FIRST PRINCIPLES MODELING FOR LIDAR SENSING OF COMPLEX ICE SURFACES

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ABSTRACT

Lidar sensing has been found to be a useful method of monitoring the dynamics and mass balance of glaciers, ice caps, and ice sheets. However, it is also known that ice surfaces can have complex 3-dimensional structure, which can challenge their accurate retrieval with lidar sensing. In support of future lidar sensing satellite missions, such as the upcoming ICESat-2, a joint research project was recently initiated between the Rochester Institute of Technology (RIT) and the University at Buffalo to study lidar sensing of complex ice surfaces. This effort is supported by NASA's Remote Sensing Theory program and is aimed at advancing the science of lidar sensing. The general approach is to 1) define realistic complex ice surfaces, 2) render lidar image simulations, and 3) compare the resulting data to the known surfaces to gain insight into the phenomenology of lidar sensing of snow and ice. The project will build on existing scientific understanding of light scattering from snow and ice as well as lidar sensor system modeling with a systems engineering end-to-end perspective. Initial results show the simulations capturing realistic scattering of photons in snow volumes and the resulting point clouds measured by a model spaceborne lidar system.

Index Terms— lidar, glaciers, phenomenology, simulation, modeling

1. INTRODUCTION

Lidar sensing has been found to be a useful method of monitoring the dynamics and mass balance of glaciers, ice caps, and ice sheets [1,2]. However, it is also known that ice surfaces can have complex structure, which can challenge their accurate retrieval with lidar sensing [3]. In support of future lidar sensing satellite missions, such as the upcoming ICESat-2 [4], a joint research project was recently initiated between the Rochester Institute of Technology (RIT) and the University at Buffalo to study lidar sensing of complex ice surfaces. This effort is supported by NASA's Remote Sensing Theory program and is aimed at advancing the science of lidar sensing.

2. APPROACH

The general approach is to 1) define realistic complex ice surfaces, 2) render lidar image simulations, and 3) compare the resulting data to the known surfaces to gain insight into the phenomenology of lidar sensing of ice. The project will build on existing scientific understanding of light scattering from snow and ice as well as lidar sensor system modeling with a systems engineering end-to-end perspective.

2.1. Complex Ice Surface Simulation

The most challenging application of lidar ranging for monitoring cryospheric changes is measuring the surface evolution of fast flowing outlet glaciers and ice streams. Areas where ice is moving by velocities of up to 10 kilometers per year are often characterized by rapid elevation variations. However, current processing algorithms assume smooth surfaces with random surface roughness for extracting surface elevations from lidar measurements, rather than the complex geometry of deep crevasses of fast flowing glaciers [5].

Understanding the impact of crevasses on the returned pulse will require scene descriptions with a resolution on the order of tens of centimeters. This fine sampling is necessary to characterize the detailed structures in crevassed regions so that the multiple bounce effects of the lidar pulse can be accurately captured. Moreover, in order to study the effects of system parameters on the retrieval of ice sheet volumetric changes and other dynamical events, a temporal sequence of scenes is required.

Realistic ice surface complexity is extracted from sequences of high-resolution airborne stereo imagery of Greenland outlet glaciers. An example derived digital elevation model (DEM) is shown in Section 3. Following facetization of the surface, each facet is attributed with models of scattering characteristics from the literature [6].

2.2. Lidar Imagery Simulation

The simulation of realistic lidar data for the ice surfaces is done using RIT's Digital Imaging and Remote Sensing

Image Simulation (DIRSIG) computer code. While DIRSIG was developed to simulate passive electro-optical imagery [7], it has recently been extended to simulate lidar imagery [8,9]. Extensions include the capability to predict received photon counts as a function of space and time. The temporal structure of these returns is driven by the spatial structure of the scene and the total travel time accrued during multiple bounce and scattering events within the scene. A numerical modeling technique called photon mapping is used to estimate the multiple-bounced and multiple-scattered radiation [10]. This technique is a hybrid of traditional forward and backward Monte-Carlo ray tracing techniques that was developed by the computer graphics community to estimate global illumination in high scattering environments. For the lidar case, the original photon mapping methodology was expanded to include tracking travel time. The output of the simulation for a given pulse is a time profile of arriving photon counts for each pixel captured. This focal plane arriving flux profile can then be feed to different detection models that handle the characteristics of Linear-mode, Geiger-mode and waveform detection systems.

