

Short-wave infrared radiometer for airborne validation of satellite snow products

Shannon M. Hamp; Riley D. Logan; Eric A. Sproles;
Joseph A. Shaw

Accessibility Disclaimer:

For a more accessible version of this document, please submit an accessibility request form through the Montana State University Library website.

Short-wave infrared radiometer for airborne validation of satellite snow products

Shannon M. Hamp^{1a}, Riley D. Logan^{1a}, Eric A. Sproles^{1b}, and Joseph A. Shaw^{1a,*}

^aMontana State University, Optical Technology Center, Electrical and Computer Engineering Department, Bozeman, Montana, United States

^bMontana State University, Geospatial Core Facility, Earth Sciences Department, Bozeman, Montana, United States

ABSTRACT. Surface reflectance determines how much solar radiation is retained, making it a critical component of the Earth's energy and water balance. Several satellites, including Landsat and Sentinel-2, measure surface reflectance; however, the limited temporal resolution and spatial resolution of these satellites introduce uncertainties, especially in areas of high temporal and spatial variability such as mountainous regions dominated by seasonal snowpack, trees, and fluctuating slopes. Unoccupied aerial vehicles (UAVs) provide a platform for frequent measurement of surface reflectance with user-selected coverage during critical times of snowpack change. UAVs can enable higher spatial resolution than satellites while covering a larger spatial area than *in situ*, tower-based sensors. We present the design and calibration of a custom UAV-based radiometer system for validating the shortwave infrared Landsat Operational Land Imager Band 7 and Sentinel-2 MultiSpectral Imager Band 12 surface reflectance measurements. Two sensors enabled surface reflectance correction: an upwelling radiation sensor was designed to measure scene-reflected radiance [$W/(m^2 sr)$], and a downwelling radiation sensor was designed to measure incident irradiance [$W/(m^2)$]. Both radiometers were constructed with single-pixel photodiodes and custom bandpass filters to match the spectral range of Landsat Band 7 (2110 to 2290 nm), and the half-angle field of view of the upwelling system was designed and measured to be 3.43 deg. When flown 120 m above the ground, this corresponds to a ground swath diameter of 14.39 m, a spatial resolution over four times finer than the 30 m Landsat Band 7 pixel. Radiometric and temperature calibrations reduced uncertainties for both sensors. The custom radiometer was flown on a UAV in alignment with a Landsat 9 satellite overpass in Southwestern Montana, United States (45.23 deg, -111.48 deg). The resulting airborne measurements were used to assess the implications of surface topography on radiometer-measured reflectance, where the preliminary airborne measurements indicated a significant correlation between surface reflectance variability and slope angle.

© The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.20.017501](https://doi.org/10.1117/1.JRS.20.017501)]

Keywords: radiometer; unoccupied aerial vehicle; snow; remote sensing; Landsat

Paper 250587G received Aug. 28, 2025; revised Dec. 4, 2025; accepted Jan. 6, 2026; published Jan. 22, 2026.

1 Introduction

Snow reflectance, the ratio of reflected irradiance to incident irradiance on a snowy surface, directly influences Earth's climate¹ and is a primary component of the energy balance of the

*Address all correspondence to Joseph A. Shaw, joseph.shaw@montana.edu

Handling Editor: Xiangqian Wu, Associate Editor

snowpack, influencing hydrological cycles and the timing and availability of water resulting from seasonal runoff.^{2,3} Fluctuations in snow reflectance have been estimated by satellite imagery from sensors such as the Operational Land Imager (OLI) instruments on Landsat 8 and 9, as well as the MultiSpectral Imager (MSI) on Sentinel-2; however, uncertainties in satellite retrievals of snow reflectance propagate to uncertainties in climate and water runoff models.^{4–6} The uncertainties can arise due to measurement error and noise, as well as limited temporal resolution, atmospheric variability, and sub-pixel spatial variability.

Although satellite retrieval uncertainties can be reduced by *in situ* measurements that provide frequent validation for satellite-based measurements of snow reflectance, these station-based methods are not always representative of the surrounding terrain. Vegetation, snow cover, and reflectance can vary greatly within the 10 to 30 m scale of a satellite pixel, whereas station-based sensors are limited to the point scale.^{7,8} Unoccupied aerial vehicles (UAVs) provide a platform for frequent measurement of snow reflectance with custom coverage during critical times of snowpack change—such as after a snowfall event or at the onset of ablation—and can be deployed multiple times throughout a single day to capture diurnal changes in surface reflectance. UAVs also enable measurements with higher spatial resolution than satellite-based sensors while covering a larger spatial area than *in situ* methods.^{7–20}

Hyperspectral imagers offer a unique solution that provides not only higher spatial resolution when flown on a UAV but also higher spectral resolution than the multispectral bands on satellite-based sensors such as OLI. For this reason, UAV-based hyperspectral imagers have been used for the validation of satellite-based snow products in the visible and near infrared wavelength regions.^{9,21} Due to the higher cost associated with short-wave infrared (SWIR) sensors, few hyperspectral imagers are commercially available with spectral ranges that extend into the SWIR, limiting validation measurements for OLI Band 7, the second SWIR channel (SWIR2). The SWIR2 band extends the spectral range of broadband snow albedo retrievals, has been used to differentiate between clouds and snow,²² and appears to be indicative of snow grain size.⁹ In addition to snow applications, the SWIR2 band has been used to measure moisture content in soil and vegetation^{23–27} and to map mineral deposits for improved resource management.^{28,29}

To advance the UAV-based validation of SWIR2 satellite snow retrievals, this paper presents the design and calibration of a custom UAV-based OLI Band 7 replica radiometer (UBRR), along with airborne surface reflectance measurements from the system that were compared to satellite-based surface reflectance retrievals from Landsat 9 OLI Band 7. Although the custom sensor presented in this paper was designed for the validation of satellite-based snow products, it could also be deployed to validate satellite surface reflectance retrievals of vegetated and rocky landscapes.

This paper builds on work initially reported in an SPIE Proceedings conference paper³⁰; however, the scope of the conference paper has been expanded in accordance with the SPIE publication policy.³¹ Compared with the previous conference paper, this paper includes an updated system design that features onboard temperature sensors, results from an airborne data collection campaign, and a discussion of the airborne surface reflectance measurements and system limitations.

2 Radiometer Design and Calibration

2.1 System Design

The Landsat 8/9 OLI Band 7 sensor has a center wavelength of 2200 nm, a spectral bandwidth of 200 nm, spatial resolution of 30 m, and a 12-bit dynamic range.³² These satellite-based sensor specifications were used to inform the optical and electrical design of the UBRR system. The UBRR system used two sensors to measure surface reflectance: an upwelling radiation sensor measured the radiance reflected from the scene [$W/(m^2 sr)$], and a downwelling radiation sensor measured the irradiance incident on the scene [W/m^2]. Both sensors used independent, single-pixel photodiodes (Hamamatsu InGaAs PIN photodiode, G12183-030K, Shizuoka, Japan) electrically connected to separate high-gain, low-noise amplifiers (Hamamatsu Amplifier, C4159-03). The weight of the airborne system was limited to 5 kg according to the maximum payload specifications of the UAV (Vision Aerial Vector Hexacopter³³).

2.1.1 Optical design

The spectral range of UBRR replicated Landsat 8/9 OLI Band 7 using custom bandpass filters designed and fabricated by Materion Corporation, the manufacturer of the original OLI Band 7 spectral filters. A single filter was used in each detector assembly, and each filter had a manufacturer-specified average transmittance of 97.1% across the spectral range of 2110 to 2290 nm.

