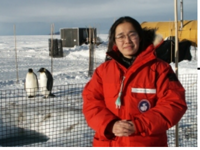
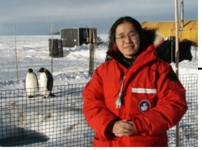


Lecture 39. Lidar Bathymetry & Analog and Digital Detection of Light

- Review: Rangefinding Techniques
  - Pulsed laser rangefinding
  - Phase shifting rangefinding / CW laser amplitude modulation
  - CW laser chirp / Chirp pulse compression
- Lidar Bathymetry
  - Challenges for deep or costal water
  - Challenges for shallow water
  - Polarization applications in bathymetry
- Analog Detection vs. Photon Counting
  - Challenges of photo-detection in lidar



Rangefinding Techniques

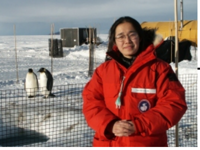
❑ There are several different approaches to determine range, including the triangulation method with a very long history. We introduce three (or four) major rangefinding techniques.

(1) Geometric-based technique: the classical triangulation by projection of a light beam onto a target.

(2) Interferometry: using interferometry principle to measure distance to high accuracy; Diffraction range measurement techniques, like speckle tech. and diffraction imaging.

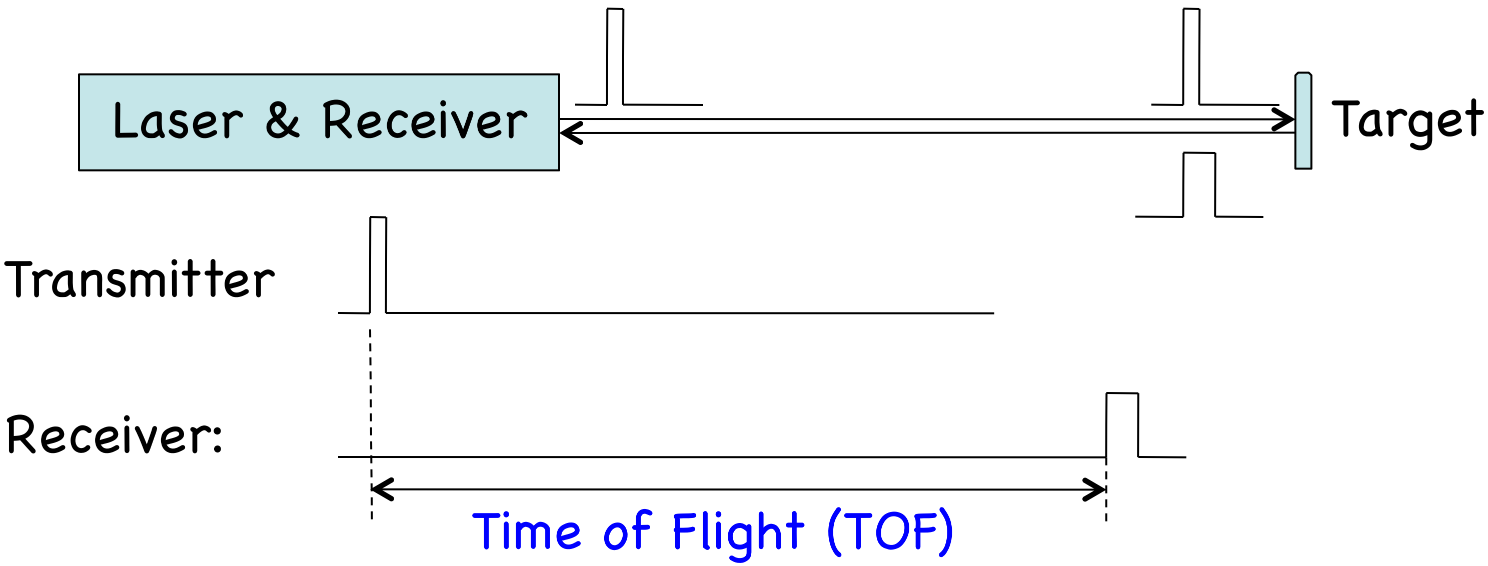
(3) Time of flight techniques: these are for the majority of laser range finders and laser altimeters. Time of flight (TOF) is also used in all other atmosphere lidars to determine the range where scattering signals come from. There are various ways to measure the time of flight.

$$\boxed{R = c \cdot \Delta t / 2}$$

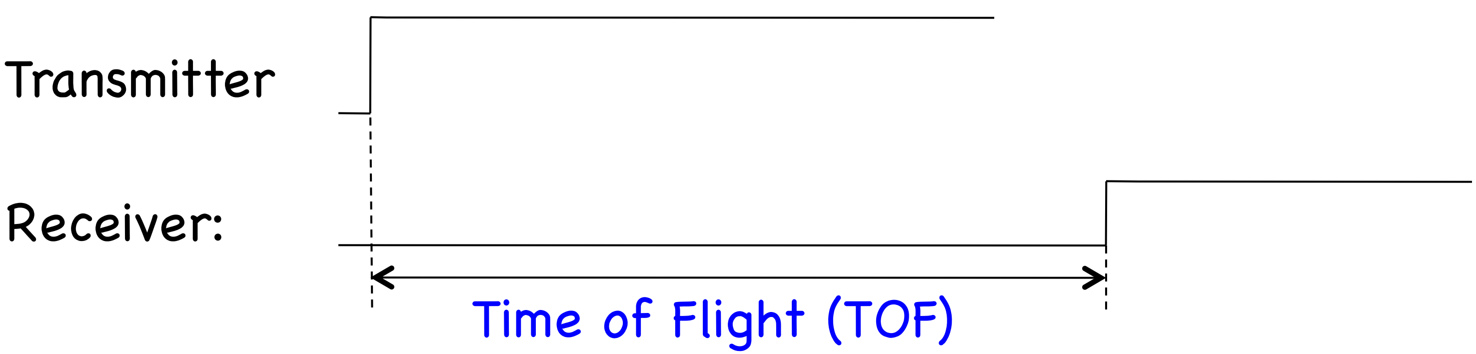


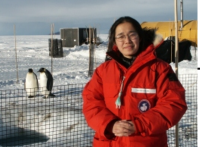
Time Of Flight (TOF) Rangefinding

- Pulsed laser TOF rangefinding:



How about if the laser is a very long pulse?



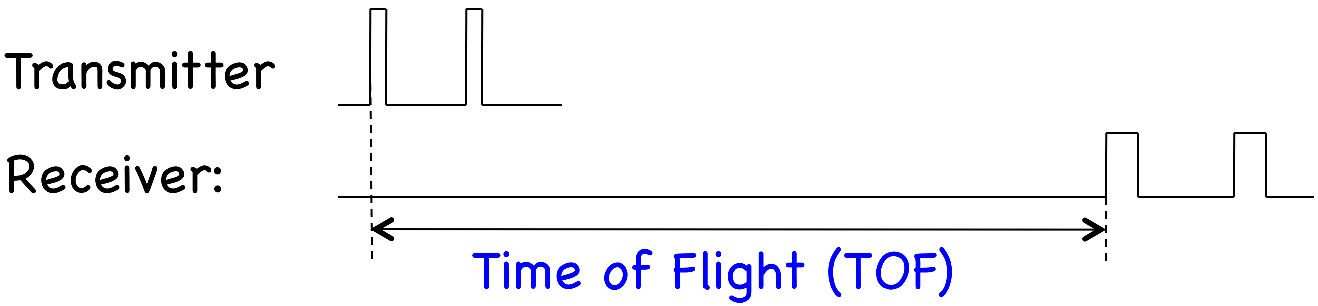


Time Of Flight (TOF) Rangefinding

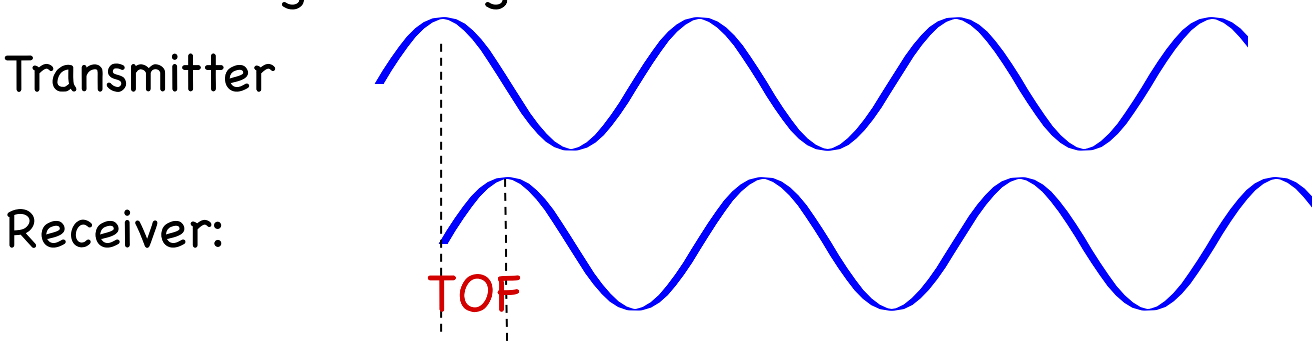
- Phase-shifting rangefinding technique: CW amplitude modulation

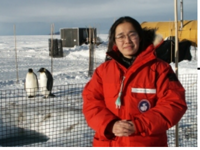
How about if you are given a cw laser, not pulsed?