The DIRSIG model scene geometry is described by combinations of analytical primitives, polygon models and voxel models. Each geometry element can be assigned a material with a unique set of optical properties. Surfaces can be assigned a variety of spatially varying hemispherical, directional or bi-directional reflectance models and volumes can be assigned spatially varying absorption, scattering and extinction models. The complex ice surface scenes previously described can be ingested into the DIRSIG model to simulate a variety of passive electro-optical and active lidar systems under different concept of operations (CONOPs) scenarios.

3. RESULTS

During the initial phase of the project an example test site has been identified and the surface DEM created, as well as initial visible image and lidar simulations performed.

3.1 Example Glacier Surface

Figure 1 depicts the surface of a 200 by 300 m area on a small outlet glacier, called Sermeq Avannarleq, located north of Jakobshavn Glacier in west Greenland. The elevation data were obtained from stereo aerial imagery collected by NASA's Digital Mapping System (DMS) in 2010. DMS uses a commercial digital camera with a nadir looking geometry to obtain subdecimeter resolution imagery from a height of 400 meters. First the images were oriented using a laser point cloud acquired by the co-flying NASA Airborne Topographic Mapper (ATM) system. Then elevations were extracted from the stereo image pairs automatically by image matching. Visual inspection of the measured points displayed on the oriented stereo imagery in 3D revealed that while the automated processing provided accurate surface topography on the upper, smoother surface of the glacier, it underestimated the depth of narrow, deep crevasses. Therefore, additional points within the crevasses were manually derived from the stereo image pair displayed on the 3D monitor of the softcopy workstation.

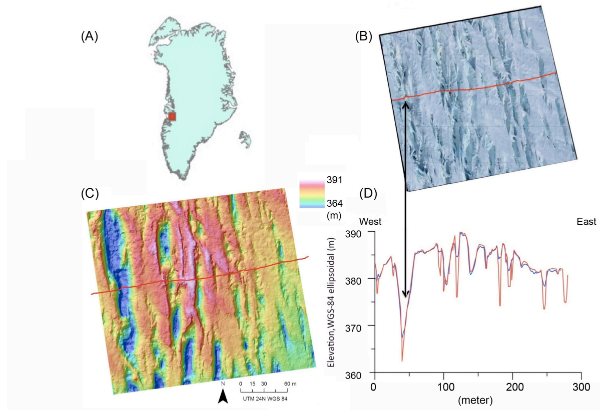

Figure 1. Detailed surface topography of a crevassed glacier (Sermeq Avannarleq, W Greenland) from stereo DMS imagery. (A) Location of the Sermeq Avannarleq in Greenland. (B) Orthophotograph generated from DMS imagery. (C) DEM computed automatically using ImageStation (Intergraph Corporation). (D) Comparison of surface elevations along a profile extracted automatically (blue) and measured manually (red). Profile is marked on the DEM and the orthophotograph.

3.2 Visible Panchromatic Simulations

This surface was attributed with the bidirectional reflectance distribution function (BRDF) characteristics of snow taken from [6] and a visible image simulated for a nadir-viewing sensor at 1300 local solar time (LST). Figure 2 shows this image including shadows in the crevassed regions.

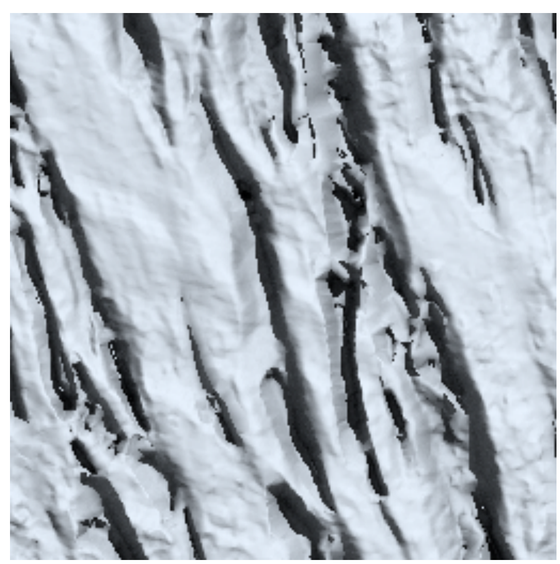

Figure 2. Simulated visible panchromatic image.

