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# Modeling biases in laser-altimetry measurements caused by scattering of green light in snow

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ABSTRACT

Laser altimetry offers the potential to monitor ice-sheet elevation changes with millimeter accuracy. While previous missions have used infrared lasers to make these measurements, NASA's upcoming ICESat (Ice, Cloud, and land Elevation Satellite)-2 mission will use a green laser. Because ice absorbs green light very weakly, in the absence of light-absorbing impurities, green photons can scatter off many snow grains before returning to the surface, delaying the return pulse and leading to an apparent downward shift in the snow surface. In this paper, we explore the effects of snow-grain size and impurity content on these measurements, and investigate strategies that might help minimize the biases they introduce. We find that an uninformed choice of measurement parameters (a windowed mean including a large range of photons around the surface) can result in $> 0.45$ m of apparent surface-height variation between large and small grain sizes. Other choices of measurement parameters, such as a windowed median, can reduce this uncertainty by a factor of two to three. In addition, measurements of surface reflectance at green and infrared wavelengths, and interpretation of return-pulse shapes may be used to estimate and correct for these biases.

## 1. Introduction

Laser altimetry has proven to be an invaluable tool for monitoring change in the global cryosphere (land ice and sea ice) by providing accurate near-repeat measurements of surface elevation. It has been used for a wide range of scientific applications such as estimating sea level rise contributions from ice sheets and mountain glaciers, assessing temporal changes in sea ice freeboard, mapping subglacial lakes, and estimating basal melting under ice shelves (Gardner et al., 2011; Kwok et al., 2009; Moholdt et al., 2012; Pritchard et al., 2009; Pritchard et al., 2012; Smith et al., 2009; Sorensen et al., 2011; Zwally et al., 2011). Assuring centimeter accuracy of the repeat elevation measurements is critical for all of the aforementioned applications. For example, a uniform $-1\,\mathrm{cm\,yr^{-1}}$ bias over the period 2003 to 2008 would result in a ~50% over estimation of ice-sheet contributions of sea level rise (Shepherd et al., 2012). Seemingly small biases can translate into large errors for many geophysical estimates derived from near-repeat high-accuracy laser altimetry.

We have identified multiple scattering within snow and ice as a potential source of centimeter to decimeter bias in elevations estimated from ICESat-2 and other 532-nm altimetry measurements (e.g. NASA's Airborne Topographic Mapper (Krabill et al., 2000)) collected over snow and ice surfaces. If not properly corrected for, multiple scattering can result in spatially and temporally coherent time delays in photon returns. The time delay results from very low absorption and strong forward scattering by ice particles at 532 nm (Warren and Brandt, 2008); at this wavelength, a photon reflected from a pure snow surface will have scattered, on average, 2000 to 8000 times within the ice-air matrix (Fig. 1). The long, sinuous paths traveled by these photons during this scattering process delay the reflected photons by up to a few nanoseconds, making the surface appear, to the altimeter, lower than it actually is. These delays are much longer than the time that would be required for a photon to travel directly to the maximum depth it reaches within the snow and return directly to the surface, because the actual path taken involves a "random walk" made up many small steps in different directions, that begins and ends at the surface. For the purposes of this paper, we will term this problem volume-scattering (VS) bias, and refer to multiple scattering within the snow as "volume scattering."

The overall effect of volume scattering on the return depends on the optical properties of the snow and ice. Compared to aged snow or glacier ice, fresh snow has a larger specific surface area (surface area to

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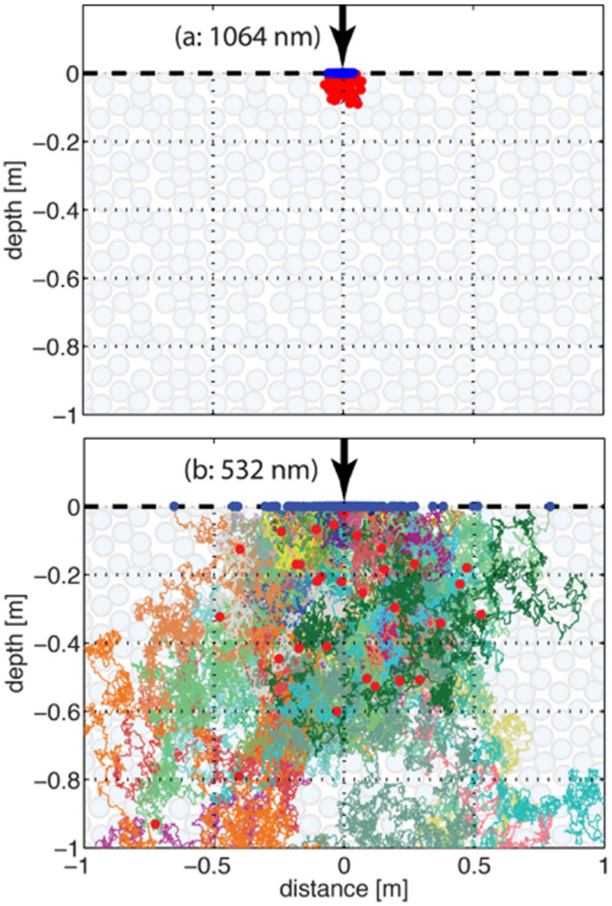

