EVALUATION OF GEOSCIENCE LASER ALTIMETER SYSTEM (GLAS) WAVEFORMS FOR VEGETATED LANDSCAPES USING AIRBORNE LASER ALTIMETER SCANNING DATA

Claudia C. Carabajal[1] and David J. Harding[2]
[1]NVI, Inc. @ NASA/Goddard Space Flight Center, Space Geodesy Branch – Code 926
Greenbelt, MD 20771, U.S.A.
claudia@stokes.gsfc.nasa.gov
[2]NASA/Goddard Space Flight Center, Geodynamics Branch – Code 921
Greenbelt, MD 20771, U.S.A.
harding@core2.gsfc.nasa.gov

Commission III, Working Group 3

KEY WORDS: LIDAR, laser altimetry, laser waveform analysis, waveform simulations, topography, vegetation

ABSTRACT

The Geoscience Laser Altimeter System aboard NASA's Ice, Cloud and land Elevation Satellite will record the height distribution of laser energy reflected from surfaces within 70 m diameter footprints. For land surfaces, post-processing of this waveform data will be used to estimate the within-footprint mean elevation and surface relief due to ground slope and roughness, vegetation cover, buildings and other structures. A methodology is described for validating the derived surface properties for vegetated and urbanized landscapes using a GLAS waveform simulator applied to high-resolution, airborne, scanning laser altimeter data being acquired by the Puget Sound Lidar Consortium (PSLC) in northwestern Washington state. The GLAS waveform simulator is being modified to operate on 3-dimensional representations of topography and vegetation cover with the incorporation of digital elevation models derived from the airborne laser data and representations of the spatial distribution of surface reflectance, the transmitted laser energy measured on a per-pulse basis by the GLAS instrument, and detector's field-of-view responsivity. The attributes of the PSLC airborne laser mapping data are also described.

1 INTRODUCTION

The Geoscience Laser Altimeter System (GLAS) is a NASA Earth Observing System facility instrument planned for launch in the summer of 2002 aboard the Ice, Cloud and land Elevation Satellite (ICESat). The ICESat mission will measure polar ice-sheet topography and temporal changes in topography, cloud heights, planetary boundary heights, aerosol vertical structure, and land and water topography. GLAS will operate continuously in a 600 km, 94 degree inclination orbit, acquiring globally distributed elevation profiles consisting of 70 m diameter laser footprints spaced every 175 m along the profile. Precise pointing control of the ICESat spacecraft will enable specific ground tracks to be profiled repeatedly with a cross-track location accuracy of 30 m (1 sigma). Geolocation processing will yield footprint position and elevation accurate to 5 m and 13 cm, respectively (1 sigma for flat surfaces). A waveform recording laser backscatter energy as a function of time will be digitized for each footprint with a vertical sampling of 15 cm. The waveform, a measure of the height distribution of laser-illuminated surfaces, will be used to quantify within-footprint relief (i.e. vertical structure) due to surface roughness, slope, vegetation cover, and man-made features.

Laser profile and waveform matching to a Puget Sound airborne lidar data set has been proposed to validate ICESat footprint products [Schutz et al., 2000]. Comparison of laser altimetry profile geolocation results to topographic profiles derived from accurate digital elevation models (DEMs) has shown to be useful in assessing the absolute accuracy and systematic errors of the laser footprint position [Rowlands et al., 2000; Luthcke et al., 2001]. An additional geolocation comparison can be done based on matching synthetic waveforms produced from DEMs of high-resolution and accuracy to the backscatter energy digitized by the laser instrument at the footprint location [Blair and Hofton, 1999]. Waveform-to-DEM matching can also be used to validate parameters related to the quality of the laser beam, such as pulse width, footprint diameter and circularity. In addition, quantities derived from the footprint, like mean elevation, slope, roughness and vegetation height, can be validated. Well characterized DEMs of very high accuracy and spatial resolution covering large areas with significant relief, varying on short spatial scales, are the best suited for profile and waveform matching purposes. The Puget Sound data set possesses these characteristics.

Simulated laser waveforms can be made using the technique first described by Blair and Hofton (1999). They used a 33 cm horizontal spacing, 10 cm vertical accuracy DEM of dense, tropical rainforest in Costa Rica derived from a FLI-MAP helicopter-based, high-resolution laser altimeter survey to construct simulated waveforms that were then compared to waveforms for 25 m diameter laser footprints acquired by the Laser Vegetation Imaging Sensor (LVIS). Maximizing a Pearson correlation coefficient for all waveforms was used to estimate goodness of the agreement. Shifts in the horizontal and vertical direction, pulse width and footprint diameter variations yielded well defined correlations, which showed 0.01 m precision for the vertical shift and pulse width variation, and 0.1 m precision for the east, west and diameter parameters.