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



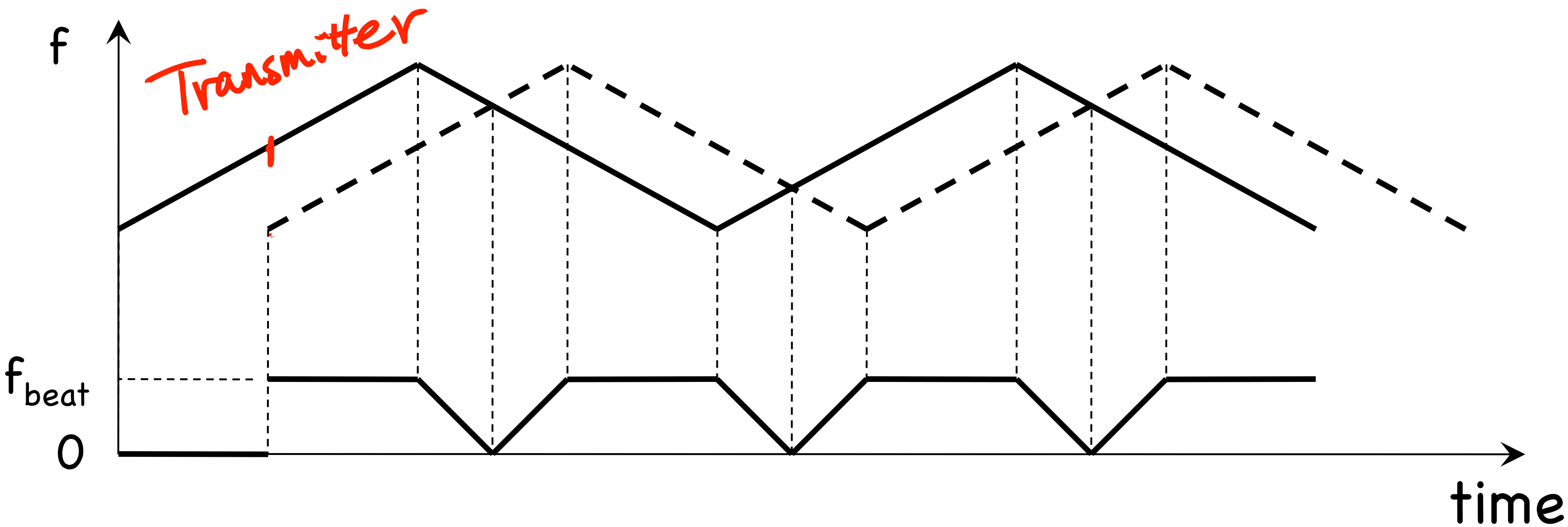
Solution 2: Modulate continuous wave amplitude, and then shift the received signals in time to maximize the correlation between the transmitted and received light. Random coding can help remove ambiguity when the range is longer than half of the modulation frequency/λ.





Time Of Flight (TOF) Rangefinding

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

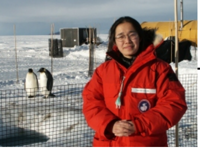


$$f_{return} = f_0 + K\,t$$

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

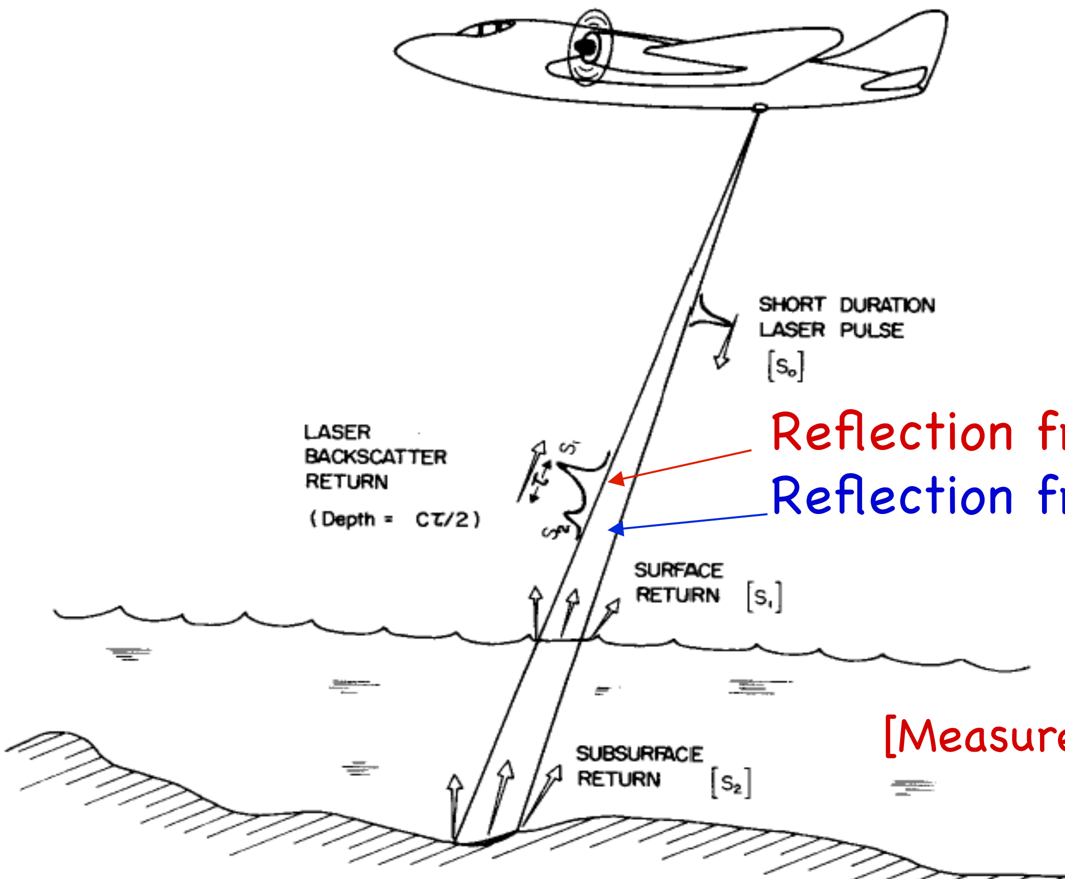
$$\Rightarrow \quad f_{beat} = f_{transmitter} - f_{return} = K\,\Delta t$$

