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Assessing the performance of 20–25 m footprint waveform lidar data collected in ICESat data corridors in Greenland

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[1] The precision and accuracy of surface elevation measurements of the Greenland ice sheet provided by 20–25 m-footprint waveform laser altimetry is assessed using data collected by NASA's LVIS airborne lidar in September 2007. Repeated data acquisitions from two ~850 km long transects over the ice sheet and a ~30 km-long transect in the Summit area are evaluated for consistency and compared to in situ data for validation. Comparisons to data collected by NASA's ICESat system reveal good agreement. In the Summit area, differences are better than 0.07 m (1σ) (except for L3C where it is 0.13 m), with mean offsets of −0.09 to 0.16 m depending on the campaign. Within the feeder zone to Jakobshavn Glacier, ice elevation decreases of up to 12 m, 2004–2008, are observed. The results suggest that 25 m waveform lidar can measure ice sheet elevation precisely and accurately and that the measurement scheme could be used to complement the legacy ICESat measurements. **Citation:** Hofton, M. A., J. B. Blair, S. B. Luthcke, and D. L. Rabine (2008), Assessing the performance of 20–25 m footprint waveform lidar data collected in ICESat data corridors in Greenland, *Geophys. Res. Lett.*, *35*, L24501, doi:10.1029/2008GL035774.

1. Introduction

[2] The systematic monitoring of polar regions is essential to improving our knowledge of ice sheet mass changes [e.g., *Luthcke et al.*, 2006]. Laser altimetry (also referred to as lidar) has shown great utility for this purpose since it provides an efficient method of precisely and accurately mapping ice sheet surface elevations from which ice volume changes can be inferred. Using this technique, the two-way travel time of a pulse of light from the laser to the ground is combined with positioning and pointing data to obtain the position and elevation of the laser footprint on the ground. In Greenland, numerous airborne lidar mapping surveys of portions of the surface of the ice sheet have been carried out [e.g., *Krabill et al.*, 2002]. Typically scanning within a data swath <250 m wide, surveys have been flown at low altitude (<0.5 km above ground) to generate high resolution (<1 m) surface elevation maps along transects. These data have been used to quantify ice sheet thickening and thinning, revealing a complex picture of ice sheet changes [*Krabill et al.*, 2002].

[3] Enhancing and extending the airborne data, NASA's Ice, Cloud and land Elevation Satellite (ICESat) was launched in January 2003 to detect ice elevation changes that are indicative of ice volume changes over time [*Zwally et al.*, 2002]. The ICESat mission includes a single beam laser altimeter that generates ~60 m-wide footprints separated by ~170 m along track. Utilizing an enhanced measurement approach in which the return laser pulse shape (waveform) is recorded and interpreted in post-processing, ICESat measurements provide precise and accurate elevation data. Although not continuous, data from near-contiguous repeat tracks combined with other remote sensing data confirm the complex spatial and temporal patterns of ice sheet changes [e.g., *Howat et al.*, 2008].

2. Greenland Mission and Data Processing

[4] Two airborne lidar surveys in Greenland were performed on 20–21 September, 2007, using NASA's Laser Vegetation Imaging Sensor (LVIS) [*Blair et al.*, 1999]. The LVIS is a medium-altitude, medium-footprint lidar system that digitally records the shapes of the transmitted and reflected laser pulses. During the surveys, the LVIS was mounted in NASA's P3-B Orion aircraft and flown from Kangerlussuaq airport, Greenland (Figure 1). An operating altitude of 7600–8300 m was used to generate a 1.1–1.5 km-wide swath of data composed of 20–25 m-wide slightly-overlapping footprints (dependent on the ice surface elevation). Primary data collection areas included areas of smooth and crevassed ice and coincided with 91 day orbit reference track corridors of the ICESat sensor, including two, 850 km-long portions of ICESat reference tracks 204 and 419 and a 30 km-long portion of reference track 412 in the Summit area (Figure 1). Each area was overflown twice. This data collection was intended to emulate critical measurement parameters (footprint size and laser pulsewidth) of the National Research Council recommended Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI, http://desdyni.jpl.nasa.gov/index.cfm) multibeam lidar.

