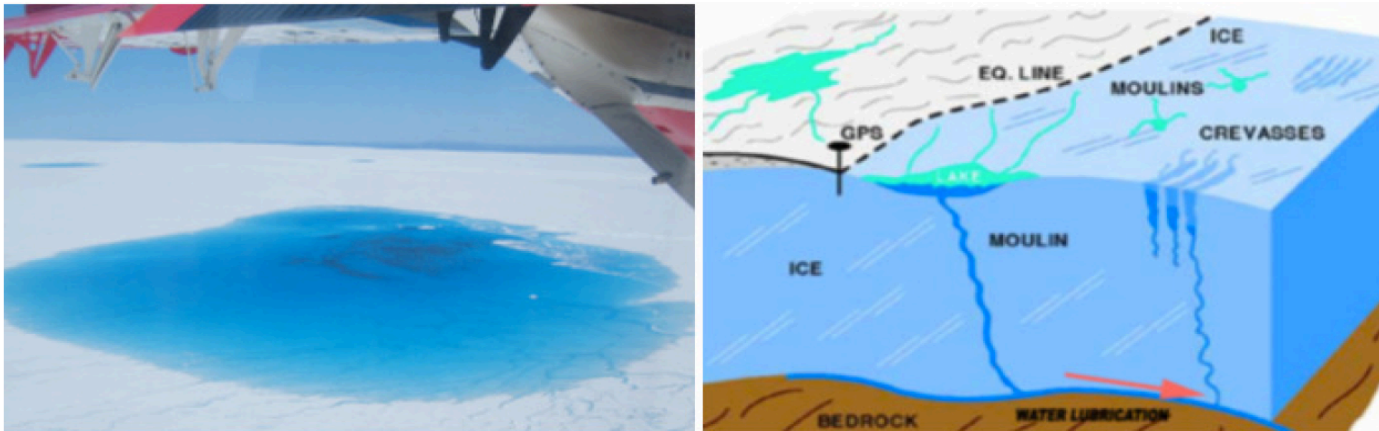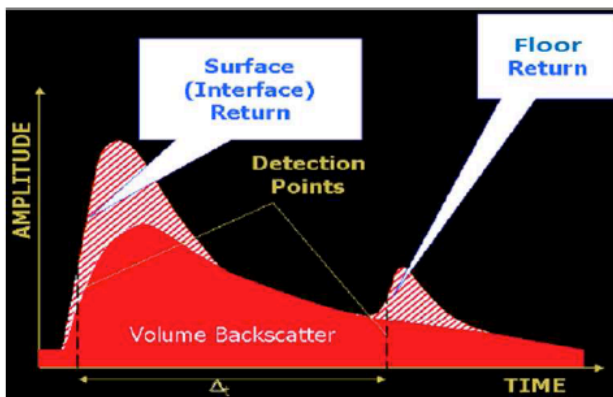

Figure 2.4: Aerial view of a typical glacial meltpond (left) [photo *S. Das*]; illustration of a meltpond and drainage route through a moulin (right) [*Zwally et. al.*, 2002]

