The Swath Imaging Multi-polarization Photon-counting Lidar (SIMPL): A Technology Demonstration for Space-based Laser Altimeter Swath Mapping

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***Abstract* - We report on progress in developing a new bush-broom, swath-mapping laser altimeter measurement approach for future spaceflight missions using multiple laser beams from fiber lasers, photon counting detectors, and event timers.**

I. INTRODUCTION

Space based laser altimetry has been established as an invaluable technique for studying the surface height of the planets and the Earth from orbit. The present generation of orbital laser altimeters all measure surface height along a single profile. An example currently operating in Earth orbit is the Geoscience Laser Altimeter System (GLAS) aboard NASA's Ice, Cloud and land Elevation Satellite (ICESat) [1,2]. All use Q-switched Nd:YAG laser transmitter with a Si APD detector operating in the analog mode. Scanning laser altimeters, now routinely flown on aircraft, have demonstrated unprecedented resolution and the value of mapping land topography and vegetation structure. These use low energy lasers, which are pulsed at 10's of KHz rates, whose beams are mechanically scanned to achieve cross-track coverage. Many science disciplines will significantly benefit if spaceflight laser altimeters can make full 3-dimensional maps of surface elevation from orbit with spatial resolution of 5-10 m and swath widths of greater than 200m. The National Research Council Committee on Earth Science and Applications from Space has recommended that such mapping be conducted on a global basis as a part of their Decadal Survey recommendations to NASA.

The Swath Imaging Multi-polarization Photon-counting Lidar (SIMPL) is an airborne prototype in development to demonstrate laser altimetry measurement methods and components that enable efficient, high-resolution, swath mapping of topography and surface properties from space. This instrument development is sponsored by the NASA Earth Science and Technology Office (ESTO). In their 2004 Instrument Incubator Program (IIP) solicitation, ESTO requested proposals for advanced topographic mapping instruments capable of providing precise elevation and imagery data for detailed monitoring of ice sheet, sea ice and glacier change. Although currently emphasizing these polar-region cryosphere objectives, the SIMPL approach is also applicable in other scientific applications where high-accuracy repeat imaging of elevation change is an important measurement. These include topographic change associated with natural hazards, changes in vegetation canopy height and structure associated with disturbance and recovery, and changes in lake, reservoir, river and snow cover height and extent associated with water storage and discharge.

II. MEASUREMENT APPROACH

The SIMPL approach utilizes short-pulse, high-rate, laser transmitters, photon-counting detectors, and high-speed, event timer electronics in a push-broom configuration (Figure 1). By replicating these components and displacing the beams across-track, multiple adjacent altimetry profiles can be made simultaneously over a swath producing a topographic image without the need for scanning. The resulting swath image, in combination with precision spacecraft pointing, will ensure overlapping, along-track, repeated coverage of surface features from low Earth orbit (Figure 2). This is a key capability for unambiguous, direct measurement of elevation and surface property changes needed in studies of ice sheet, glacier and sea ice processes and mass balance.

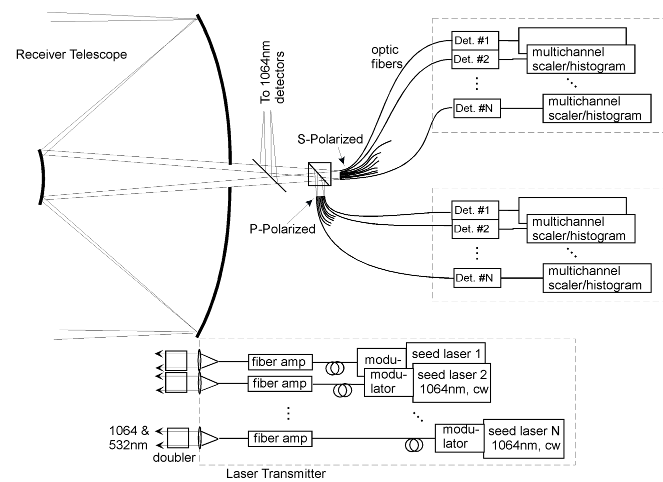

Fig. 1. Push-broom photon counting laser altimeter measurement approach using multiple fiber lasers, single photon counting detectors, and event timing electronics configured for dual wavelength measurements of surface elevation and depolarization ratio.

