Instruments and Methods

Laser profiling over Antarctic ice streams: methods and accuracy

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ABSTRACT. We assess the accuracy and precision of the U.S. National Science Foundation's Support Office for Aerogeophysical Research (SOAR) laser profiling system for mapping topography and detecting surface elevation changes of West Antarctic ice streams. The procedures used to process, calibrate and validate the laser, navigation and global positioning system (GPS) data are presented. The primary objective is to produce surface elevations with the best possible resolution. Repeat surveys of a grid of lines over Whillans Ice Stream and Ice Streams C and E were conducted in the 1997/98 and 1999/2000 seasons. The procedure has been calibrated using special test flights conducted over areas that have been surveyed with precise geodetic GPS equipment mounted on snowmobiles. After calibration, agreement between the two surfaces is ±10 cm rms. The accuracy and precision of the procedure have been evaluated at points where laser flight-lines cross over one another. The accuracy of the system is found to range from 0.09 to 0.22 m.

1. INTRODUCTION

Airborne laser altimetry is capable of solving many important problems in Antarctica. One issue is how ice thickness may be changing and affecting global sea level. Previous studies have shown laser altimetry to be a valuable tool in mapping and monitoring glacier elevation change in Alaska (Echelmeyer and others, 1996; Aðalgeirsdóttir and others, 1998), Greenland (Garvin and Williams, 1993; Krabill and others, 1995, 1999; Csatho and others, 1996; Christensen and others, 2000) and Antarctica (Spikes and others, 1999, 2003). Equipment that is suitable for precise surface elevation mapping is part of the U.S. National Science Foundation's (NSF) Support Office for Aerogeophysical Research (SOAR) facility. The development of a routine to turn raw laser altimeter data into measurements of the surface elevation of parts of the Antarctic ice sheet is the subject of the present contribution.

The purpose of this study was to determine the limit of unambiguous change detection that is possible using the SOAR laser, navigation and global positioning system (GPS). This paper describes the methods used during data collection, processing, calibration and validation as well as analysis of crossover results of precision airborne laser altimetry in Antarctica. The first flights were conducted during austral summer 1997/98. Repeat flights were flown during austral summer 1999/2000. Numerous flight-to-flight crosses have been compared with one another to assess repeatability. In addition, flights that covered areas that were also surveyed using snowmobile-mounted GPS receivers have been used to calibrate the laser system and assess its accuracy. Four West Antarctic ice streams were the focus of this study (Fig. 1): Ice Stream C (ISC), Ice Stream E (ISE), and the two tributaries (Whillans-1 and Whillans-2) that come together to form the Whillans Ice Stream (formerly known as Ice Stream B).

2. THE LASER ALTIMETER SYSTEM

2.1. Instrument platform

The laser altimetry system is part of the SOAR airborne geophysical suite installed in a ski-equipped Twin Otter aircraft (Bell and others, 1999; Blankenship and others, 2001). The geophysical-mapping systems on board the aircraft include a gravimeter, magnetometer, laser altimeter and ice-penetrating radar. Other equipment mounted on the aircraft includes a central processing unit, time code generator, three dual-frequency GPS receivers and an inertial navigation system (INS). During most of the surveys performed by SOAR, all sensors collected data simultaneously, providing direct measurements of ice surface elevation, internal layering of the ice, bedrock geometry and composition, and basal water conditions. However, only measurements from the laser-altimeter system, which includes the auxiliary components mentioned above, are presented here. The laser altimeter measurements are made while the aircraft flies along a predetermined flight path guided by real-time GPS.

2.2. Differential GPS positioning

The accuracy of differential GPS positioning is largely dependent upon the accuracy of the base-station positioning. This is an especially important consideration for this project,

