Lecture 09. Lidar Simulation and Error Analysis Overview

- Review non-range-resolved lidar simulation
- Overview of Lidar Simulation and Error Analysis
- Range-resolved lidar simulation procedure
- Summary

Review Lidar Simulation/Estimate

- What we did on Friday was to estimate the return photon counts from the entire K layers using lidar equation and lidar/atomic/atmospheric parameters.
- 1st, write down all fundamental constants used in lidar.
- 2nd, gather lidar, atomic/molecular & atmosphere parameters.
- 3rd, start with the laser source of transmitter and follow the lidar picture from transmitted photons, through atmosphere transmission, backscatter probability, collection probability, and receiver efficiency, to detected photon numbers.
- 4th, understand the physical process of light interaction with objects to calculate the backscatter probability.
- 5th, background estimate considering many factors (both atmosphere conditions and lidar parameters like filter, FOV, …)
- 6th, get the final results and verify them with reality.

Fundamental Constants, Lidar Parameters, Atomic or Molecular Parameters, Atmospheric Parameters

- Always use NIST latest fundamental constants
- Try to use NIST atomic and molecular parameters
- Gather all possible lidar parameters
- Gather possible atmospheric parameters
- Another possible way is to scale from existing lidar measurements

K Lidar Estimate Procedure

$$N_L(\lambda_L) = \frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L} = \frac{E_{pulse}}{hc/\lambda_L}$$

$N_L = 3.88 \times 10^{17}$

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

$N_{Trans} = 3.08 \times 10^{17}$

$$N_{Fluorescence} = N_{Trans} \cdot P_{scattering} = N_{Trans} \cdot \sigma_{eff} \cdot KAbdn$$

$N_{Fluorescene} = 1.85 \times 10^{14}$

$$N_{Sphere} = N_{Fluorescence} \cdot T_{atmos}$$

$N_{Sphere} = 1.48 \times 10^{14}$

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

$N_{Sphere} = 730.8$

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

$\eta_{receiver} = 6.06\%$

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

$N_{S(K)} = 44.3$

Comparison to reality: 10-50 count/shot

Lidar Simulation and Error Analysis

- Why are lidar simulation and error analysis necessary?

- Analogy to atmospheric modeling: a complex code to integrate everything together to see what happens in a complicated system like the atmosphere. The basis is the atmospheric science theory.

- Lidar remote sensing is a complicated procedure with many factors involved (both human-controllable and non-controllable). It is difficult to imagine what happens from a simple lidar theory (lidar equation). So we want to write a computer code to integrate all factors together in a proper way based on the lidar theory. By doing so we can investigate what the lidar outcome is supposed to be and how the outcome changes with the factors.

- The basis for lidar simulation and error analysis is the lidar theory, spectroscopy, and measurement principles.

- Practice of lidar simulation and error analysis help deepen our understanding of every process, especially physical processes, in the entire lidar detection procedure.

Lidar Simulation and Error Analysis

- Four Major Goals of Lidar Simulation and Error Analysis

1. Estimate of expected lidar returns (signal level and shape)
2. Analysis of expected measurement precision & resolution, i.e., errors (uncertainty) introduced by photon noise
3. Analysis of expected measurement accuracy & precision (caused by uncertainty in system parameters) and lidar measurement sensitivity to atomic, lidar, and atmospheric parameters
4. Forward model to test data retrieval code and metrics

Lidar Simulation and Error Analysis

- Merits, Functions, or Applications of each aspect

1. Estimate of expected lidar returns (signal level and shape)

- Show what signals you can expect to see on real systems;
- Assess the potential of a lidar system;
- Comparison to actual signals to help diagnose lidar efficiency and other system problems, including reality check

2. Analysis of expected measurement precision & resolution, i.e., errors (uncertainty) introduced by photon noise

- Help determine needed laser power, receiver aperture, system efficiency, filter width, FOV, etc
- Help determine whether daytime measurement is doable
- Trade-off between resolution and precision

Lidar Simulation and Error Analysis

- ❑ Merits, Functions, or Applications of each aspect

3. Analysis of expected measurement accuracy & precision (caused by uncertainty in system parameters) and lidar measurement sensitivity to atomic, lidar, and atmospheric parameters

- Help define requirements on lidar system parameters, like frequency accuracy, linewidth, stability, etc.
- Provide a guideline to system development
- Help determine measurement accuracy (bias)

4. Forward model to test data retrieval code and metrics

- Test data retrieval code and its sensitivity to noise
- Help compare different metrics to minimize cross-talk between different measurement errors

Lidar Simulation Build-up

- Analogy to atmospheric modeling, it is not practical to make a lidar simulation code complete for the first try, because so many things are involved. Therefore, we will build up a lidar simulation code step by step.
- First, we set up a platform using MatLab: gather needed information, set up necessary variables, and put these parameters into right places. For some parameters, you may use a place-holder before getting into the details.
- Then, we begin the simulation based on lidar equations and particular lidar procedure of each application. For commonly used or complicated parts, you may write 'functions' for each individual function, and then call them from the main code.
- The more we understand the lidar detection procedure and the more factors we consider, the more sophisticated will the lidar simulation code become.

