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Broadband time-domain diffuse optical spectroscopy to measure and monitor snow

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Abstract: We investigate light propagation in snow using broadband time-domain diffuse optical spectroscopy from 550–1100 nm on snow phantoms. We analyze absorption spectra, presence of contaminants, and scattering changes due to snow density variations.

1. Introduction

On of the biggest modern threats is global warming, which accelerates glacial melting, alters climate and snowfall patterns, causes glacial algal blooms increases avalanche risks due to snowpack variations, among others. Algae growth in frozen seawater further intensifies CO emissions and radiation absorption, expediting ice shelf degradation. Characterizing snowpacks is crucial for climate monitoring. Snow's micron-to-millimeter scale crystalline structure [2] makes it ideal for diffuse optics, particularly time-domain diffuse optical spectroscopy (TD-DOS) [1]. This technique, based on distribution of time-of-flight (DTOF) of photons, enables distinguishing absorption and scattering properties, probing depths of a few centimeters. In this work, we explore the feasibility of TD-DOS for snow assessment by analyzing artificial snow-like samples. Using broadband spectroscopy (550–1100 nm), we extract optical spectra, absorption features, and structural variations. We also investigate changes due to colored contaminants, different snowpack densities and melting.

2. Materials and methodology

A state-of-the-art TD-DOS system [3] at Politecnico di Milano was used for this experimental campaign (shown in Figure 1(a)). A supercontinuum laser (SuperK Extreme, NKT Photonics) operated at 40 MHz generated picosecond pulses which were dispersed spatially using a Pellin - Broca prism and focused into a 62 μm fiber. Mounting the prism on a precision rotating stage, allowed us to select the wavelength being focused into the fiber, thus allowing us to scan from 550-1100 nm. Light is injected into the sample using a 200 μm fiber, via a variable attenuator to control the input power. Photons are detected with a 1 mm core fiber and coupled into a 1 mm^2 active

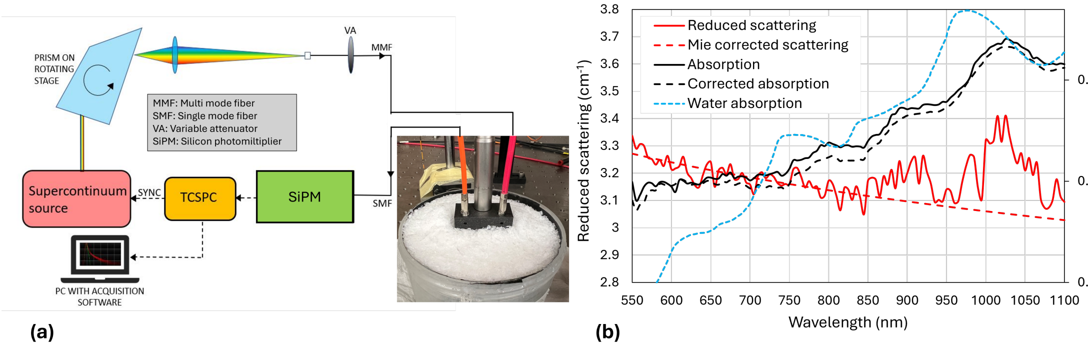

Fig. 1. (a) Schematic of the experimental setup with an image of a snow phantom, (b) Retrieved optical spectra along with a correction using the Mie law.

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area SiPM, which produces voltage pulses that are then processed by a time-correlated single photon counting (TCSPC) board (SPC-130, Becker and Hickl) to create a timing histogram of the photon arrival times - the DTOF.

The optical properties were retrieved by solving an inverse problem, fitting the instrument response function (IRF) convolved with the diffusion equation (DE) solution to DTOFs using the Levenberg-Marquardt algorithm [4]. Three experiments were conducted: (i) retrieving broadband absorption and scattering spectra of lab-prepared 'snow' phantoms, (ii) detecting dye contaminants via absorption spectra, and (iii) differentiating phantoms by packing fraction through scattering coefficients, and (iv) monitoring changes in optical properties during the melting of snow. The phantoms, mimicking snow, were made by crushing distilled water ice with a granita ice crusher, ensuring reproducibility for proof-of-concept testing, and hence are not real snow samples but are adequate as phantoms.

3. Results

Fig. 1(b) shows the absorption spectra in black, which is indeed similar to that of ice from literature. It has a characteristic peak at 1030 nm which is shifted as compared to the water absorption at 980 nm, shown in blue. Further, the other minor peaks at 900 nm are also visible. There also exists some coupling at the absorption peak wavelengths and is expected due to high μ_a values. Using a Mie law fitting, we can extrapolate the scattering, and give it as an input parameter to obtain a corrected absorption as shown with the dotted lines. Further, we prepared multiple snow phantoms and and found minimal differences in the retrieved reduced scattering values, showing that our phantom preparation technique was quite reproducible. On the other hand, Fig. 2(b) shows four snow phantoms made from ice with different added contaminants of yellow, red, green and blue dye inks. These goal of this experiment was to mimic algal bloom infestations in snow which is a huge concern as it leads to larger CO_2 emissions and traps more radiation. The corresponding absorption spectra are shown in Fig 2(a) and evidently show absorption peaks in the wavlength ranges complementary to the visible colour of the dye. This shows us that broadband TD-DOS can be used to differentiate coloured algal entities spectrally, and could potentially be used to even determine their concentrations with a more refined analysis.

