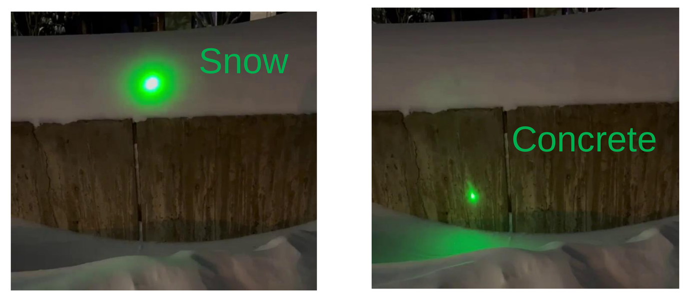
Measurement of Snowpack Density, Grain Size, and Black Carbon Concentration Using Time-Domain Diffuse Optics

Connor Henley[1,2,*], Joseph Hollmann[2], Colin Meyer[3], and Ramesh Raskar[1]
[1]MIT Media Lab, [2]The Charles Stark Draper Laboratory, [3]Dartmouth College
*chenley390@gmail.com

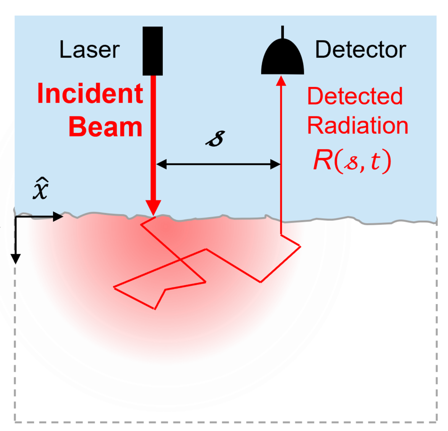
1. Introduction

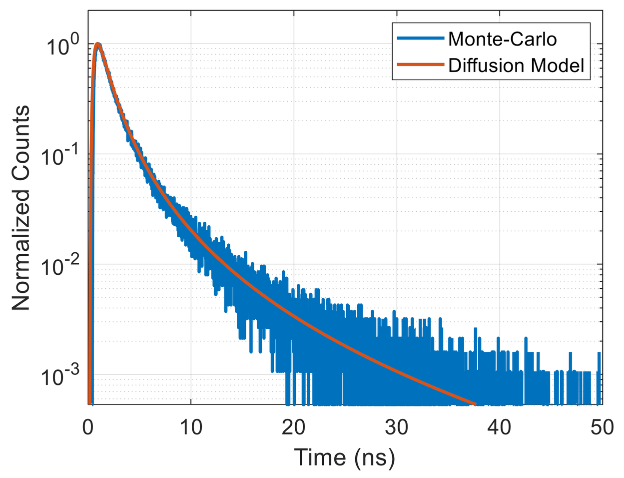
- Lidar is widely used to map **snowpack surface geometry** (i.e. depth, area)
- Most photons in laser pulse scatter many times within **snowpack volume** before returning to receiver
- We use the signature of **volumetric scattering** to estimate following snowpack properties:
  - **Ice volume fraction**: Equivalent to density, required to compute snow-water equivalent
  - **Ice grain radius**: Controls snowpack albedo and melt-rate
  - **Light absorbing impurities:** Concentration of soot, dust, or organic carbon.
- **Potential Applications:** Measuring snow-water equivalent (SWE), snow-melt forecasting, glacier mass balance, avalanche prediction

Subsurface scattering in laser-irradiated snow



2. Photon Diffusion Model





Photon Diffusion Model [1]

$$R(s,t) = \alpha \frac{z_0^2}{(2Dc_*t)^{5/2}} \exp\left(-\mu_a c_* t - \frac{s^2 + z_0^2}{4Dc_*t}\right)\left[1 + \frac{7}{3}\exp\left(-\frac{10z_0^2}{9Dc_*t}\right)\right]$$

Geometric Scattering Model [2, et al.]

$$\mu_s' = \frac{3}{2}(1-g)\frac{v_*}{r_*} \qquad c_* = \frac{c_0}{1 + (n_{ice}B - 1)v_*}$$

$$\mu_a = B\Gamma v_* + \mathrm{MAE}_{bc}\rho_{ice}C_{bc}v_*\left[1 + (B-1)v_*\right]$$