The optical design goal of the UBRR system was to achieve a measurement footprint area with higher spatial resolution than Landsat OLI Band 7 while covering the greatest number of satellite pixels per UAV flight. This was achieved by flying at the maximum FAA flight altitude of 120 m above ground level, with a minimum half-angle field of view (FOV) of 3.576 deg. This flight altitude and FOV corresponded to a circular ground footprint with a diameter of 15 m, one-quarter of the footprint of an OLI Band 7 pixel. In addition to the flight height, the FOV was also informed by the sampling rate of the UBRR system, where the sensor circuit was specified to have a bandwidth of 15 kHz, but the total system sampling rate was limited to a lower value by the flight computer. The sample period that was comfortably achieved by the embedded computer for sampling the detectors, temperature sensors, and GPS was 4.0 s, limiting the UAV flight speed to 3.6 m/s for the collection of proof-of-concept measurements, where the circular measurement swaths were adjacent to one another. Accordingly, the upwelling radiation sensor was constructed using a lens assembly designed to achieve a half-angle FOV of 3.576 deg. All optical designs and simulations were completed in Zemax OpticStudio.

The minimum entrance aperture of the UBRR system was determined through radiometric analysis, where the detector area, noise equivalent power, and electrical bandwidth were used to estimate the signal-to-noise ratio (SNR) of the system corresponding to common lens sizes:

$$\text{SNR} = \frac{T_o(\text{RSR})L_\lambda\Delta\lambda A\Omega}{\text{NEP}_f\sqrt{\Delta f}}, \quad (1)$$

where T_o was the optical transmittance of the filters and lenses in the optical assembly, RSR was the relative spectral response of the system, $L_\lambda\Delta\lambda$ was the expected radiance in the optical bandwidth of the bandpass filter, $A\Omega$ was the detector throughput, NEP_f was the noise equivalent power of the detector, and Δf was the electrical bandwidth of the preamplifier circuit.

Although larger lens diameters corresponded to higher SNR values, a lens diameter of 25.4 mm was selected because this diameter achieved an SNR of 133, which met the design specification SNR of ≥ 100 , without the additional cost and weight of a larger lens. Off-the-shelf lenses were used to minimize the cost of the system; however, the desired FOV could not be achieved with a single off-the-shelf lens due to the detector size and entrance aperture diameter. To maximize the FOV and throughput of the system, the largest commercially available SWIR detector was selected: a photodiode with a 3-mm photosensitive area. When simulated with a single commercial lens, the largest achievable half-angle FOV was 3.24 deg without producing a spot size that exceeded the photodiode active area. To achieve the desired FOV, a three-lens system was designed and optimized to focus on and off-axis rays on the photosensitive area of the photodiode (Fig. 1). The final design consisted of an objective lens with a diameter of 25.4 mm and a focal length of 150 mm (Thorlabs LA1433-D, Newton, New Jersey, United States), a custom spectral bandpass filter (Materion Corporation, bandpass region from 2110 to 2290 nm), and a field lens assembly composed of a lens with a diameter of 25.4 mm and a focal length of 25 mm (Thorlabs LA1951-D), and a second lens with a diameter of 12.7 mm and a focal length of 15 mm (Thorlabs LA1540-D). This optical design achieved a spot size with a diameter of 3.0 mm in simulations, meeting the 3 mm specification required for the photodiode.

Although the upwelling radiation sensor assembly was designed with a narrow FOV, the downwelling radiation sensor was designed to measure the total direct and diffuse solar radiation across the full-sky hemisphere. This was accomplished using a piece of 220 grit ground glass (Thorlabs DG10-220) to create a diffuser in front of the photodiode, resulting in a full-angle FOV approaching π steradians (the projected solid angle of a hemisphere). A custom spectral bandpass filter was also included between the ground glass and photodiode to match the spectral range of the upwelling radiation sensor.

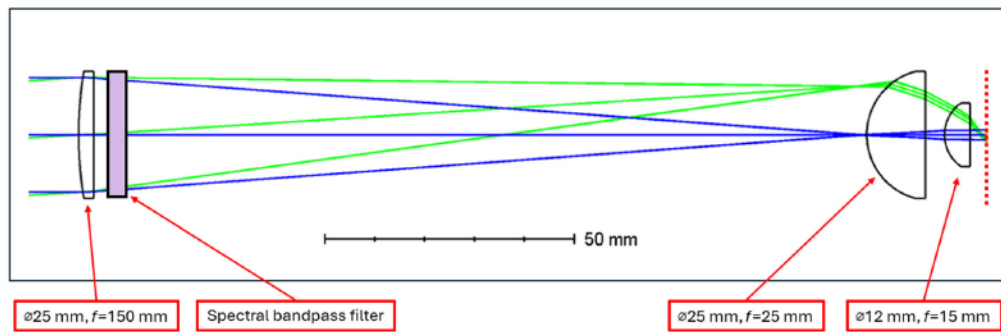


Fig. 1 Zemax OpticStudio design for the upwelling radiation sensor, including on-axis rays in blue and 3.576 deg off-axis rays in green (representing the desired half-angle field of view of the system). The dotted line on the far right represents the image plane. The optical system consists of three lenses and a spectral bandpass filter and was optimized for a spot size less than the photo-sensitive area of the photodiode.

2.1.2 Electrical design

The UBRR system was designed to use a low-cost Arduino Giga embedded computer that enabled concurrent measurements of the signal from the upwelling and downwelling photodiode amplifiers using onboard 16-bit analog-to-digital converters. To map airborne surface reflectance measurements to specific locations at a field site, the Arduino was connected to an Arduino MKR GPS shield to store GPS data (timestamp, latitude, longitude, and altitude). Due to temperature-dependent photodiode responses (Sec. 2.2.3), two temperature sensors (HiLetGo DHT22) were integrated into the system as well. A temperature sensor was mounted inside the lens tube of the downwelling radiation sensor, and a second temperature sensor was mounted adjacent to the upwelling radiation sensor. Arduino code was written to continually save photodiode measurements, GPS location information, and temperature sensor measurements to a USB drive at a time interval specified by the user, where the fastest sampling period of 4.0 s was used in this study.

The photodiode assemblies, GPS antenna, and temperature sensors were integrated with the Arduino through a custom printed circuit board (PCB) designed to mount directly on top of the Arduino and interface with its input and output pins (Fig. 2). The PCB included power and switching circuitry to power the Arduino, photodiode amplifiers, GPS antenna, and temperature sensors from the UAV batteries. A DC-to-DC converter was included to convert the

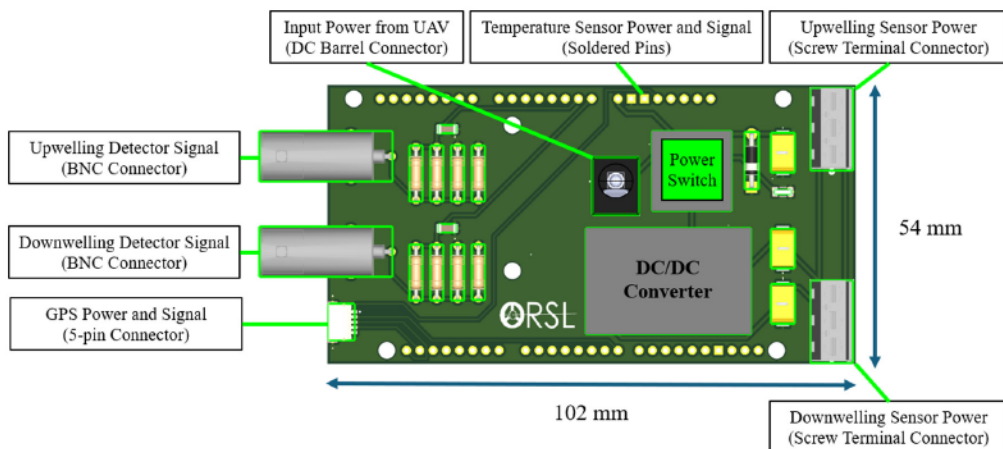


Fig. 2 PCB designed to interface with the Arduino Giga, photodiode amplifiers, temperature sensors, and GPS antenna to power the individual system components from the UAV batteries and interface the sensor signals with the Arduino Giga analog inputs. The PCB was 102 mm long and 54 mm wide, matching the dimensions of the Arduino Giga and allowing for direct mounting to the Arduino embedded computer.

15 V source from the UAV to ± 15 V to provide the bias voltage necessary to power the photodiode amplifiers. The PCB was also designed to connect the photodiode signal from each amplifier to the internal analog-to-digital converters on the Arduino via overvoltage protection circuitry.

