Remote Sensing of the Mixed Layer Depth

Outline

- The Mixed Layer
- Measurement concept
    1. Lidar penetration depth
    2. Particulate scattering
    3. Turbulence scattering
- Conclusions

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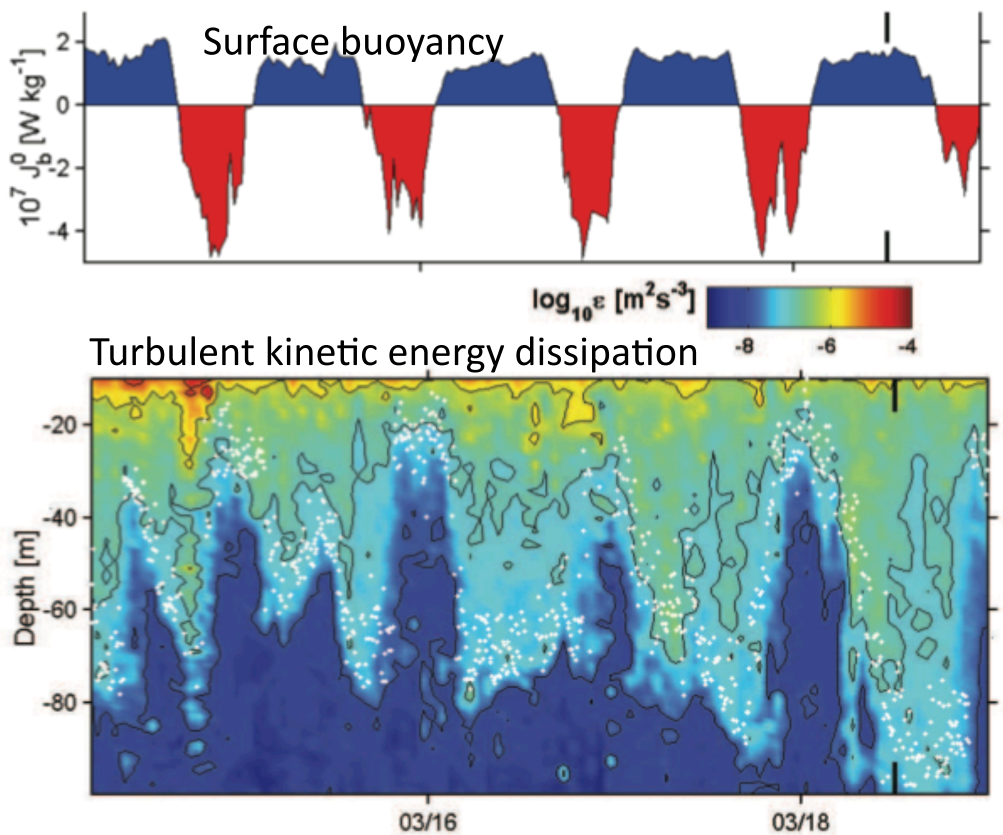
The Ocean Mixed Layer

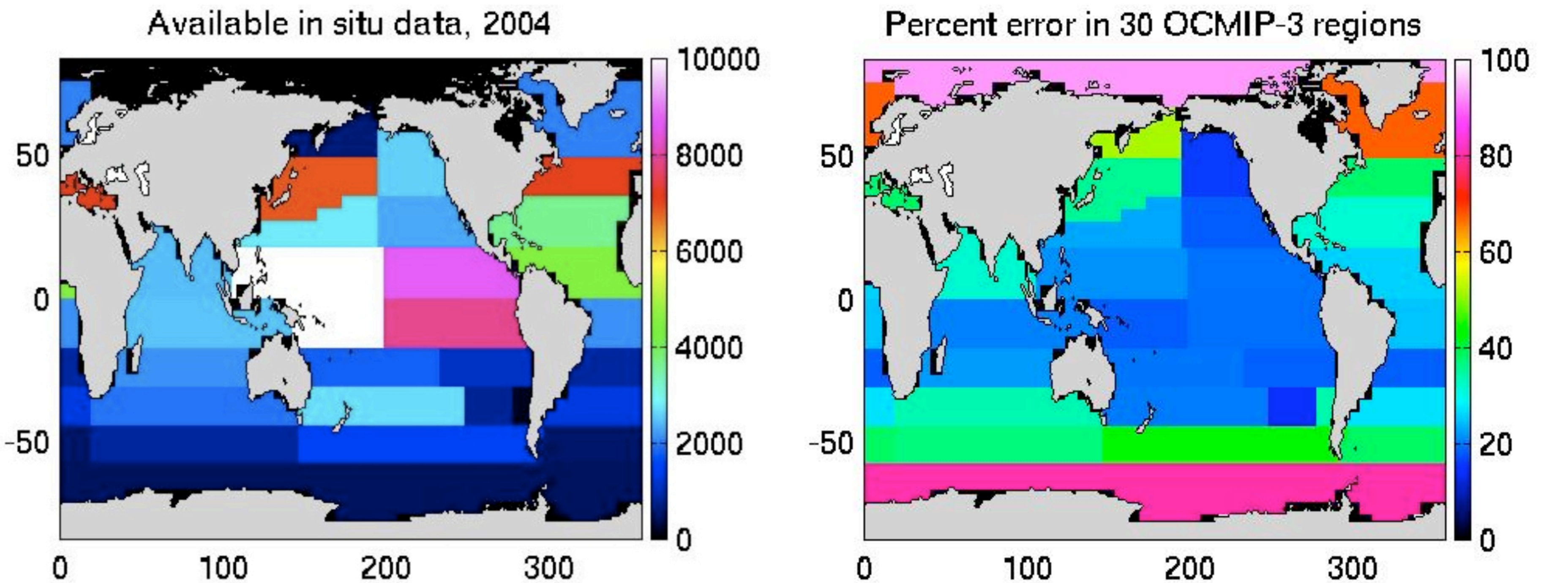
- The mixed layer is the surface ocean boundary layer, mediator of all interaction between the deep ocean and atmosphere.
- Air-sea transfer of energy, heat, and gases (such as CO2) occurs via the mixed layer.
- The depth of the mixed layer (MLD) responds to surface forcing on subdiurnal to interannual time scales.
- Knowledge of MLD is critical to inventory heat, gases, biological productivity, and ecosystem dynamics.
- The ocean's ability to regulate climate is linked to the dynamics of mixing in the upper ocean and the degree of stratification.
- Defined by turbulence
- Temperature and density profiles are used as proxy
- Particulate distribution is not a very good proxy but is often used
- The proposed measurements are expected to retrieve both the particulate and the turbulence profiles

Observed time series of turbulence



Moum and Smyth (2000)

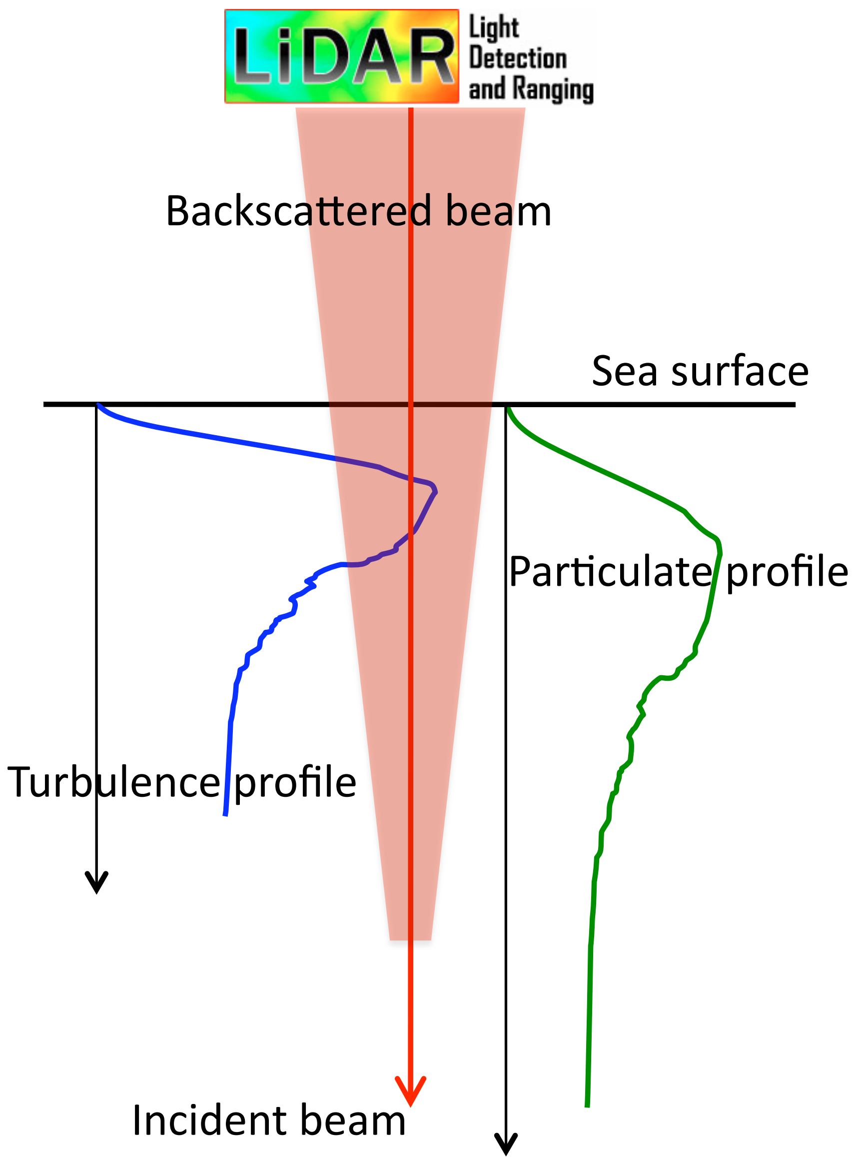
Ocean Mixed Layer Depth Sampling Induced Error