Scattering Parameters

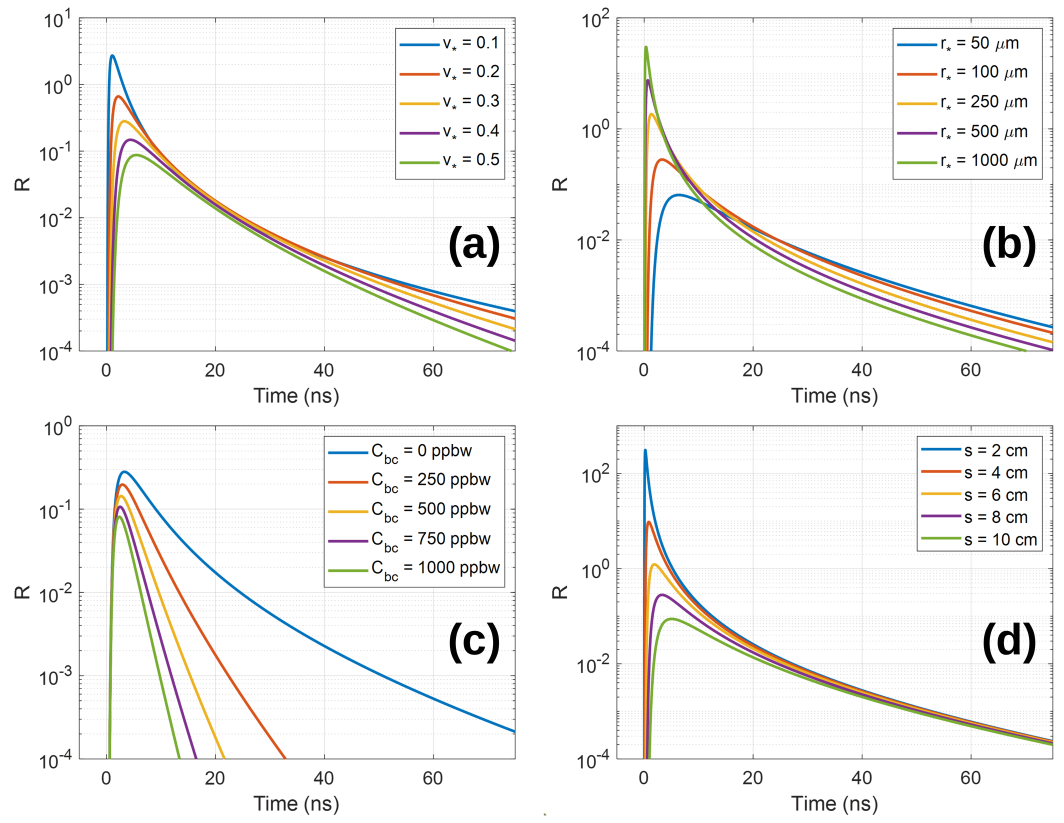
μ_a = absorption coefficient (m^{-1})
μ_s = scattering coefficient (m^{-1})
g = scattering asymmetry factor (unitless)
c_* = mean speed of light (m/s)

Snowpack Parameters

v_* = ice volume fraction (unitless)
r_* = grain radius (m)
C_{bc} = black carbon concentration (g b.c. / g snow)

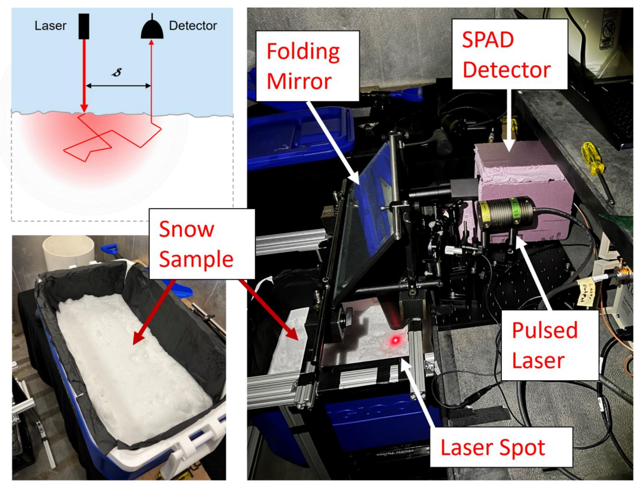
- Model solves the **photon diffusion equation**, an approximation to the radiative transfer equation
- Scattering parameters derived using **Mie scattering model** that assumes spherical ice grains

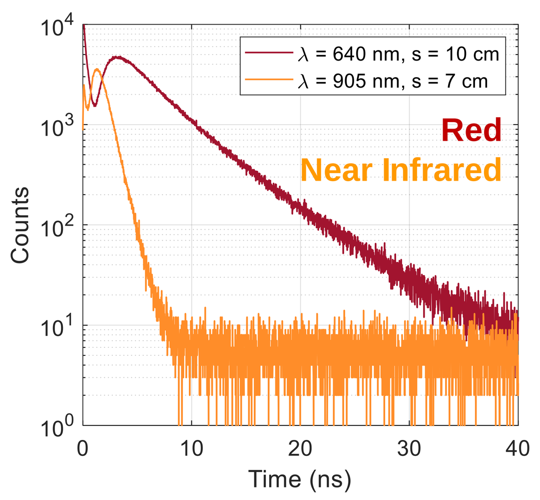
2. Photon Diffusion Model (cont.)