The total weight of the assembled UBRR system was 1.60 kg, with the downwelling radiation sensor weighing 0.55 kg, and the upwelling radiation sensor and accessory electronics weighing 1.05 kg. The total weight of the system fell within the maximum payload specification of 5 kg for the Vision Aerial Vector Hexacopter.³³

2.2 Characterization and Calibration

The UBRR system stored measurements from the upwelling and downwelling radiometers as uncalibrated values digitized by a 16-bit analog-to-digital converter. For accurate data processing and comparison with other systems, such as the Landsat 8/9 OLI Band 7 sensor, calibration to a unit-based scale was required. Therefore, a radiometric calibration was performed to convert the digital numbers of the upwelling radiation sensor to radiance [$W/(m^2 sr)$], and the downwelling radiation sensor to irradiance [$W/(m^2)$] (Sec. 2.2.2). Approximating snow as a Lambertian reflector, surface reflectance was then computed as the ratio of upwelling radiance to downwelling radiance:

$$\rho_{\text{scene}} = \frac{L_{\text{upwelling}} - L_{\text{dark}}}{L_{\text{downwelling}} - L_{\text{dark}}} = \frac{L_{\text{upwelling}} - L_{\text{dark}}}{\frac{E_{\text{downwelling}}}{\pi} - L_{\text{dark}}}, \quad (2)$$

where $L_{\text{upwelling}}$ is the reflected radiance of the scene measured by the upwelling radiation sensor, $L_{\text{downwelling}}$ is the downwelling radiance, L_{dark} is the dark signal corresponding to the upwelling and downwelling radiation sensors, $E_{\text{downwelling}}$ is the downwelling irradiance measured by the downwelling radiation sensor, and π is the projected solid angle into which the irradiance is scattered by the surface.

2.2.1 Field of view characterization

Following the optical assembly of the upwelling and downwelling radiation sensors, the FOV of both sensors was experimentally verified. This was accomplished by mounting each sensor on a rotation stage in front of an integrating sphere, illuminating a secondary aperture with a diameter of 1 cm to approximate a pinhole. The upwelling sensor was mounted 1 m from the pinhole, where the measured signal strength from the integrating sphere limited the distance. Similarly, the downwelling sensor was mounted 36 cm from the pinhole to maintain adequate signal strength. The full-angle FOV of the downwelling radiation sensor was anticipated to be nearly 180 deg; therefore, measurements were taken in 5-deg increments [Fig. 3(a)]. Conversely, the FOV of the upwelling radiation sensor was expected to be much narrower, so measurements were taken in 0.5-deg increments [Fig. 3(b)].

Assuming the FOV to be defined by the angle at which the signal was reduced to 10% of the maximum signal at normal incidence, the half-angle FOV of the downwelling radiation sensor was measured to be ~ 59.4 deg after interpolating the FOV measurements at a resolution of

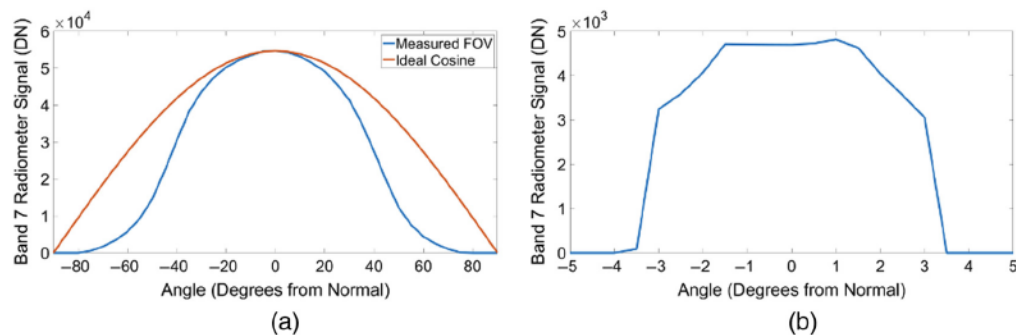


Fig. 3 Experimentally derived field of view of (a) the downwelling radiation sensor measured in 5-deg steps and (b) the upwelling radiation sensor measured in 0.5-deg steps

0.05 deg [Fig. 3(a)]. Using the same FOV definition and interpolated resolution, the half-angle FOV of the upwelling radiation sensor was measured to be ~ 3.4 deg [Fig. 3(b)].

2.2.2 Radiometric calibration

A radiometric calibration was performed for each radiometer to convert uncalibrated digital numbers to radiance (upwelling radiation sensor) and irradiance (downwelling radiation sensor). The calibration was completed by measuring the known radiance output of an integrating sphere (Labsphere V3ND-NNNN-NSL-NS00-0000, North Sutton, New Hampshire, United States). The radiance of the sphere was controlled by a variable aperture that was set to six different positions. For the spectral range of the bandpass filters in the UBRR system (2110 to 2290 nm), these positions corresponded to exposing the system to radiance values ranging from 0.0452 to 6.712 $[W/(m^2 sr)]$. In each position, the output radiance was measured with the upwelling and downwelling radiation sensors for three photodiode amplifier gain settings (“low,” “medium,” and “high”), averaged across 50 samples. From these measurements, a linear relationship between digital number and radiance was determined for each gain setting for the upwelling radiation sensor. Similarly, a linear relationship between digital number and irradiance was determined for each gain setting for the downwelling radiation sensor by multiplying the radiance of the Lambertian source by a projected solid angle of π . The linear fit for both sensors for the gain settings used during the outdoor field campaign discussed in Sec. 2.3 produced R^2 values greater than 0.99.

2.2.3 Temperature calibration

Although the radiometric calibration measurements were completed at room temperature, the UBRR system could be deployed on a UAV in a wide range of temperatures. During snow measurements, the temperature was expected to range from approximately -10°C to 5°C , where colder field conditions exist, but sensor deployment was limited by the minimum operating temperatures of the UAV and photodiode amplifiers. To maintain an accurate radiometric calibration, the temperature dependence of each sensor was assessed over the range of -10°C to 40°C , supporting the possibility of summer measurements as well. This temperature characterization was completed in a controlled thermal chamber for amplifier gain settings that aligned with those used during the field campaign presented in this study (“medium” gain setting for both sensors). The radiation sensors were pointed directly toward a halogen light source mounted outside the thermal chamber. The stability of the external halogen source was evaluated throughout the duration of the measurements using a pyranometer (Li-Cor Pyranometer 54977, Lincoln, Nebraska, United States) with a temperature dependence of $\pm 0.15\%$ per $^\circ\text{C}$ maximum that was accounted for in post-processing.

Measurements were recorded by the upwelling and downwelling radiation sensors every 60 s for ~ 7 h, where the temperature of the chamber was incremented in 5°C steps from -10°C to 0°C , then 8°C steps from 0°C to 40°C . The temperature of the chamber was monitored by its internal thermometer and an independent thermocouple placed inside the chamber. While temperature measurements from both sensors were in agreement, the thermocouple measurements were used due to their proximity to the radiation sensors. The duration of each temperature step was the sum of the time required for the chamber to reach the desired temperature and an additional 30-min period to allow the devices to reach thermal equilibrium. The temperatures measured by the thermocouple, along with the corresponding radiation sensor measurements, are shown in Fig. 4. Upwelling radiation sensor measurements collected before 8:03 MST were removed because the sensor orientation was adjusted for better alignment with the light source at 8:02. The X’s along the temperature plot indicate the times at which the temperature and signal data were extracted to calculate a relationship between signal and temperature for each radiation sensor. These individual points were selected because they were representative of the temperature of the devices once they reached thermal equilibrium, rather than the ambient air temperature.