<u>Estimate of sampling error</u>

- Data is collected by floats, ships and buoys (temperature and salinity profiles)
- Computed MLD is sampled and interpolated linearly for the rest of the ocean
- Comparison with actual model results provides an estimate of the sampling-induced error
- Error ranges from about 20% in the equatorial regions to about 100% in the Antarctica

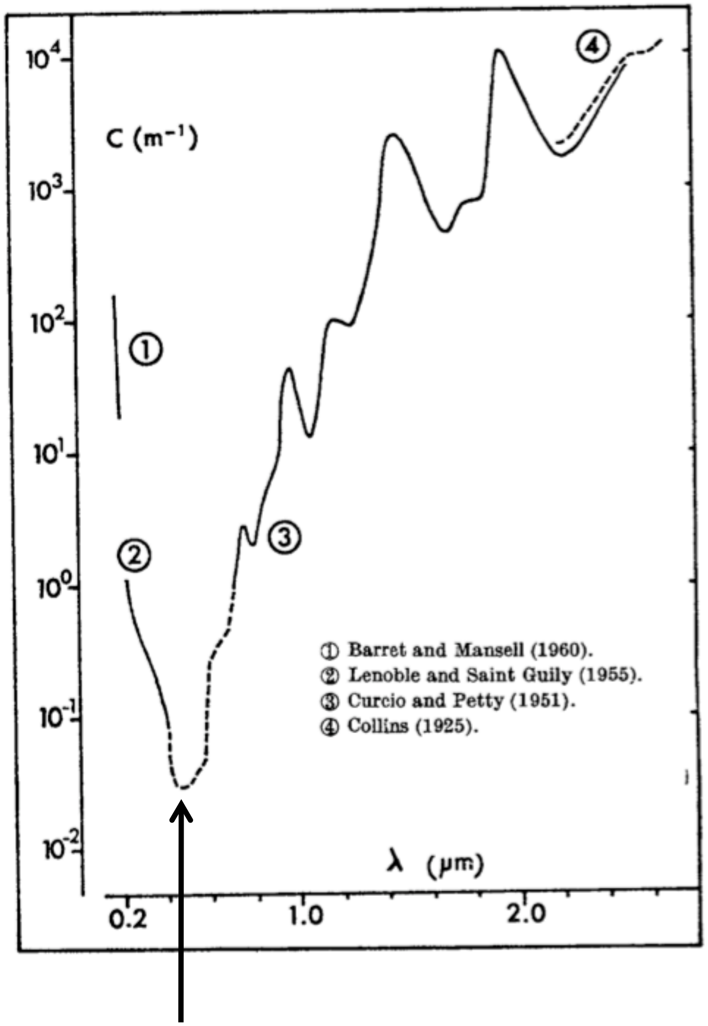
Measurement Concept



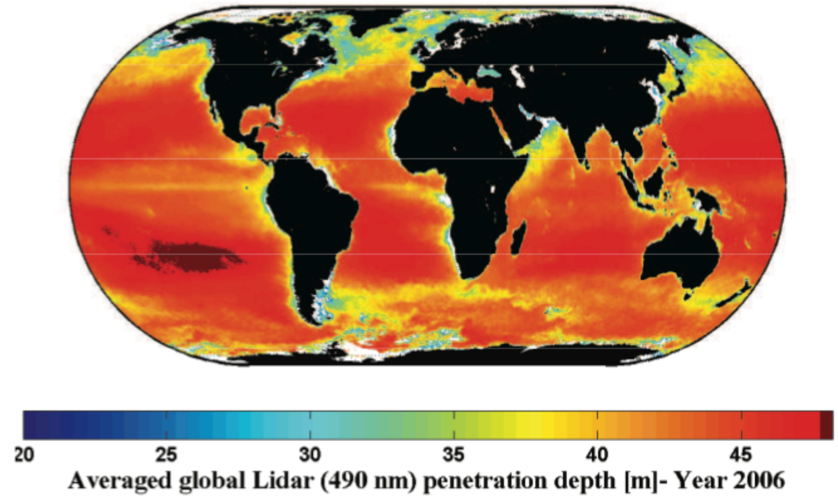
- Lidar wavelength around 532 nm to benefit from the minimum in the water absorption
- Multiple field of view instrument:
  - *Large angles* (< 2 degrees): particulate backscattering profile
  - *Small angles* (<1e-4 rad): forward scattering profile due to turbulence
- Current studies: sensitivity, angular resolution, temporal resolution

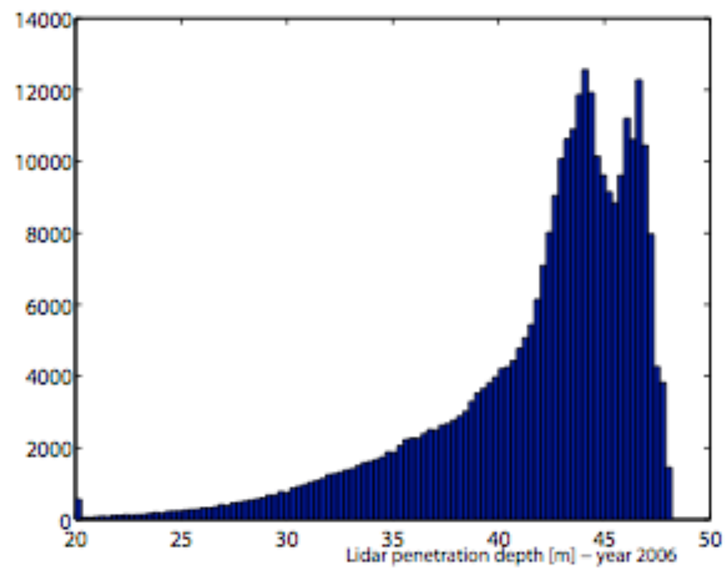
Lidar Penetration Depth

Attenuation curve for water



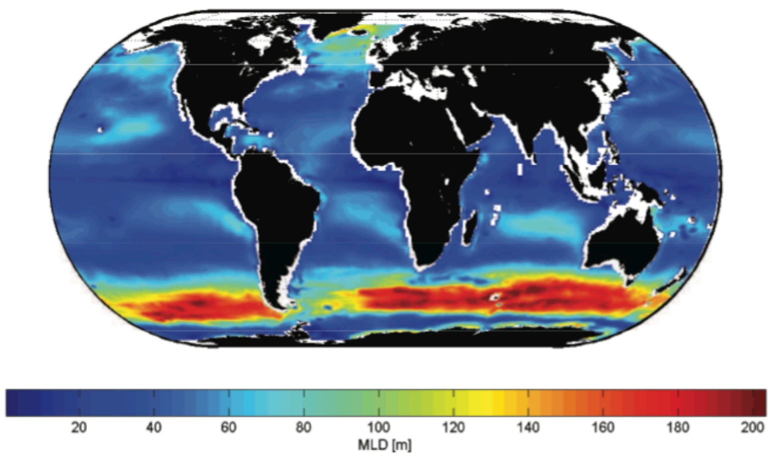
Lidar penetration map using lidar specifications in Churnside et al. 1998