[5] Data collected included aircraft position, aircraft orientation, laser ranges to the surface and laser scan angles. Aircraft positioning was obtained using differential kinematic GPS techniques relative to base stations at Kangerlussuaq and Summit where dual frequency receivers logged data at 10 Hz and 2 Hz respectively. Aircraft orientation data (roll, pitch, and yaw) were recorded at 200 Hz by an inertial measurement unit. The data were combined to generate the final data products using NASA's Variable Estimation, Geolocation and Analysis Software (VEGAS) system. Using this software, system biases and parameters (e.g., angular offsets between the various reference frames

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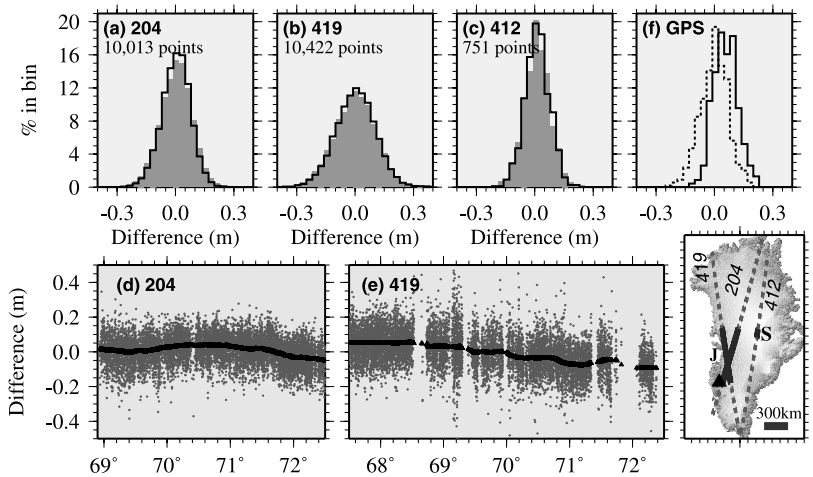

Figure 1. Distribution of elevation differences between near-coincident LVIS footprints along data lines (a) 204, (b) 419 and (c) 412 after comparing LVIS elevation products (gray-shaded) or LVIS waveforms using the pulse correlation method (solid outline). Locations of the data lines and corresponding ICESat tracks are shown in the inset in the lower right of the figure by solid and dashed lines respectively. Elevation differences between near-coincident LVIS footprints vs. latitude along data lines (d) 204 and (e) 419, and smoothed using a boxcar filter of width 0.01° (solid). (f) Distribution of elevation differences between near-coincident LVIS and GPS data along track 412 in the Summit area (solid) and at Kangerlussuaq airport (dashed). Locations of Summit, Jakobshavn and Kangerlussuaq are shown in the inset by letters S, J and a triangle respectively.

on the aircraft and the timing offsets between the various data inputs) were determined for each flight, and the laser footprint geolocated relative to the ITRF05 reference frame [*Hofton et al.*, 2000]. Laser ranges corresponded to the distance between specific reference points on the transmitted and returned waveforms, in this case the location of the peak of the lowest mode (pulse) defines the mean elevation of the lowest ice surface. In order to intercompare surface elevations collected at various times, the laser elevations were computed with the effects of earth tides removed. LVIS horizontal geolocation accuracy is typically <2 m [*Blair and Hofton*, 1999]. After quality checks, ~7.4 million waveforms were available for comparison. Missing data were caused predominantly by clouds and instrumentation issues due to extreme cold temperatures on the aircraft.

3. Lidar Data Precision and Accuracy

[6] To determine the precision of the ice sheet elevations measured using the LVIS, we compared the elevations of LVIS footprints whose centers were within 1 m of each other. The comparison involved data from two separate flight lines collected either ~1 hour apart (line 412) or ~24 hours (lines 204 and 419) apart; data from within the same line were not intercompared. Figure 1 shows the elevation differences of the near-coincident footprints along data lines 204, 419 and 412. The differences are normally-distributed (Figures 1a–1c) with mean differences of 0.00 m along lines 204 and 419, and 0.01 m along line 412, showing that on average no systematic errors remained in the measurement process. The standard deviations of the differences were 0.08 m, 0.11 m and 0.06 m along lines 204, 419 and 412 respectively.