$$\Rightarrow \quad \Delta t = f_{beat} / K$$



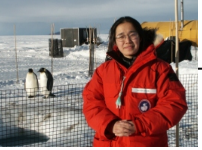
Lidar Bathymetry

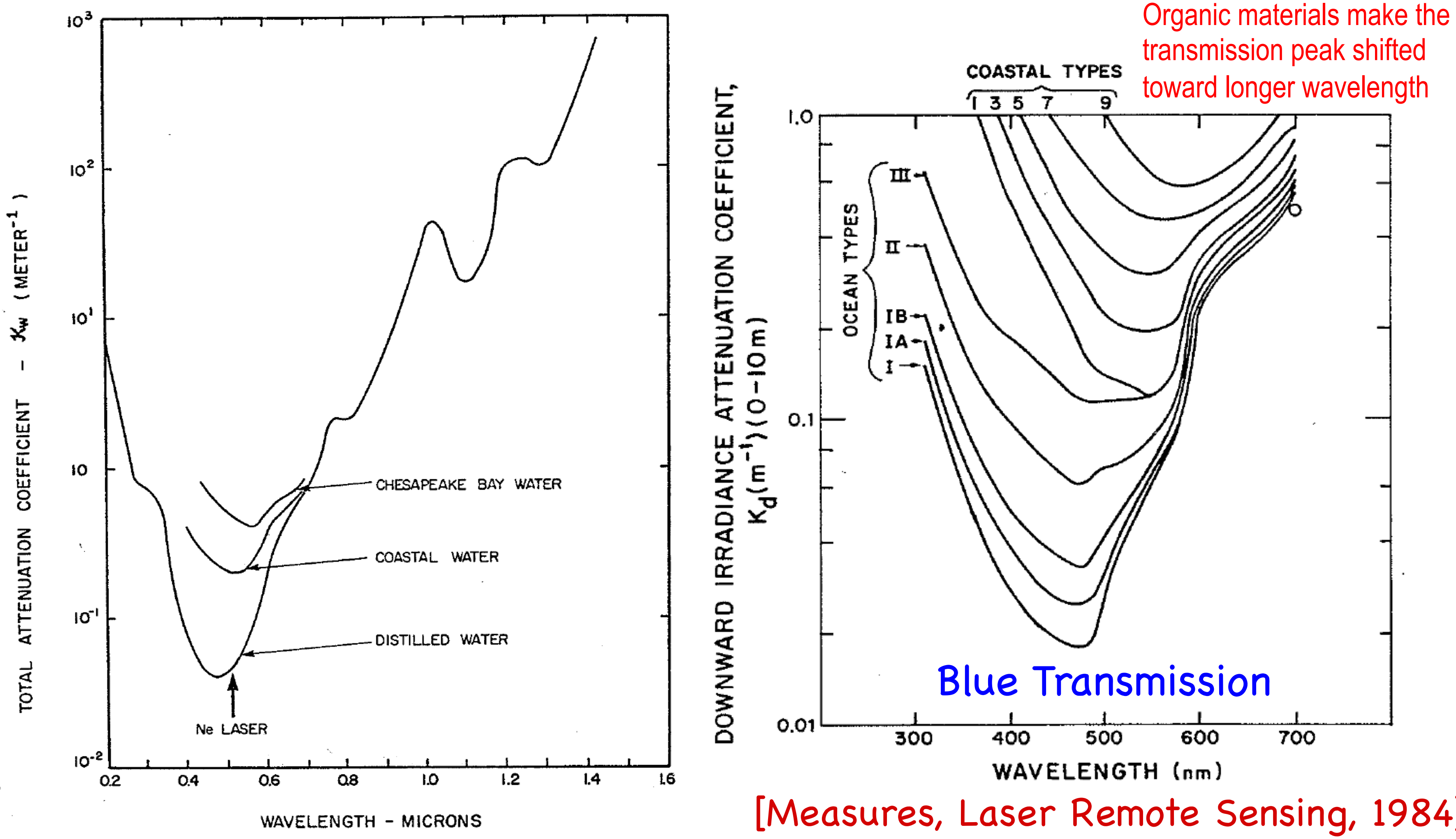
- Lidar bathymetry can face issues different than other laser altimeters: One is the laser penetration of any water body when dealing with deep water or costal water, and another is to deal with shallow water when the water depth is comparable to or smaller than the laser pulse width.



[Measures, Laser Remote Sensing, 1984]

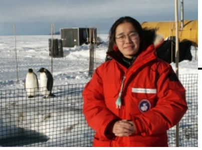
Water Transmission vs. Wavelength





[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.

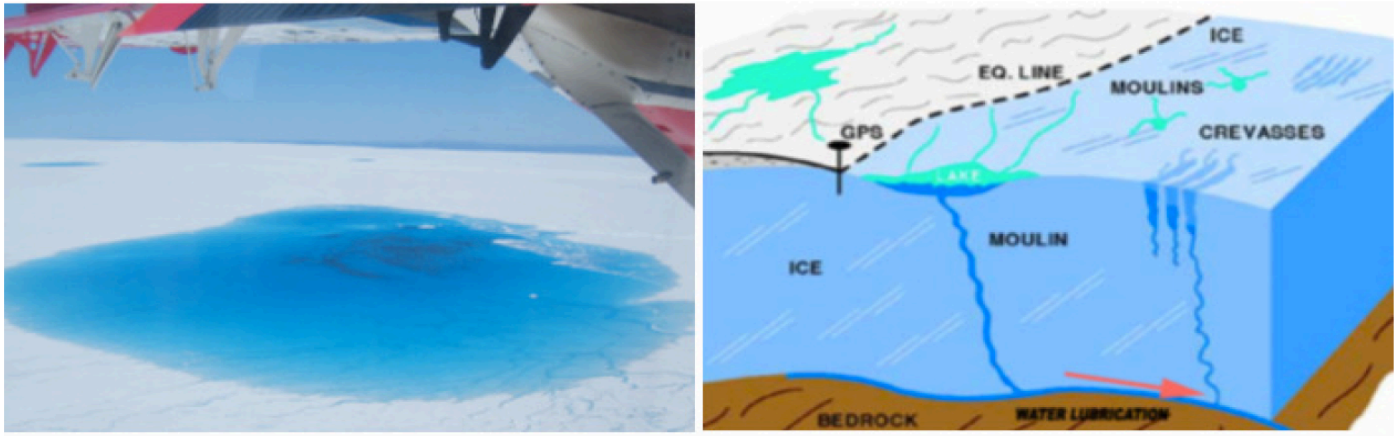
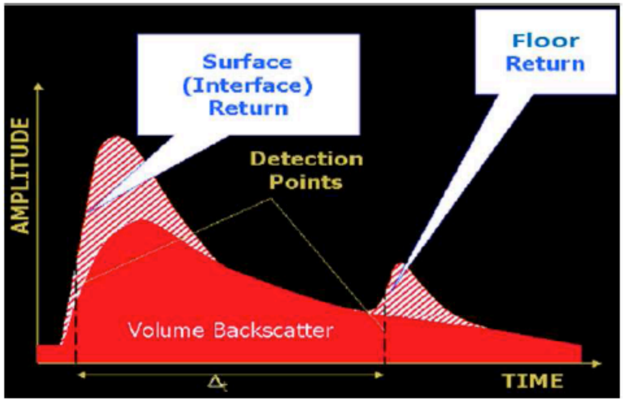
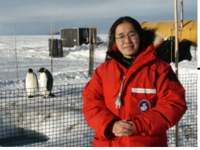


Figure 2.4: Aerial view of a typical glacial meltpond (left) [photo *S. Das*]; illustration of a meltpond and drainage route through a moulin (right) [*Zwally et. al.*, 2002]



[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).

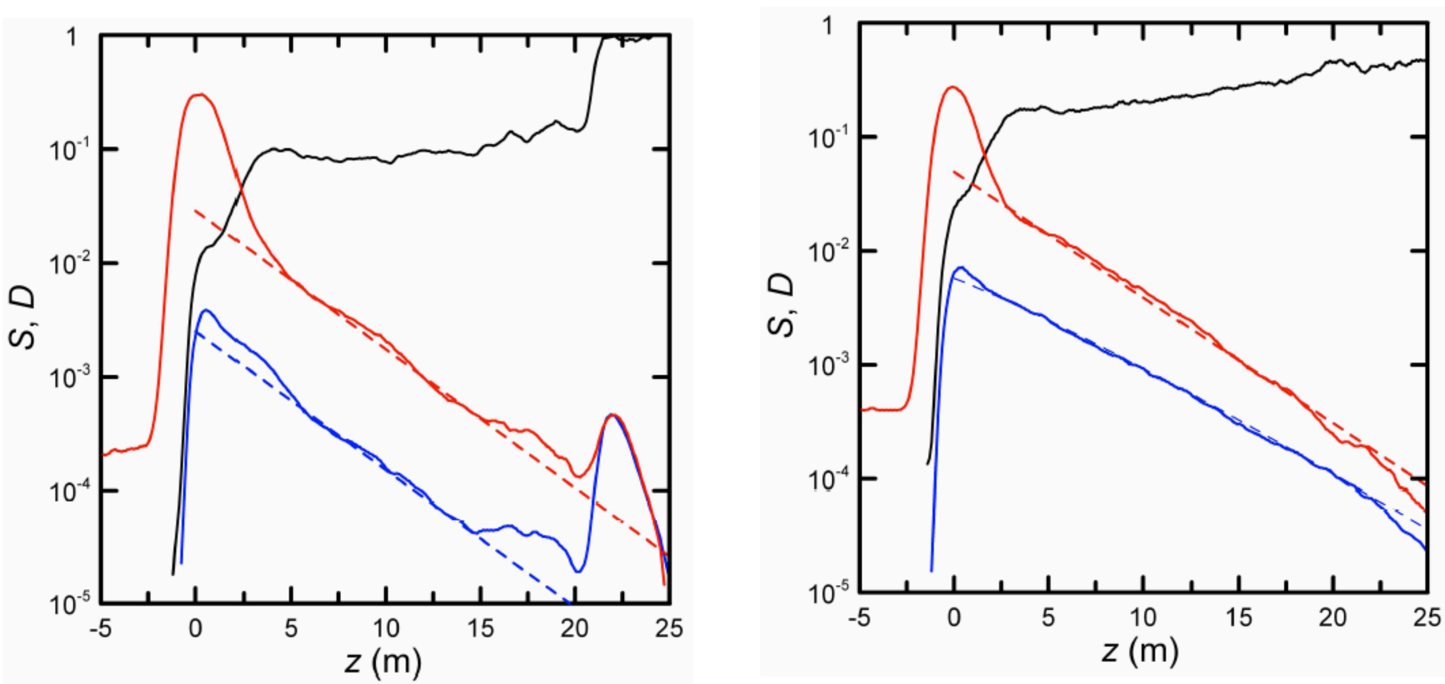


Fig.4. Typical depth profiles of the co-polarized return S_C (red), cross-polarized return S_X (blue), and depolarization D (black). The solid lines are measured values, and the dashed lines are the theoretical profiles from Eq. (8). The left panel is from the near-shore region. The large, unpolarized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