Because the waveforms to be provided by ICESat will cover approximately 8 times the area of an LVIS footprint, they will typically have a smoother distribution of surface elevations with fewer well-defined waveform peaks, and thus will likely yield less precision when matched to high-resolution DEMs. None-the-less, waveform to DEM matching should provide a useful evaluation of ICESat geolocation, laser beam quality, and derived surface properties. Simulated waveforms will also be used to evaluate the GLAS on-board acquisition algorithm prior to launch and during mission operations.

Here we describe a methodology for validating ICESat products using a GLAS simulator to generate synthetic waveforms from high-resolution DEMs. The GLAS simulator incorporates a representation of terrain elevation and reflectivity and models all the components of the instrument including transmitter characteristics and detector and digitizer responses. We describe the original simulator version and some of its applications, modifications that have been implemented to date, and future plans that will make this tool evolve into a more useful estimator of the instrument and processing algorithms performance. The characteristics of the Puget Sound data set will also be presented, as it will serve as the primary data set to be used for ICESat calibration and validation of products generated for vegetated and urbanized terrains.

2 THE GLAS WAVEFORM SIMULATOR

The GLAS simulator was developed as a first-generation tool to explore the relationship between the altimeter design, performance, and terrain characteristics [Abshire et al., 1994]. The original version of the simulator calculates the performance of the altimeter in a simplified two-dimensional measurement geometry (elevation vs. along track distance). The simulator includes the entire optical laser path and detector propagation paths, also calculating an estimate of the receiver's noise. The optical intensity waveform of the laser altimeter is calculated as it propagates to and from the terrain surface and, through the altimeter's receiver after detection of the laser energy. The transmit signal has a specified energy, duration (pulse width), angular width (beam divergence) and angular pointing offset from Nadir.

As designed originally, time is quantized in 100 psec bins (1.5 cm in range), and the transmit beam's intensity and far-field pattern are assumed to be Gaussian. The laser's optical wavefront is approximated by a finite number of rays distributed in the along-track angle, calculating the range delay and intensity for each one. The interaction with the terrain surface is calculated by projecting the beam in the along-track direction, ignoring any cross-track terrain height variations. Instrument parameters such as the transmitter's wavelength, divergence angle, and tilt angle of the altimeter can be specified. It assumes the terrain encountered by the laser beam is a diffuse reflector, and the height and reflectivity can be specified for every point along track. The receiver model includes a telescope, an optical band-pass filter, with the option to use either a photomultiplier or an avalanche photodiode optical detector, a low-pass filter, a timing discriminator, a time interval unit and a digitizer. The signal collected at the receiver is calculated based on 3-D diffuse scattering and a 3-D receiver telescope, and includes solar illumination effects. For every shot, it independently calculates the receiver waveform by adding the signal with the appropriate delays and the background light. The noise-only portion of the received waveform is used to calculate the threshold detector for the receiver. The received waveform is low-pass filtered to account for detector bandwidth, producing a smoothed version of the input waveform, and the simulated digitizer response is then calculated. The digitizer's sampling rate, number of bits and voltage scaling can be specified. A coarse estimate of the range is calculated from the time between the laser fire and the first threshold crossing. Fine range corrections can be calculated from the digitized waveform using different estimators (50% rise-time, midpoint, center of area, mean and peak of the received waveform). An estimate of the received energy can be inferred from its proportionality to the pulse area. Atmospheric refraction effects are not included in the calculations.

Csathó and Thomas [1995; 1997] have developed an algorithm to determine sea ice roughness from altimeter waveforms, based on the knowledge of sea ice properties (reflectance, surface roughness). They used the 2-D simulator to evaluate estimates of surface roughness from waveforms generated for a set of sea ice models and profiles acquired by airborne laser altimeter surveys. Spectral albedos observed under different conditions were used in creating realistic sea ice surface models. For horizontal surfaces with Lambertian reflectance, the RMS surface roughness (standard deviation of elevations within the footprint) is estimated from the mean-square width of the received pulse [Gardner, 1982]. Equivalent horizontal, Lambertian, random rough surfaces producing the same RMS laser pulse width can be defined. Decoupling surface roughness from slopping terrain effects on the waveforms represents a problem, and equivalent roughness estimates are obtained for different models indicating that further studies are needed to understand the influence of the various factors in the accuracy of the determination. These factors include the scale at which roughness contributes to pulse spreading, and the need for a more accurate description of elevation changes within the footprint.