[7] A closer inspection of the elevation differences along data lines 204 and 419 however reveals that although on average the elevation differences between coincident footprints were zero, they varied locally by up to ~0.05 m (Figures 1d–1e). If the surface is presumed not to have changed significantly in the 24 hours between LVIS observations, this variation must be related to error sources in the lidar data on one or both flight days. One possible source of the variation is inconsistent interpretation of the waveform, for example, a higher elevation mode in the waveform was misinterpreted as the ground. To eliminate any potential waveform interpretation errors we used a method dubbed "pulse correlation" (see *Hofton and Blair* [2002] for details) that uses waveforms in their entirety, rather than an interpreted proxy, to determine the relative vertical offsets of the laser-measured surfaces at their intersection points. Using this method, we investigated the shape similarity of each waveform pair (using Pearson correlation) whilst offsetting them vertically relative to each other. The offset at which each correlation was maximized indicated the precision of the measurements. The method has been used to assess the relative precision of coincident waveforms [*Blair and Hofton*, 1999] as well as relative vertical changes between epochs [*Hofton et al.*, 2006].

[8] Results for data lines 204, 419 and 412 showed the coincident waveforms were similar in shape and precisely geolocated relative to each other. The mean and median maximized Pearson correlations of the coincident waveform pairs were 0.996 and 0.997 for data line 204, 0.986 and 0.991 for data line 419 and 0.996 and 0.997 for data line 412. The distributions of the relative vertical offsets needed to maximize the correlations of each waveform pair are shown in Figures 1a–1c and are similar to those derived from comparing the coincident elevation data. The mean and standard deviation of the vertical offsets were 0.00 m and 0.07 m for data line 204, 0.00 m and 0.10 m for data line 419, and 0.01 m and 0.06 m for data line 412. Furthermore, along lines 204 and 419, the local variation in the data vertical offsets were similar in magnitude to the

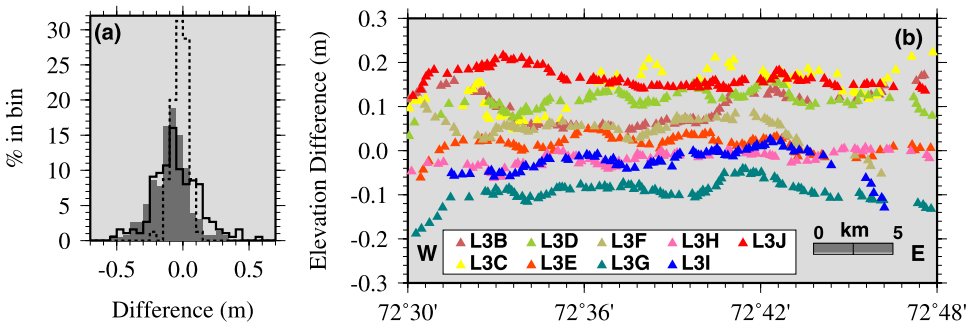

Figure 2. (a) Distribution of vertical offsets between LVIS and L3I ICESat geolocated waveforms (LVIS minus ICESat) along tracks 204 (solid), 419 (gray) and 412 (dashed). 189, 233 and 73 points were compared. (b) Vertical offsets between LVIS and ICESat geolocated waveforms along track 412 in the Summit area colored by ICESat observation. Offsets are smoothed using a boxcar filter of width 0.01°.

results involving the elevation data. These results suggest that any misinterpretation of the waveform data was not a significant cause of the observed along-transect elevation differences.

[9] Another possible source of the along-transect variation in the elevation differences is related to the precision of the airplane position on one or both flights, most likely related to inaccurate modeling of the tropospheric delay. Previous studies using trajectory data collected in Greenland showed that over a 17 day period the average elevation change introduced by troposphere modeling was small, but day-to-day mean elevation differences of up to 6.8 cm were possible [*Krabill et al.*, 2002]. Although the troposphere modeling approach implemented in this study is not identical to the one employed by *Krabill et al.* [2002], similar magnitude errors can not be ruled out in this comparison.

[10] The accuracy of the LVIS lidar elevation data was assessed by comparing with available in situ data, including data from a sled-based GPS survey of the ice surface in the Summit area on 18 September 2007 (R. Hawley, personal communication, 2007). These data were processed using GPS kinematic PPP techniques. The GPS measurement closest to the center of each LVIS footprint (within a 5 m search radius) was identified and the elevations compared, a total of 519 points. The differences are normally distributed (Figure 1f) with a mean difference of 0.03 m and a standard deviation of 0.06 m. Similar results were obtained when comparing the LVIS elevations to data from a kinematic, differential GPS survey of portions of the ramp and runway at Kangerlussuaq airport (E. Frederick, personal communication, 2007). Using a 1 m search radius, 552 comparison points were found. The differences are normally distributed (Figure 1f) with a standard deviation of 0.07 m. The mean elevation difference is not informative since the results of this comparison were used to calculate the system "ranging bias" for the mission.