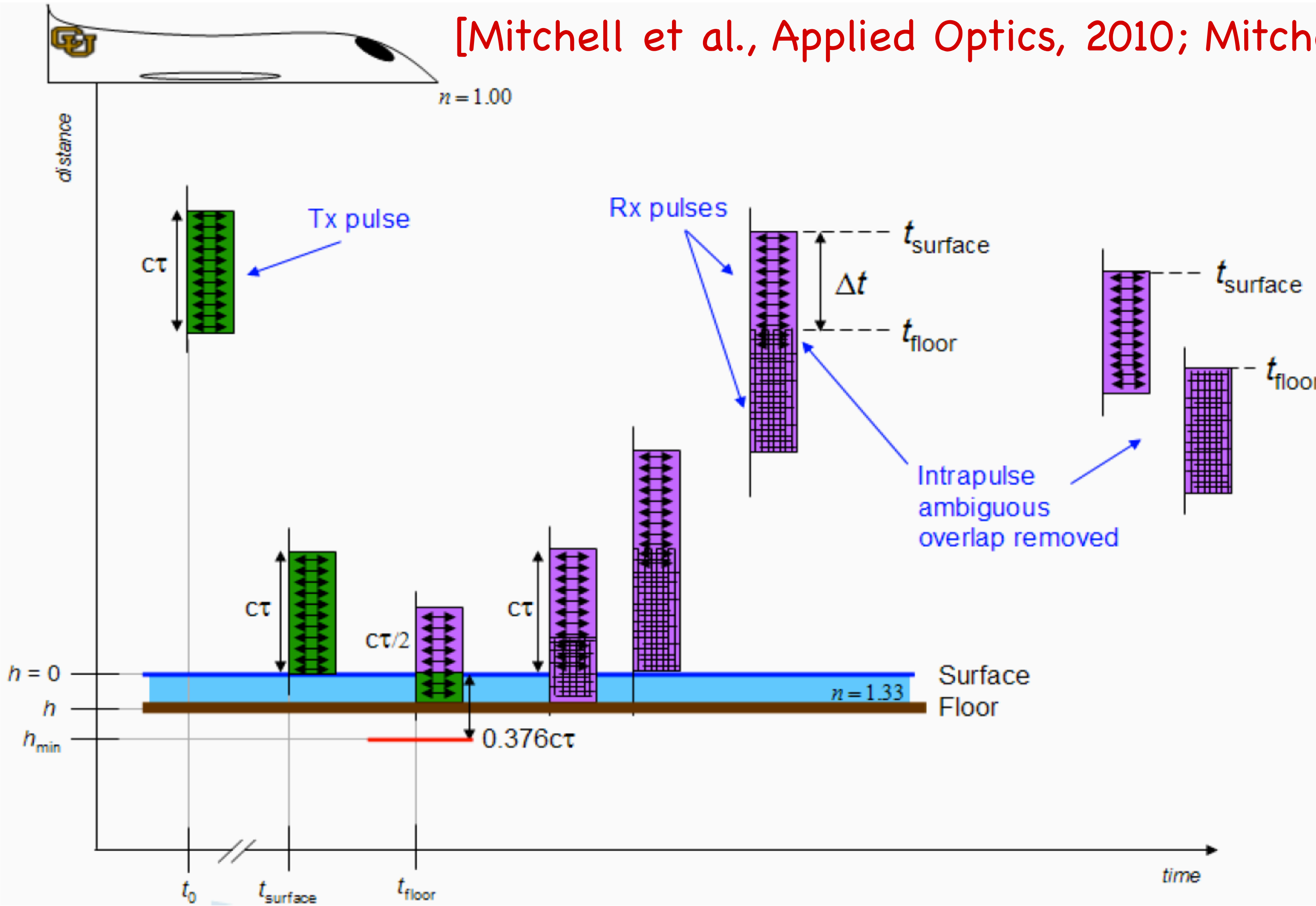
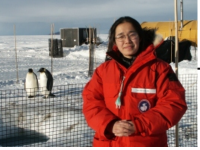
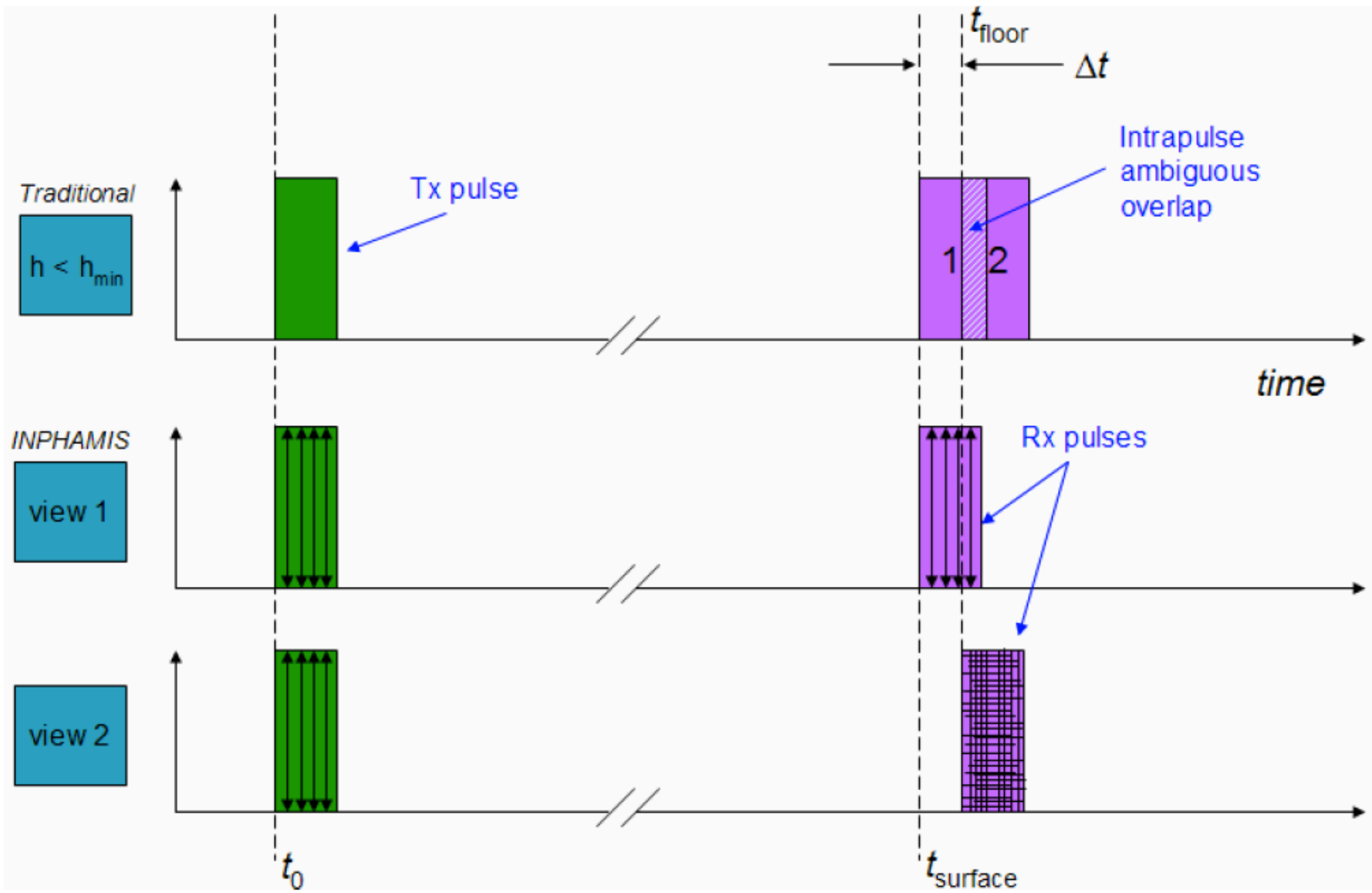


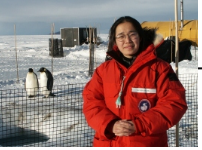
Figure 3.2: Incorporation of polarization discrimination into bathymetry lidar enables the instrument to measure water depths shallower than h_{min}



Comparison between Traditional and Polarization Bathymetry



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



More Considerations on Bathymetry

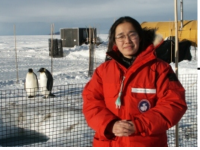
- Waveform recoding and digitizing

- 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



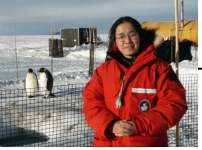
Summary

- 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.

