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Exploring optical properties of snow using broadband time-domain diffuse optical spectroscopy

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ABSTRACT

We present a preliminary study of light propagation in snow using broadband, time-domain diffuse optical spectroscopy (TD-DOS) – which is based on the detection of the distribution of Time-of-Flight (ToF) of photons traveling into the sample. By performing broadband measurements in the range of 600 – 1100 nm on artificially prepared snow phantoms, we retrieve the absorption spectrum with the distinct peak of ice observed at 1030 nm. Consequently, we measure samples with added coloured contaminants and attempt to characterize their absorption when frozen along with the snow. Finally we attempted to distinguish phantoms with different snowpack density using changes in reduced scattering coefficients.

Keywords: time-domain, diffuse optical spectroscopy, snow absorption, environmental monitoring

1. INTRODUCTION

One of biggest threat of modern age has turned out to be global warming and its consequent environmental effects. The rise in temperatures across the world directly leads to melting of glaciers and ice caps. Melting and refreezing of snow could cause structural variations in the bulk of the glacial sheets. Further, the growing presence of algae in these regions due to sea water freezing leads to larger CO_2 emissions and also higher radiation absorption in the bulk of the ice shelf, leading once again to faster melting. Finally, uneven snow patterns due to erratic weather changes can cause large variations within the snowpack with varying flake sizes and density, potentially leading to sliding of ice sheets and thus avalanches.

All these phenomena require proper characterization and monitoring of the glacial ice sheets and snowpacks to be able to corroborate with existing weather tracking techniques for a better plan to tackle global warming. Snow being composed of crystals/snowflakes on the order of a few 100 microns to a few mm[1] makes it an ideal sample to be probed using the technique of diffuse optics, which allows us to retrieve information from diffusely distributed photons.[2] In particular, time-domain diffuse optical spectroscopy (TD-DOS) – based on the detection of the distribution of time-of-flight (DTOF) of photons traveling into the sample – offers several advantages: (i) the ability to disentangle the absorption coefficient μ_a from the reduced scattering coefficient μ_s'; (ii) relatively larger probed depths (few cm); (iii) insensitivity to amplitude fluctuations, which could be useful to remove effects of laser fluctuations.[3]

In this work, we present initial measurements to test the feasibility of TD-DOS as a technique to measure and monitor snow. We attempt to prepare artificial, snow mimicking samples using finely crushed ice and perform broadband spectroscopy in the range of 600-1100 nm and retrieve its optical spectra, and detect its absorption peaks and information about particle size and packing density. Further, we will aim to monitor the effect of added coloured contaminants on the absorption spectra, and also samples with varying snowpack densities.

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2. MATERIALS AND METHODS

The experiments were performed using a state-of-the-art TD-DOS at Politecnico di Milano, shown in Figure 1.[4] A supercontinuum laser (SuperK Extreme, NKT Photonics) was operated at a repetition rate of 40 MHz and the generated picosecond regime supercontinuum pulses were dispersed spatially using a Pellin - Broca prism. The dispersed light was then focused into a 62 μm fiber. The rotation of Pellin - Broca prism using a precision rotating stage on which it is mounted, allows one to select the wavelength being focused into the fiber, thus enabling scanning across the wavelength from 600-1100 nm. The fiber is coupled onto the sample using a 200 μm, via a variable attenuator, used to control the input power injected into the sample. The photons are detected using a 1 mm core diameter fiber and them coupled into an SiPM with a 1 mm^2 active area. The voltage pulses generated by the SiPM on detection of the single photons 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, henceforth referred to as distribution of time-of-flight (DTOF) curve.