The upwelling and downwelling radiation sensors both exhibited a decreasing signal with increasing temperature, where a -20°C change from room temperature produced an 11.79% change and a 63.02% change in the signal of the upwelling and downwelling radiation sensor, respectively. A second-order polynomial was used to relate the change in radiometer signal to the temperature of each sensor. Seven temperature values ranging from -5°C to 40°C were used for

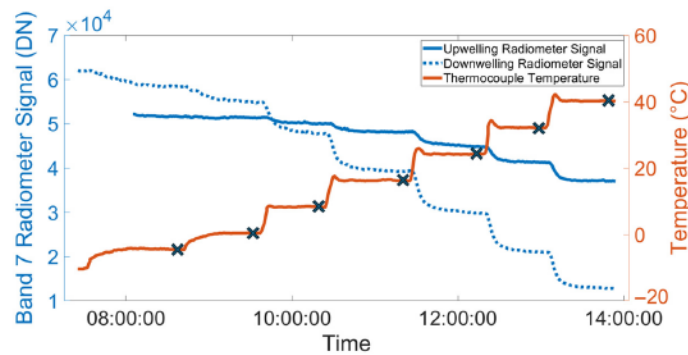


Fig. 4 Upwelling and downwelling radiation sensor signals (blue) and thermal chamber temperature (orange) measured by a thermocouple mounted near the radiation sensors. The X's indicate points that were selected to relate the temperature to the radiation sensor signal for temperature correction of the UBRR system.

the upwelling radiation sensor, and eight temperature values ranging from -10°C to 40°C were used for the downwelling radiation sensor. The second-order fits produced R^2 values greater than 0.99 for both the upwelling and downwelling radiation sensors.

2.3 Field Methods and Testing

The UBRR system was flown on a UAV in alignment with a Landsat 9 overpass in Southwestern Montana, United States, on April 7, 2025. The study site, Namaste Valley (45.2316°N , 111.4768°W , elevation 2650 m), is located at the head of the Muddy Creek drainage,⁷ which flows into the upper reaches of the Gallatin River, a tributary of the Missouri River (Fig. 5). In winter, the site is a snow-covered alpine meadow containing several stands of conifer trees. The variable topography of this open meadow allowed for assessment of Landsat retrievals over a variety of illumination angles and has been used in previous UAV-based snow albedo studies.^{7,8}

The UAV flight was completed on April 7, 2025, at 17:03 UTC, corresponding to a calculated solar elevation angle of 40.68° .³⁴ The UBRR system was rigidly mounted to the UAV, with the upwelling radiation sensor and embedded computer mounted beneath the UAV chassis, the downwelling radiation sensor mounted on top of the UAV chassis, and the GPS antenna mounted to a ground plane on top of the UAV [Fig. 6(a)]. All UAV flights were conducted by a pilot certified with an FAA Part 107 license. Following manual takeoff, the UAV autonomously flew a predetermined survey pattern at a speed of 3.6 m/s. This flight speed was selected

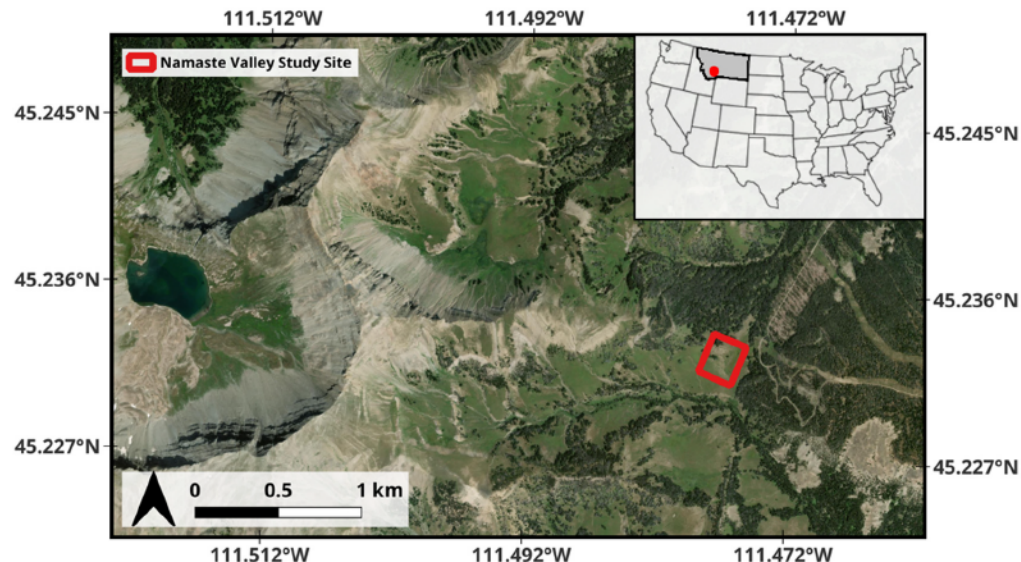


Fig. 5 Flight area at the Namaste Valley field site in southwest Montana, United States.

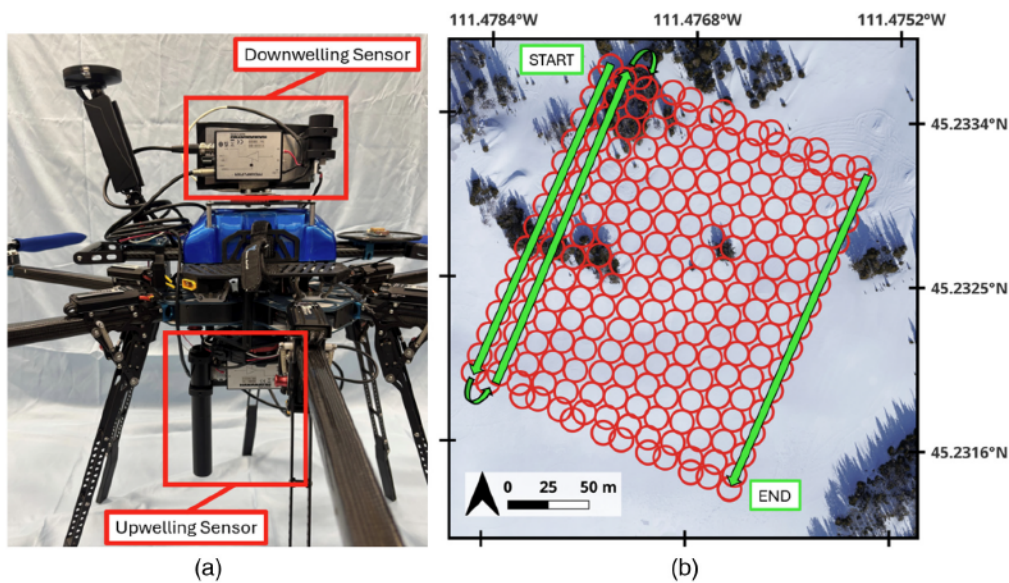


Fig. 6 UBRR system flight configuration. (a) UAV mounting configuration with the upwelling radiation sensor and embedded flight computer mounted rigidly beneath the UAV chassis, and the downwelling radiation sensor mounted rigidly on top of the UAV. (b) Flight path of the UBRR system overlaid on UAV-based RGB imagery captured during April 7, 2025, UAV flights, where the green arrows indicate the direction of UAV flight, and the red circles correspond to footprints of UBRR system measurements.

to align with the fastest system measurement period of 4 s that was used throughout the flight to capture measurements without spatial overlap, such that each circular footprint was directly adjacent to the next [Fig. 6(b)]. Following completion of the flight, the UAV was placed on a reflectance target (Group 8 Technology Type 822) specified to have a reflectance of 11% over the spectral range of the UBRR system. The measured reflectance of the target was calculated using the upwelling and downwelling radiation sensor measurements [Eq. (2)] and then cross-referenced with the manufacturer-specified reflectance to empirically validate the airborne measurements collected at the field site.

To assess the relationship between surface reflectance and surface topography, a second UAV flight was completed to collect airborne topographic measurements using a commercial lidar system (YellowScan Mapper+) rigidly mounted to the UAV. The UAV flight path for the lidar measurements also followed a predetermined survey pattern, but unlike the UBRR system, the lidar system was flown at a speed of 8 m/s based on manufacturer guidelines. Four ground control points were collected to correct the lidar data using an Emlid Reach RS2 Global Navigation Satellite System (GNSS) receiver.