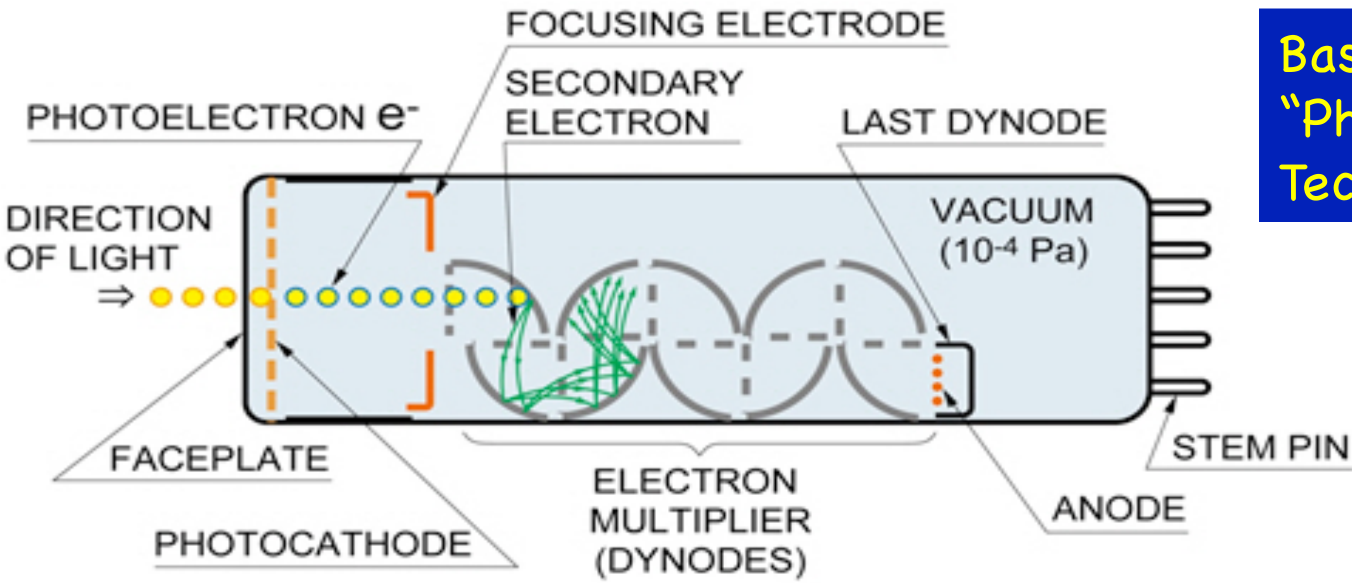
- Geometric-based triangulation laser rangefinding, optical interference rangefinding (interferometer vs. diffraction), and time of flight (TOF) are the three major categories of laser rangefinding.

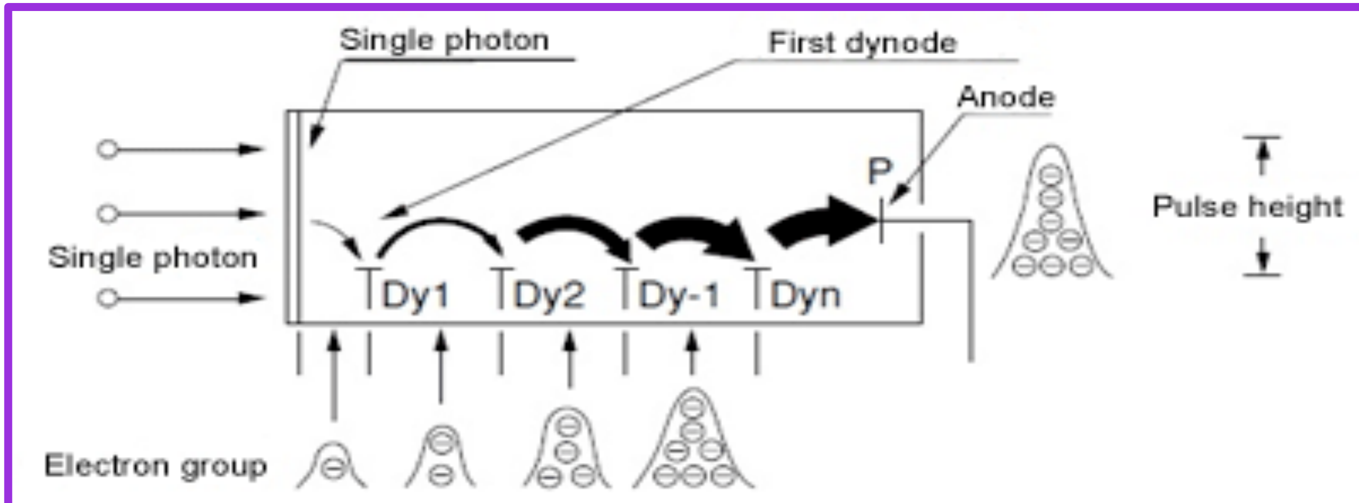
- There are various TOF techniques, in addition to a traditional single-channel pulsed-laser-based lidar TOF. Multiple channels with distinctly different features (e.g., polarization) can be used to determine TOF with resolutions higher than the pulse width. CW laser amplitude modulation, CW laser frequency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

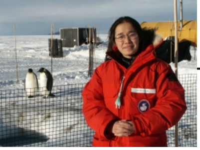


Photomultiplier Tube (PMT) for Photon/Light Detection

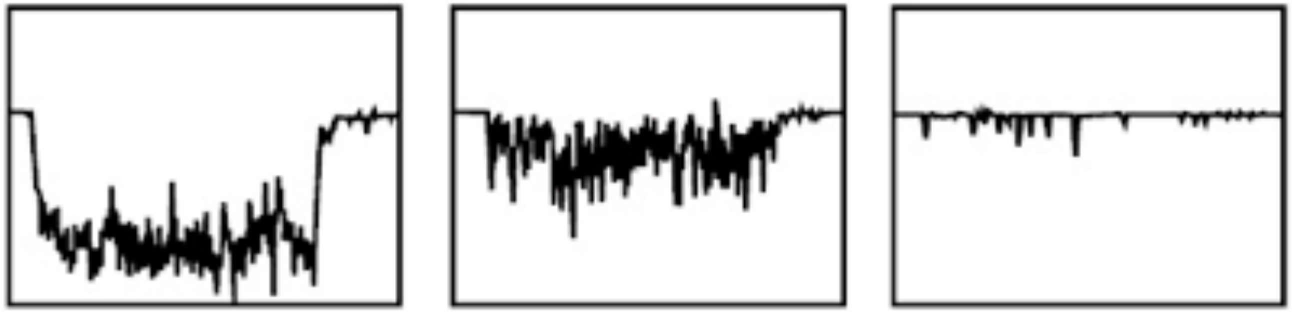
Based on Hamamatsu "Photon Counting" Technological Paper





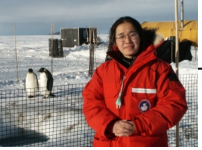


PMT Output Waveforms Observed at Different Light Levels



(a) High (b) Low (c) Very low

- In analog mode, the output signal is the mean value (or integration) of the signals including the AC components shown in (a). In contrast, the photon counting can detect each pulse shown in (c), so the number of counted pulses equals the signal.
- This photon counting mode uses a pulse height discriminator that separates the signal pulses from the noise pulses, enabling high-precision measurements with a higher signal-to-noise ratio compared to the analog mode and making photon counting exceptionally effective in detecting low level light.



Parameters in PMT Photon Counting

Quantum Efficiency (QE) is the ratio of the number of photoelectrons emitted from the photocathode to the number of incident photons per unit time.