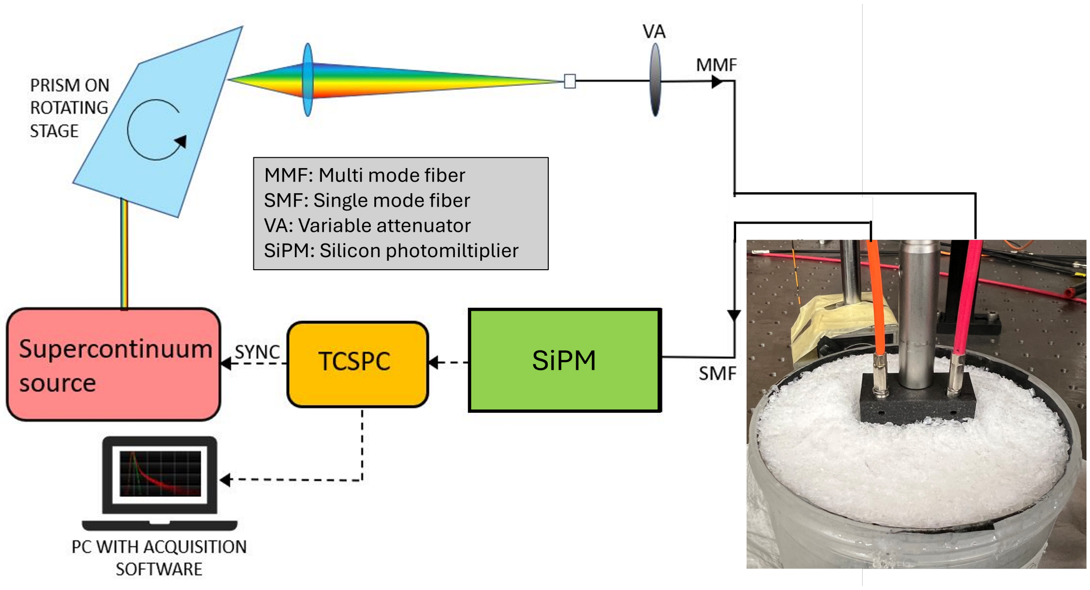

Figure 1. Schematic of the experimental setup with an image of a snow phantom under measurement.

The optical properties were retrieved by solving an inverse problem. The instrument response function (IRF) was convolved with the appropriate solution of the diffusion equation (DE) and was fitted to the DTOFs using the Levenberg - Marquardt algorithm.[5] Three types of experiments were performed - (i) To retrieve the broadband absorption and scattering spectra of the lab prepared 'snow' phantoms; (ii) To detect the presence of various added dye contaminants using the retrieved absorption spectra; (iii) To differentiate phantoms with different packing fractions of snow by monitoring the scattering coefficients. The phantoms were prepared using lab-crushed ice, so as to mimic the physical appearance of snow, as shown in Figure 1 . Ice cubes prepared with distilled water were crushed into the sample holder, using a standard ice-crusher for granita preparation, and had a physical appearance similar to that of snow. While it is true that this is not the same as a natural snow sample, the use of the ice crusher ensures reproducibility for sample preparation for a proof-of-concept.

3. RESULTS

Figure 2 shows the absorption and reduced scattering spectra retrieved from three measurements on three different samples, to test the reproducibility of the phantom preparation. As can be seen from the μ_s' spectra in Figure 2(b), the various measurements have a similar value of μ_s', and hence a similar macrostucture, thus showing us that the snow phantoms prepared are reproducible. Figure 2(a) shows the absorption spectra, similar to that of ice from literature, with its characteristic peak at 1030 nm shifted as compared to the one of water at 980 nm. This can be seen from the individual spectra in Figure 4(a). Further, one can also see the minor