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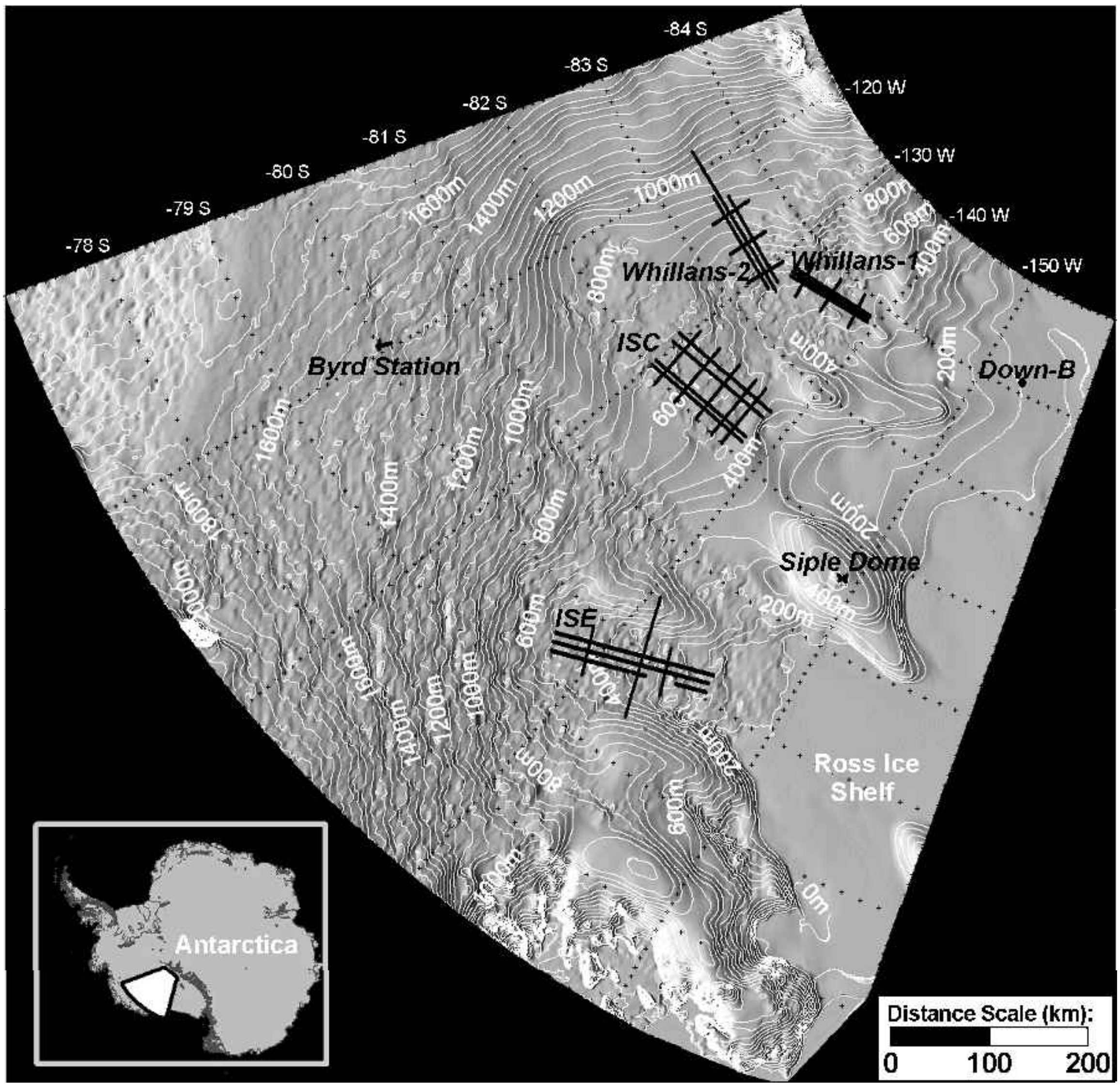

Fig. 1. Laser altimetry surveys in West Antarctica (black lines) superimposed on a shaded relief version of the RADARSAT-1 Antarctic Mapping Project (RAMP) 1 km digital elevation model (DEM) (Liu and others, 2000). RAMP DEM data provided by the Earth Observing System (EOS) Distributed Active Archive Center at the National Snow and Ice Data Center, University of Colorado, Boulder, CO.

because the base stations are located on a moving ice sheet. Several Ashtech Z-12 dual-frequency receivers located at different base camps were used as static base stations for laser altimetry flights. Because the base stations were moving, new positions had to be determined on a daily basis. Base-station GPS receivers collected data on each day that laser flights were conducted. SOAR provided the daily position of each base station, which was calculated using the automated GPS inferred positioning system (GIPSY) developed by the Jet Propulsion Laboratory (JPL) at the California Institute of Technology, Pasadena, CA. GIPSY reported a maximum root-mean-square (rms) error of 0.02 m for each position coordinate. Figure 2 illustrates the horizontal and vertical positions reported by GIPSY for all 24 hour surveys of one station. The daily positions are plotted and a fit is calculated to remove random positioning errors. The base-station position used for each survey flight is taken from the fitted line.

In 1997/98, base camps were at Siple Dome and Down-B. Byrd Station and Siple Dome were used in 1999/2000 (Fig. 1). The daily GIPSY positions were used to track the movement of each of the stations. Two of these base stations, Byrd Station and Siple Dome, are located on slow-moving (12.5 and 1.5 m a^{-1}, respectively) portions of the ice sheet. The Down-B base station is located near the middle of the fast-moving (>500 m a^{-1}) Whillans Ice Stream. Laser surveys last 3–7 hours, with an average flight time of approximately 4 hours. In 4 hours, the reference GPS receivers at Down-B, Byrd Station and Siple Dome moved horizontally about 0.23, 0.006 and 0.0007 m, respectively. Consequently, errors in GPS positioning due to ice movement are only expected for the five flights that originated at the Down-B base camp. For Down-B flights, small errors (<0.23 m) in horizontal aircraft positioning are expected, though there should be almost no effect on the vertical positioning.