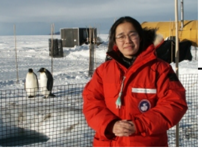
$$QE = \frac{\text{number of photoelectrons emitted from photocathode}}{\text{number of incident photons}}$$

Collection Efficiency (CE) is the probability that the primary photoelectrons will impinge on the first dynode and contribute to gain.

Detection Efficiency (DE) is the ratio of the number of counted pulses (output pulses) to the number of incident photons.

$$DE = \frac{\text{number of counted pulses}}{\text{number of incident photons}} = QE \times CE = \eta_{QE} \times \alpha$$

Quantum Efficiency (QE)	X	Collection Efficiency (CE)	=	Detection Efficiency (DE)

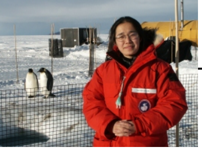


Photon Counting vs. Analog Detection

Analog detection is suitable for high-level light detection.

Photon counting is suitable for very-low-level light detection, ideally in the single photoelectron region.

The goals are to maximize the signal to noise ratio (SNR) and achieve the most sensitive detection of light.



Principles of Photon Counting

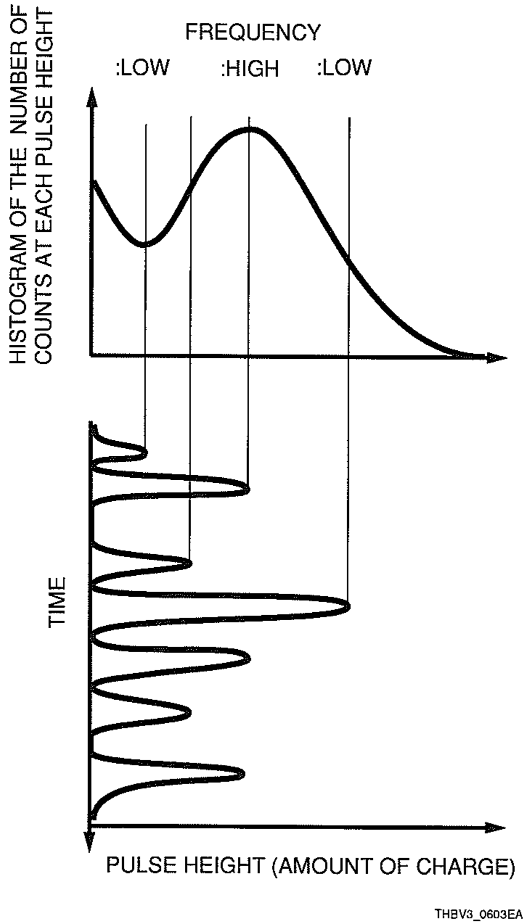
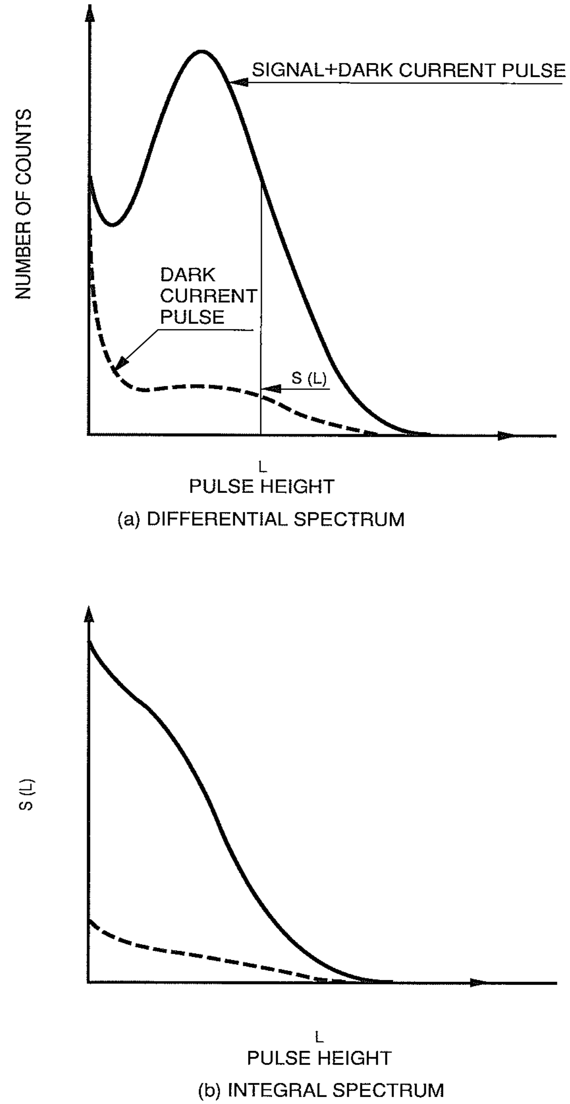
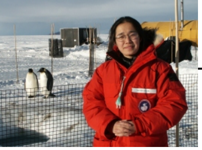


Figure 6-3: Photomultiplier tube output and its pulse height distribution





Principles of Photon Counting

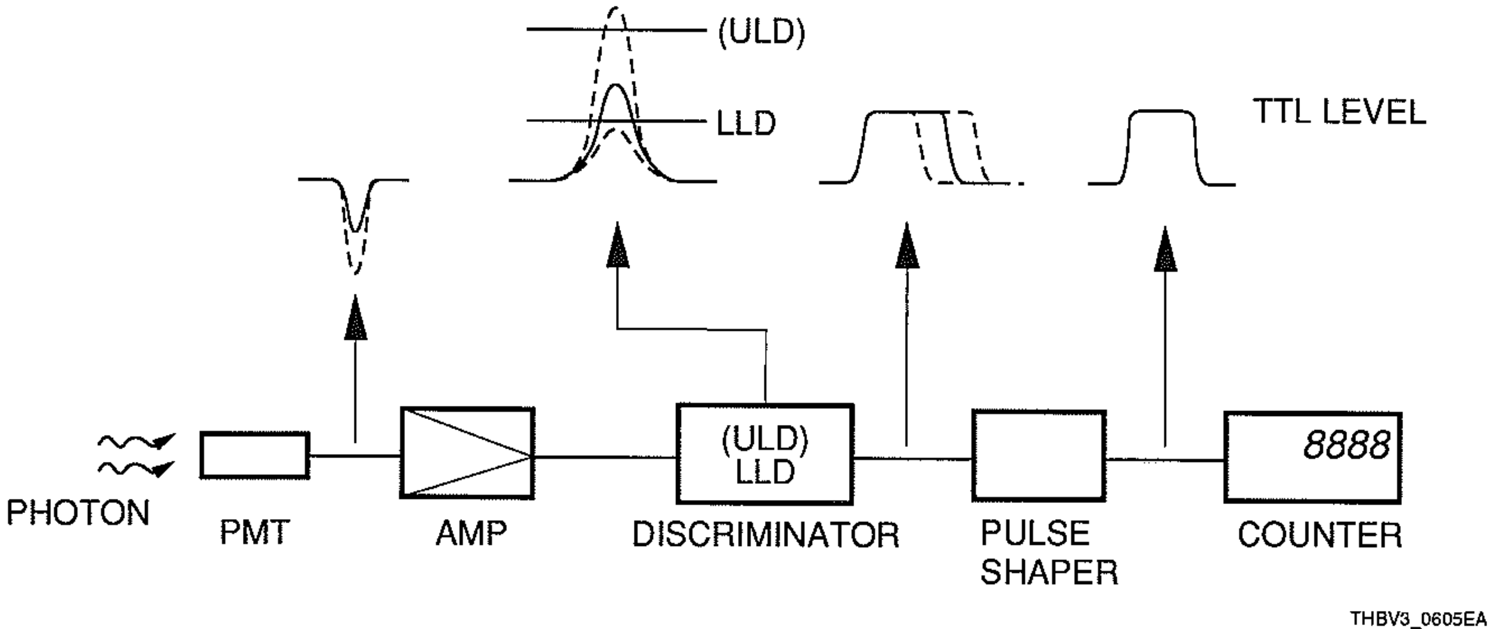
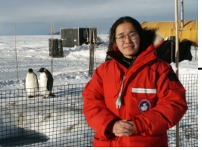


Figure 6-5: Circuit configuration for photon counting

In the above system, current output pulses from a photomultiplier tube are converted to a voltage by a wide-band preamplifier and amplified. These voltage pulse are fed to a discriminator and then to a pulse shaper. Finally the number of pulses is counted by a counter. The discriminator compares the input voltage pulses with the preset reference voltage (threshold level) and eliminates those pulses with amplitudes lower than this value. In general, the LLD (lower level discrimination) level is set at the lower pulse height side. The ULD (upper level discrimination) level may also be often set at the higher pulse height side to eliminate noise pulses with higher amplitudes. The counter is usually equipped with a gate circuit, allowing measurement at different timings and intervals.