Yi and Bentley [1999] studied the relationship between surface topography and laser waveforms using theoretical 3-D surface topographies and a Gaussian beam pattern and pulse shape to simulate waveforms. A non-linear least square minimization scheme was used to compare the derived surface roughness and slope parameters derived from the generated waveforms to the ones derived from various theoretical models. Their study illustrated the difficulties in de-coupling the slope and roughness effects, even when theoretical models are used. In addition, atmospheric forward scattering effects (which depend on cloud height, optical depth, cloud particle size and shape, and receiver field of view) can be a significant source of error in the elevation estimates, as well as in the slope and roughness estimates derived from waveform pulse widths [Duda et al., 2000; Mahesh et al., 2001].

To model the expected GLAS response to the intercepted surfaces in vegetated and urbanized sites, the current version of the GLAS waveform simulator is being modified to input 3-D terrain surfaces, incorporating the ingestion of DEM and surface reflectance surfaces gridded at 1 m resolution. Furthermore, instrument characteristics that convolve with the terrain properties are being incorporated in the modified simulator. These include a non-Gaussian laser spatial energy distribution, which for GLAS will be measured on a shot-by-shot basis by the instrument's Laser Profiling Array (LPA) which records a two-dimensional image of the transmit laser energy. In addition, the detector's responsivity across the field-of-view will be simulated to assess potential boresight misalignment between the transmit beam and detector. Surface elevation, reflectance, transmit beam spatial energy, and detector sensitivity all are input into the simulation as gridded, spatially varying parameters. No immediate inclusion of atmospheric effects is planned, but it would clearly be useful to use the simulator to re-create the effects of multiple scattering under various conditions.

3 THE PUGET SOUND DATA SET

Airborne LIDAR mapping in the Puget Sound region, is now being conducted by the Puget Sound Lidar Consortium (PSLC) [Harding and Berhoff, 2000]. The PSLC is an association of local government agencies, the United States Geological Survey, and NASA, which has contracted with Terrapoint, LLC to acquire and process multi-return laser altimeter data, yielding 'bald Earth' and 'canopy top' Digital Elevation Models (DEM) gridded at 6 ft resolution. To date 4,000 km^2 of the Puget

Lowland region has been mapped during leaf-off conditions. The data is being collected for a variety of purposes, including topographic mapping, identification of landforms related to active faults, hydrologic modeling, flood plain assessment, and urban planning. For the nominal flight conditions at 920 m altitude and 150 knots ground speed, a 600 m wide swath results in 0.9 m diameter footprints spaced 1.5 m along- and across-track. The Terrapoint ALTMS laser transmitter operates at 20 KHz and 1064 nm, with an 8 ns FWHM (full width at half maximum) pulse. The ±18° scan mirror operates at 50 Hz. About thirty percent of the laser swath is illuminated by the footprints, and up to 4 returns from vertically separated surfaces (with a minimum separation of 1.4 m) are collected per laser pulse. Using 50% overlap between adjacent swaths, the footprint density is doubled and all areas are imaged at two scan angles, providing multi-return laser data with dense sampling and very high spatial resolution.

The region being mapped includes a diverse assemblage of land cover types, including forests, agricultural pastures and fields, and suburban and urban communities [Harding and Berghoff, 2000]. The expected character of GLAS waveforms for a diverse set of vegetation cover and ground slope conditions will be illustrated in order to assess retrieval of ground elevation, vegetation height, and canopy structure. Point clouds of individual, geolocated laser returns acquired by Terrapoint are aggregated over 70 m diameter footprints, into height distributions that approximate the within-footprint relief to be detected by GLAS waveforms. The Terrapoint 1.5 m laser shot spacing within a swath nominally yields 1,700 laser shots per height distribution. Comparisons of height distributions obtained from the two overlapping swaths demonstrate good reproducibility of the height distributions.