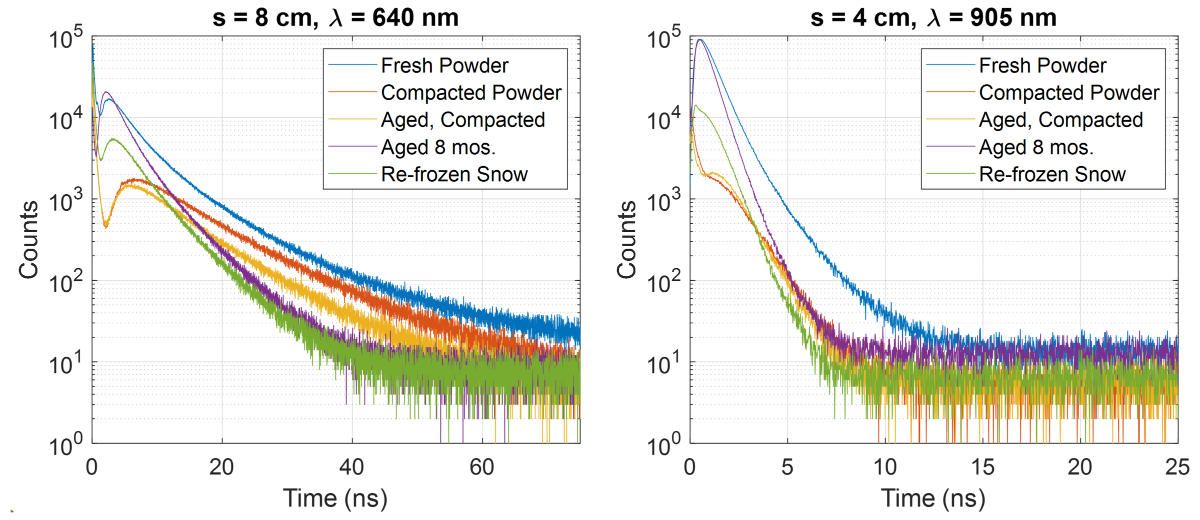
Effect of (a) density, (b) grain size, (c) black carbon content, and (d) separation of laser and focus spots, on time-dependent optical response of snowpack

3. Experiment





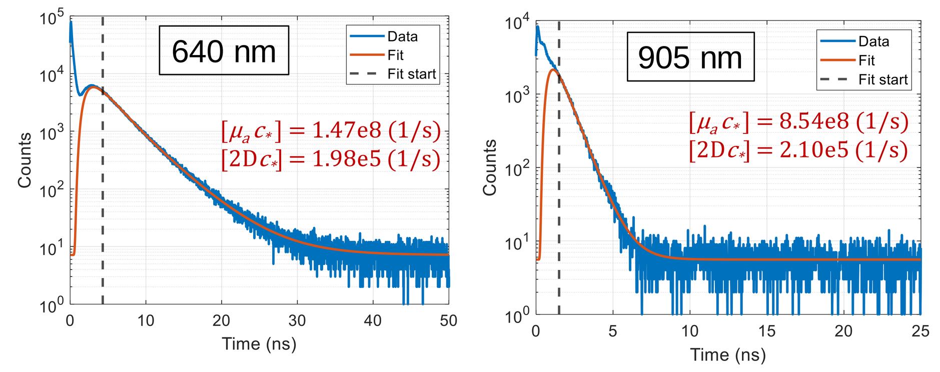
- Assembled simple **photon-counting lidar** system consisting of two diode lasers (λ = 640, 905 nm) and a single-photon avalanche diode (SPAD) detector
- Laser illuminates point on snow surface, detector measures light that exits snow surface a small distance (4-10 cm) away



