Diffuse LiDAR and laser reflectometry for measuring snow and ice properties

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***Abstract*—Constraining the optical properties of glacier ice and snow is required for accurate forecasts of sea levels and water resources. Here we present two active sensing techniques for measuring the optical properties of snow and ice which can be used to inform models.**

Keywords—remote sensing, LiDAR, active sensors, light scattering, diffusion, glaciology, snow hydrology

I. INTRODUCTION

The cryosphere (including snow, grounded and floating ice, and permafrost) is an integral component of the global climate system that is undergoing substantial change due to climate warming [1]. Glacier ice and snow act as a natural reservoir of fresh water by capturing water in solid form during cold months and releasing it during warm months coincidently with maximum demand. As the climate warms, the quantity and timing of water delivered to downstream communities is changing [2]. Tracking these changes from watershed to continental scales presents a major challenge to which require novel approaches to environmental sensing from field-deployed to spaceborne sensors. LiDAR has played a major role in monitoring the cryosphere [3, 4]. Multi-temporal digital elevation models (DEMs) produced by LiDAR are commonly used to monitor changes in ice sheet surface mass balance and seasonal snow depth. Active LiDAR measurements can also provide insight into optical properties, such as the scattering and absorption coefficients, of ice and snow which, in turn, enable the derivation of size and distribution of bubbles in glacier ice, grain size of snow, and concentration of and type of light-absorbing particulates in glacier ice and snow. Observationally constraining these properties would substantially improve our ability to model ice and snow melt. Here, we present two optical measurement techniques for the scattering and absorption coefficients of snow and ice that take advantage of the diffusion approximation of multiple scattering [5].

II. PULSE BROADENING IN DIFFUSE LIDAR

In the context of light scattering, the diffusion kernel describes the time evolution of the intensity distribution emitted from an instantaneous, i.e. short pulsed, point source. This measurement is implemented in the field using a nanosecond-pulsed laser source (Thorlabs), a photon counting photo-multiplier tube (Hamamatsu), and a data acquisition module (NI) to facilitate time-gated photon counting [6]. The setup in the field is shown in Fig. 1a. The laser and detector are placed at some distance on the glacier ice during field work on Collier Glacier, Oregon, USA. This range is much larger than the scattering mean-free path, which ensures that all detected photons are in diffusive regime. Fig. 1b shows a measured time-of-flight histogram for a range of 1.8 meters. The diffusion kernel is fitted to data and is unique in respect to scattering and absorption coefficients. This enables us to retrieve these properties from the measurement and relate them to reflectance and albedo. The absorption coefficient is directly related to the concentration of

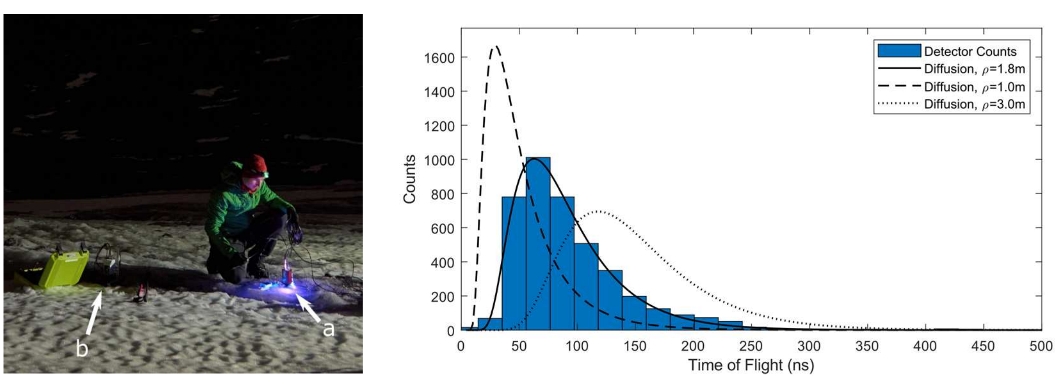

Fig. 1. Left: The pulsed laser source (a) and photon-counting detector (b) are separated by 1.8m on the surface of the glacier. Right: Measured histogram data (blue) with fitted pulse shape in the diffusion approximation (solid line) and pulse shapes for shorter (dashed line) and longer range (dotted line). Theory curves are normalized to equal area.