The point cloud of all laser returns is classified into returns thought to be from vegetation and from ground by means of a Virtual Deforestation (VDF) filter discussed in Haugerud and Harding [2001, this volume]. A 'bald Earth' DEM gridded at 6 ft resolution is then constructed from those returns classified as ground. The accuracy of the 'bald Earth' DEM has been established by comparison to ground control points established by Global Position System (GPS) surveying in five land cover classes (three non-forested: bare, tall grass, and urban; two forested: coniferous and deciduous). The mean and RMS difference of the Ground Control Point (GCP) elevations with respect to the DEM interpolated to the GCP locations for a total of 36 sites is –2.3 cm and 17.4 cm, respectively. As expected, the results for 23 non-forest sites (0.6 and 10.6 cm) are better than for 13 forested sites (-7.5 and 25.3 cm) where in several cases the derived DEM is above the actual ground surface due to the presence of dense understory vegetation. A histogram of GCP elevation differences is shown in Figure 1.

For input into the GLAS waveform simulator, a DEM gridded at 1 m is constructed by nearest-neighbor resampling of the complete all-return Terrapoint point cloud. Nearest neighbor resampling is used to preserve the original data's height distribution, rather than introducing heights not actually present as is caused by interpolation schemes. The type (ground versus not-ground) of each 1 m DEM cell is identified based on the VDF classification of the nearest-neighbor return, so that the elevation of the ground surface in the simulated GLAS waveform can be tracked.

In order to use the Puget Sound data as a basis for modeling GLAS waveforms, it is assumed that the surface is uniformly sampled spatially and that individual returns represent illuminated surfaces of equivalent area. Although the former assumption is well justified by the laser shot density and distribution, the latter is not well established. The Terrapoint ALTMS system uses a constant-fraction discriminator threshold detection scheme to identify multiple returns. The sensitivity of detection may not be equal for each return in a sequence of multiple returns. Furthermore, for a complete simulation, the spatial variation of surface reflectance must be minimal or independently known, because the simulated return intensity depends on the reflectance of the surface elements. Use of high-resolution, multi- and hyper-spectral imaging data is being considered as a source for the necessary reflectance information.

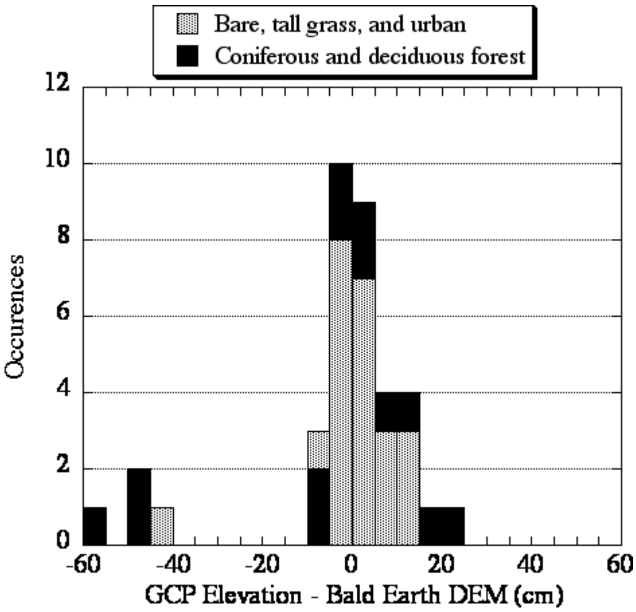

Figure 1. Elevation difference between 36 GCPs established by GPS surveying and the Puget Sound 'bald Earth' DEM, gridded at 6 ft resolution and then projected to the GCP location using bilinear interpolation.

4 PRODUCTS TO BE VALIDATED

The products to be validated by profile and waveform matching are the x and y horizontal geolocation of ICESat footprints, and the land parameters derived from the waveform. The latter are parameters like the mean, minimum, and maximum elevation, slope, roughness, vegetation height, and Gaussian fits to the multiple within-footprint surfaces [Brenner et al., 2000]. Because the Terrapoint data is classified as returns from ground and non-ground surfaces, using these data will enable the assessment of which peaks in the GLAS waveforms correspond to the actual ground surface as a function of vegetation cover and slope conditions. This measurement in turn allows for validation of GLAS derived vegetation height measurements, since it greatly depends on the correct identification of the ground return in the waveform. The transmit beam quality can also be validated, including the FWHM (full width at half maximum) of the pulse, and the diameter and circularity of the footprint energy distribution.

The steps to accomplish this validation will consist of first matching GLAS elevation profiles to the Puget Sound DEM to test the geolocation accuracy of the laser footprints [Rowlands et al., 2000; Luthcke et al., 2001]. Second, observed GLAS waveforms will be matched to synthetic waveforms created using the GLAS simulator applied to the Puget Sound laser point cloud data to refine the geolocation test. Having established the best footprint geolocation, the surface parameters derived from the observed waveforms via the GLAS processing procedures will be evaluated with respect to the known surface properties defined by the Puget Sound high-resolution data.