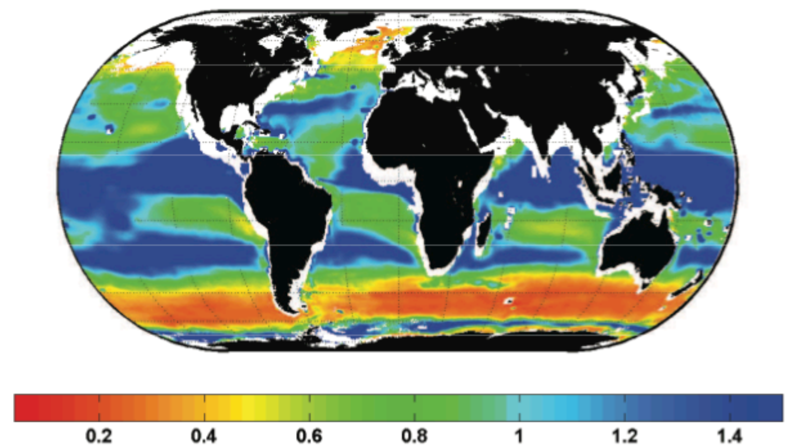


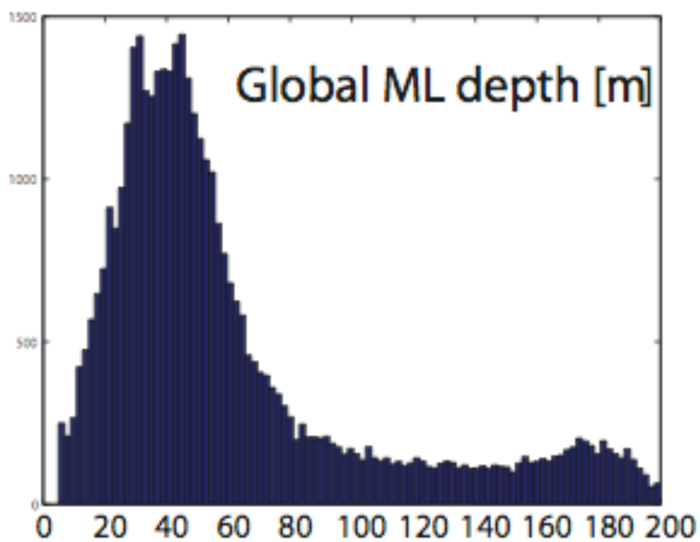
Comparing Lidar Penetration Depth and MLD

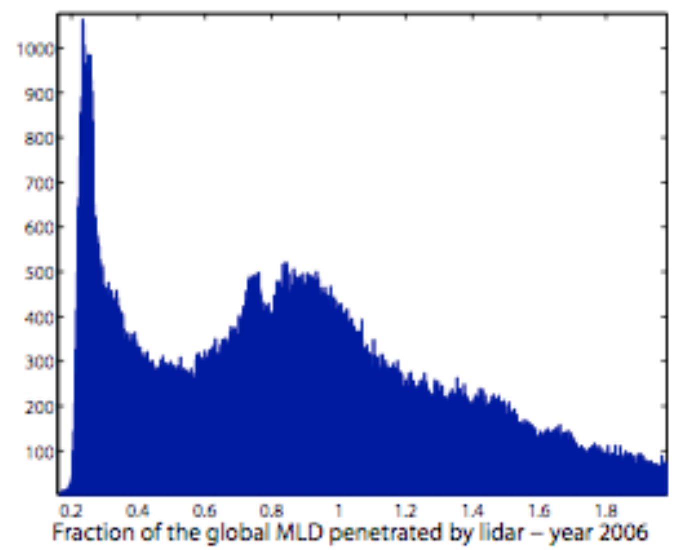
MLD map



Ratio of lidar depth to MLD



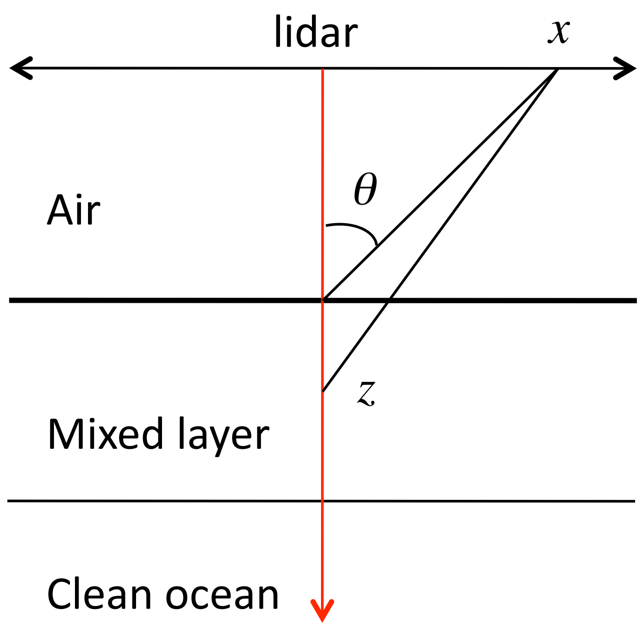




Two Numerical Scattering Models

Single scattering model

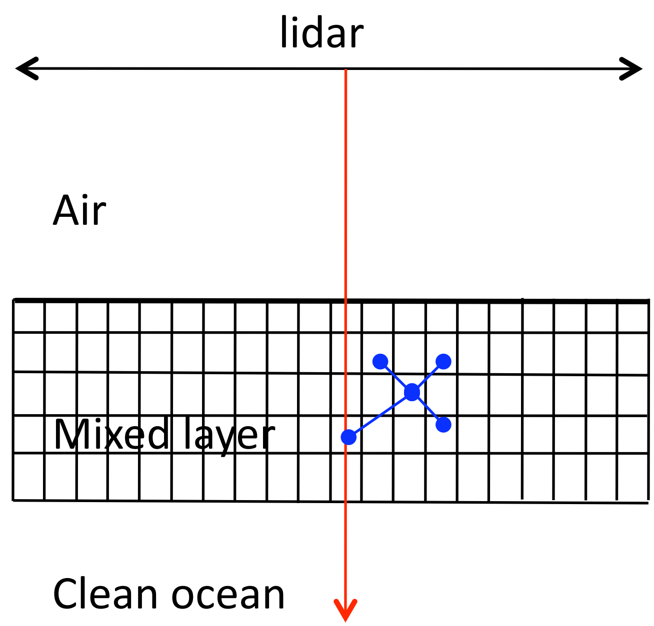
Large angle profile (< 2 degrees)



- One single backscattering event
- No forward scattering
- Backscattered signal equal to the sum of backscattered light in mixed layer

Multiple scattering model

Small angle profile (< 1e-4 rad)

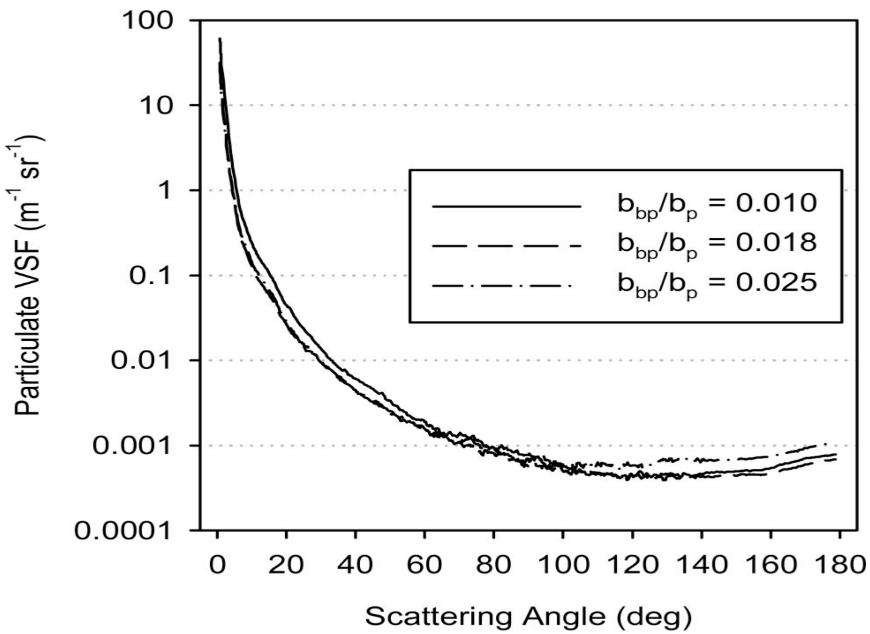


- Full radiative transfer equation solved
- Forward and backscattering included
- Angle sampling restricted to near forward and near backscattering

