

Interdisciplinary Research (IDR) Origination Awards

Cover Page

Project Title

Title: Calibrating Lidar Intensity for Snow Reflectance and Grain Size Retrieval

Principal Investigator(s) (full-time faculty)

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Track

Track one

Abstract

Snow grain size is a primary control on snow albedo in the near-infrared wavelengths, a critical parameter for modeling surface energy balance and estimating snowmelt timing. However, current remote sensing approaches rely on passive optical measurements that are limited by solar illumination and the challenge of mixed pixels, often leading to biased grain size retrievals. Although aerial lidar intensity has the potential to retrieve snow grain size without these limitations, it is often treated as noise because it lacks a physics-based calibration framework. This project is the first to address this gap by (1) quantifying fundamental laser-snow interactions through controlled laboratory experiments; (2) developing a radiometric calibration that relates lidar intensity to snow reflectance; and (3) producing a lidar-derived snow grain size retrieval workflow applicable across sensor platforms and snow conditions. Aerial lidar is widely used for high-precision snow depth and avalanche forecast mapping; thus, calibrating lidar intensity would create new scientific value from datasets that are already routinely collected worldwide and archived for topographic mapping. This interdisciplinary effort brings together expertise in laser physics, imaging spectroscopy, and snow remote sensing. Together, these outcomes will transform lidar intensity from an underutilized byproduct of elevation mapping into a physically interpretable snow remote sensing measurement, with broad applications in cryospheric science and water resource prediction.

Summary of Plans for External Funding

This project provides seed funding to generate the preliminary data and calibration framework needed for competitive external proposals in snow hydrology and remote sensing. Primary targets include the National Science Foundation (NSF) Earth Sciences Division (Hydrologic Sciences) and NASA Earth Science (Terrestrial Hydrology). Results will support submission of an NSF EAR proposal, an NSF CAREER proposal, and future NASA proposals following completion of laboratory characterization, calibration development, and initial field validation (anticipated 2027-2028). The project will also establish interdisciplinary collaborations that position the team for future multi-investigator funding.

PROJECT NARRATIVE

1. OVERVIEW AND OBJECTIVES

1.1. Background

Snow is a critical freshwater resource in many regions of the world. Across the western United States, mountain snowpack functions as a natural reservoir, storing water during winter and releasing it during spring and summer melt. Accurate monitoring of snow conditions, therefore, is essential for predicting water availability, managing hydropower and agriculture, and understanding regional climate processes.

Remote sensing provides the primary means of observing snowpack across large and often inaccessible watersheds. These observations enable repeated, spatially continuous estimates of key variables such as snow depth, snow albedo, and snow water equivalent (Bhardwaj et al., 2016; Painter et al., 2016). Snow albedo, the fraction of incoming solar radiation reflected by the surface, plays a central role in snowmelt dynamics: bright snow reflects more energy and melts more slowly, whereas darker snow absorbs more energy and accelerates melt. Grain size strongly influences how light interacts with snow in the near-infrared, with smaller grains reflecting more light, while larger, metamorphosed grains that develop later in the season increase absorption and reduce albedo (Warren, 1982). Different remote sensing approaches provide complementary information. For instance, aerial lidar (light detection and ranging) is widely used for precise elevation measurements, allowing accurate mapping of snow depth by comparing terrain elevations before and after snowfall, often with sub-decimeter accuracy across watersheds (Deems et al., 2013). Imaging spectroscopy, in contrast, measures reflected sunlight across multiple wavelengths and is commonly used to estimate snow albedo and effective grain size (Painter et al., 2009).

Despite its widespread use, imaging spectroscopy has several inherent limitations that hinder reliable measurements of snow albedo. First, imaging spectroscopy relies on solar illumination, indicating that measurements are sensitive to the solar zenith angle, and data acquisitions are limited to certain times of the day or even times of the year at high latitudes. Notably, peak snow accumulation and melt often occur during periods with low sun angles in the winter and early spring in the northern hemisphere. These conditions exacerbate shadows induced by vegetation and terrain in mountainous regions, which can lead to substantial underestimation of snow cover extent and introduce bias into albedo retrievals. Another limitation is the mixed-pixel problem, in which a single pixel represents reflected energy from multiple surface types (e.g., snow, vegetation, and bare ground), increasing uncertainty in snow property estimates.

