Lecture 05. First Example: A Real Lidar

- Brief review of lidar basics
- K Doppler lidar system architecture
- K lidar signal estimate from lidar equation
- Comparison of estimate to reality
- Summary
Review of Lidar Basics

Interaction between radiation and objects

$\beta(\lambda, \lambda_L, \theta, R)$

$T(\lambda_L, R)$
Radiation Propagation Through Medium

$T(\lambda, R)$
Signal Propagation Through Medium

$\eta(\lambda, \lambda_L)G(R)$

$N_L(\lambda_L)$

Transmitter (Radiation Source)

Receiver (Detector)

System Control & Data Acquisition

Data Analysis & Interpretation

$\frac{A}{R^2}$
Review Lidar Architecture

- Basic architecture: three subsystems
  1. Lidar Transmitter
  2. Lidar Receiver
  3. Data Acquisition and Control System

- Basic function of each subsystem

- Major components for each subsystem
  - **Transmitter**: laser(s), collimating and steering mirrors, diagnostic equipment, wavelength control
  - **Receiver**: telescope(s), collimating optics, filters, photo-detectors
  - **DAQ and Control**: discriminator, multichannel scaler, DAQ card and code, computer, electronics for trigger control, timing control, etc.
Review Lidar Equation

- Keep in mind the big picture of a lidar system –
  - Radiation source
  - Radiation propagation in the medium
  - Interaction with the objects
  - Signal propagation in the medium
  - Photons are collected and detected

Can you derive a lidar equation by yourself?
Arecibo K Lidar Architecture

**Lidar Transmitter**

- CCD Beam Profiler
- Wavemeter/Spectrum Analyzer
- Injection-Seeded Pulsed Alexandrite Ring-Laser
- Diode/Laser
- Beam Expander
- PD Mon Out Lamp trig Out
- O'Scope Pulse Monitor
- O'Scope Cavity Monitor
- O'Scope Spectrum Analyzer
- K Vapor Cell Doppler-free Feature
- O'Scope Locking Signal
- Feedback Locking

**Lidar Receiver**

- Telescope
  - D = 800 mm, f/15
  - Cassegrain + 50 mm f lens
- Rotating Chopper
- Optical Fiber
- Narrowband Interference Filter
- PMT Detector (Going to be APD)
- Amplifier
- Computer
- MCS-1
- MCS-2
- MCS-3
Lidar Transmitter

- A pulsed alexandrite ring laser injection seeded by an external cavity diode laser.
- Seed laser frequency is locked to K D1a Doppler-free feature.
- Twin dual-pass acousto-optic modulators shift seed laser to two wing frequencies.
- Diagnostic equipment: CCD beam profiler, fast photo diode, spectrum analyzer, and oscilloscopes, monitor the spatial, temporal, and spectral features of the lasers to ensure fidelity operation.
Lidar Receiver

- A Cassegrain optical telescope
  80-cm in diameter
- An optical fiber
  couples signals to receiver chain
- A rotating chopper
  blocks lower atmosphere return
to avoid saturating photo detector
- Coupling/collimating optics
- An interference filter and a Faraday filter
  compress bkg while transmits signals
- A photomultiplier tube (PMT)
  detects photons in photon counting mode
**DAQ and Control System**

- **Amplifier**
  - to amplify PMT signal
- **Discriminator**
  - to judge whether it is real photon signal
- **Multichannel scaler**
  - to record data along time bins
- **Computer with DAQ card and code**
  - to control system and record data
- **Trigger control**
  - to coordinate the entire system
- **Pulse build-up time monitor**
  - to preclude signals from bad pulses
Arecibo K Lidar Estimate

- We want to use the fundamental lidar equation to estimate the detected photon counts of return K signals using the Arecibo K lidar parameters.
- This is the first step for lidar simulations to assess a lidar potential and system performance.
- Let us start with the general lidar equation

\[
N_S(\lambda, R) = N_L(\lambda_L) \cdot [\beta(\lambda, \lambda_L, \theta, R) \Delta R] \cdot \frac{A}{R^2} \cdot [T(\lambda_L, R)T(\lambda, R)] \cdot [\eta(\lambda, \lambda_L)G(R)] + N_B
\]

- Resonance fluorescence lidar uses the lidar equation

\[
N_S(\lambda, R) = \left( \frac{P_L(\lambda)\Delta t}{hc/\lambda} \right) (\sigma_{\text{eff}}(\lambda, R)n_c(z)R_B(\lambda)\Delta R) \left( \frac{A}{4\pi R^2} \right) \left( T_a^2(\lambda, R)T_c^2(\lambda, R) \right) [\eta(\lambda)G(R)] + N_B
\]
Lidar Estimate Procedure (1)

- First, estimate the transmitted laser photon numbers for single lidar pulse
  
  \[ N_L(\lambda_L) = \frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L} = \frac{E_{\text{pulse}}}{hc/\lambda_L} \]

- Arecibo K Doppler lidar parameters:
  - Laser pulse energy: \( E_{\text{pulse}} = 100 \) mJ
  - Laser central wavelength: \( \lambda_L = 770.1088 \) nm

- \( h \) is Planck constant and \( c \) is light speed

- Therefore, a single lidar pulse sends out photons of
  \( N_L = 3.88 \times 10^{17} \)
Lidar Estimate Procedure (2)