3 Results

3.1 Surface Reflectance from UBRR

To account for the influence of air temperature on the raw digital numbers collected by the UBRR system, the temperature calibration discussed in Sec. 2.2.3 was applied to correct the digital numbers to room temperature (21°C), corresponding to the temperature at which the radiometric calibration was performed. The calibration was independently applied to each photodiode measurement based on temperature measurements made by the upwelling and downwelling temperature sensors, all collected at the same interval (every 4.0 s) throughout the flight. Next, a radiometric calibration was applied to convert the temperature-corrected digital numbers to radiance or irradiance for the upwelling and downwelling radiation sensors, respectively. The surface reflectance was then calculated as the ratio of the upwelling radiance to the downwelling irradiance [Eq. (2)].

Each UBRR surface reflectance value corresponded to a geographic coordinate measured by the GPS antenna. Based on the measured FOV of the upwelling radiation sensor assembly, the

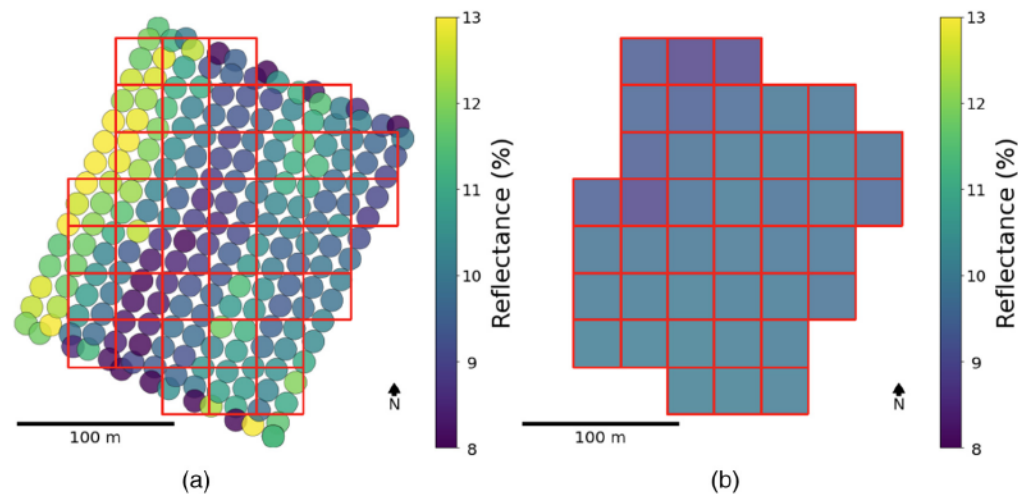


Fig. 7 Surface reflectance retrievals from (a) the UBRR system corresponding to a UAV flight on April 7, 2025, overlaid with Landsat 9 Band 7 satellite pixels and (b) Landsat 9 OLI Band 7 corresponding to an ascending overpass on April 6, 2025.

Table 1 Summary of surface reflectance statistics included in the box-and-whisker plot [Fig. 8(a)] for the UBRR sensor and Landsat 9 OLI Band 7. The statistics were calculated across the full spatial extent of the field site, where the median indicates the median surface reflectance, Q1 is the 25th percentile surface reflectance, Q3 is the 75th percentile surface reflectance, and the minimum and maximum are the minimum and maximum non-outlier surface reflectances.

Sensor	Median (%)	Q1 (%)	Q3 (%)	Minimum (%)	Maximum (%)
UBRR	10.10	9.40	11.15	6.93	14.68
Landsat OLI Band 7	9.76	9.56	9.88	8.81	10.01

on-ground circular swath of each upwelling measurement was assumed to have a diameter of 14.39 m at the UAV flight height of 120 m. Therefore, each surface reflectance measurement was mapped to a circular area with a diameter of 14.39 m centered on the measured latitude and longitude coordinates [Fig. 7(a)]. This mapping did not account for local changes in surface elevation; however, such changes were small in comparison to the size of the footprint. Table 1 presents a summary of the surface reflectance statistics for the UBRR system presented in Fig. 7(a), where the median reflectance measurement was 10.10%, with a range of 7.75%. The processing pipeline was validated through measurements of the reflectance target in the field, where the UAV-based Band 7 system measured the reflectance of the 11% reflectance target to be 12.41% following the UAV flight (using an average of 10 measurements, with a standard deviation of 0.02%).

3.2 Surface Reflectance from Landsat 9 OLI Band 7

Landsat 9 OLI Band 7 surface reflectance measurements (Collection 2 U.S. Analysis Ready Surface Reflectance Data) were acquired from an ascending overpass with clear skies on April 6, 2025, at 18:12 UTC (Path: 39, Row: 28). UAV data were acquired 1 day after the overpass, 69 min before the time of the overpass the preceding day. An ascending Landsat overpass also occurred on April 7 (the day of the UAV flight); however, the imagery was obscured by evenly distributed clouds and therefore not used for comparison with the UBRR system. Although April 7 was cloudier than April 6, the ground and meteorological conditions were otherwise very similar across the two-day period: the ground was snow-covered, no new snow had fallen, the temperature on April 6 increased from -7.8°C to 8.9°C throughout the day, and the temperature on April 7 increased from -6.1°C to 10°C .

To compare the same area between the UBRR system and satellite-based measurements from Landsat 9 OLI Band 7, the satellite surface reflectance products were cropped to the region of the UAV flight, where Landsat pixels with less than 50% coverage from the UBRR system measurements were removed, leaving 41 satellite pixels (Fig. 7). Table 1 presents a summary of the surface reflectance statistics for the Landsat 9 OLI Band 7 retrievals presented in Fig. 7(b), where the median reflectance measurement was 9.76%, with a range of 1.19%.

3.3 Spatial Variability

The FOV of UBRR was selected to measure surface reflectance with higher spatial resolution than Landsat 8/9 OLI Band 7 to ultimately assess the implications of enhanced spatial resolution in snow-covered areas. The differences in spatial variability of surface reflectance captured by UBRR versus Landsat 9 OLI Band 7 were evaluated and visualized using box-and-whisker plots [Fig. 8(a)], where the percentile, minimum, and maximum values contained in the plots are presented numerically in Table 1. The spatial variation in the surface reflectance measurements was also evaluated by calculating the percent difference between the UBRR system surface reflectance values and the Landsat 9 OLI Band 7 retrievals. The percent difference was calculated for each UBRR system surface reflectance measurement and its corresponding Landsat surface reflectance measurement using the satellite pixel containing the majority of each UBRR pixel:

$$\text{Percent Difference} = 100 * \frac{2 * (\rho_{\text{UBRR}} - \rho_{\text{Landsat}})}{\rho_{\text{UBRR}} + \rho_{\text{Landsat}}}, \quad (3)$$

where ρ_{Landsat} was the surface reflectance retrieved from Landsat 9 OLI Band 7, and ρ_{UBRR} was the surface reflectance measured by the UBRR system. The UBRR surface reflectance measurements varied up to +46.9% and −27.0% with respect to the Landsat OLI Band 7 measurements [Fig. 8(b)].

To relate the spatial variation in surface reflectance measurements to the spatial variation in the scene, the surface topography of the field site was evaluated using elevation measurements captured by the UAV-based lidar with 50 cm resolution, where the elevation and slope angle were plotted for the same area as the previously determined Landsat pixels (Fig. 9). The black regions in Fig. 9 correspond to areas containing trees that were removed prior to analysis.