Sample measurements for a variety of snow types

4. Estimation Algorithm

1. Fit diffusion model to time-of-flight histograms at two wavelengths



Fit parameters

$$\beta = \mu_a c_* \qquad \gamma = 2Dc_* \qquad \delta = z_0^2$$

2. Compute snowpack properties

Constants

$$a_i = B\Gamma_i$$
$$b_i = \rho_{ice}\mathrm{MAE}_{bc}(\lambda_i)$$
$$d_i = n_{ice}(\lambda_i)B - 1$$
$$e_i = 3(1-g)/2$$
$$f = B - 1$$

Ice Volume Fraction

$$v_* = \frac{b_2\beta_1 - b_1\beta_2}{c_0(a_1b_2 - a_2b_1) - d_1b_2\beta_1 + d_2b_1\beta_2}$$

Black Carbon Concentration

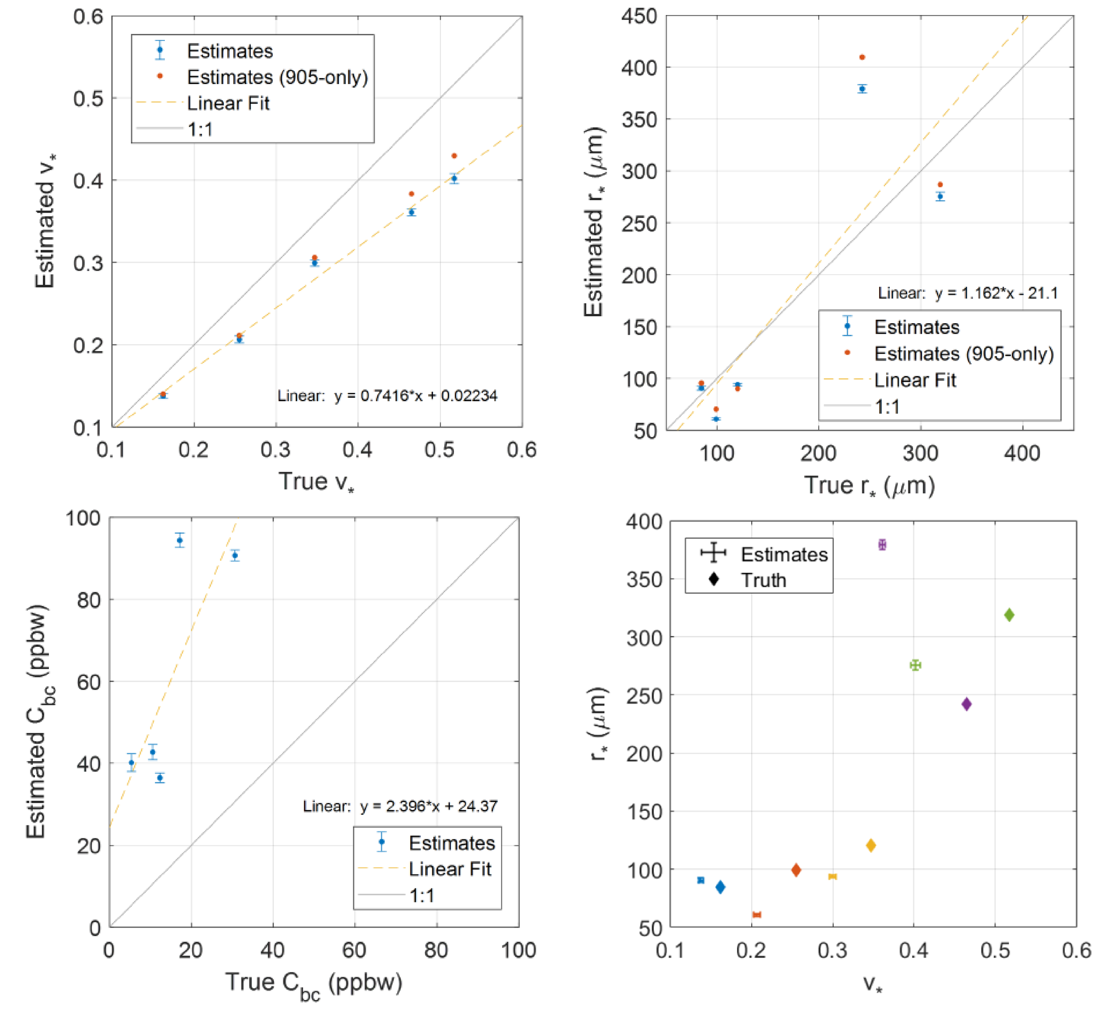
$$C_{bc} = \frac{1}{c_0 b_1(1 + f v_*)}\left[\left(\frac{1}{v_*} + d_1\right)\beta_1 - c_0 a_1\right]$$