4. Comparison to ICESat Data

[11] To investigate the relative accuracy of the LVIS and ICESat data, including the effects of the differences between sensor footprint sizes (25 m and 60 m) and laser pulse-widths (9 ns and 6 ns), vertically-georeferenced LVIS and ICESat waveforms whose footprint centers were within 2 m of each other were compared using the pulse correlation method. The use of this method eliminates any elevation offsets that may be introduced as a result of different waveform interpretation methods. For example, the standard LVIS elevation product uses the location of the peak of the lowest mode in the waveform, whereas the standard ICESat ice elevation product (GLA12) uses the location of the center of a gaussian fit to the largest-amplitude mode in the waveform, which is not necessarily the lowest reflecting surface. Portions of ICESat reference track corridors 204,

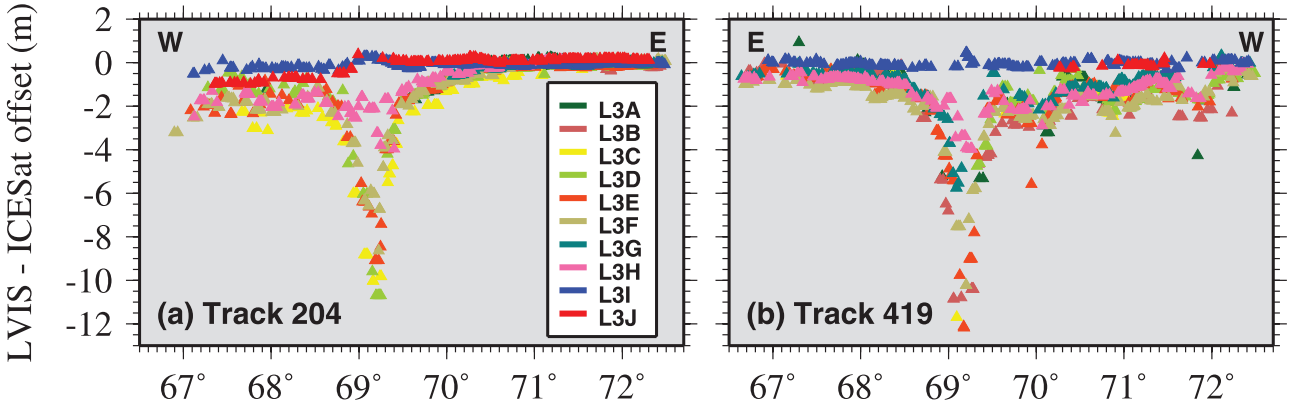

Figure 3. Same as Figure 2b, except along ICESat tracks (a) 204 (1462 footprints) and (b) 419 (1473 footprints). L3A, L3D, L3G and L3I are the 2004 to 2007 October–November observation periods. L3B, L3E, L3H and L3J are the 2005 to 2008 February–March observation periods. The latitudinal range shown is ~700 km.

Table 1. Summary of Vertical Offsets Between ICESAT and LVIS Data Along Track 412

ICESat ID	Date	Number of Points	Mean (m)	1σ (m)
L3B	3/23/05	71	0.08	0.06
L3C	6/22/05	70	0.10	0.13
L3D	11/23/05	86	0.10	0.07
L3E	3/23/06	87	0.00	0.06
L3F	6/26/06	78	0.05	0.06
L3G	11/26/07	96	−0.09	0.05
L3H	4/13/07	93	−0.02	0.06
L3I	11/4/07	80	−0.02	0.06
L3J	3/21/08	102	0.16	0.05

419 and 412 were overflown (Figure 1). Since the ICESat laser is consistently pointed to within ±150 m of the reference ground tracks, the LVIS data swath encompassed the majority of ICESat data within the mapped portions of the track corridors. Only ICESat waveforms from the Laser 3 campaigns were included in this comparison (Figures 2–3 and Table 1). Waveforms showing significant effects of saturation where the detector did not respond to the incoming photon flux in a linear manner were excluded. These were identified as waveforms with peak amplitudes greater than 230 counts. Detector saturation significantly degrades the precision of waveform analyses including correlation methods. Any effects of forward scattering, either on the ICESat or LVIS waveforms, were not considered in this comparison.