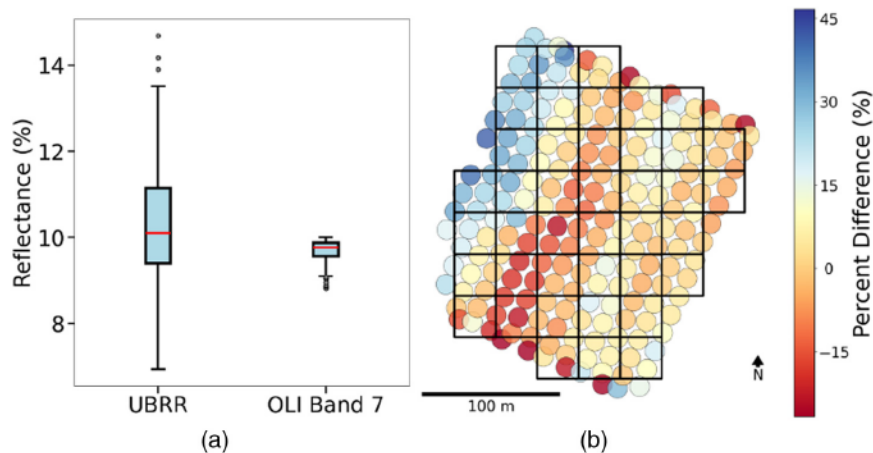


Fig. 8 (a) Box and whisker plots for the UBRR surface reflectance measurements and the Landsat 9 OLI Band 7 surface reflectance retrievals, where the red lines mark the median, the bottom of the boxes are the 25th percentiles, the top of the boxes are the 75th percentiles, the whiskers represent the range of nonoutlier data, and the points represent outliers. (b) Circular UBRR system pixel footprints showing percent difference and direction of difference between each UBRR surface reflectance measurement and the corresponding Landsat 9 OLI Band 7 surface reflectance retrieval using Eq. (3), where negative values indicate that the UBRR system measured a lower reflectance value than Landsat 9 OLI Band 7.

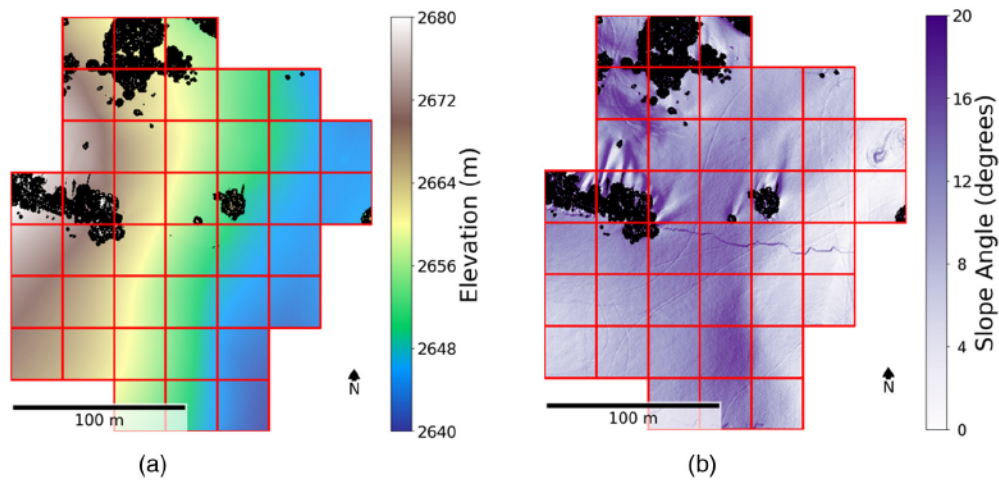


Fig. 9 (a) Elevation of the field site terrain contained within the 41 satellite pixels as measured by a UAV-based commercial lidar. (b) Slope angle calculated from the elevation measurements, where black areas correspond to regions containing trees that were masked out from elevation and slope angle measurements.

3.4 Topographical Dependence

To determine whether the surface reflectance measurements between the UBRR system and Landsat 9 OLI Band 7 diverge more in areas with variable surface topography, the percent difference measurements were compared with the average slope angle and the standard deviation of the slope angle contained within each satellite pixel. Regions with tree canopy were removed from the elevation and slope data by creating a mask to remove slope angles greater than 28 deg. The relationship between surface reflectance and surface topography was initially evaluated by plotting the percent difference between the UBRR system and Landsat 9 OLI Band 7 surface reflectance retrievals with respect to the average slope angle contained within each pixel [Fig. 10(a)], and with respect to the standard deviation of the slope angle within each pixel [Fig. 10(b)]. In both scatter plots, the red lines represent lines of best fit that were intended to provide a qualitative reference. To provide a quantitative measurement, a Pearson correlation was used to determine the strength of the relationship between surface reflectance variability and surface topography.

To meet the assumption of the Pearson correlation that all data were normally distributed, a Box-Cox power transformation³⁵ was applied to both the average slope values (with a lambda value of -2.144) and the standard deviation of the slope values (with a lambda value of -0.478). Similarly, a Yeo-Johnson transformation³⁶ was applied to the surface reflectance

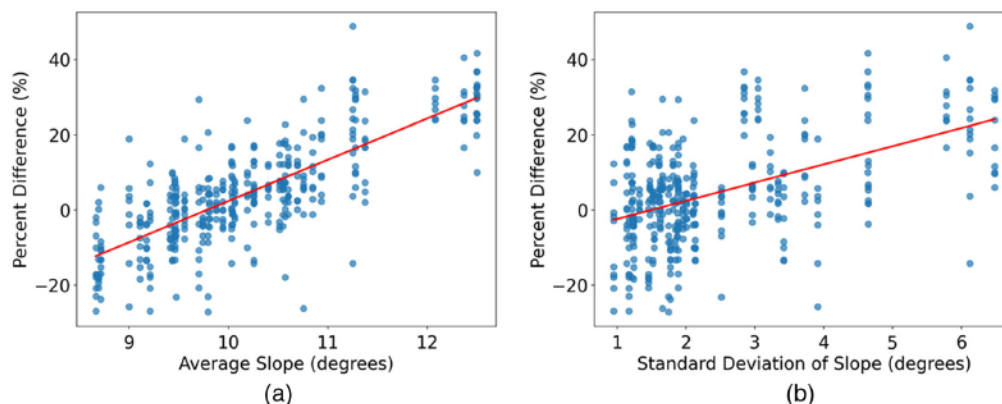


Fig. 10 Percent difference between UBRR system surface reflectance measurements and Landsat 9 OLI Band 7 surface reflectance retrievals with respect to (a) the average slope angle within each of the 41 satellite pixels, and (b) the standard deviation of slope angle within each of the 41 satellite pixels.

percent difference values (with a lambda value of 0.961). The relationship between surface reflectance percent difference values and surface topography was then assessed using a Pearson correlation, where a critical value of 0.001 was selected to formulate conclusions based on the resulting *p*-values. Using the transformed data, a Pearson correlation coefficient of 0.9651 and 0.5735 (both with *p*-values < 0.001) was calculated for the relationship between the percent difference in surface reflectance measurements and the average slope angle, and the standard deviation of slope angle, respectively. The correlation results indicated that the null hypothesis could be rejected and that a statistically significant relationship existed between the percent difference values and the average slope values, as well as the standard deviation of slope values within each satellite pixel, such that steeper slope angles and higher slope variability correlated to larger differences in the surface reflectance measurements between the UBRR system and Landsat 9 OLI Band 7.

4 Discussion and Conclusions

4.1 Spatial Variability

The UBRR system was designed to be flown on a UAV, enabling custom coverage and achieving higher spatial resolution than Landsat 8/9 OLI Band 7. This allowed the UBRR system to measure smaller surface regions with increased sensitivity to changes in the scene and surface topography. The difference in spatial resolution is demonstrated in Fig. 7(a), which shows multiple UBRR pixels contained within each satellite pixel. Figure 7 also presents the surface reflectance measurements for both UBRR and Landsat 9 OLI Band 7, where the median reflectance measurement from UBRR was 10.10%, and the median reflectance measurement from Landsat was 9.76%. This elevated value from UBRR was consistent with the results from the empirical validation, where the UBRR system measured the reflectance of an 11% reflectance target to be 12.41%, though the day difference in collection times between the UBRR system and the satellite retrievals could have also contributed to this difference. In addition, the range of UBRR surface reflectance measurements presented in Fig. 7(a) was much larger than the range of satellite surface reflectance retrievals presented in Fig. 7(b), indicating that higher spatial resolution enabled more variability to be captured in the surface reflectance measurements.

