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Portable spectral profiler probe for rapid snow grain size stratigraphy

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ABSTRACT

We present a portable spectral profiler probe to measure snow grain size stratigraphy in mountain snowpack at up to 5 mm vertical resolution, without the need for snow pit excavation. The probe infers grain size using near-infrared reflectance spectroscopy by inserting into the snowpack an optical package consisting of a light source and fiber optic receiver, which views the snow laterally and sends the collected reflected light to a spectrometer at the surface. The instrument can be easily dismantled and transported in a backpack, and rapidly deployed in the field. Grain size profiles from the probe, along with snow-pit contact spectroscopy and hand lens measurements were gathered and compared during winter and spring 2010 field campaigns in Colorado. Results from the probe agree to within 30% with snow-pit contact spectroscopy measurements, except when thin layers are present, which are detected at better vertical resolution by the profiler probe. The results highlight the lateral heterogeneity inherent in most mountain snowpacks, which is impractical to measure with conventional techniques. This type of measurement, along with density measurements, can greatly impact the accuracy of remote passive and active microwave retrievals.

1. Introduction

Snowmelt from mountainous regions provides more than 70% of fresh water for the western United States and represents the dominant water source for 60 million Americans and over one billion people globally (Bales et al., 2006; National Research Council, 2007). Snowpack in low to mid-latitude mountain ranges is highly affected by global and local climate changes, including temperature variations and particulate pollutants from industrial sources and windblown dust (Flanner et al., 2007; Flanner et al., 2009; Painter et al., 2007a). The remote sensing community is actively pursuing techniques with the ultimate goal of measuring all relevant snowpack properties from orbital platforms, to enable the study of worldwide climate patterns and their effect on local snow levels and water availability.

Current technologies for observing snow remotely include synthetic aperture radar (Rott et al., 2010; Shi and Dozier, 2000), passive microwave radiometers (Chang et al., 1982; Durand and Margulis, 2006; Foster et al., 1997, 2005; Kelly et al., 2003), and space-borne and airborne multispectral and hyperspectral optical sensors (Dozier et al., 2009; Nolin, 2010). Several space missions and airborne radar campaigns will provide data that can be significantly improved and enable greater understanding of terrestrial snow and ice when combined with in-situ measurements of grain size stratigraphy. Among these are the NASA ICESat II (Ice, Cloud, and land Elevation Satellite-2), AMSR2 (Advanced Microwave Scanning Radiometer 2), and the European Space Agency's CoReH20 (Cold Regions Hydrology High-resolution Observatory).

Many of these measurements are acutely sensitive to snow grain size stratigraphy (Brucker et al., 2011) and spatial variation, yet the effect on the observed signals is not well understood (Durand et al., 2008a, 2008b). Thus, the range of measurements across the electromagnetic spectrum requires ground measurements of grain size for accurate data interpretation. To fully understand the radiative and convective energy balance in snowy regions, large datasets of ground-based grain size measurements are needed (Langlois et al., 2010). This is only possible with new techniques allowing for much more rapid acquisition than previously available.

Current techniques for measuring grain size include more direct observations such as hand lens estimation (American Avalanche Association, 2004; Fierz et al., 2009), stereology (Matzl and Schneebeli, 2010), and X-ray tomography (Brzoska et al., 2001; Chen and Baker, 2010). Optical or indirect methods include near infrared photography (Matzl and Schneebeli, 2006), laser reflectance with an integrating sphere (Gallet et al., 2009), and contact spectroscopy (Painter et al., 2007b). Additionally, methane absorption provides a measure of specific surface area (Kerbrat et al., 2008; Legagneux et al., 2002). All of these techniques require excavation of a snow pit, which can significantly disturb the snowpack and require an hour to days of labor to obtain a single sample of grain size stratigraphy. This sample is then extrapolated spatially to the scale of a remote sensing ground instantaneous field of view (e.g. 25–40 km for passive microwave) with unknown but likely great uncertainty, given the spatial variability of deposition/

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redistribution of snow and energy fluxes to that snow column (Marshall et al., 2007).

A more applicable length scale for radiative transfer through snow is the optical equivalent grain diameter (OGD), defined as the diameter of a spherical pure ice grain which gives close approximation of hemispherical fluxes compared to observed fluxes (Grenfell and Warren, 1999). A more precise physical description for understanding the dimensions that impact radiation within the snow column (given that snow is generally a sintered medium and not usually a collection of distinct particles) can be given in terms of specific surface area (SSA), which is the surface area per unit mass of the grain (Domine et al., 2008; Warren, 1982). Under the assumption of spherical particles, the relationship between OGD and SSA is given by:

$$\mathrm{OGD} = \frac{6}{\rho \cdot \mathrm{SSA}} \quad (1)$$

where ρ is the snow mass density.

NIR photography, laser reflectance with an integrating sphere, and contact spectroscopy are optical techniques that infer the OGD by NIR reflectance from the wall of a snow pit. NIR photography uses absolute reflectance in the 840–940 nm wavelength band to estimate grain size simultaneously for every pixel in the image of the pit wall, providing high (~1 mm) horizontal and vertical spatial resolution (Brucker et al., 2011; Langlois et al., 2010; Matzl and Schneebeli, 2006). SSA is calculated from an empirical relationship between NIR reflectance and stereology SSA measurements. This technique requires great care in preparation of the pit face, camera setup, and lighting conditions, but for shallow pits can be performed very rapidly.