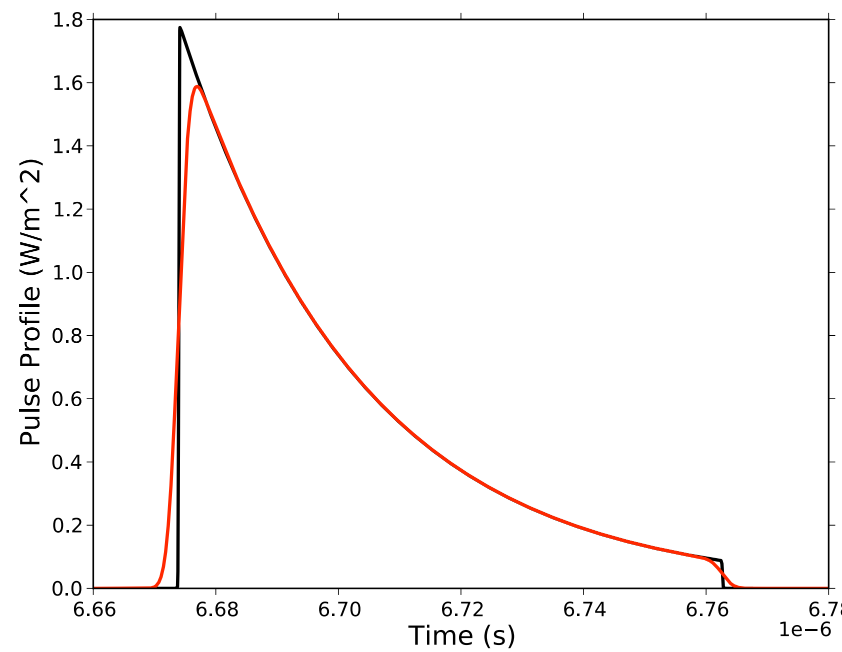
Particulate Scattering

Single scattering model

Particulate volume scattering function



Backscattered pulse



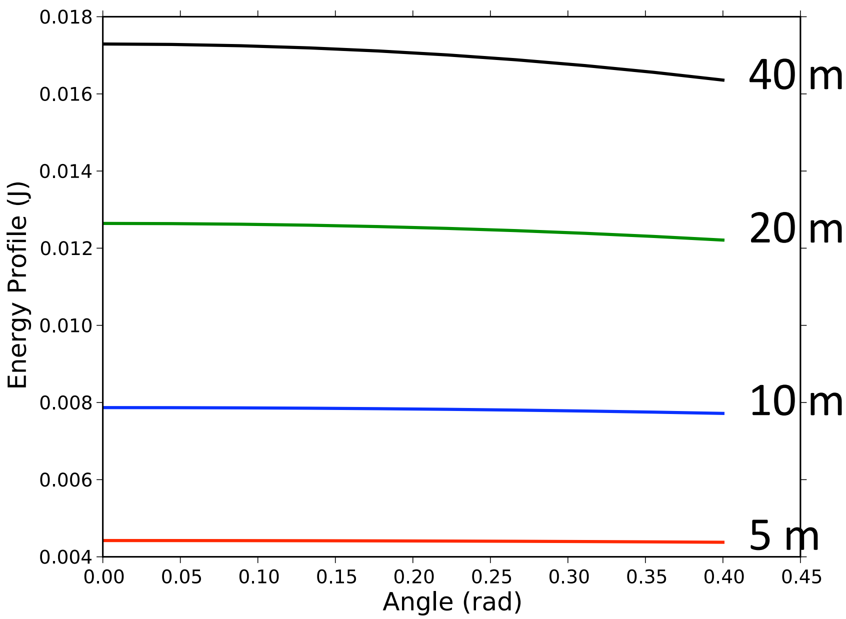
Approximation

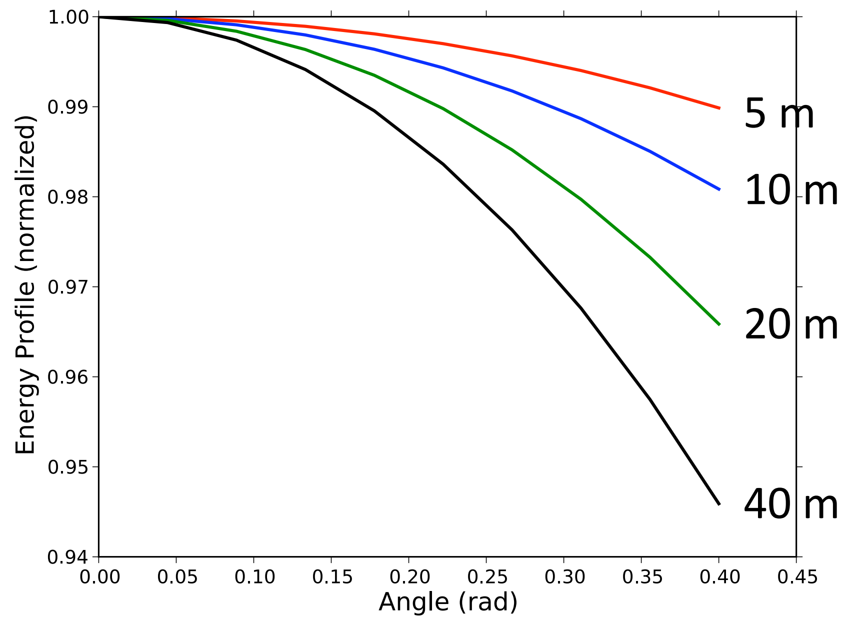
- Backscattering flat between 90 and 180 degrees
- Forward scattering only at 0 degree

- Incident pulse is Gaussian: black is for 100 ps width and red is for 2 ns width
- Spatial resolution for 2 ns pulse is about 1e-8 X (speed of light) = 3 m

Particulate Scattering

Single scattering model





a = 5e-2 m^{-1}
b = 1e-3 m^{-1}
tau = 100 ps
E = 1 J
Lidar at 1000 m from sea surface

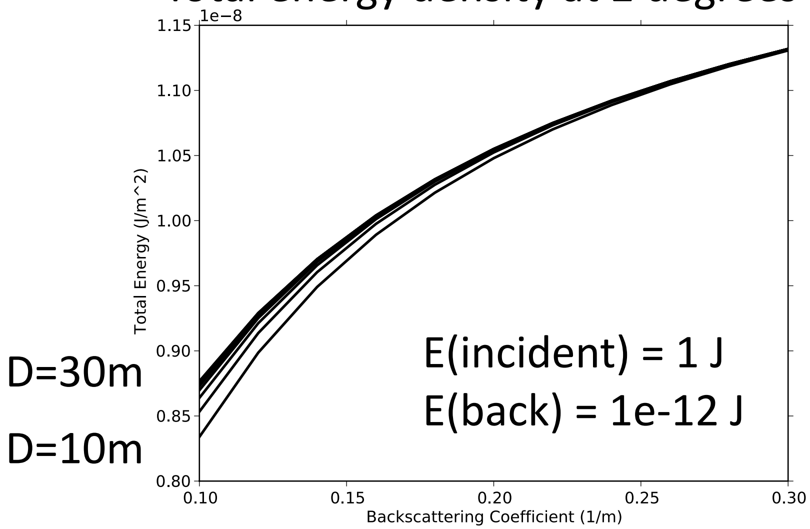
<u>Inversion potentially gives the following parameters:</u>