Lidar intensity, or the strength of the backscattered laser signal, offers a promising alternative for characterizing snow surface optical properties. Because lidar is an active sensor, it operates independent of solar illumination and is not subject to the same shadowing limitations that affect passive remote sensing approaches. Lidar data are also collected as individual geolocated returns in a point cloud rather than aggregated image pixels, substantially reducing uncertainty associated with mixed surface types. Lidar systems used for snow applications typically operate in the near-infrared, where higher backscattered intensity is expected to correspond to smaller snow grain size and higher reflectance. However, raw lidar intensity is not directly interpretable without appropriate correction and, therefore, is often treated as noise (Yan and Shaker, 2018). Instead, most applications focus on lidar's altimetry capabilities for snow depth mapping and avalanche forecasting, which has prevented lidar intensity from being fully exploited as a meaningful measurement of snow optical properties.

Currently, no physics-based radiometric framework exists to convert raw lidar intensity into calibrated snow reflectance or grain size. This gap limits the scientific value of lidar datasets

that are already collected worldwide. Establishing such a framework would transform lidar from a primarily topographic tool into a quantitative optical measurement system capable of characterizing snow surface properties. This capability would improve representation of snow processes in hydrologic models and strengthen predictions of snowmelt and water availability for the millions of people downstream who depend on this important resource.

1.2. Preliminary Studies

The PI has conducted preliminary analyses demonstrating the potential for lidar intensity to characterize snow surface optical properties when appropriate geometric corrections are applied. In particular, aerial lidar intensity was corrected for range and incidence angle to reduce topographic effects, revealing clear sensitivity to snow grain size and surface reflectance. Using data acquired by the Airborne Snow Observatory (ASO) during a February 2017 flight, corrected lidar intensity showed strong agreement with in situ grain size observations collected using a field spectroradiometer, with a median difference of 32 μm , corresponding to approximately 1% error in estimated snow albedo (Ackroyd et al., 2024). Lidar intensity also successfully identified snow covered area that was misclassified as shadows in imaging spectroscopy data, increasing detected snow covered area by 5.4% within the study basin. Comparable results were observed over Place Glacier, British Columbia, using aerial lidar intensity from the Airborne Coastal Observatory acquired later in the melt season (May 2021). Despite larger grain sizes during this period, lidar-derived estimates demonstrated similar performance, with a 2% error in albedo (Ackroyd et al., under review). Together, these findings indicate that lidar intensity retains sensitivity to snow optical properties across varying snow conditions.

While geometric corrections for range and incidence angle are necessary to reduce terrain-driven variability, these steps alone are insufficient to establish a direct relationship between lidar intensity and snow reflectance. Current calibration approaches typically rely on coincident imaging spectroscopy measurements, limiting robustness and cross-platform applicability. These preliminary results, therefore, demonstrate both the promise of lidar intensity for snow characterization and the critical need for a physics-based radiometric calibration framework, motivating the proposed laboratory experiments and calibration development described in this project.

1.3. Goals

The long-term goal of this project is to establish calibrated lidar intensity as a remote sensing measurement for snow hydrology, enabling lidar to function not only as an altimetry tool for snow depth mapping but also as a quantitative instrument for characterizing snow surface optical properties. Because aerial lidar datasets have been collected for decades primarily for elevation mapping, this work could immediately unlock new scientific value from existing archives while expanding the utility of future lidar acquisitions. By converting lidar intensity into a physically meaningful measurement, this project creates a new observational data source for snow hydrology without requiring additional data collection. The resulting calibration framework is designed to be transferable across UAV, airborne, and satellite lidar platforms. For example, NASA's recently announced Earth Dynamics Geodetic Explorer (EDGE) mission will deploy the first global swath-imaging lidar in the early 2030s, creating opportunities for large-scale application of calibrated lidar intensity over snow and ice. Beyond Earth, similar approaches could inform cryospheric investigations in planetary environments such as Mars, where lidar observations are already available.

The short-term goal of this project is to develop the foundational physics-based calibration framework required to realize this long-term vision. Specifically, the project focuses on establishing a transferable radiometric calibration that relates lidar intensity to snow surface reflectance, supported by controlled laboratory experiments and field validation. This short-term effort is intentionally scoped to produce the preliminary data and calibration workflow needed to

support future external funding proposals and broader deployment. To achieve this objective, three specific aims are proposed: **Aim 1**: quantify fundamental laser-snow interactions through controlled laboratory experiments; **Aim 2**: develop a radiometric calibration that relates lidar intensity to snow reflectance; and **Aim 3**: produce a lidar-derived snow grain size workflow that is scalable across aerial lidar platforms and diverse snow conditions.