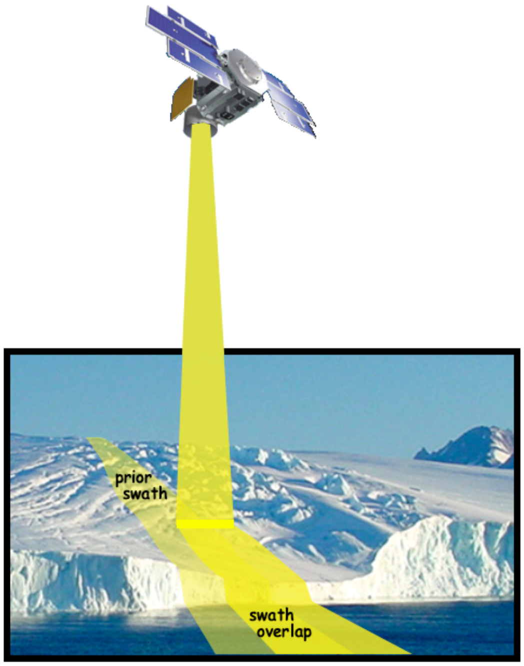

Fig. 2. Space-based, push-broom laser altimeter measurement concept. Repeating measurement along an orbit track separated in time using a swath elevation image and precision spacecraft pointing permits direct observation of surface elevation changes.

In this approach accurate (cm-level) ranging is achieved with only ~10's of detected photons by (1) transmitting short (~1 nsec), low-energy (1 μJ), high-rep rate (300 kHz) laser pulses, (2) illuminating small footprints (~10 m) thus limiting pulse broadening due to surface relief, (3) precisely timing (0.1 nsec) the detection of single photons per pulse, (4) applying time-space correlation of transmit pulses and receive photons, and (5) accumulating surface return photons from successive pulses. These factors substantially improve the measurement power efficiency as compared to prior orbital laser altimeters, such as the GLAS instrument on ICESat. This improved efficiency enables swath mapping with multiple, parallel profiles, significantly advancing beyond the single-profile measurement acquired by GLAS. The spaceflight measurement goal for our approach is 10 m spatial sampling with <10 cm vertical precision in a swath ~300 m wide, achieved using long-life, Yb fiber lasers (leveraging substantial investments by the telecommunications industry in this laser transmitter technology).

The depolarization ratio of the surface return will also be mapped by utilizing filters to measure the backscatter energy with polarization parallel and perpendicular to the laser transmit pulse (Figure 1). The depolarization ratio, a function of composition and micro-roughness, is a measure of the proportion of photons that undergo single- and multiple-scattering reflection from a target. The SIMPL airborne prototype will operate at 1064 and 532 nm in order to evaluate the depolarization response of natural surfaces at near-infrared and visible wavelengths.

In order to define an optimal instrument implementation, initial work was focused on characterization of natural surface retro-reflection properties, a survey of commercially available components (laser transmitters, 532 and 1064 nm photon counting detectors, and high-speed timing electronics), and development of analysis tools that assess measurement efficiency and ranging precision as a function of measurement conditions (surface reflectance and atmospheric transmission).

III. Initial Results

A. Laboratory Measurements

Laboratory measurements we have performed of range-resolved, laser retro-reflection at 532 and 1074 nm wavelengths documents that the depolarization ratio can be used to differentiate surface types, including water, snow and ice (similar to the well-established use of depolarization ratio data acquired by atmospheric lidars to differentiate liquid water and ice crystal clouds, and aerosol particle size). Prior work has documented that laser depolarization measurements at 1064 and 532 nm differentiate needle-leaf and broad-leaf vegetation based on differences in their wavelength-dependent scattering properties [3].

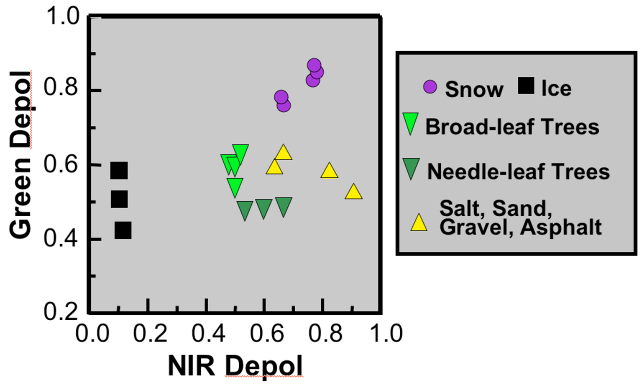

Fig. 3. Laboratory and field measurements of the depolarization ratio (perpendicular / parallel polarization) for natural surfaces at 532 and 1064 nm. Tree, gravel and asphalt data are from [2]. Snow and ice samples collected in New England and Greenland, and were preserved in a frozen state during transportation, storage and measurement.