- Absorption in water a
- MLD (particulate)
- Particulate backscattering b

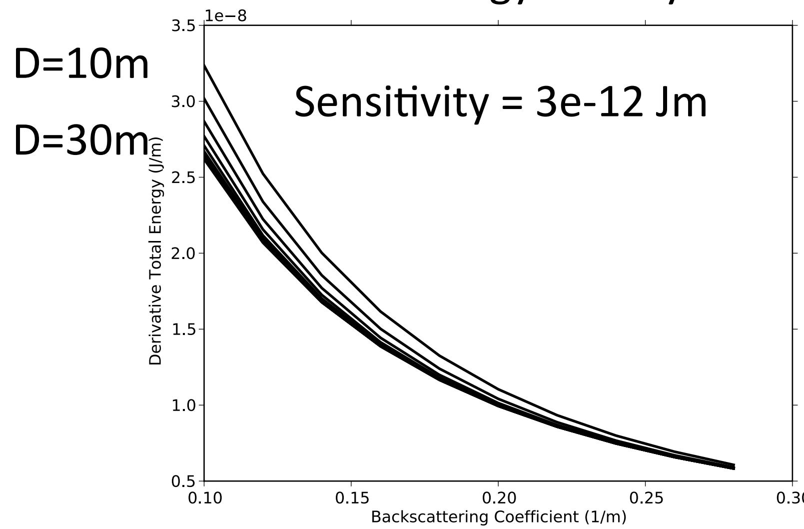
Particulate Scattering

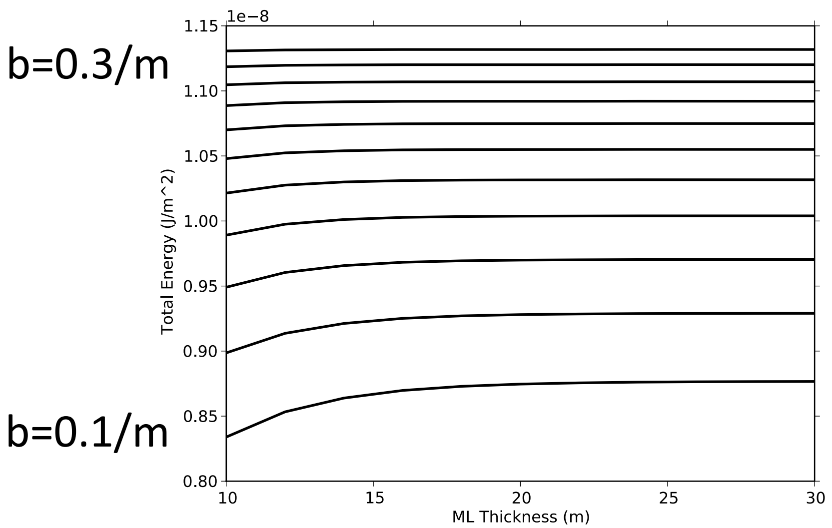
Absolute total energy

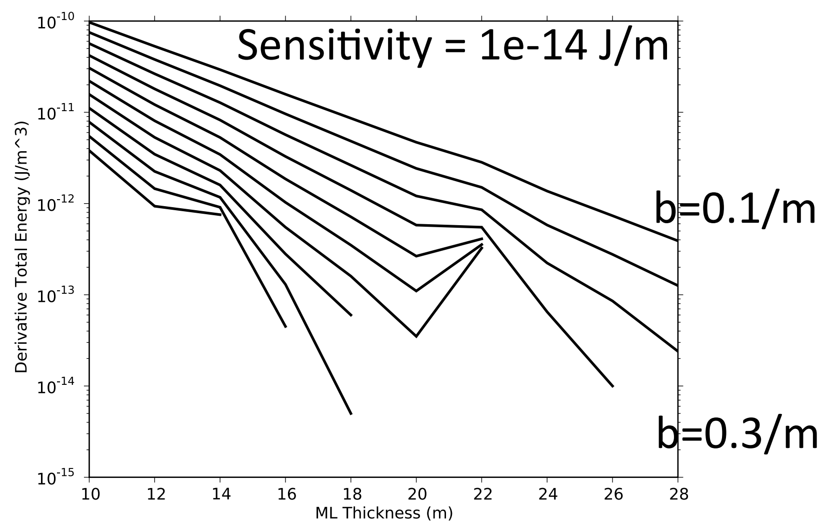
Total energy density at 2 degrees



Derivative of total energy density at 2 degrees





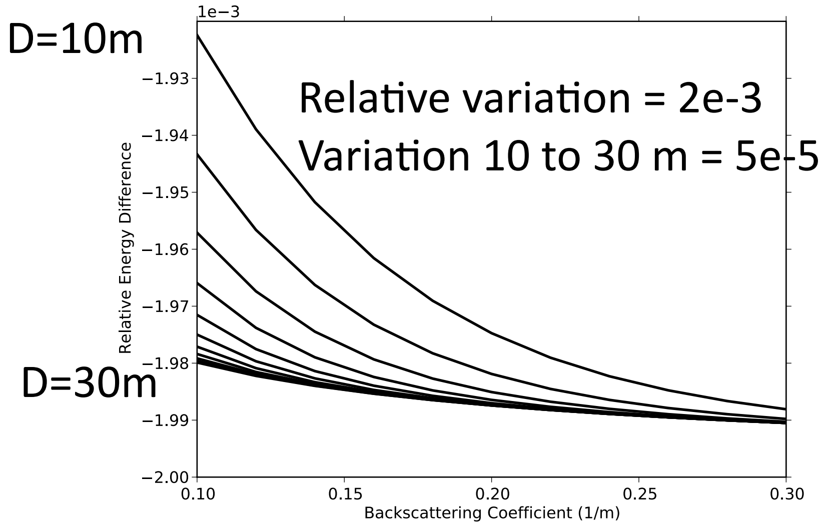


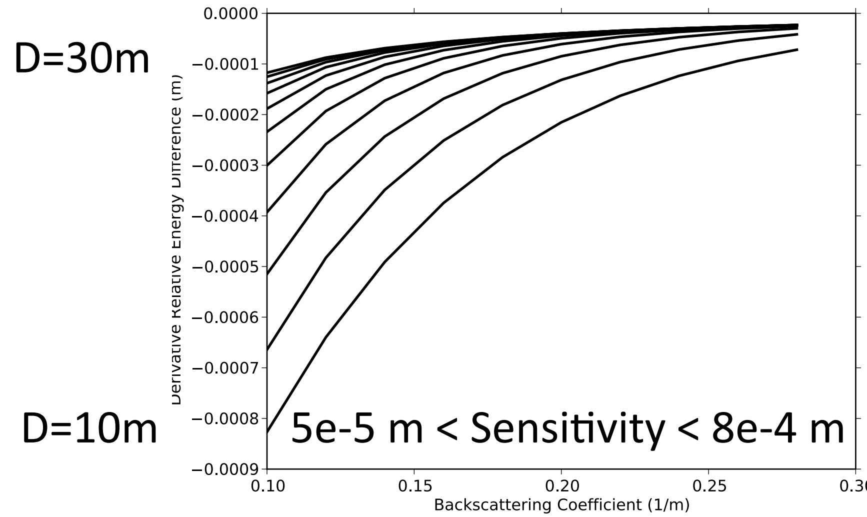
Pulse width = 2 ns; assuming 1 cm^2 detector; airplane is at 1000 m

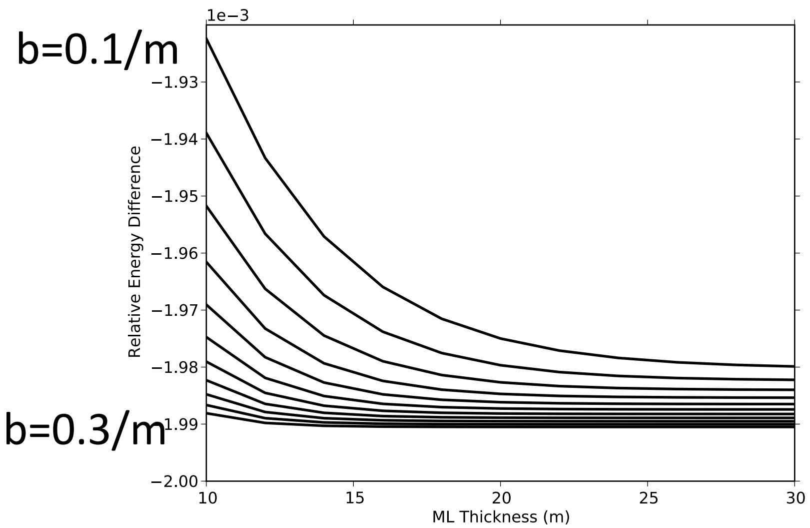
Particulate Scattering

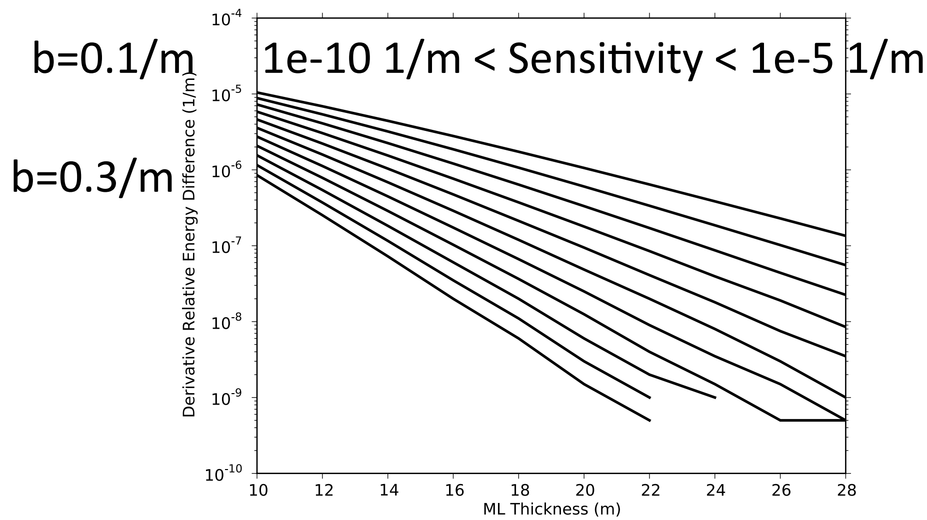
Relative angular variation of total energy