Setting Up PMT Supply Voltage

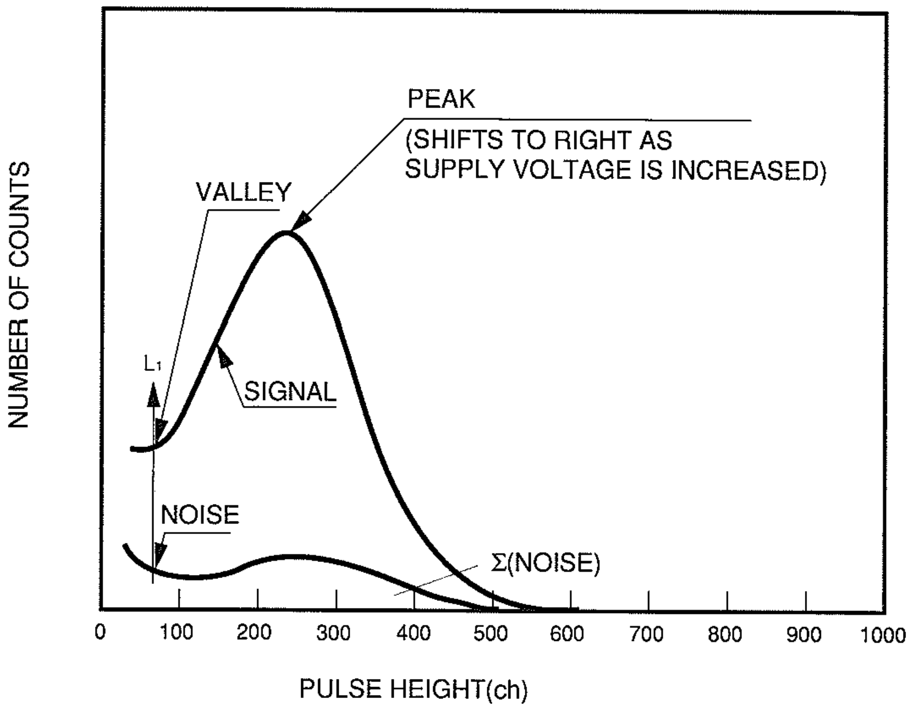


Figure 6-6: Typical example of pulse height distributions

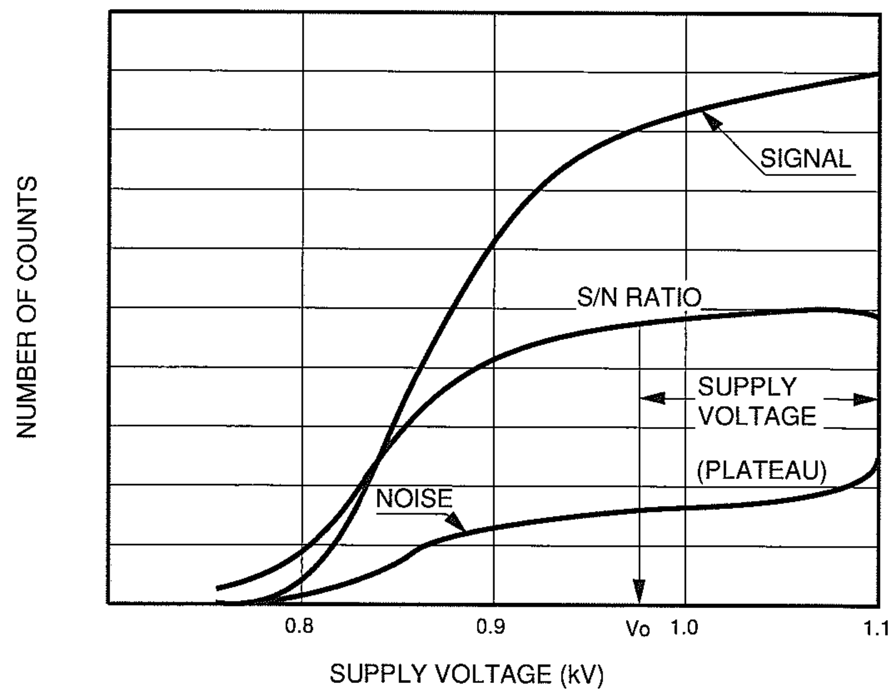
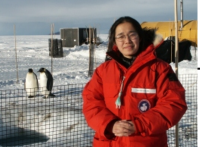


Figure 6-7: Plateau characteristics



Count rate linearity

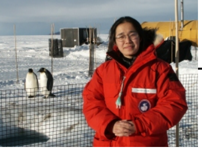
The photon counting mode offers excellent linearity over a wide range. The lower limit of the count rate linearity is determined by the number of dark current pulses, and the upper limit by the maximum count rate. The maximum count rate further depends on pulse-pair resolution, which is the minimum time interval at which each pulse can be separated. The reciprocal of this pulse pair resolution would be the maximum count rate. However, since most events in the photon counting region usually occur at random, the counted pulses may possibly overlap. Considering this probability of pulse overlapping (count error caused by pulse overlapping), the actual maximum count rate will be about one-tenth of the calculated above. Here, if we let the true count rate be N (s^{-1}), measured count rate be M (s^{-1}) and time resolution be t (s^{-1}), the loss of count rate N - M can also be expressed using the dead time M·t caused by pulse overlapping, as follows:

$$N - M = N \cdot M \cdot t$$

The true count rate N then becomes

$$N = \frac{M}{1 - M \cdot t} \quad \text{(Eq. 6-2)}$$

The count error can be corrected by using this relation.



Count rate linearity

Figure 6-8 shows examples of count rate linearity data before and after correction, measured using a system with a pulse pair resolution of 18 nanoseconds. The count error is corrected to within 1 % even at a count rate exceeding 10^7 s^{-1}.

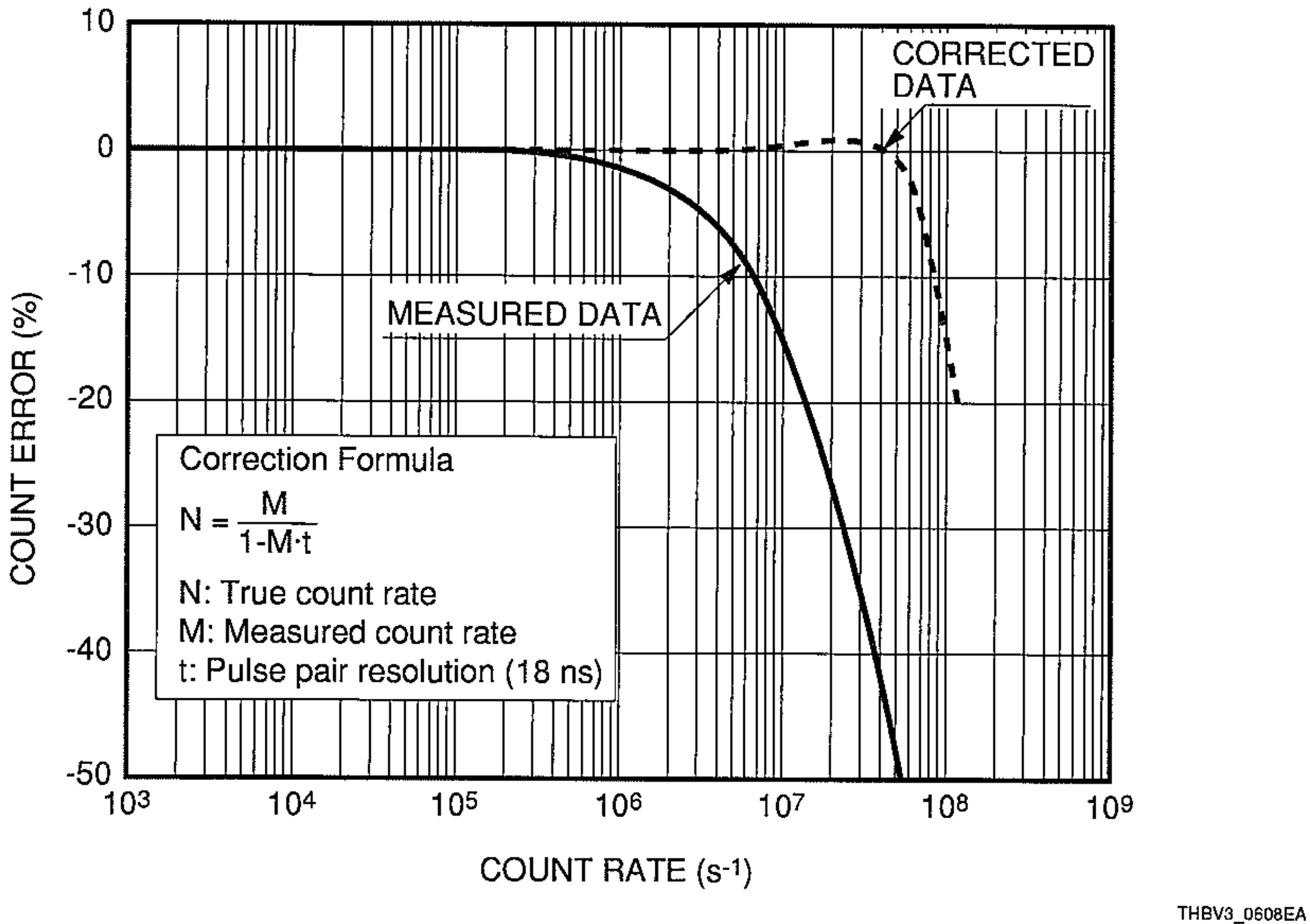
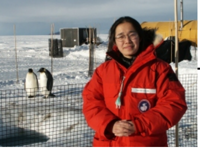