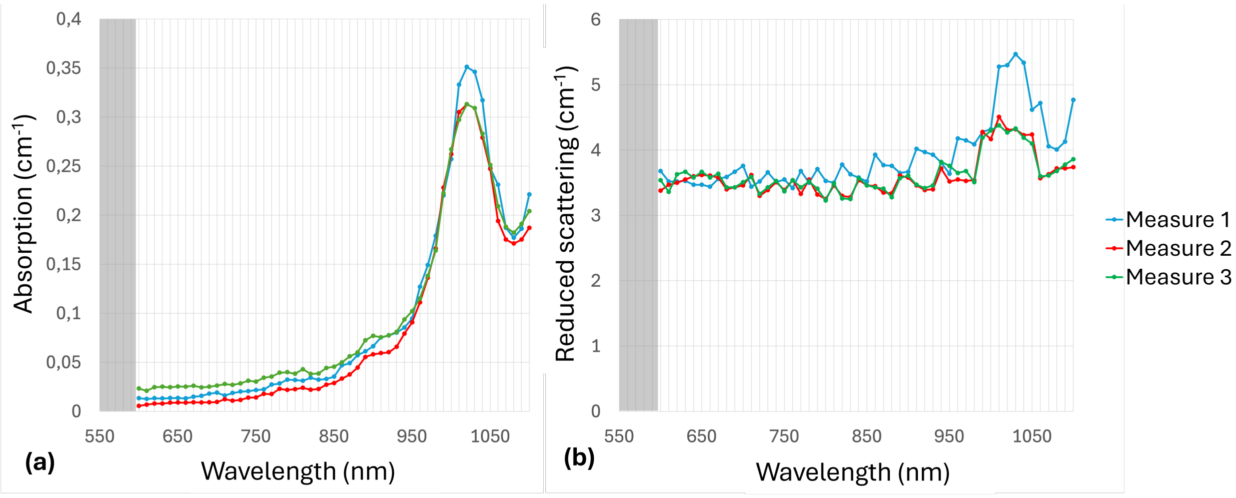

Figure 2. (a) Absorption and (b) reduced scattering spectra of three different snow phantom samples prepared using the same protocol, to retrieve the optical prooperties and test for reproducibility of the sample preparation process.

peaks at 900 nm. While we see some coupling at the absorption peak wavelengths, this is expected due to high μ_a values. Figure 3(b) on the other hand shows four snow phantoms prepared from ice with different added contaminants - red, yellow, green and blue dyes. These samples were prepared to mimic snow infested with algal blooms which is a growing phenomenon leading to larger CO_2 emissions and radiation trapping. Figure 3(a) shows the corresponding absorption spectra. Clearly, we observe an absorption peak at the spectral regions complementary to the colour of the dye. This shows us that broadband spectroscopy can be used to differentiate different algal entities, and with more refined analysis, even potentially estimate their concentrations.

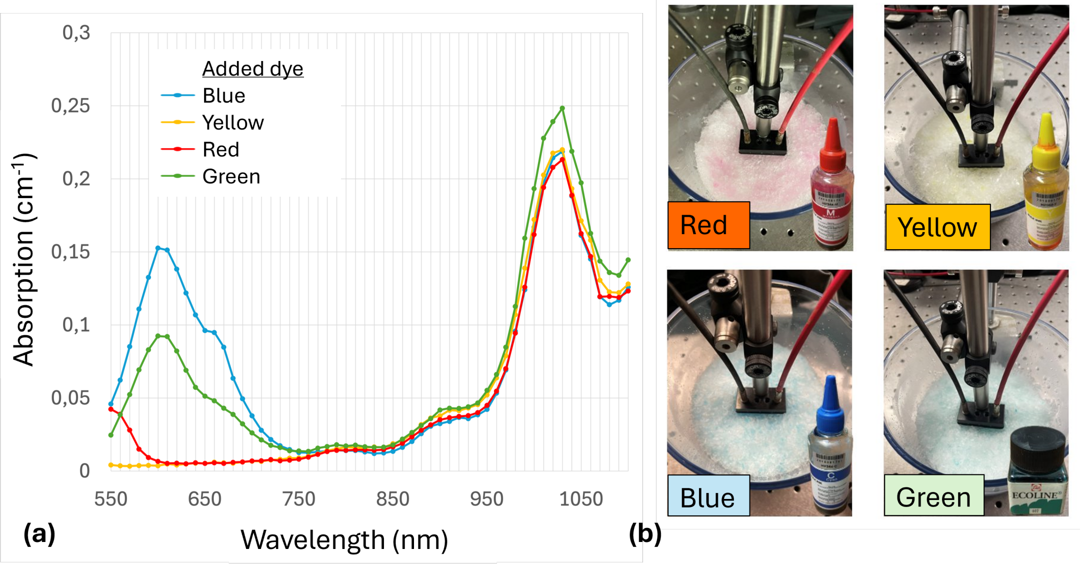

Figure 3. (a) Absorption spectra of four snow phantoms with different dye colours used in their preparation. (b) Picture of the snow phantoms with the corresponding added dyes.