Our laboratory measurements also document that visible light penetration into snow and ice does not cause any appreciable (< 0.1 nsec) broadening of the laser pulse echo, presumably because little of the volume scattered laser energy is returned in the retro-reflection direction. Thus, laser altimetry at 532 nm is suitable for precise elevation measurements of snow and ice surfaces. Because visible light penetrates 10's of meters through clear water, operation at 532 nm should also enable measuring the depth of melt water ponded on ice sheets, glaciers and sea ice. This is an important component of the cryosphere effecting surface albedo, energy exchange and warming. Melt water infiltrating to the base of glaciers and ice sheets also accelerates their flow velocity [4]. Measurements of water depth, as well as land topography and vegetation canopy structure, have previously been demonstrated using the Multikilohertz Microlaser Altimeter, an airborne, photon-counting, single-beam, scanning laser altimeter operating at a 10 kHz pulse rate and 532 nm [5].

B. Component Selection

A survey of candidate instrument components was completed that assessed performance, reliability, efficiency, technical readiness, commercial availability and likely development path for improvement in these attributes. Where adequate performance data were not available, units were acquired and tested. Based on this assessment, a near-infrared IPG fiber laser was procured for use in the SIMPL instrument which has a 1 ns FWHM output pulse width, a user selectable pulse repetition rate up to 2 MHz, and 10 W average power at 1 MHz. Frequency doubling is being used to generate both 532 and 1064 nm energy in the transmit pulse. PerkinElmer Single Photon Counting Modules in a quad configuration have been procured as the primary detector for operation at 532 and 1064 nm. Because of the low detection efficiency of this device in the near-infrared, we are also evaluating a newly-available InGaAsP photocathode hybrid photomultiplier (HPMT) detector for use in the SIMPL 1064 nm channel. Our testing of this new detector demonstrates performance that is well suited for use in laser altimeter implementations (25% detection efficiency, 60,000/s dark count rate, a few ns dead time, 780 MHz electrical bandwidth, wide dynamic range, and no after-pulsing). Single photon detection event timing will be performed using the FastComTec P7889 timer card, which achieves 22 mega-event per second average throughput with 100 psec timing resolution.

C. Measurement Performance Assessment

To establish a consistent framework to compare the performance of different laser altimeter measurement approaches, analyses were conducted that utilize equations for probability of detection, background count rates and ranging precision. Probability of detection and RMS range error are assessed for daytime and nighttime conditions as a function of transmit energy per pulse. We plot the results as a function of the measurement environment, defined as the product of surface reflectance and the square of the atmospheric transmission (i.e., the apparent surface reflectance). Figure 4 shows an example for 1064 nm photon counting ranging using a 100 KHz laser transmitter and the HPMT detector. Similar assessments have been performed at 532 and 1064 nm for approaches using analog detection, pseudo-noise encoded transmit signals, and single- and multi-hit photon detection.

IV. Future Plans

A one-beam, breadboard version of SIMPL is currently being assembled to test and validate the measurement approach. Measurements will be performed using laboratory targets, by horizontal ranging through tree canopies and potentially in-flight on an airborne platform.

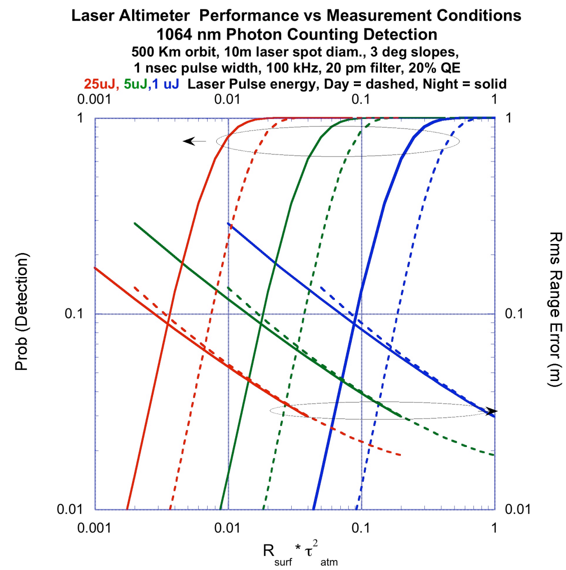

Fig. 4. Performance assessment of one laser ranging implementation, showing detection probability (positive sloped curves) and range error (negative sloped curves) as a function of apparent reflectance, with cases for nighttime (solid) and daytime (dashed) observing and three pulse energies (colors).

In early 2008, a four-beam version of the SIMPL prototype will be completed, tested, and available for airborne missions conducted as a part of the International Polar Year. IPY is an international program of interdisciplinary research and observations in the Earth's polar regions.

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