[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).
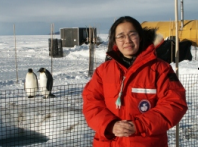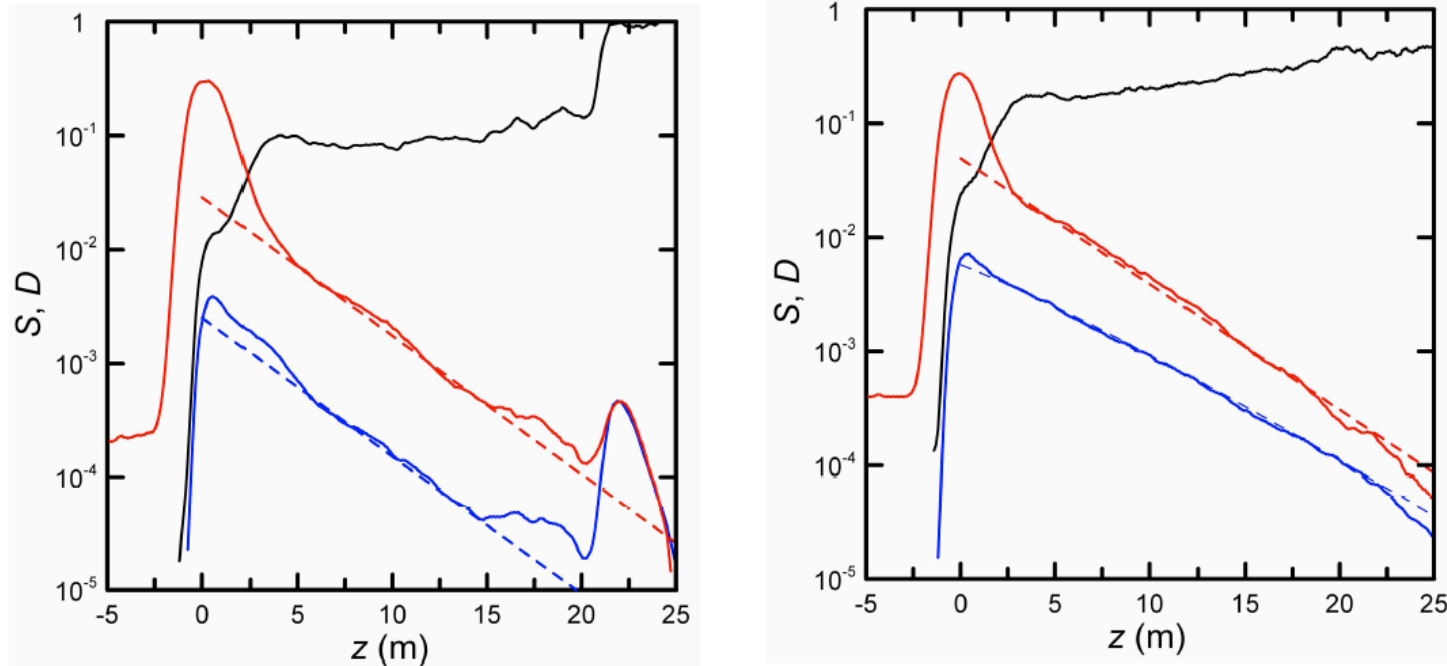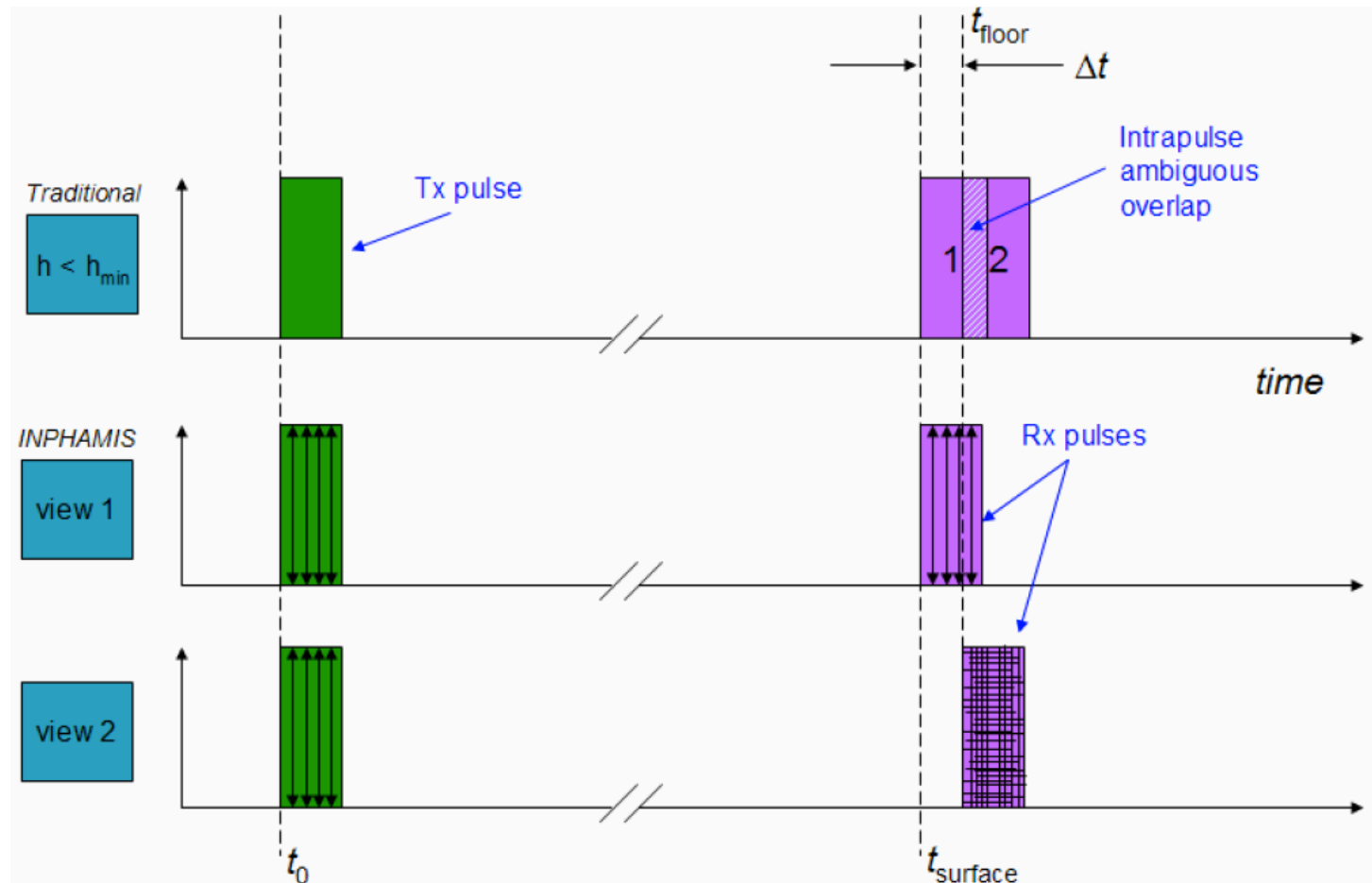