Once the base-station position was established, the relative position of the Ashtech or TurboRogue receiver on the aircraft was calculated using the Trimble GPSurvey processing software. A variety of base/rover combinations were processed for each flight to insure that the best possible solution was obtained. This was most important when the aircraft departed from one base and landed at another. The best solutions were consistently obtained when the base station located at the origin of each flight was used.

Shi and Cannon (1995) show that the accuracy of differ-

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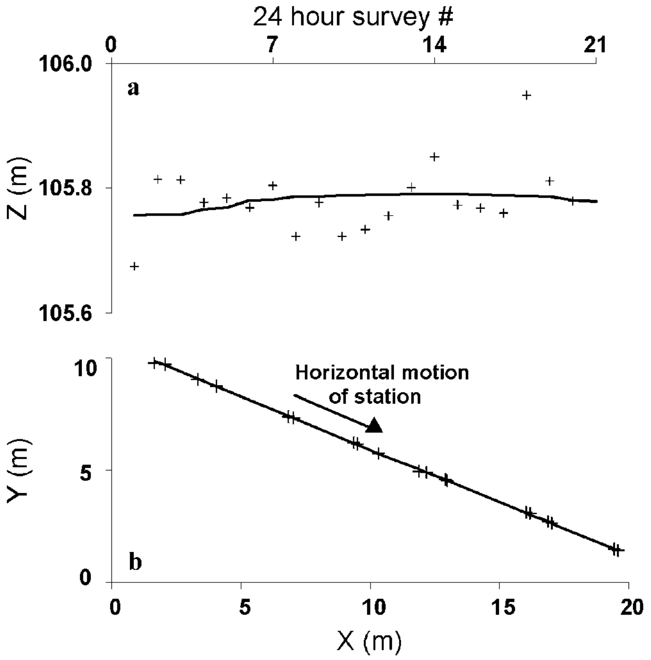

Fig. 2. Positions reported by GIPSY (crosses) for one 1997/98 base station set up at Down-B. (a) The distribution of vertical positions for each 24 hour survey. (b) The horizontal positions for each 24 hour survey. Coordinates are based on a polar stereographic projection with the same orientation as Figures 1, 8 and 9. SOAR provided the positions and calculated the fits (black line) that are drawn through the data points.

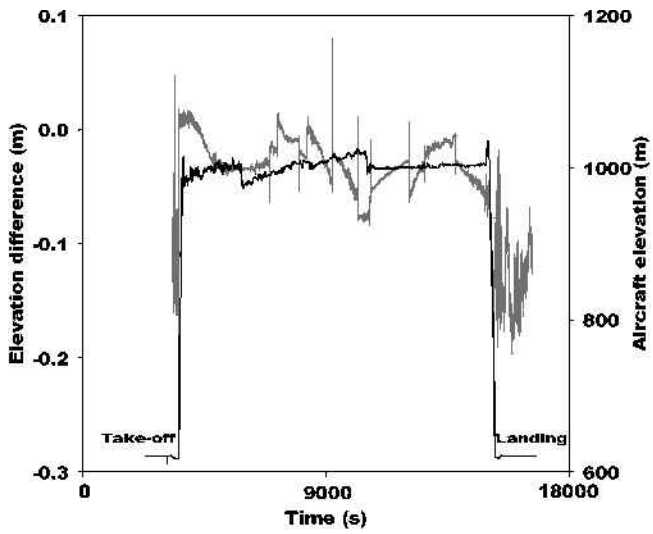

Fig. 3. Comparison of two GPS solutions for the same flight produced using different software, GPSurvey and GITAR (J. Sonntag, EG & G, NASA Wallops Flight Facility, VA). Black line is the elevation of the aircraft during the flight. Gray line is the elevation difference found when the GPSurvey solution is subtracted from the GITAR solution. The agreement is poorest during take-off and landing of the aircraft.

ential GPS positioning on a moving aircraft can be at the 0.1 m level if tropospheric, ionospheric, precise satellite orbits (ephemerides) and multipath corrections are used during differential, carrier phase post-processing. All of these corrections were applied with GPSurvey, which reported a maximum rms of 0.2 m for the 22 flights used during the two seasons. Flights with larger positioning errors were excluded from this analysis. Bell and others (1999) reported similar errors when using the Kinematic and Rapid Static (KARS) software to process SOAR GPS data.