The DUFISSS instrument (Gallet et al., 2009) uses an integrating sphere to measure hemispherical reflectance from an NIR laser from snow samples collected from a snow pit wall. This provides highly repeatable measurements under controlled conditions, but requires snow pit excavation and sample removal. Moreover, the DUFISSS' technique requires an empirical correction due to the contamination of signal by the sampling dish when samples are optically thin.

NIR contact spectroscopy uses a broadband illumination source and a fiber optic pickup mounted in a handheld probe that is placed in near contact with the pit face with 2 cm vertical sampling (Painter et al., 2007b). Grain size is determined by integrating an ice absorption feature with a local maximum at 1030 nm and comparing the integral to that obtained from ideal spectra from a radiative transfer model for spherical grains (Nolin and Dozier, 2000; Painter et al., 2007b; Stamnes et al., 1988). The stratigraphic profile is obtained by stepping the probe incrementally down the pit face.

Although highly advanced, all of these techniques require snow pit excavation, which requires significant labor to obtain a single profile. One recent and promising prototype instrument has been developed to measure grain size without snow pit excavation (Arnaud et al., 2011). The POSSSUM device uses a powered drill to bore a hole into glacial snow/firn, into which a mechanical winch lowers the instrument. The instrument uses reflection from a single-frequency laser to obtain SSA, and a second frequency laser to measure distance to the surface. This presents an attractive means to measure deep profiles in glacial environments and other deep snowpacks. However, for snowpacks of moderate depths and in mountainous terrain, a smaller, more portable instrument can facilitate rapid acquisition of many profiles in a given area.

We have developed a prototype lightweight, portable probe that performs contact spectroscopy measurements in-situ, by inserting an optical probe into the snowpack instead of digging a pit. It should be noted that the grain size measurement technique presented here is not new. The probe is an application of the existing technique of contact spectroscopy in a novel delivery package, which enables the collection of data at least an order of magnitude faster than snow-pit techniques, and lessens disturbance to the measurement of grain size by avoiding exposing the underlying snow grains to the atmosphere and direct or once-reflected sunlight. In the following sections we present the design and construction of the prototype, along with results from testing against snow-pit contact spectroscopy and hand lens measurements from winter and spring field campaigns in Colorado.

2. Methods

2.1. Probe mechanical design

The basic design of the probe consists of a hollow aluminum sleeve that is inserted vertically into a hole in the snowpack, an optical package that is lowered inside the sleeve, and an above-ground manual clamping and drive mechanism for raising and lowering the optical package. The probe irradiates the snow surface laterally (orthogonal to the probe axis) with a broadband shortwave source (useful wavelength range 300 nm to 2500 nm) through slits in the sleeve, and a fiber-optic pickup couples the reflected light from the snow into an optical fiber that carries the signal out to a spectrometer on the surface which records the reflected spectrum.

Fig. 1 shows diagrams of in-bore and aboveground components of the instrument. The sleeve consists of a standard, 41 mm inner-diameter Federal snow sampler (www.unionforge.com), assembled in sections, that has been modified with a welded cap at the bottom end and milled slots of 16 mm width. These slots allow the probe to view the snow laterally from within the sleeve. An aluminum bore rider carries all of the probe optics, allowing the entire package to be moved vertically and rotated inside the sleeve by a hollow aluminum drive shaft.

At the lowermost tip of the bore rider, a cylindrical nylon "bottle brush" protrudes downward to sweep loose snow and debris from in front of the probe. A black, opaque plastic tarp of area 1 m^2, lain flat on the snow surface, blocks sunlight from penetrating to the probe location. The unit packs into a small backpack, with a separate pack for the spectrometer. It is possible to fit all of the hardware into a single pack with the spectrometer, however for this series of tests, we chose to keep the two packs separate to take advantage of the custom-made spectrometer pack supplied by ASD.

2.2. Optics

The optical package carried by the bore rider consists of a bifurcated fiber optic reflectance probe, an optical camera, and a halogen light source. The reflectance probe views the snow at a 28° angle of incidence through a protected gold front surface mirror, allowing it to collect reflected radiance from the snow and send it to the spectrometer at the snow surface via fiber optic cable (Fig. 2, Table 1).

The halogen light source shines onto the snow at a 52° angle of incidence and the reflected light is picked up at a 28° incidence angle, in the forward scattering direction. This light source consists of a bulb with output roughly 150 lumens (~2 W/cm^2) and reflector identical to those used in the contact probe (to be discussed later), but with a slightly trimmed reflector to make it more compact. Either this light, or an external light source can be used depending on the desired configuration.

The spectrometer used for all experiments presented here is an ASD FieldSpec Pro (www.asdi.com), powered from a small 12 V battery. The unit covers the spectral range from 350 to 2500 nm with 3 nm spectral resolution at 700 nm and 10 nm resolution at 1400 nm, splined to 1 nm spectral reporting. The optical camera (Ridgid MicroExplorer inspection camera—http://www.ridgid.com/Tools/micro-Explorer) views the snow at approximately normal incidence through a plastic mirror, allowing a partial view of the snow at the measurement location for qualitative comparison between locations. The camera also provides a partial view of the backside of the probe mirror, and is used here for alignment purposes only.

The bifurcated fiber-optic reflectance probe is a commercially available part from Analytical Spectral Devices, Inc. (ASD) (www.asdi.