Figure 4(b) shows the μ_s' spectra obtained from three samples with three different compressions - minimum, medium and maximum compression. The different levels of compression led to different packing densities - 424, 580 and 530 mg/cm^3 for the minimum, medium and maximum compression respectively, which is still comparable to standard densities of snow.[6] As is evident from the figure, as the compression/density increases, the scattering also increases. This is indeed a direct prediction of the Mie scattering law.[7] Since the crystal size remains the same due to the reproducibility of the ice crusher, the density directly acts on the reduced scattering coefficient. This could be an interesting application to predict the changes in snow packing density between different layers of snow, and could be helpful to predict avalanches due to sliding of adjacent sheets. Finally, Figure 4(a) shows a comparison of the water spectrum obtained from a water+intralipid liquid phantom, with that of a solid snow phantom. The distinct shift of the peak from 980 to 1030 nm is an interesting point that holds potential to quantify melting of snow, firn or ice.

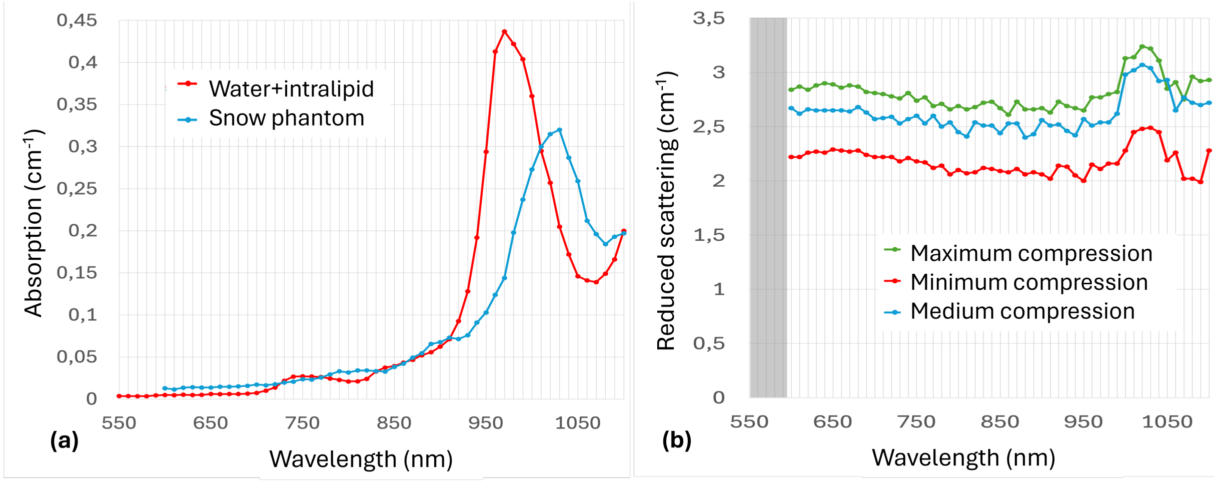

Figure 4. (a) Comparison of the water and ice absorption spectra with their characteristic peaks at 980 and 1030 nm respectively. (b) Change in reduced scattering spectra due to external compression of the snow phantoms, leading to change in densities.

4. CONCLUSIONS

We have demonstrated a proof-of-concept measurement to test the feasibility of broadband TD-DOS to retrieve optical properties of snow. Having tested the reproducibility of the lab prepared ’snow phantoms’ to mimic the properties of snow, we retrieved the snow absorption spectrum with its peak at 1030 nm. Further, we were able to distinguish the presence of different coloured contaminant dyes in the snow phantoms. Finally, we were able to differentiate different levels of snowpack density using changes in reduced scattering spectra. These experiments show the potential of TD-DOS to quantify and characterize the properties of snow, the presence of contaminants, various levels of ice layers, among others. Future directions would look to measure natural snow samples, preferable onsite. With additional modalities such as interstitial or non-contact measurements, one could perform various levels of monitoring. Further work could also point to refine and quantify accurately these optical properties, with a goal to also monitor the melting of snow in the long term.

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The authors declare no conflict of interest.

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