Figure 6-8: Linearity of count rate



Advantages of Photon Counting

(I) Stability

One of the significant advantages photon counting offers is operating stability. The photon counting mode is resistant to variations in supply voltage and photomultiplier tube gain. If the supply voltage is set within the plateau region, a change in the voltage has less effect on the output counts. In the analog mode, however, it affects the output current considerably. Immunity to variations in the supply voltage means that the photon counting mode also assures high stability against gain fluctuation of the photomultiplier tube. Normally the photon counting mode offers several times higher immunity to such variations than the analog mode. (Refer to Figure 6-9.)

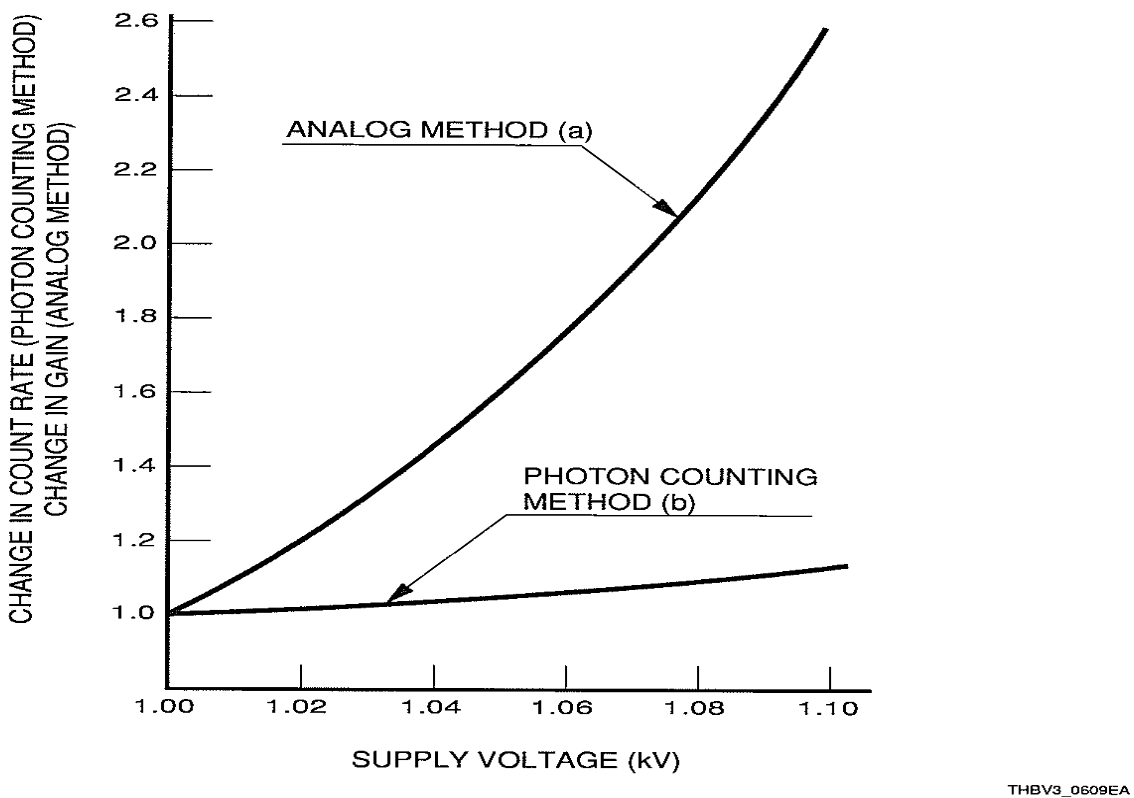
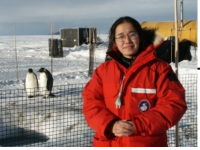


Figure 6-9: Stability versus changes in supply voltage



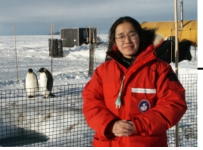
Advantages of Photon Counting

(II) Signal-to-noise ratio

When signal light strikes the photocathode of a photomultiplier tube, photoelectrons are emitted and directed to the dynode section where secondary electrons are produced. The number of photoelectrons produced per unit time and also the number of secondary electrons produced are determined by statistical probability of events which is represented by a Poisson distribution. The signal-to-noise ratio is also described in 4.3.7 in Chapter 4. The AC component noise which is superimposed on the signal can be categorized by origin as follows

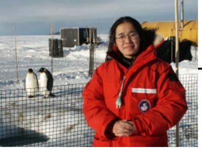
(1) Shot Noise resulting from signal light
(2) Shot Noise resulting from background light
(3) Shot Noise resulting from dark current

Through the above analysis, it is understood that the photon counting mode provides a better signal-to-noise ratio by a factor of the noise figure NF. Since the dark current includes thermal electrons emitted from the dynodes in addition to those from the photocathode, its pulse height distribution will be shifted toward the lower pulse height side. Therefore, the dark current component can be effectively eliminated by use of a pulse height discriminator while maintaining the signal component, assuring further improvement in the signal-to-noise ratio. In addition, because only AC pulses are counted, the photon counting mode is not influenced by the DC leakage current. Amplifier noises can totally be eliminated by a discriminator.



Various Photodetectors

Photomultiplier tube (PMT)
Avalanche photodiode (APD)
Micro-channel plate (MCP)
MCP photomultiplier tube
Multi-channel PMT
CCD camera
… …



Challenges of Photo-detection in Lidar

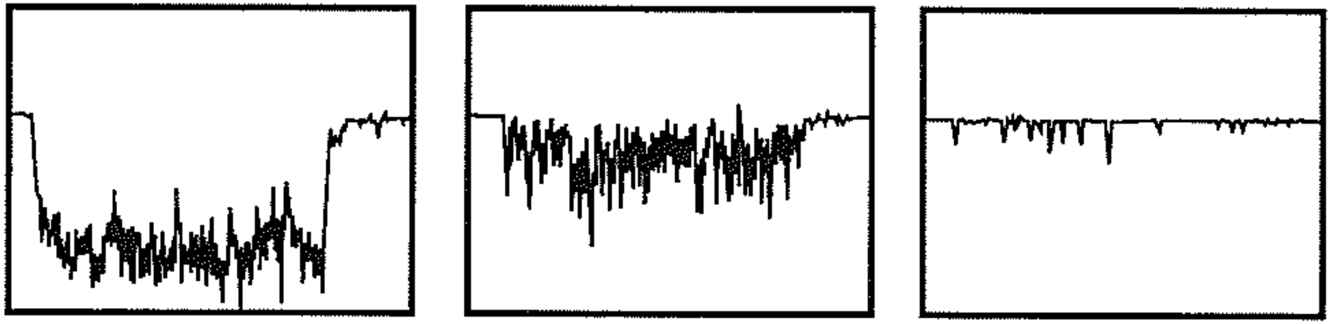


Figure 6-2: Photomultiplier tube output waveforms observed at different light levels

- Real lidar signals, especially upper atmosphere lidars, cover a very large range of light levels from PMT saturation in the lower atmos to the single photoelectron region in the upper atmosphere.
- Analog detection or photon counting? None of the modes alone can address the entire lidar signal ranges.
- Hybrid – simultaneous analog and digital detection?
- High speed digitizer and then do post processing?
- Split signals with certain ratios and do multiple channel detection?
- Any new ideas … … ?