- Second, consider the transmitter steering mirror reflectivity and atmosphere transmission, and estimate the number of laser photons that reach K layers

\[ N_{Trans} = N_L \cdot R_{Tmirror} \cdot T_{atmos} \]

- Arecibo K Doppler lidar parameters:
  - Transmitter mirrors: 3 mirrors @ R = 99.8%
  - \[ R_{Tmirror} = (0.998)^3 = 0.994 \]
  - Lower atmosphere transmission at 770 nm:
  - \[ T_{atmos} = 80\% \]

- Therefore, the number of photons reaching K layers
  \[ N_{Trans} = 3.08 \times 10^{17} \]
Lidar Estimate Procedure (3)

- Third, consider the absorption and spontaneous emission procedure, estimate scattering probability and estimate the number of resonance fluorescence photons produced by entire K layers (ignoring extinction in K)

\[ N_{\text{Fluorescence}} = N_{\text{Trans}} \cdot P_{\text{scattering}} = N_{\text{Trans}} \cdot \sigma_{\text{eff}} \cdot K\text{Abdn} \]

- Peak effective cross-section of K D1a line:
  \[ \sigma_{\text{eff}} = 10 \times 10^{-16} \, \text{m}^2 \]

- K layer column abundance:
  \[ K\text{Abdn} = 6 \times 10^7 \, \text{cm}^{-2} = 6 \times 10^{11} \, \text{m}^{-2} \]

- The scattering probability is given by:
  \[ P_{\text{scattering}} = \sigma_{\text{eff}} \times K\text{abdn} = 6 \times 10^{-4} \]

- Therefore, the number of fluorescence photons
  \[ N_{\text{Fluorescence}} = 1.85 \times 10^{14} \]
Fourth, consider the atmosphere transmission for return signals and estimate the number of fluorescence photons that reach the sphere surface at receiver range

\[ N_{Sphere} = N_{Fluorescence} \cdot T_{atmos} \]

Lower atmosphere transmission at 770 nm:
\[ T_{atmos} = 80\% \]

Note: we ignore the extinction caused by K layers

Thus, the number of photons reaching the sphere
\[ N_{Sphere} = 1.48 \times 10^{14} \]
Fifth, consider the telescope primary mirror area, estimate the collection probability, and estimate the number of photons reaching the primary mirror

\[
N_{\text{Primary}} = N_{\text{Sphere}} \cdot P_{\text{collection}} = N_{\text{Sphere}} \cdot \frac{A}{4\pi R^2}
\]

- Arecibo K lidar telescope: primary mirror diameter
  \( D = 80 \text{ cm} \Rightarrow A = 0.50 \text{ m}^2 \)
- K layer centroid altitude:
  \( R = 90 \text{ km} = 9 \times 10^4 \text{ m} \)
- The collection probability is given by:
  \( P_{\text{collection}} = \frac{A}{4\pi R^2} = 4.94 \times 10^{-12} \)
- Therefore, the number of photons reaching the primary mirror:
  \( N_{\text{Sphere}} = 730.8 \)
Lidar Estimate Procedure (6)

- Sixth, estimate the receiver efficiency considering primary mirror reflectivity, collimating optics transmission, filter transmission, and PMT QE

\[ \eta_{receiver} = R_{primary} \cdot \eta_{fiber} \cdot T_{Rmirror} \cdot T_{IF} \cdot QE \]

- Arecibo K lidar receiver parameters:
  - primary mirror reflectivity \( R_{primary} = 91\% \)
  - Fiber coupling efficiency \( \eta_{fiber} = 75\% \)
  - receiver mirror transmittance \( T_{Rmirror} = 74\% \)
  - Interference filter peak transmission \( T_{IF} = 80\% \)
  - PMT quantum efficiency \( QE = 15\% \)

- Therefore, the receiver efficiency is
  \[ \eta_{receiver} = 6.06\% \]
Lidar Estimate Procedure (7)

- Seventh, consider the receiver efficiency and estimate the number of photons detected by PMT

\[ N_{S(K)} = N_{primary} \cdot \eta_{receiver} \]

- Using the results from steps 5th and 6th,
  \[ N_{S(K)} = 730.8 \times 6.06\% = 44.3 \]

- Therefore, the number of photons detected by PMT, (i.e., the K lidar return signal counts), for each single lidar pulse from the entire K layers are
  \[ N_{S(K)} = 44.3 \]

- Note: these photon counts originate from \[ 3.88 \times 10^{17} \] laser photons!!!
Comparison to Actual Lidar Return

- Typical lidar return signals of the Arecibo K Doppler lidar are about 10-50 counts per shot from the entire K layers, depending on seasons and atmosphere conditions.

- Our estimate is surprisingly close to the actual situation - K lidar people have tried their best to measure the system efficiencies precisely.

- From this estimate, how do you feel about the upper atmosphere lidar: What is the major killer of the signal strength?

  Long range - weak signal!
Raw data Profile of K Lidar
Rawdata Profile: Log Scale

Altitude (km) vs. Raw Photon Counts
We use a real lidar – the Arecibo K Doppler lidar – as an example to examine the basic concepts of lidar picture, lidar architecture, and lidar equation.

High level lidar systems are sophisticated, mainly on the transmitter (laser) aspect. But receiver and DAQ also strongly affect system performance.

The major difficulty in upper atmosphere lidar is the tiny collection efficiency ($10^{-12}$) caused by the long range ($A/R^2$) ⇒ weak signals.

Receiver efficiency is another important factor that must be given careful considerations.