The IDR Origination Award is critical for accomplishing these aims because it enables interdisciplinary collaboration spanning laser physics, imaging spectroscopy, and snow remote sensing, expertise that rarely converges within a single discipline. The award also provides access to the lidar instrumentation required to generate preliminary datasets and validate the proposed calibration framework. Together, these resources will establish the foundation for competitive external funding proposals to agencies such as the National Science Foundation (NSF) and NASA Earth Science, while also enabling future research by a new student cohort using UAV-based lidar intensity to collect snow observations and evaluate calibration transferability.

2. RESEARCH PLAN

2.1. Aim 1: Quantify the physical drivers of lidar backscatter from snow across wavelength, geometry, and microstructure

Objective: Establish a physics-based understanding of how snow optical and physical properties control laser backscatter across wavelengths, with emphasis on wavelength dependence and penetration depth, using controlled laboratory experiments to characterize BRDF (Bidirectional Reflectance Distribution Function), a function that quantifies how surface reflectance changes with illumination and observation geometry, under active illumination.

Methodology: Snow samples representing a range of grain sizes will be collected throughout the snow season and preserved under frozen conditions prior to laboratory analysis to minimize metamorphic evolution. In the lab, samples will be scanned using lasers at three wavelengths (ultraviolet, green, and near-infrared) to establish the angular response of snow backscatter under controlled illumination geometry. PI Bergeson currently has ultraviolet, green, and near-infrared laser systems, along with the instrumentation to measure backscattered signals at ultraviolet and green wavelengths, enabling immediate execution of multi-wavelength lab experiments. The IDR Award will be used in part to acquire a near-infrared (1064 nm) sensor to enable measurement of backscattered signals at wavelengths commonly used in lidar systems. Each sample will be scanned across a range of incidence angles (0° to 80°) to characterize BRDF-like behavior adapted for lidar viewing geometry and to quantify wavelength-dependent sensitivity to snow optical and physical properties. This approach follows the conceptual framework of Painter and Dozier (2004), adapted for active laser illumination rather than passive solar radiation. To assess laser penetration depth, nadir scans will be conducted over snow layers of increasing thickness with an underlying reference target, allowing penetration depth to be inferred from the depth at which the target signal is detected. Together, these experiments will isolate the physical controls on lidar backscatter from snow and provide the foundation for subsequent radiometric calibration and retrieval development.

Measures of Success: Wavelength-specific angular response functions, penetration depth estimates, and a physically grounded parameterization linking snow microstructure to backscatter behavior, forming the basis for quantitative radiometric calibration.

2.2. Aim 2: Develop and validate a calibration framework that converts raw lidar intensity to snow surface reflectance

Objective: Translate the understanding of wavelength-dependent angular response and penetration depth of snow from a controlled environment into a transferable calibration framework

that removes instrument- and geometry-driven variability from lidar intensity measurements and retrieves snow surface reflectance with quantified uncertainty (<5% absolute reflectance).

Methodology: We will develop a physics-constrained calibration framework that decomposes measured lidar intensity into instrument response, observation geometry (e.g., range and incidence angle), and snow surface scattering components. Laboratory experiments will quantify how snow microstructure and wavelength control angular scattering behavior and laser penetration depth. These physically based relationships, which are independent of lidar platform, will be used to constrain the surface-scattering component of the calibration framework. Additional parameters will be estimated directly from airborne lidar observations using flight metadata and repeat passes. Uncertainty will be quantified through propagation of measurement and model uncertainties using resampling or Monte Carlo approaches. The framework will be evaluated through internal consistency tests across viewing geometries, repeat pass agreement over homogeneous snow surfaces, and limited independent reflectance references when available (e.g., field targets or coincident spectroscopy).

Measures of Success: Consistent lidar-derived snow reflectance estimates across repeat passes and snow conditions, and agreement within uncertainty bounds with in situ reflectance measurements, indicating successful transfer of laboratory-derived constraints to field observations.

2.3. Aim 3: Retrieve snow grain size from calibrated lidar reflectance and evaluate against in situ measurements

Objective: Apply the calibration framework to UAV lidar observations to retrieve snow grain size and evaluate retrieval performance across snow conditions using in situ measurements.