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light-absorbing impurities such as black carbon and dust. Shown alongside the data are pulse shapes for identical optical properties but different range to illustrate the evolution of the pulse shape.

III. Active Reflectometry Sensor

If integrated over all times, the diffusion kernel describes the stationary fluence, related to radiance from the surface of the medium in a steady-state case. The radiance decreases exponentially as a function of distance (range) to the source, depending on a diffuse attenuation coefficient that is the product of the scattering and absorption coefficients. As such a measurement does not require pulsed lasers or time-resolved photon counting, it can be implemented with basic tools such as low-cost diode laser modules and a smartphone camera [7]. The instrument in the field is shown in Fig. 2a. We use two lasers: A first measurement of the attenuation coefficient at a wavelength of 650 nanometers serves as reference, as the absorption of snow is dominated by clean ice absorption. This allows us to extract the scattering coefficient. We then take advantage of the wavelength-independence of the scattering coefficient of snow in the visible spectrum. We measure the attenuation coefficient again at a shorter wavelength of 405 nanometers. As the scattering coefficient is already known, we can now extract the absorption coefficient at 405 nanometers from the second measurement, yielding an equivalent set of data compared to a pulsed measurement. The procedure for extracting the attenuation coefficient at each wavelength relies on a third spatial camera calibration measurement: The photo shown in Fig. 2b is scaled to actual units. Pixels are then sorted by their range from the center (brightest) pixel. Data points are then averaged in 0.25-millimeter bins and fitted with the integrated diffusion equation, as shown in Fig. 2c. The scattering and absorption coefficients obtained this way can be used to infer the spectral albedo of snow, similar to that of glacier ice, along with impurity concentrations.

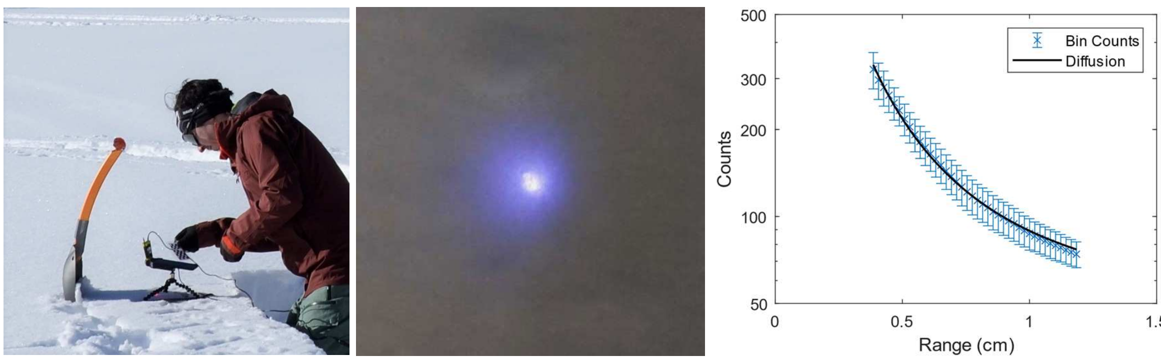

Fig. 2. Left: The sensor with two diode laser modules and cellphone camera in the field. Middle: Backscattered light disribution shows an intensity falloff as a function of distance (range) from the center. Right: Scaled and averaged data (blue symbols) fitted with the diffusion model (black line).

IV. Conclusion

Precise knowledge of glacier ice and snow properties are a prerequisite for accurately modeling the cryosphere's response to climate change. We developed two diffuse-optical sensors to measure the scattering and absorption coefficients of snow and ice. Our instrument is portable, rugged, and successfully deployed across isolated regions of the Cascade Range in Oregon. The optical coefficients provide access to both the microscopic properties, i.e. porosity, grain size and concentration of light-absorbing impurities [8], and apparent properties. i.e. albedo. Therefore, they can provide additional information that radiance measurements alone cannot. Diffuse-optical sensors can provide field data where spatial resolution of remote sensing is insufficient or serve as calibration and validation for remotely sensed data. The techniques can also potentially be integrated into airborne or space-based (e.g. ICESat-2) platforms to remotely sense the optical properties and depth of snow [4].

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