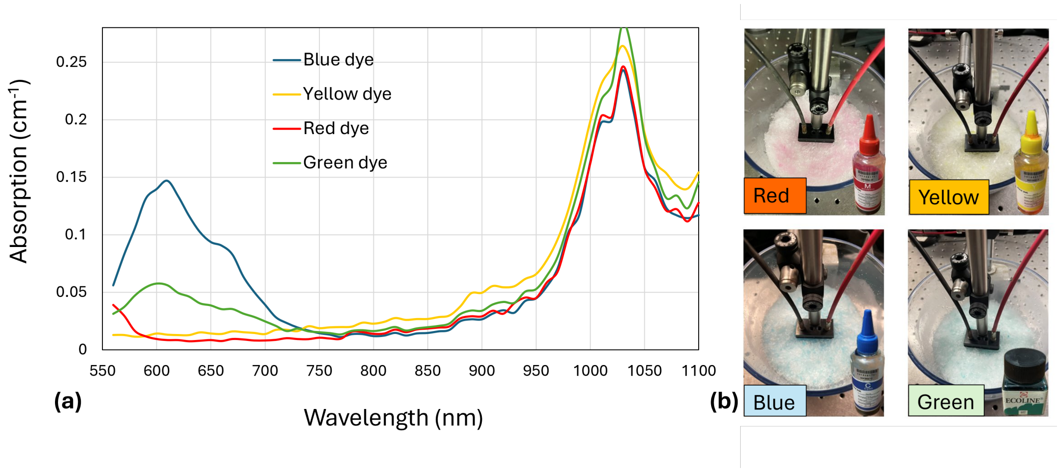

Fig. 2. (a) Absorption spectra of the phantoms with the different dyes, (b) Pictures of the various phantoms with their corresponding dyes.

Figure 3(a) shows the reduced scattering spectra obtained from three phantoms with varying levels of compressions - minimum, medium and maximum. This difference in compression led to phantoms with varied packing densities of 424, 580 and 530 mg/cm^3 for the minimum, medium and maximum compression respectively, and these values are comparable to standard snowpack densities of natural snow [5]. As can be seen from the spectra,an increasing compression/density leads to a higher scattering. This result is indeed a direct prediction of the Mie theory of scattering [6]. Due to the reproducible nature of phantom preparation due to the ice crusher, the 'crystal/granule' size of the samples remains the same. Thus, an increase in scattering corresponds only to a increase in the value of the 'a' factor or the packing density, confirming our experimental protocol of increasing the compression. This indeed provides for an interesting application to allow us to measure changes in snowpack density between various layers of snow. This could be helpful then to determine loose and sheets/layers of snow and thus predict avalanches that are caused due to sliding of adjacent unstable sheets.

Finally, Fig. 3(b) shows the reduced scattering coefficient of a snow phantom during a natural melting process.

The phantom was left at a room temperature of about 17°C and a spectrum was acquired every minute. The scattering at various wavelengths shows the same trend, it first increases for the first 15 minutes and then starts to decrease. While the initial increase seems counterintuitive, it can be explained by considering that as the small snow crystals start to melt, they tend to stick to other crystals/flakes due to cohesion and refreeze thus forming larger particles and this leads to an increase in the scattering. This is indeed the process of formation of firn - a type snow which is formed due to refreezing of fresh snow over many months, before it slowly turns to ice. Thus, these changes in scattering could be useful to track snowfall patterns and firn formations.

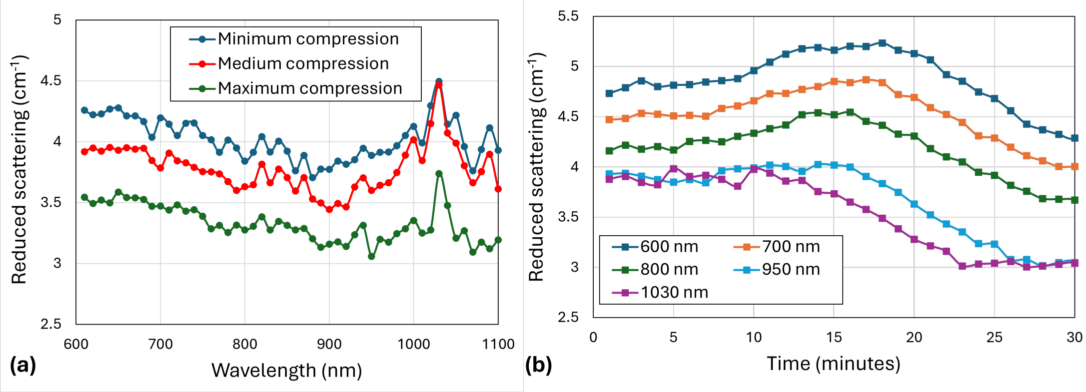

Fig. 3. (a) Reduced scattering spectra from snow phantoms with varying snowpack densities, (b) Variation in scattering due to natural melting processes.

4. Conclusions

We successfully conducted a proof-of-concept experiment to evaluate the feasibility of broadband TD-DOS for retrieving the optical properties of snow. After testing the reproducibility of lab-prepared 'snow phantoms' designed to replicate snow samples, we retrieved the absorption spectrum of snow with a characteristic peak at 1030 nm. Additionally, we were able to detect and differentiate different coloured contaminant dyes in the snow phantoms and also detect varying snowpack densities of samples by analyzing differences in the reduced scattering spectra. Finally, we also monitored the changes arising due the melting of the samples. These results highlight the potential of TD-DOS to quantify and characterize snow optical properties, including contaminant presence and varying layer snowpack densities, monitoring of melting, among others. Future work will focus on measuring natural snow samples, ideally in-situ, and incorporating additional modalities such as interstitial or non-contact measurements for more comprehensive monitoring. Further research could also aim to refine and accurately quantify these optical properties to track pollutants and impurities and monitor snow melting over the long term.

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