Methodology: We will conduct repeated field campaigns across a range of snow conditions (e.g., fresh/dry, wet/melting, wind-affected) to build a time series of coincident UAV lidar observations and in situ snow measurements at a study site near Sundance, Utah, equipped with an instrumented study plot. Students will receive training through the CUAHSI field school to ensure standardized collection of snow microphysical measurements, including grain size (primary validation variable), density, and liquid water content, as well as surface reflectance measurements using a field spectroradiometer to provide validation of lidar-derived reflectance. These complementary measurements will enable assessment of potential confounding influences on reflectance and ensure radiometric consistency. UAV lidar flights will be conducted using consistent flight plans throughout the melt season, with student operators certified under the FAA Part 107 remote pilot exam to ensure compliant data acquisition. Raw lidar intensity will be converted to snow surface reflectance using the calibration framework, producing reflectance with quantified uncertainty. We will then develop and test a retrieval workflow that estimates snow grain size, and ultimately snow albedo, from calibrated lidar-derived reflectance, using in situ measurements for model validation. This effort will produce a transferable workflow that enables snow grain size and albedo estimation from calibrated lidar intensity, advancing the use of lidar as a quantitative tool for monitoring snow optical properties and strengthening the integration of lidar into hydrologic science.

Measures of Success: Lidar-derived snow grain size will agree with independent in situ measurements within propagated uncertainty bounds, demonstrating low bias and acceptable RMSE across diverse snow conditions, with field spectroradiometer observations confirming the radiometric accuracy of calibrated reflectance.

2.4. Expected Outcomes

External funding: This project will provide the preliminary data needed to support submission of competitive external proposals to federal funding agencies such as NSF Earth Sciences Division

(Hydrologic Sciences) and NASA Earth Science (Terrestrial Hydrology), focused on cryospheric processes, snow hydrology, and remote sensing.

Conference presentations: Results will be presented at major snow and geoscience meetings, including the Western Snow Conference (2027, 2028) and the American Geophysical Union (AGU) Fall Meeting (2027, 2028).

Scholarly publications: The project is expected to produce at least two peer-reviewed journal articles at minimum: (1) a paper describing the physical basis and calibration framework for lidar intensity over snow, and (2) a paper demonstrating retrieval of snow grain size from calibrated lidar-derived reflectance and evaluation against in situ measurements.

Student mentoring: This project will support one master’s student and two undergraduate research assistants, providing hands-on training in laboratory experiments, UAV lidar operations (including FAA Part 107 certification), field-based snow measurements (e.g., grain size, density, and optical properties), and professional development through participation in the CUAHSI Snow School.

Scientific outcomes: The project will establish a physics-constrained calibration framework and transferable workflow for interpreting lidar intensity over snow, enabling retrieval at the point cloud of snow grain size from lidar datasets. This project will also support future interdisciplinary research, student training, and externally funded research related to this new development of calibrated lidar intensity.

2.5. Timeline

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Aim 1: Snow sample collection; Lab experiment								
Aim 1: Constrain physics of laser-snow interactions								
Aim 2: Calibration framework development								
Aim 2: Uncertainty analysis								
Aim 3: UAV lidar flights and in situ measurements								
Aim 3: Grain size retrieval workflow								
Preparation of manuscripts and external funding proposals								

Table 1. IDR Work Schedule (Q1-Q8 indicate each quarter throughout the 2-year timeline).

2.6. Interdisciplinary Team

Dr. Bergeson (Co-PI) provides expertise in laser physics and atomic spectroscopy, leading the design and execution of controlled laboratory experiments quantifying laser-snow interactions (Aim 1). He directs an established laser laboratory with existing ultraviolet, green, and near-infrared laser systems and the infrastructure required to measure angular backscatter response and penetration depth under controlled conditions.

Dr. Porter (Co-PI) contributes expertise in mechanical engineering, imaging spectroscopy, and radiative transfer modeling, and leads development of the physics-constrained calibration framework and associated uncertainty characterization (Aim 2). He is responsible for translating laboratory-derived constraints into a scalable calibration approach applicable to airborne lidar systems.

Dr. Ackroyd (PI) leads integration and field-scale application of the calibration framework using UAV lidar observations over snow (Aim 3). Her expertise in snow remote sensing, lidar data processing, and field-based snow measurements enables direct application of laboratory and modeling advances to realistic cryospheric settings.