Lidar Simulation Levels or Layers

- There are many different levels or layers of lidar simulation, depending on what we care about and how complicated the lidar detection procedure is. Three major levels are

1. Envelope estimation (non-range-resolved): integrated photon returns from an entire layer or region

2. Range-resolved simulation: photon returns from different ranges

3. Range-resolved and spectral-resolved simulation: photon returns from different ranges and distribution in spectrum at each range

- Other factors to consider:

1) Background (MODTRAN code is a good resource),

2) Noise (Poisson distribution),

3) Geometry,

4) Polarization,

5) ……

Range-Resolved Lidar Simulation

- Three main steps:

(1) Initialization

- Define constants and parameters

(2) Simulation of photon counts vs. altitude (range)

- Rayleigh, resonance fluorescence, background, aerosol, noise

(3) Computation of signal-to-noise ratio (SNR)

- SNR will be useful in the error analysis

Range-Resolved Simulation: Initialization

- Initialization: to define constants and parameters

1) Fundamental constants: c, h, Q_e, M_e, ...
2) Atomic parameters: resonance wavelengths, frequencies, strength, oscillator strength, A_{ki}, degeneracy factors, isotopes, abundance, ...

or Molecular parameters: CO_2 structure, etc.

3) Lidar transmitter and receiver parameters: pulse energy, linewidth, frequency, repetition rate, telescope diameter, R, T, η_{QE}, T_{IF}, ...
4) User-controlled parameters: integration time (shots number), bin width Δz, pointing up or down, base altitude, pointing angle, model choice, ...
5) Atmospheric parameters (taken from model, e.g., MSIS00): number density, pressure, temperature, transmission, ...
6) Na/K/Fe layer parameters: distribution, Z_0, σ_{rms}, Abdn, ...

Range-Resolved Simulation: N(R) or N(z)

- Photon counts vs. altitude: Sum of the following terms

1) Rayleigh scattering signals: take number density distribution profile n(z) from a model, e.g., MSIS00, set bin width Δz = 0.5 km, compute $\sigma_R \cdot n(z) \cdot \Delta z$ or further considering the pointing angle, then follow the normal simulation procedure for each bin
2) Resonance fluorescence signals: compute the Na/K/Fe density distribution profile from Z_0, σ_{rms}, Abdn, compute effective cross-section σ_{eff} from atomic and laser spectroscopy, compute $\sigma_{eff} \cdot n_{Na}(z) \cdot \Delta z$ or further considering the pointing angle, consider the transmission (extinction) caused by atomic absorption, follow the normal simulation procedure for each bin
3) Aerosol signals: usually in specific regions
4) Background counts: scale from real measurements or use MODTRAN code to compute background (needing lidar parameters, like FOV, filter function, etc.)
5) Noise: Poisson distribution from photon counts $\Delta N(z) = \sqrt{N(z)}$

Range-Resolved Simulation: SNR

- Computation of signal-to-noise ratio (SNR) from simulation results

$$SNR(z) = \frac{N_{Signal}(z)}{\Delta N_{Signal}(z)}$$

- However, we must consider how the N(z) is obtained

$$N_{Signal}(z) = N_{Total}(z) - N_B$$

$$\Delta N_{Signal}(z) = \Delta N_{Total}(z) - \Delta N_B$$

$$\left(\Delta N_{Signal}(z)\right)_{rms} = \sqrt{\left(\Delta N_{Total}(z)\right)^2 + \left(\Delta N_B\right)^2}$$

$$\left(\Delta N_{Signal}(z)\right)_{rms} = \sqrt{N_{Total}(z) + \left(\Delta N_B\right)^2} \approx \sqrt{N_{Total}(z)}$$

Summary

- Lidar simulation and error analysis are an integral of our understanding of lidar principle, technology and actual application procedure.
- It provides a model to investigate how the lidar returns depend on different parameters and how measurement accuracy, precision, and resolution depend on different parameters.
- It can be used to verify lidar return shapes, assess lidar potentials, guide lidar design and instrumentation, test data retrieval code and metrics, etc.
- A complete lidar simulation and error analysis code is very complicated. We will go step by step to approach it.