3.3 First-principles Scattering of a Lidar Pulse in Snow

To help understand the scattering of lidar pulses in snow, a simple scene was created consisting of a large volume containing uniform snow particles. The results of various single pulse simulations are included in this section. The plots in Figure 3 and Figure 4 show a vertical slice of the internal photon map employed by DIRSIG for 50 micron and 500 micron snow particle scenarios, respectively. The color code indicates the relative travel time of the photon packets represented by the points. Note that the 50 micron snow results in less penetration compared to the 500 micron snow. However, the 50 micron snow results in a higher amount of backscattered energy compared to the 500 micron snow (see Figure 5).

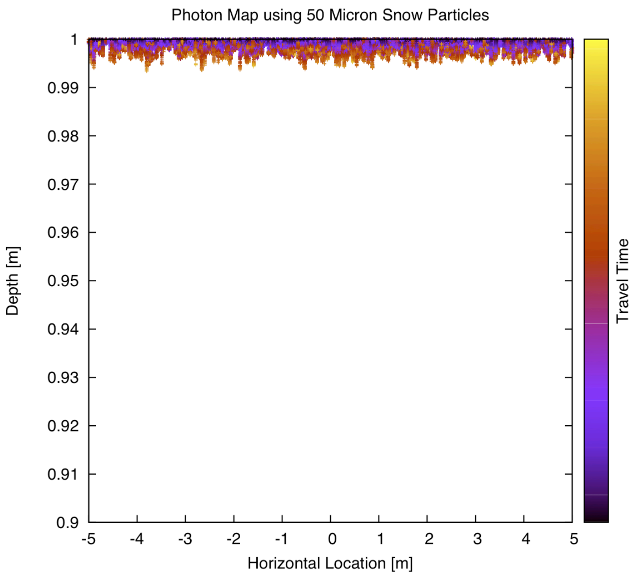

Figure 3. Plots of the photon penetration for 50 micron snow particles.

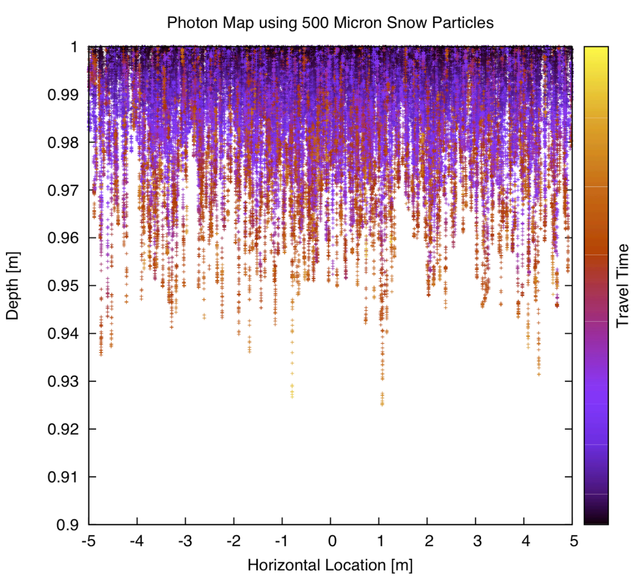

Figure 4. Plot of photon penetration for 500 micron snow particles.

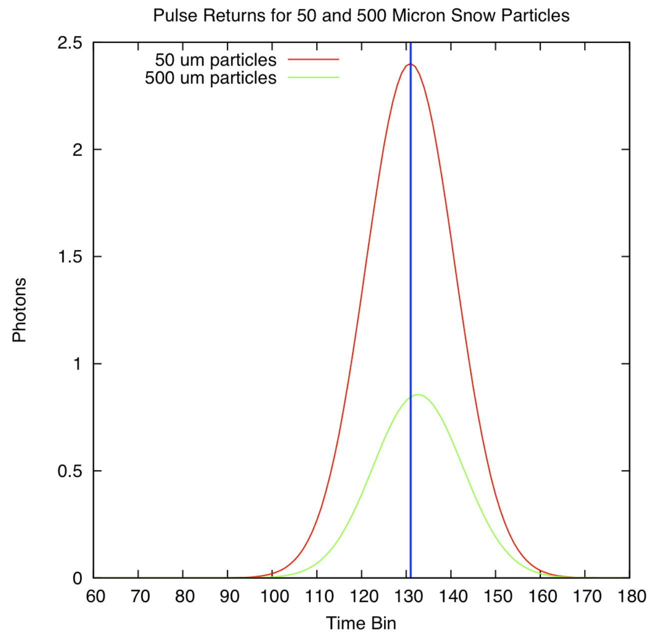

Figure 5. Plot of pulse returns for 50 and 500 micron snow particles using a relative time scale.