**Fig. 1.** Individual photon paths (irregular curves, with distinct colors for each photon) for 1000, 1064 nm (a) and 532-nm (b) wavelength photons within a homogeneous snow pack composed of snow grains with 0.25 mm effective grain radii and having a bulk density of 250 kg m$^{-3}$. Dashed black line shows the snow surface, the black arrow shows the photon entrance location, red dots show absorption events, and blue dots show photon exits locations. The size of the snow grains is here exaggerated for clarity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

volume ratio), and thus a smaller effective grain radius (Cabanes et al., 2002; Domine et al., 2006). This means that a photon in fresh snow will experience more scattering events per distance traveled than a photon traveling through aged snow and/or glacier ice, and will have a much higher probability of exiting the snowpack sooner (Gardner and Sharp, 2010). Because photons absorbed by impurities are not included in the mean effective path of detected photons, increased absorbing impurity (e.g., dust, black carbon, algae, and ash) content is associated with decreased effective path lengths, but the magnitude of this decrease is modulated by the impurity optical properties, concentrations, and locations relative to the ice particles (Flanner et al., 2012; Gardner and Sharp, 2010).

We expect multiple scattering of 532-nm photons to introduce a repeatable time delay in those places where the optical properties of the snow and ice are nearly constant in time (e.g. snow covered areas of the Antarctic Plateau). For these areas, the bias will have minimal impact on elevation change estimates. In those locations with seasonal and/or interannual variability in snow and ice optical properties (e.g. Greenland Ice Sheet, Antarctic ice shelves, sea ice, and mountain glaciers) we expect changes in the photon time delay to introduce centimeter to decimeter biases in elevation change estimates. Trends in climate also have the potential to introduce trends in the VS bias and, if uncorrected, trends in derived elevations.

Until recently, the effect of subsurface scattering on altimetry data has likely not produced large biases in altimetry measurements. Some data (e.g. ICESat (the Ice Cloud and land Elevation Satellite), LVIS (the Land ice and Vegetation Sensor) (Hofton et al., 2008)) were collected with near-infrared lasers, at wavelengths for which subsurface scattering delays are small because infrared is moderately absorbed by ice. Others (e.g. most Operation Ice Bridge and ATM data) were collected using green lasers, but mainly at times and in places where the ice sheet was mostly covered with fine-grained snow. The question of how large this effect may be, and how it may change, is, however, now timely because in mid 2018, NASA will launch the ATLAS laser altimeter on the ICESat-2 spacecraft, which will measure surface elevations with a 532-nm (green) photon-counting laser altimeter (Markus et al., 2017). This mission will make measurements year-round, over all types of snow and ice surfaces. 532-nm lasers and detectors were chosen because of (1) the high reflectivity of snow at this wavelength resulting in higher signal strength, (2) the flight readiness of sensitive, high-bandwidth detectors that allow the use of lower-power lasers. The lower operating power is expected to allow the ICESat-2 lasers to last longer than the high-power lasers used on ICESat. ICESat-2 will have an unprecedented ability to measure seasonal changes in ice sheet elevation change, provided that the effect of VS can adequately be corrected. The use of robust statistical measures to identify the timing of the surface return can help to reduce the impacts of 532-nm volume scattering on elevation retrievals but, as we will discuss, substantial bias is still likely when large-grained ice surfaces are measured.

### 1.1. *Modeling subsurface scattering delays*

We investigate the potential impact of VS on altimetry using a hybrid radiative transfer model. Our model describes the reflected photons, from a semi-infinite snowpack with assigned optical properties, at time *t* after a downgoing pulse of photons is incident on the surface. Neglecting atmospheric scattering, the rate of upgoing photons returning from the snow surface as a function of time gives the Surface-Response Function (SRF) of the snowpack. Altimetry measurements are made by reflecting a pulse of light of finite duration off a surface that may be rough or sloping, and detecting the reflected pulse with a receiver with finite time resolution. Each of these effects leads to a broader recorded return as a function of time, which we term the Impulse-Response Function (IRF) of the altimeter. The combination (temporal convolution) of the SRF and the IRF produce the recorded waveform (WF). We model the SRF, and combine it with an example IRF based on that expected for ICESat-2 to demonstrate the effects of subsurface scattering on altimetry measurements.

#### 1.1.1. *Radiative transfer model*

We model the snow as a collection of ice grains and absorbing particles, surrounded by air. Instead of explicitly modeling the distribution of grain sizes within the snowpack, we approximate the distribution with the bulk optical properties of grains of a uniform effective grain radius ($r_{eff}$) that approximates the effect of various true size distributions and particle shapes on the radiative transport within snow (Grenfell and Warren, 1999). The density of the snowpack and the effective radii of the grains determine the number of grains per volume, which, combined with the scattering ($Q_{sca}$) and absorption ($Q_{abs}$) efficiencies of the snow grains, determine the probabilities per unit distance traveled of a photon being scattered ($\mu_s$) or absorbed ($\mu_a$). The statistics of the angular distribution of photons after a collision with a snow grain are described by the asymmetry parameter ($g$), which gives the mean cosine of the angle between incoming and scattered photons for a single encounter. We use the *isotropic δ-Eddington* approximation, in which the effects of the phase function are approximated by reducing the true scattering coefficient to a smaller, effective scattering coefficient, where $\widehat{\mu_s} = (1-g)\mu_s$, and the corresponding scattering length is