Fig.4. Typical depth profiles of the co-polarized return S_C (red), cross-polarized return S_X (blue), and depolarization D (black). The solid lines are measured values, and the dashed lines are the theoretical profiles from Eq. (8). The left panel is from the near-shore region. The large, unpolarized 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}
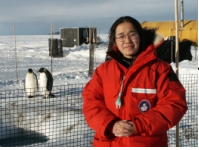
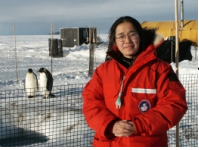# Comparison between Traditional and Polarization Bathymetry

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

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

Summary

❏ Laser rangefinding is an important lidar category, and it finds many fantastic applications in science research, environment monitoring, industry, daily life. It has various names like laser rangefinder, laser altimeter, lidar bathymetry, ladar, etc., depending on actual applications.

❏ Different rangefinding applications have different challenges, e.g., tiny motion/range change vs. absolute altitude determination, long-path penetration vs. shallow-water discrimination, etc.

❏ Geometric-based triangulation laser rangefinding, optical interference rangefinding (interferometer vs. diffraction), and time of flight (TOF) are the three major categories of laser rangefinding.

❏ There are various TOF techniques, in addition to a traditional single-channel pulsed-laser-based lidar TOF. Multiple channels with distinctly different features (e.g., polarization) can be used to determine TOF with resolutions higher than the pulse width. CW laser amplitude modulation, CW laser frequency chirp, etc. all can be used to determine fine and long range (TOF). Keep an open mind to more possibilities.