3.4 Photon Counting Detector Transect Simulation

One of the differences between the upcoming ICESat-2 lidar and that which was aboard ICESat-1 is the use of photon counting detectors versus the full waveform digitizing detectors of the earlier system. Geoscientists will need to become familiar with the characteristics of such detectors and their impact on analysis results.

As a step to ICESat-2, NASA has developed and is flying the airborne MABEL lidar system, which includes photon counting detectors [11]. Recent data collected over Greenland will help the science team gain familiarity with these data.

DIRSIG also includes models for photon counting detectors; in particular it incorporates a model for Geiger-mode Avalanche Photodiodes (GmAPD), which are one type of photon counting detectors.

To illustrate the characteristics of these data, a simulated transect of a 532 nm laser with a GmAPD detector was performed across the model glacier surface. The laser beam diameter and detector field of view was 10 meters. The detector was modeled after a Princeton Lightwave commercial single photon avalanche detector with a dark count rate of 100 kHz. Figure 6 shows the result of this simulation. The color scale denotes the height (in meters) of the detected photon events relative to the nominal surface. The thick red line results from the majority of returns coming from the glacier surface. The photon events above and below the surface result from detector noise events due to the dark count rate. This result is very similar to the data observed by real-world photon counting systems such as NASA's MABEL.

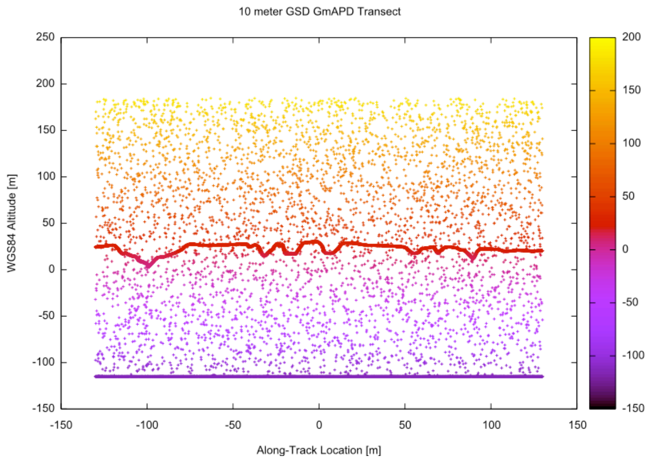

Figure 6. Simulated detection event transect across model glacier surface. Note the numerous returns from above and below the surface due to dark counts in the photon counting detector.

As an example of the different types of simulations possible, a second simulation of lidar returns is shown in Figure 7. For this example a large laser beam with a ground footprint of 100 m was used to illuminate the surface and returns collected by a 32 x 32 array of Geiger mode detectors covering 16 m x 16 m on the ground was scanned across the scene to create a 16 m wide swath over the surface.

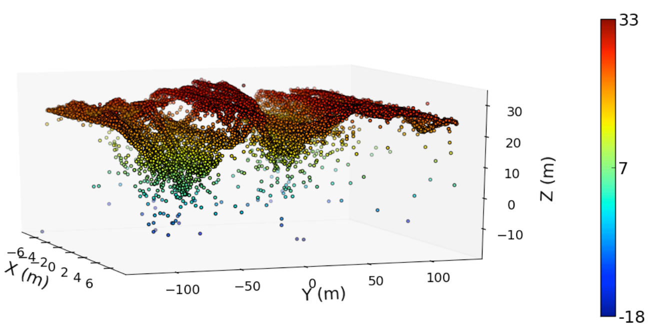

Figure 7. Simulated scan of a 32x32 array of detectors across model glacier. This figure shows the 3D features of the surface.

4. SUMMARY AND FUTURE WORK

A joint research project between scientists at the University at Buffalo and the Rochester Institute of Technology is investigating the phenomenology and science of lidar sensing of complex ice and snow surfaces. Initial work in the project has included defining a typical complex surface modeled after a real world dynamic outflow glacier and producing simulated passive imagery and lidar data. Results of these first simulations show phenomena consistent with observations of empirical data. Future work includes enhancing the surface and volume scattering models with variable snow and ice types and producing simulated lidar data sets under various conditions to better understand the scattering phenomenology in these complex environments.

5. ACKNOWLEDGMENT

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