Some spatial variation, such as the elevated UBRR reflectance measurements on the west side of the field site in Fig. 7(a), could be explained by areas of tree cover [Fig. 6(b)], where, in the spectral range of Band 7 (2110 to 2290 nm), coniferous trees typically have reflectances on the order of 10% to 20%,³⁷ whereas snow typically has reflectances on the order of 5% to 15%.^{38,39} Other regions of spatial variation, such as on the north and south edges of Fig. 7(a), correspond to locations where the UAV made 180 deg turns to continue the survey flight pattern. In field campaigns where the goal is to measure snow reflectance with minimal uncertainty, such measurements should be masked out using a margin dependent on the flight configuration; however, all measurements were presented in Fig. 7(a) to demonstrate the measurement variability due to changes in the pitch and roll of the UAV.

The larger variability in UBRR reflectance measurements in comparison to satellite retrievals was also demonstrated in Fig. 8(a), where the median reflectance values captured by the UBRR system and Landsat satellite were in close agreement, but the range of UBRR reflectance values represented by the whiskers far exceeded the range of satellite reflectance retrievals. The spatial trends of the differences in reflectance values between the UBRR system and Landsat 9 OLI Band 7 were presented in Fig. 8(b), where the UBRR system measured reflectance values higher than the satellite retrievals on the west side of the field site, but measured reflectance values lower than the satellite retrievals in the middle and on the east side of the field site. This spatial trend visually aligned with the surface topography of the field site in Fig. 9, where regions with steeper slope angles tended to align with areas where the difference in reflectance measurements between UBRR and Landsat 9 OLI Band 7 was the greatest.

4.2 Topographical Dependence

The qualitative association between the percent difference in Fig. 8(b) and the surface topography in Fig. 9 was further evaluated by plotting the percent difference as a function of slope, where a linear relationship was presented between the percent difference and average slope

[Fig. 10(a)], as well as the percent difference and standard deviation of slope [Fig. 10(b)]. This visual interpretation was supported by the results of a Pearson correlation. The correlation confirmed that the percent difference between surface reflectance values had a statistically significant linear relationship with the surface topography, quantified by the average slope angle and the standard deviation of the slope angle contained within each satellite pixel.

The results of the preliminary UBRR measurements aligned with the expectation of topographic dependence based on previous broadband, airborne albedo measurements at Namaste Valley conducted by Mullen et al.⁷; however, additional UAV-based campaigns are required to collect data during a variety of snow and illumination conditions to conduct a thorough assessment of the magnitude of the relationship between UBRR surface reflectance measurements and slope angle. In addition, the results from the comparison of the UBRR measurements and the Landsat 9 OLI Band 7 measurements suggest that increased spatial resolution produced greater variability in surface reflectance measurements that were not captured in satellite imagery. This aligns with the findings of Skiles et al.,⁹ who demonstrated that the higher spatial resolution obtained using UAV-based hyperspectral imagery produced snow reflectance measurements with higher variability, and is consistent with others who have used UAVs to achieve higher spatial resolution than satellite-based sensors.^{7,8,10–20}

4.3 System Limitations and Future Work

The surface reflectance measurements from the UBRR system were more variable at the edges of the flight area, where the UAV made 180 deg turns to continue the survey flight pattern [Fig. 7(a)]. Turns in the flight path increased the tilt angle of the UAV and led to changes in the measured upwelling and downwelling signals due to the rigid mounting geometry of the sensors. Although select pixels with higher variability at the edges of the flight area can be excluded in processing, the dependence on UAV tilt angle was magnified during validation measurements with direct solar illumination. The UBRR system measurements from April 7, 2025, were collected in cloudy conditions, where scene illumination was more diffuse; however, measurements collected on March 3, 2025, in direct solar illumination conditions showed variations in the measured surface reflectance values based on the direction of UAV flight introduced by the pitch and roll of the UAV while in motion. The variations in measured surface reflectance due to the changing viewing angle were larger than those introduced by surface topography, and therefore, the data from March 3, 2025, were not used in this study.

Although a properly sized gimbal was not available for this study, the tilt angle dependence of the sensor, due to both UAV turns at the end of each pass and changes in flight direction, could be reduced in future studies by mounting the upwelling assembly on an electronically stabilized gimbal. Without a gimbal, measurement uncertainty in future field campaigns could also be reduced through data collection from the UAV inertial measurement unit to provide real-time UAV pitch, roll, and yaw data for improved correction of sensor tilt angle. Future measurements are also expected to benefit from using topographic and angular corrections adapted from methods presented by Mullen et al.⁷ that will reduce uncertainties attributed to solar illumination angle, scene topography, UAV flight direction, and sensor tilt.

The FOV of the downwelling radiation sensor was an additional limitation of the UBRR system as it limited possible flight times and locations to periods when the solar zenith angle was within the FOV. Increasing the FOV of the downwelling radiation sensor would allow the system to be used for all but the most extreme solar zenith angles throughout the winter months; however, increases in the FOV lead to spectral shifts in the bandpass filter caused by an increased angle of incidence. In the configuration presented here, the photodiode viewed a projected solid angle of 30.1 deg, corresponding to an estimated 162 nm shift in the peak transmission wavelength, shifting the center wavelength from 2200 to 2038 nm for the greatest angles of incidence. However, the steepest incidence angles that would produce the maximum estimated shift in wavelength were only present at the edges of the sensor, such that spectral smearing outside of the spectral range of Landsat 8/9 OLI Band 7 only accounted for a small portion of the sensor response.

In future deployments, the spectral shift could be reduced by placing an iris directly in front of the downwelling radiation sensor photodiode to restrict the angles of incidence on the sensor. However, this will limit the range of sun angle conditions in which the UBRR system can operate

and reduce the SNR of the reflectance measurements [Eq. (1)]. Additional tradeoffs exist in the spatial resolution of the UBRR system. The design presented here achieved an on-ground measurement swath of 14.39 m, one quarter of the Landsat 8/9 OLI Band 7 measurement swath, but even higher spatial resolution could be achieved with a narrower FOV, where narrowing the FOV would reduce the SNR as well [Eq. (1)].

The development, calibration, and validation of a low-cost UAV-based OLI Band 7 replica radiometer system presented here can be replicated by others to collect UAV-based surface reflectance measurements and sets the stage for future field campaigns to collect surface reflectance measurements across a variety of snow and solar illumination conditions. These next steps are anticipated to provide a more robust dataset to build on existing topographic corrections to reduce uncertainties in UAV-based measurements, and ultimately support continued progress toward minimizing uncertainties in satellite-based surface reflectance retrievals of snow.

Disclosures

The authors declare that there are no financial interests, commercial affiliations, or other potential conflicts of interest that could have influenced the objectivity of this research or the writing of this paper.

Code and Data Availability

The data and corresponding code in support of the findings of this paper are publicly available in an online GitHub repository.⁴⁰

Acknowledgments

The authors would like to thank the Yellowstone Club and Yellowstone Club Ski Patrol, especially Doug McCabe, David Fandrich, Griffin Dittmar, and Nate Fusselman, for providing access to the field site and supporting measurements. We would also like to acknowledge Erich Schreier for processing lidar measurements and Morgan Hasenmyer for assisting with field measurements. Finally, we would like to acknowledge the Subzero Research Laboratory at Montana State University and Dr. Ladean McKittrick for providing access to thermal chambers and supporting our temperature calibration measurements. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant Nos. 2043105 and 2439625. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. This material is also based upon work supported by the NASA EPSCoR Research Cooperative Agreement 80NSSC22M0169.

References

1. R. E. Dickinson, "Land surface processes and climate–surface albedos and energy balance," *Adv. Geophys.* **25**, 305–353 (1983).
2. H. Douville et al., "Sensitivity of the hydrological cycle to increasing amounts of greenhouse gases and aerosols," *Clim. Dyn.* **20**, 45–68 (2002).
3. P. Y. Groisman et al., "Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations," *J. Hydrometeorol.* **5**(1), 64–85 (2004).
4. A. Roesch, "Evaluation of surface albedo and snow cover in AR4 coupled climate models," *J. Geophys. Res.: Atmos.* **111**(D15), D15111 (2006).
5. X. Qu and A. Hall, "Assessing snow albedo feedback in simulated climate change," *J. Clim.* **19**(11), 2617–2630 (2006).
6. C. G. Fletcher, C. W. Thackeray, and T. M. Burgers, "Evaluating biases in simulated snow albedo feedback in two generations of climate models," *J. Geophys. Res.: Atmos.* **120**(1), 12–26 (2015).
7. A. Mullen et al., "An operational methodology for validating satellite-based snow albedo measurements using a UAV," *Front. Remote Sens.* **2**, 767593 (2022).
8. E. A. Sproles et al., "Autonomous aerial vehicles (AAVs) as a tool for improving the spatial resolution of snow albedo measurements in mountainous regions," *Hydrology* **7**(3), 41 (2020).
9. S. M. Skiles et al., "UAV hyperspectral imaging for multiscale assessment of Landsat 9 snow grain size and Albedo," *Front. Remote Sens.* **3**, 1038287 (2023).
10. C. Cao et al., "Measuring landscape albedo using unmanned aerial vehicles," *Remote Sens.* **10**(11), 1812 (2018).