The diversity of land cover types, and the relief complexity at GLAS footprint scales introduced by local variations in building and tree heights, provides an ideal opportunity to use the well characterized Puget Sound data set for waveform matching purposes along ICESat tracks.

REFERENCES

Abshire, J. B., J. F. McGarry, L.K. Pacini, J. B. Blair, and G. C. Elman, 1994. *Laser Altimetry Simulator, Version 3.0 User's Guide,* NASA Technical Memorandum 104588, NASA/GSFC, Greenbelt, MD, 70p.

Blair, J. B. and M. A. Hofton, 1999. Modeling Laser Altimeter Return Waveforms Over Complex Vegetation using High-Resolution Elevation Data, Geophysical Research Letters, Vol. 26, No. 16, pp. 2509-2512.

Brenner, A. C., H. J. Zwally, C. R. Bentley, B. M. Csathó, D. H. Harding, M. A. Hofton, J. B. Minster, L. A. Roberts, J. L. Saba, R. H. Thomas and D. Yi, 2000. Derivation of Range and Range Distributions From Laser Pulse Waveform Analysis for Surface Elevations, Roughness, Slope, and Vegetation Heights, *Geoscience Laser Altimeter System (GLAS) Algorithm Theoretical Basis Document*, Version 3.0, 93p.

Csathó, B. and R. H. Thomas, 1995. Determination of Sea Ice Surface Roughness from Laser Altimetry Waveform, *Byrd Polar Research Center Technical Report Number 95-03*, The Ohio State University, Columbus, Ohio, 44p.

Csathó, B. and R. H. Thomas, 1997. Geoscience Laser Altimeter System: Surface Roughness of Sea Ice, *Geoscience Laser Altimeter System (GLAS) Algorithm Theoretical Basis Document*, Version 0.2, 16p.

Duda, D. P., J. D. Spinhirne and E. W. Eloranta, 2000. Atmospheric Scattering Effects on GLAS Altimetry. Part I: Calculations of Single Pulse Bias, IEEE Trans. Geoscience and Remote Sensing, Vol. 39, pp. 92-101.

Gardner, C. S. 1982. Target Signatures for Laser Altimeters: An Analysis, Applied Optics, Vol. 21, No. 3, pp. 448-453.

Harding, D. J and G. S. Berghoff, 2000. Fault Scarp Detection Beneath Dense Vegetation Cover: Airborne LIDAR Mapping of the Seattle Fault Zone, Bainbridge Island, Washington State, Proceedings of the American Society of Photogrammetry and Remote Sensing, Washington, D.C., May, 2000, 9p., also available at http://pugetsoundlidar.org.

Haugerud, R. A. and D. J. Harding, 2001. Some Algorithms for Virtual Deforestation (VDF) of Lidar Topographic Survey Data, International Archives of Photogrametry and Remote Sensing, this volume.

Luthcke, S. B., C. C. Carabajal and D. D. Rowlands, 2001. Enhanced Geolocation of Spaceborne Laser Altimeter Surface Returns: Parameter Calibration from the Simultaneous Reduction of Altimeter Range and Navigation Tracking Data, submitted to the Journal of Geodynamics Special Issue on Laser Altimetry, 32p.

Mahesh, A., J. D. Spinhirne, D. P. Duda, and E. W. Eloranta, 2001. Atmospheric Multiple Scattering Effects on GLAS Altimetry Part II: Analysis of Expected Errors in Antarctic Altitude Measurements, submitted to IEEE Trans. Geoscience and Remote Sensing.

Rowlands, D. D., C. C. Carabajal, S. B. Luthcke, D. J. Harding, J. M. Sauber, and J. L. Bufton, 2000. Satellite Laser Altimetry: On-Orbit Calibration Techniques for Precise Geolocation, The Review of Laser Engineering, Vol. 28, No. 12, pp. 796-803.

Schutz, R. E. et al., 2000. *GLAS Altimeter Post-Launch Calibration/Validation Plan*, Version 0.99, Section 6.7.7, pp. 58-61.

Yi, Donghui and C. R. Bentley, 1999. Geoscience Laser Altimeter System Waveform Simulation and its Applications, Annals of Glaciology, Vol. 29, pp. 279-285.