(E(α)-E(0)) / E(0)





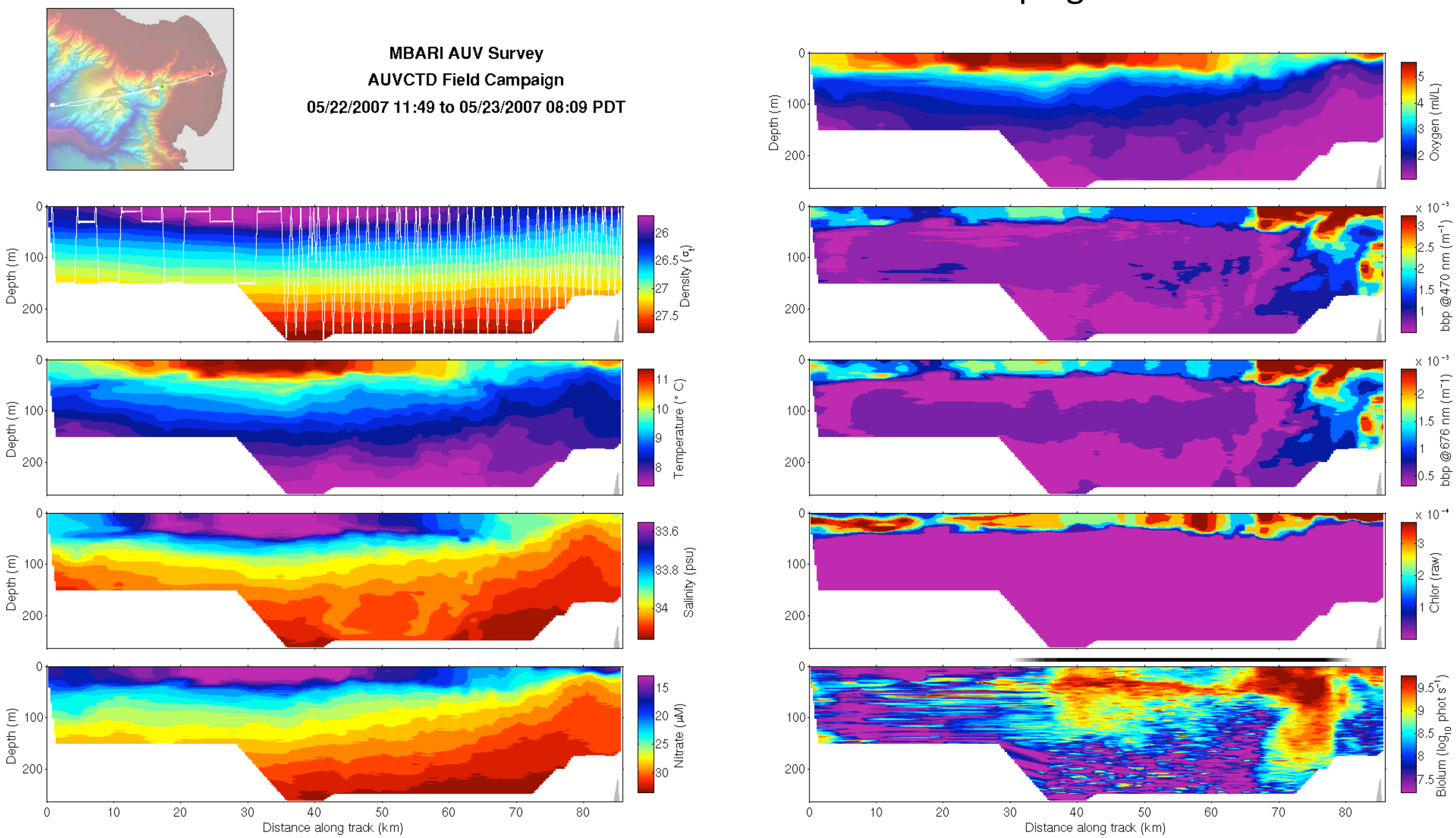




Pulse width = 2 ns; assuming 1 cm^2 detector; airplane is at 1000 m; $\alpha = 2^o$

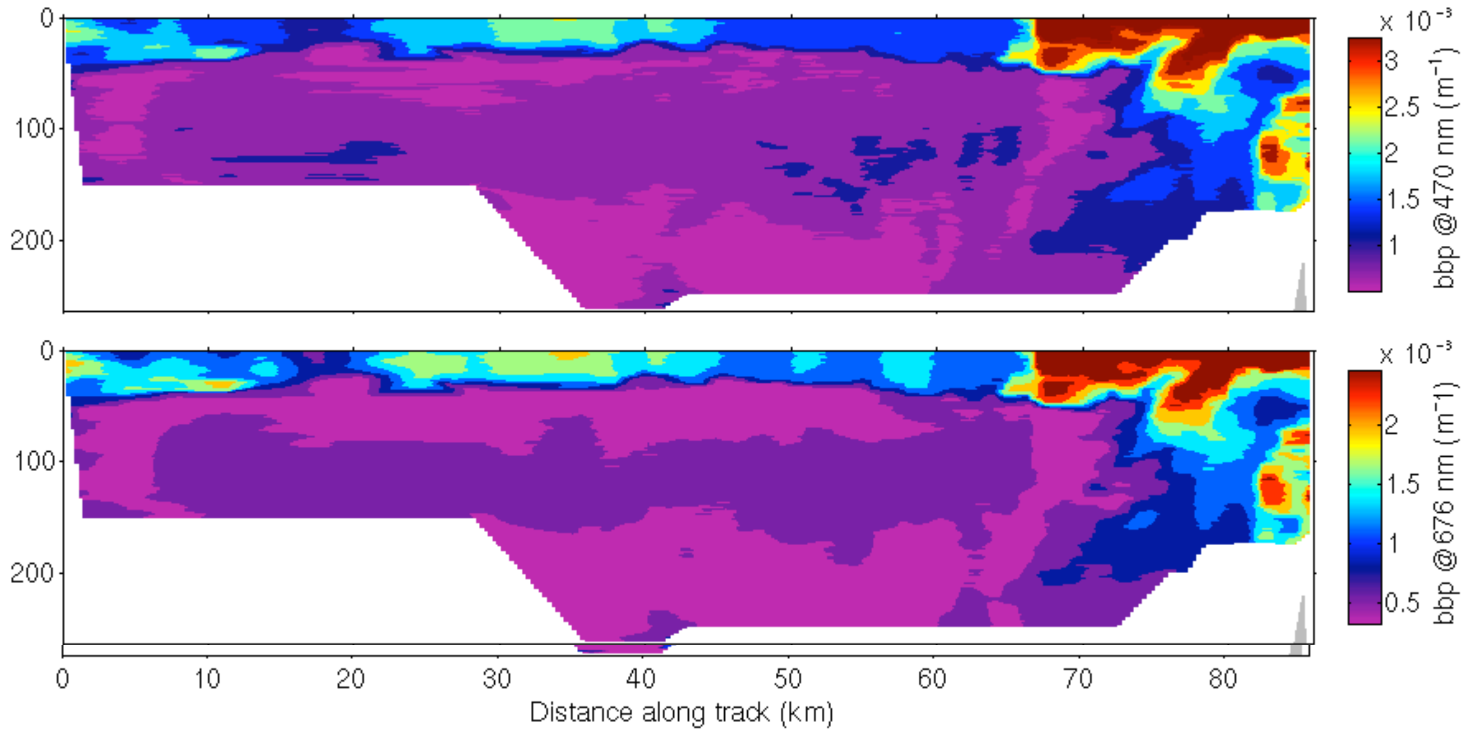
Monterrey Bay Aquarium Research Institute Observations

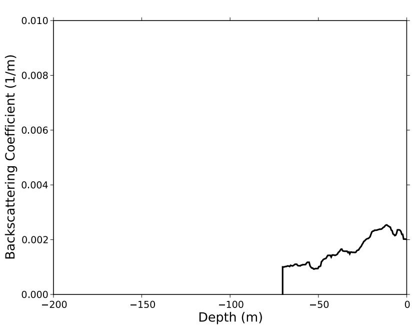
In situ field measurements with Autonomous Underwater Vehicles provide ground truth data for Lidar campaign.