[12] To assess the relative accuracy of the LVIS and ICESat data and minimize any differences caused by actual changes to the ice surface, we compared LVIS waveforms to those from the ICESat campaign closest in time to the LVIS data collection (L3I). The distributions of the LVIS–ICESat vertical offsets are noisier than those from the LVIS–LVIS comparisons (Figure 2a). Along tracks 204, 419 and 412 the mean and standard deviation of the LVIS–ICESat vertical offsets were −0.09 m and 0.14 m, −0.04 m and 0.21 m, and −0.02 m and 0.06 m respectively. Although the ICESat and LVIS data were collected within a few weeks of each other (ICESat on 4 November 2007 (tracks 419 and 412) and 21 October 2007 (track 204); LVIS on 20 September 2007), it is possible that snowfall between the LVIS and ICESat observation epochs and surface changes at outlet glaciers along the coast influenced the results. The mean and median maximized correlations of the LVIS and ICESat waveforms were 0.987 and 0.989 (track 204), 0.985 and 0.988 (track 419), and 0.974 and 0.973 (track 412), indicating that despite differences in footprint size and laser pulsewidth between the sensors, the waveforms were similar in shape even along tracks 204 and 419 where areas of rough terrain exist.

[13] Comparison of LVIS to older ICESat data reveals information on changes in the elevation surface relative to that measured using LVIS in September 2007. Unlike for ICESat data, where across-track surface slopes must be estimated from multiple missions to allow change detection from repeat, but not precisely overlapping, ICESat tracks, LVIS and ICESat measurements can be directly compared and therefore could provide more accurate changes. In the Summit area, the ICESat and LVIS measured surfaces appear offset relative to each other and the offset is variable campaign to campaign (Figure 2b and Table 1). Possible reasons include seasonal and long term elevation changes in the Summit area as well as potential remaining systematic errors in the ICESat. The standard deviations of the ICESat and LVIS differences show good agreement of the LVIS and ICESat measured surfaces, with differences better than 0.07 m for all campaigns except L3C (Table 1). These results are similar to those obtained from comparisons of L2A data from low sloped areas (<0.6°) in Greenland (0.16–0.20 m [*Brenner et al.*, 2007]), and to recent comparisons of 8-day blocks of data over Antarctica (0.08–0.11 m per observation period), and suggest that 25 m footprint lidar measures a surface very similar to that measured by ICESat's lidar.

[14] Along tracks 204 and 419 there are significant vertical differences between the ICESat and LVIS measured surfaces (Figure 3). These are largest in a zone from ~68.5°N to 70°N (corresponding to the feeder zone of the Jakobshavn Glacier) and decrease in magnitude to the north along track 204 and to the south along track 419 (Figure 3). Within the Jakobshavn feeder zone, results show an overall decrease in the ice surface elevation since 2004 (Figure 3) with a maximum of ~12 m from October 2004 to September 2007. North of the Jakobshavn zone along track 419, ~−4 m of change occurred from October 2004 to September 2007 (Figure 3). Local variations are apparent, likely related to seasonal and regional changes at outlet glaciers along the west coast. Similar patterns of changes can be seen along track 204 south of the Jakobshavn zone where the track approached the western perimeter of the ice sheet. North of about 71°N on track 204, the ICESat and LVIS data agree well (Figure 3).

5. Discussion

[15] Results show that using 20–25 m-wide footprint waveform laser altimetry, we are able to precisely and accurately measure ice sheet elevations in Greenland and infer changes in the ice surface when compared to ICESat data (despite sensor parameters differences in footprint size and laser pulse width). These results have implications for the DESDynI multibeam lidar mission for measuring ice sheet elevation and elevation change. In Greenland, the LVIS lidar emulated the measurement parameters of the DESDynI lidar including its footprint size (25 m) and laser pulse width (9 ns). Our results thus demonstrate the potential precision and accuracy of the DESDynI lidar over ice sheets and the accuracy of the ice elevation change measurements that could be made between coincident DESDynI and ICESat footprints (although this study did not address the effect of horizontal geolocation errors on the accuracy of the elevation and elevation change measurements). Considering the data accuracy and precision demonstrated by LVIS using DESDynI-like measurement parameters, we believe DESDynI lidar could provide ice elevation measurements that complement data from ICESat and future ice altimetry missions.

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