11. C. Webster and T. Jonas, "Influence of canopy shading and snow coverage on effective albedo in a snow-dominated evergreen needleleaf forest," *Remote Sens. Environ.* **214**, 48–58 (2018).
12. B. Di Mauro et al., "Mineral dust impact on snow radiative properties in the European Alps combining ground, UAV, and satellite observations," *J. Geophys. Res.: Atmos.* **120**(12), 6080–6097 (2015).
13. J. C. Ryan et al., "Derivation of high spatial resolution albedo from UAV digital imagery: application over the Greenland ice sheet," *Front. Earth Sci.* **5**, 40 (2017).
14. C. Gaffey and A. Bhardwaj, "Applications of unmanned aerial vehicles in cryosphere: latest advances and prospects," *Remote Sens.* **12**(6), 948 (2020).
15. B. V. Ivanov et al., "The studies of the Svalbard glacial surfaces albedo by an unmanned aerial vehicle," *IOP Conf. Ser.: Earth Environ. Sci.* **1040**, 012002 (2022).
16. R. Fernandes et al., "Monitoring snow depth change across a range of landscapes with ephemeral snowpacks using structure from motion applied to lightweight unmanned aerial vehicle videos," *The Cryosphere* **12**(11), 3535–3550 (2018).
17. E. A. Bash and B. J. Moorman, "Surface melt and the importance of water flow—an analysis based on high-resolution unmanned aerial vehicle (UAV) data for an arctic glacier," *The Cryosphere* **14**(2), 549–563 (2020).
18. F. Canisius et al., "A AUV-based sensor system for measuring land surface Albedo: tested over a boreal peatland ecosystem," *Drones* **3**(1), 27 (2019).
19. D. Pacheco-Ferrada et al., "Optical effect of Andean mineral dust onto snow surface spectral albedo," *Atmos. Environ.* **333**, 120608 (2024).
20. R. Eker et al., "Monitoring of snow cover ablation using very high spatial resolution remote sensing datasets," *Remote Sens.* **11**(6), 699 (2019).
21. D. Fonseca-Gallardo et al., "Evaluating uncertainties in modeled snow albedo using multispectral remote sensing and UAV-based hyperspectral imaging," in *AGU Fall Meeting Abstr.*, p. C11B–04 (2024).
22. P. P. Joshi, R. H. Wynne, and V. A. Thomas, "Cloud detection algorithm using SVM with SWIR2 and tasseled cap applied to Landsat 8," *Int. J. Appl. Earth Obs. Geoinf.* **82**, 101898 (2019).
23. H. Shokati et al., "Random forest-based soil moisture estimation using Sentinel-2, Landsat-8/9, and UAV-based hyperspectral data," *Remote Sens.* **16**(11), 1962 (2024).
24. J. Dai et al., "Spectral-radiometric differentiation of non-photosynthetic vegetation and soil within Landsat and Sentinel 2 wavebands," *Remote Sens. Lett.* **9**(8), 733–742 (2018).
25. D. Ngo Thi et al., "Effective band ratio of Landsat 8 images based on VNIR-SWIR reflectance spectra of topsoils for soil moisture mapping in a tropical region," *Remote Sens.* **11**(6), 716 (2019).
26. A. Van Deventer et al., "Using thematic mapper data to identify contrasting soil plains and tillage practices," *Photogramm. Eng. Remote Sens.* **63**, 87–93 (1997).
27. B. Jakimow et al., "Mapping pasture management in the Brazilian Amazon from dense Landsat time series," *Remote Sens. Environ.* **205**, 453–468 (2018).
28. Z. Adiri et al., "Recent advances in the use of public domain satellite imagery for mineral exploration: a review of Landsat-8 and Sentinel-2 applications," *Ore Geol. Rev.* **117**, 103332 (2020).
29. A. Beiranvand Pour et al., "Application of multi-sensor satellite data for exploration of Zn–Pb sulfide mineralization in the Franklinian basin, North Greenland," *Remote Sens.* **10**(8), 1186 (2018).
30. S. M. Hamp, E. A. Sproles, and J. A. Shaw, "Development of a SWIR UAV-based radiometer for validating Landsat 8/9 snow products," *Proc. SPIE* **13373**, 133730D (2025).
31. SPIE, "Revision of conference proceedings manuscripts for journal submission," <https://www.spiedigitallibrary.org/journals/journal-of-applied-remote-sensing/author-guidelines> (2025).
32. E. J. Knight and G. Kvaran, "Landsat-8 operational land imager design, characterization and performance," *Remote Sens.* **6**(11), 10286–10305 (2014).
33. V. Aerial, "Vector hexacopter," <https://www.visionaerial.com/products/drones/vector> (2025).
34. C. Cornwall, A. Horiuchi, and C. Lehman, "NOAA solar position calculator," <https://gml.noaa.gov/grad/solcalc/>.
35. G. E. Box and D. R. Cox, "An analysis of transformations," *J. R. Stat. Soc.: Ser. B (Methodol.)* **26**(2), 211–243 (1964).
36. I.-K. Yeo and R. A. Johnson, "A new family of power transformations to improve normality or symmetry," *Biometrika* **87**(4), 954–959 (2000).
37. M. Rautiainen et al., "Spectral properties of coniferous forests: a review of in situ and laboratory measurements," *Remote Sens.* **10**(2), 207 (2018).
38. S. Singh, A. Kulkarni, and B. Chaudhary, "Hyperspectral analysis of snow reflectance to understand the effects of contamination and grain size," *Ann. Glaciol.* **51**(54), 83–88 (2010).
39. M. Dumont et al., "High-accuracy measurements of snow bidirectional reflectance distribution function at visible and NIR wavelengths—comparison with modelling results," *Atmos. Chem. Phys.* **10**(5), 2507–2520 (2010).
40. S. M. Hamp, "Band 7 replica system data and code," ORSL_Band7ReplicaRadiometer, 2025, <https://doi.org/10.5281/zenodo.17811688>

Shannon M. Hamp is the recipient of a John Kiel SPIE scholarship and a National Science Foundation Graduate Research Fellowship. She received her BS degree in electrical engineering in 2023 and completed her MS degree in optics and photonics from Montana State University in 2025, where her work focused on the design, calibration, and deployment of remote sensing systems.

Riley D. Logan received his BS degree in electrical engineering from Montana State University, Bozeman, Montana, United States, in 2015, then returned for his MS degree in optics and photonics in 2020 and his PhD in electrical engineering in 2024. In 2025, he joined the Electrical and Computer Engineering Department at Montana State University as an assistant professor. His research interests include environmental monitoring, spectral imaging, and biophotonics.

Eric A. Sproles is an associate professor of Earth Sciences and the director of the Geospatial Core Facility at Montana State University. His research integrates GIS science and remote sensing with field-based measurements, stable isotopic tracers, and models to better understand the geospatial and climatic controls on the world's water resources.

Joseph A. Shaw is the director of the Optical Technology Center and a distinguished professor in the Norm Asbjornson College of Engineering at Montana State University in Bozeman, Montana, United States, where he develops environmental remote sensing systems. He earned his PhD and MS degrees in optical sciences (University of Arizona), his MS in electrical engineering (University of Utah), and his BS in electrical engineering (University of Alaska Fairbanks). He is the 2019 recipient of the SPIE Stokes Award and a Fellow of SPIE and Optica.