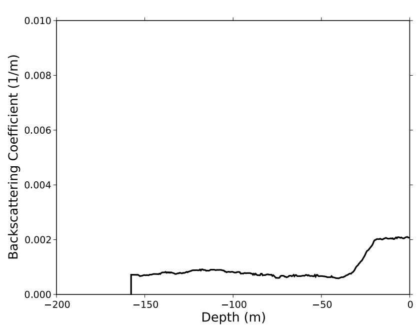
Particulate Backscattering Profiles

Total particulate backscattering coefficient

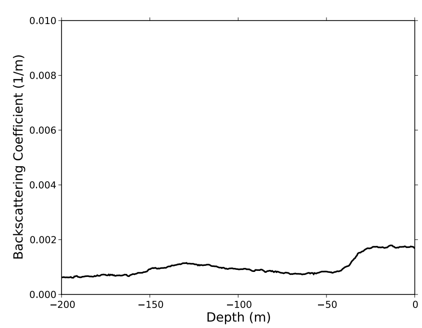




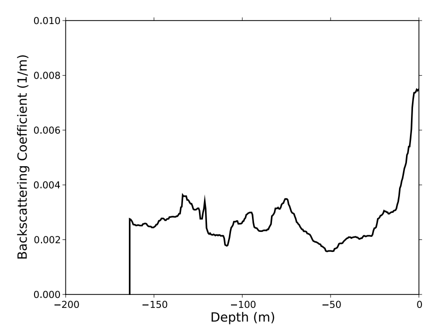
6 km



29 km

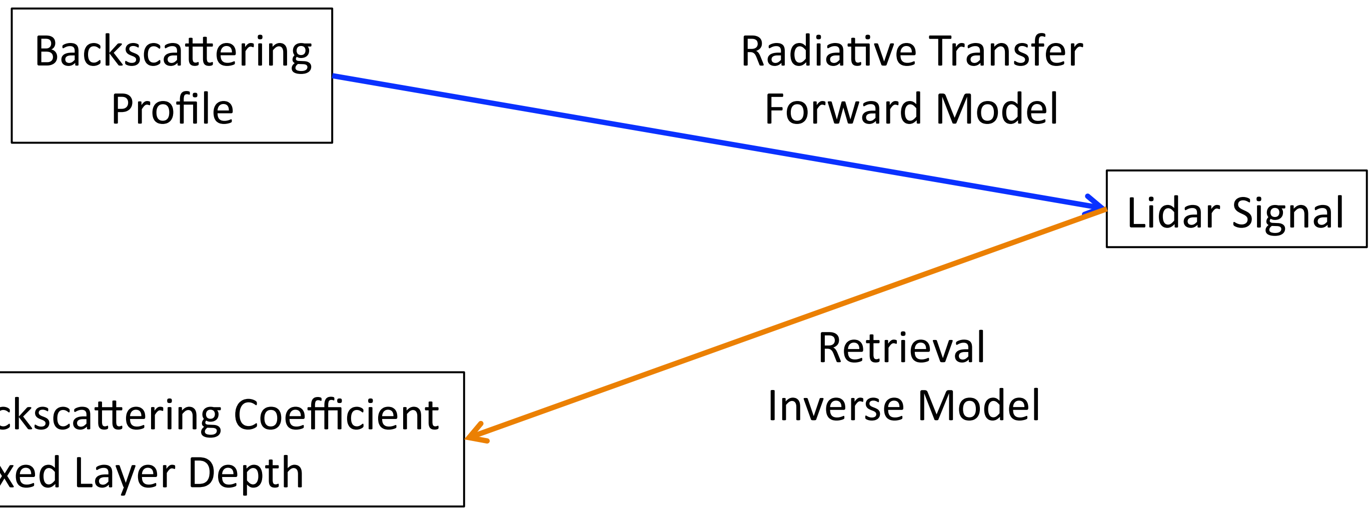


57 km

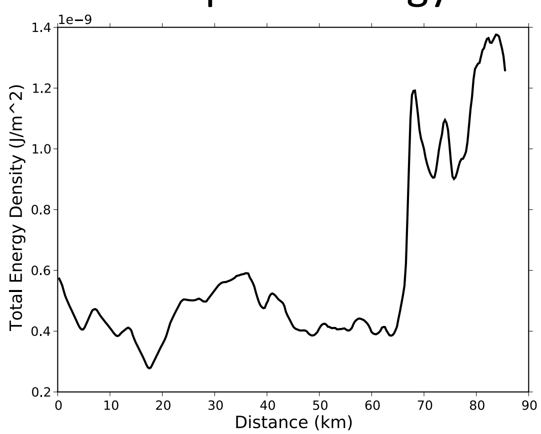


85km

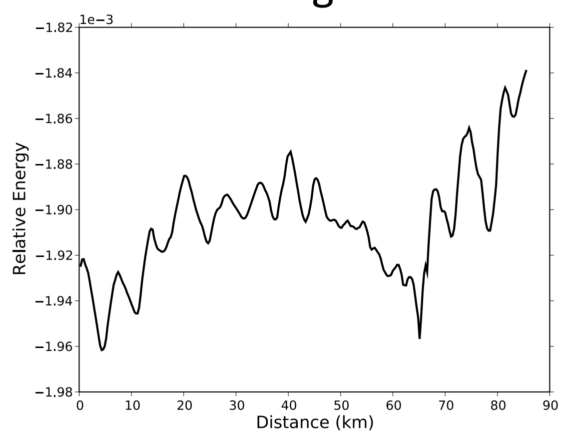
Retrieval



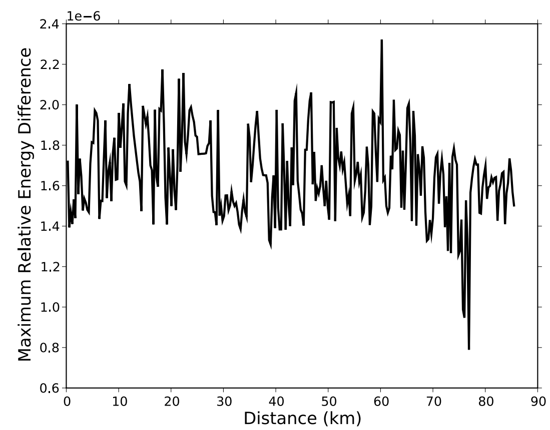
Total pulse energy



Relative energy difference at 2 degrees



Maximum pulse amplitude difference at 2 degrees

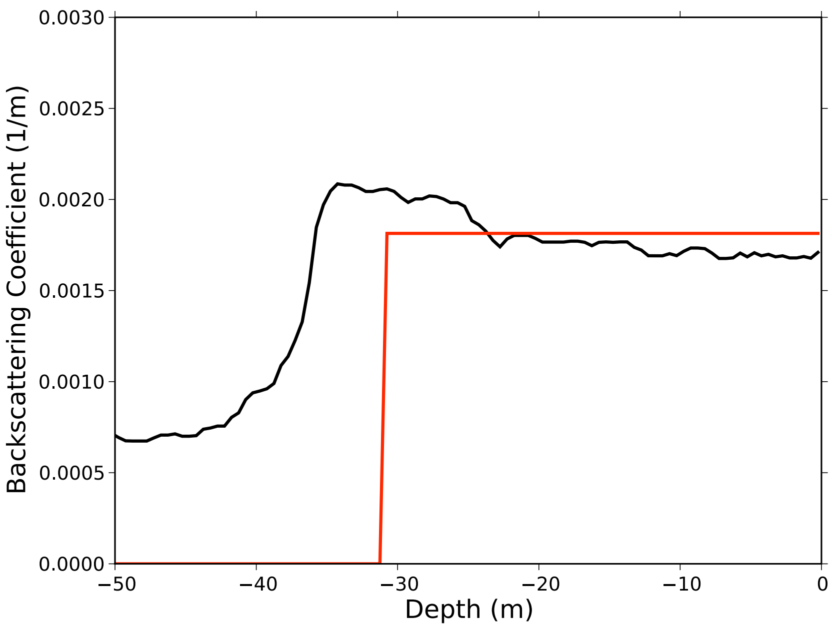


Retrieval Results

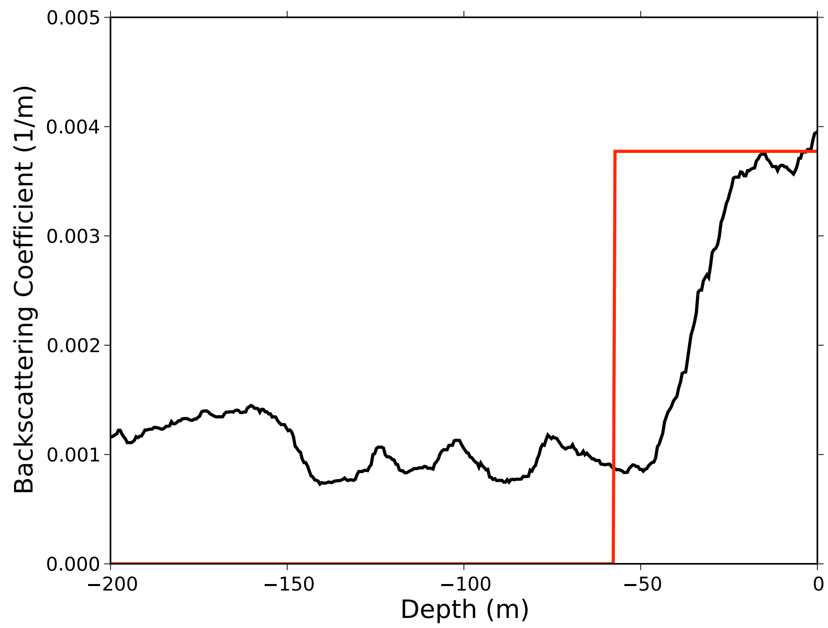
<u>Fitting procedure</u>

- Use total pulse energy and relative energy difference at 2 degrees
- Fit to uniform profile

8.6 km



72 km

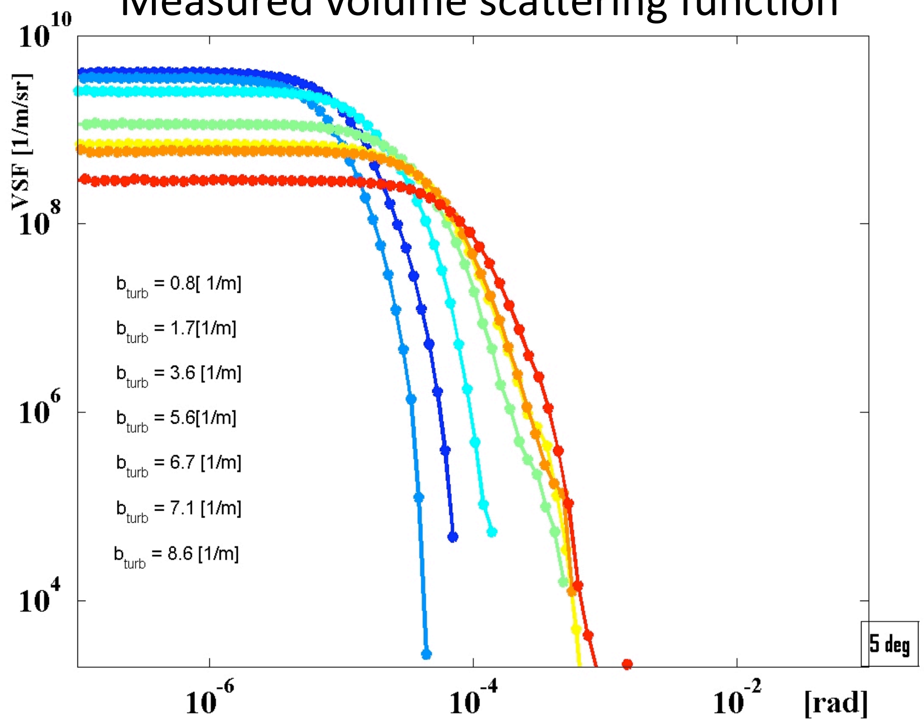


Turbulence Scattering

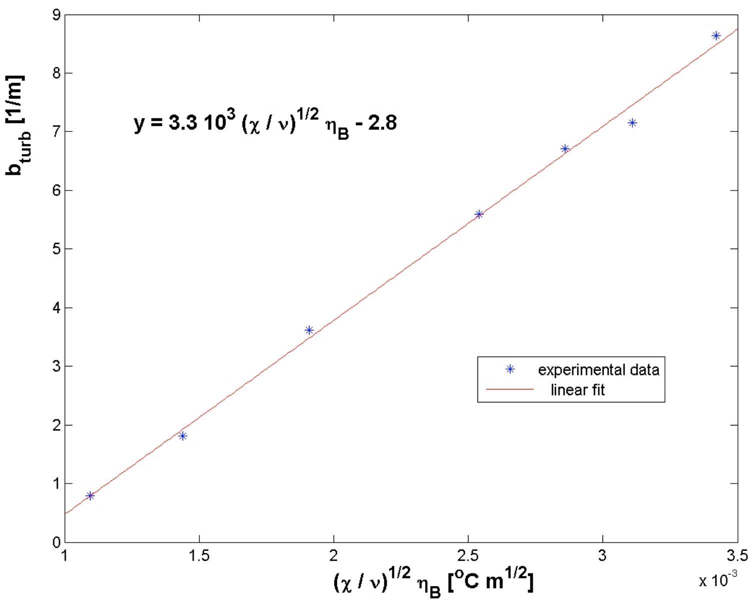
χ Temperature variance dissipation rate

ε Dissipation of turbulent kinetic energy