Grain Radius

$$r_* = e_i\left[\frac{2c_0}{3\gamma_i v_*(1 + d_i v_*)} - a_i - b_i C_{bc}(1 + f v_*)\right]^{-1}$$

5. Results

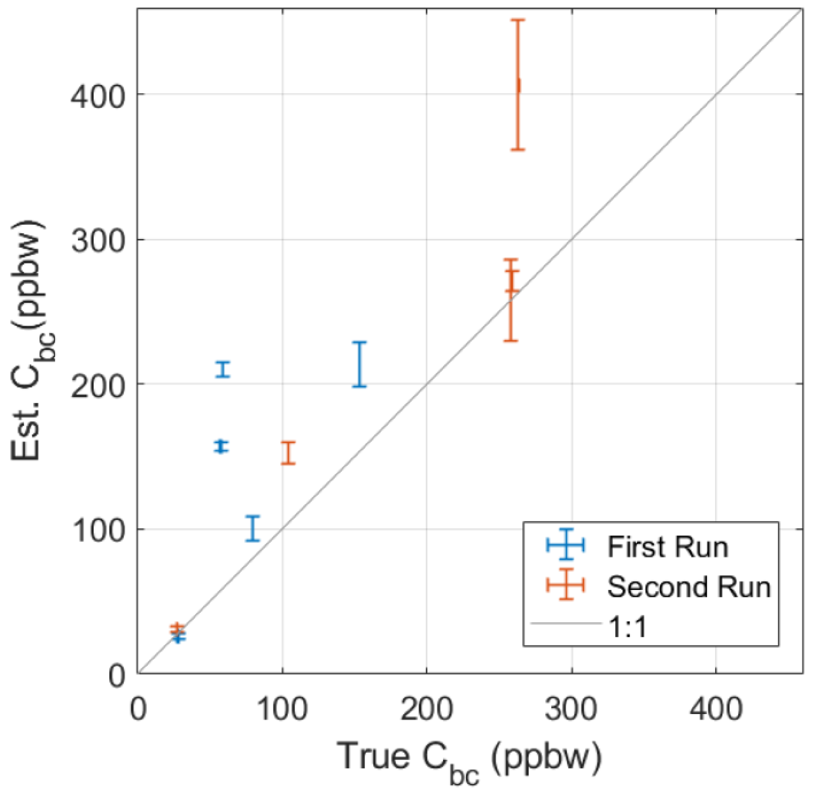
A. Natural Snow Samples



- Measured five natural snow samples with varied properties
- Ground truth sources:
  - (v_*) Melt test
  - (r_*) Micro-CT
  - (C_{bc}) Single-particle soot photometer (SP2) [3]
- Ice volume fraction linearly dependent on true values but underestimated by a factor of ~3/4
- Approximately 1:1 relationship between optical and CT **grain size** estimates
  - Correlation not as strong as ice volume fraction
- Impurity concentration overestimated by a factor of ~2.5
  - Likely cause = LAPs are not black carbon

5. Results (cont.)

B. Soot Addition Experiments



- Mixed varying amounts of Sigma-Aldrich Fullerene Soot into several coolers filled with snow
  - Snow density and grain size was nearly constant across samples
  - Soot-water suspension sprayed onto snow, and then mixed in
- C_{bc} measured using our method (Est.), and using single-particle soot photometer (True) [3]
- Correlation is linear and nearly 1:1
- Outliers likely due to error in ground truth sampling

6. Conclusions

- Time-domain diffuse optical measurements enable retrieval of grain size, ice volume fraction, and impurity content
- Experimental results are consistent with ground truth, although biases must be investigated further

Directions for Future Work

- Verify scattering model through larger measurement campaign
- Develop portable instrument for field measurements
- Explore potential to use diffuse optical signals in lidar remote sensing contexts
- Snow stratigraphy retrieval via *diffuse optical tomography*
- New modality for studying the optical properties of snow

7. References

[1] Kienle, A. and Patterson, M.S. (1997), Improved solutions of the steady-state and time-resolved diffusion equations for reflectance from a semi-infinite turbid medium. *J. Opt. Soc. Am. A*, 14, 246-254.

[2] Kokanovsky, A.A and Zege E.P. (2004). Scattering optics of snow. *Applied Optics*, 43(7), 1589-1602.

[3] Schwarz, J. P. et al. (2012) Assessing Single Particle Soot Photometer and Integrating Sphere/Integrating Sandwich Spectrophotometer measurement techniques for quantifying black carbon concentration in snow, *Atmos. Meas. Tech.*, 5, 2581–2592.

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