Measured volume scattering function



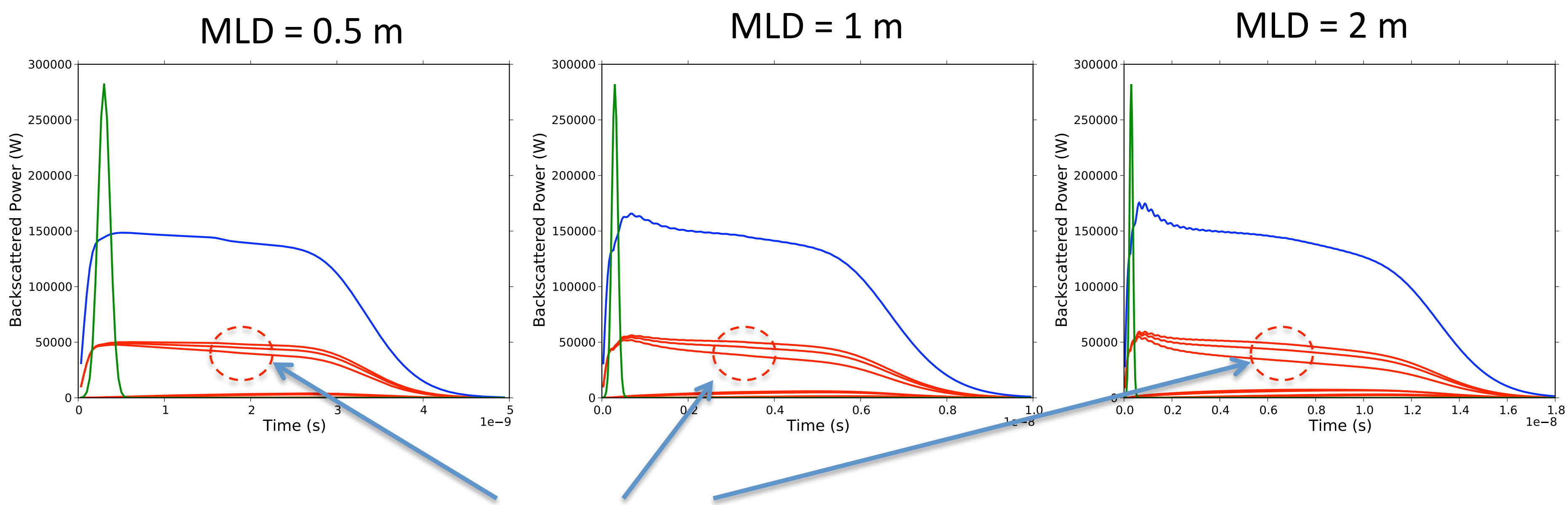
Measured total scattering cross section



Bogucki et al.

Turbulence Scattering

Full transient multi-scattering model



Angles (rad)

0

1.8e-5

2.7e-5

3.7e-5

a = 0

b(back) = 1e-3 m^{-1}

b(forward) = 1 m^{-1}

tau = 100 ps

E = 1 J

Inversion potentially gives the following parameters:

- MLD (turbulence)
- Turbulence forward scattering b(forward)

Conclusions

- Gathered evidence that particulate and turbulence profiles can be measured with an airborne lidar
- Two forward models were developed:
    1. Single scattering code for large angles to probe particulate profile
    2. Multiple scattering code for small angles to probe turbulence profile
- Proposed next steps:
    1. Validate model validation by comparing with tank experiments
    2. Complete calculations for small angle scattering
    3. Consider effect of surface
    4. Consider polarization: better SNR? Retrieving both turbulence parameters