To assess the performance of the GPSurvey processing, one 1997/98 survey was also processed with the National Aeronautics and Space Administration's (NASA) GPS Inferred Trajectories for Aircrafts and Rockets (unpublished GITAR program documentation by C. Martin in 1991). The two solutions agree well, having a maximum difference of 0.01 m in the horizontal and 0.2 m in the vertical (Fig. 3). Neglecting the take-off and landing portions of the flight, the maximum difference is 0.08 m in the vertical.

2.3. Acquiring laser ranges

The Azimuth LRY 500 is a diode pumped Nd:YAG (neodymium: yttrium aluminum garnet) pulsed laser transceiver, operating in the near-infrared domain (1064 nm). Pulsed lasers measure the travel time of a laser pulse from the laser firing point (LFP) to the surface and back to the receiver. To measure the time between the transmitted and the received pulses, the Azimuth LRY 500 rangefinder uses 50% constant fraction discrimination. The timer starts at some consistent point on each transmitted pulse. Each timing event ends when the return pulse strength reaches half of its maximum amplitude. Thus the need of a "range walk" correction is eliminated. The manufacturer reports a single-pulse accuracy of 0.1 m for distances up to 1.7 km. When the beam divergence is set for 4.5 μrad, it produces a footprint with 1.5 m diameter from the 300 m nominal flight altitude. The system is capable of 1000 pulses per second, but only 500 pulses are measured here to reduce the size of the data stream. To avoid measuring surface roughness and to further reduce the size of the data stream, 64 pulses were integrated 8 times per second (Blankenship and others, 2001). This results in one average elevation for every 1.5 m by 8 m area when the aircraft flies at 300 m terrain clearance.

2.4. Measuring aircraft attitude

The attitude of the aircraft, i.e. the heading, pitch and roll angles, determines the pointing direction of the laser. These angles are measured with a laser gyroscope that is part of the Litton Aero Products LTN-92 INS unit. The INS has a quoted accuracy of 0.05° in all three angles (Vaughn and others, 1996), which translates to a <0.06 m error in calculated surface elevations when the aircraft is flying at <300 m terrain clearance and the off-nadir pointing angles are $<15°$. These angles are not exceeded during survey missions, so the measured attitude contributes very little to the overall error of the procedure.

2.5. Solving timing issues

Each data-collecting system operates independently and not in synchrony with the others. Universal Time Coordinated (UTC) is used to reference the system collections. Laser and INS measurements are tagged with a counter time that is corrected to UTC using information provided by the GPS timecode generator. An additional correction is required for the individual attitude parameters, because the attitude angles measured by the INS are not instantaneously available on the local digital bus. The manufacturer specifies that these time lags are as follows: 110 ms in true heading, 60 ms in pitch

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and 50 ms in roll for the LTN-92 (Vaughn and others, 1996). To check whether these values are correct, pitch and roll maneuvers were conducted over a flat test field, because timing offsets cause deformation of the measured surface when off-nadir angles are large. This test yielded slightly different time lags of 60 ms in roll and 85 ms in pitch. The measured time lags are preferred over the reported ones. The final step in correlating the data streams is to interpolate the INS and GPS data for the times when laser ranges have been recorded. Interpolation is necessary because the GPS data are recorded at 2 Hz, while laser measurements are recorded at 500/64 Hz, and INS measurements at 8 Hz. Different interpolation schemes were tested and provided essentially the same results. Therefore a simple linear interpolation was used.

2.6. Computing the laser footprint position

The laser range recorded during the flight is a slant range to the surface. To compute the position of the laser footprint in a global, geographic coordinate system, the laser range, aircraft position and aircraft attitude are combined according to the scheme described in Lindenberger (1993), Vaughn and others (1996) and Hofton and others (2000). We developed FORTRAN computer programs to filter and combine the different data streams so that the position of the illuminated laser spot on the snow surface could be reliably determined. Figure 4 shows individual measurements from each instrument and the calculated ice surface elevation for one laser flight.

Equation (1) includes a series of coordinate transformations starting at a local reference system centered at the LFP (indicated by subscript L) and ending in the World Geodetic System 1984 (WGS84) Cartesian reference frame (indicated by subscript W). Rotations are indicated by **R**.

$$\vec{\mathbf{P}}_{\mathrm{W}}^{\mathrm{footprint}} = \vec{\mathbf{P}}_{\mathrm{W}}^{\mathrm{GPS}} + \mathbf{R}_{\mathrm{WGS}}\mathbf{R}_{\mathrm{INS}}\Delta\mathbf{R}_{\mathrm{INS}} \left[\vec{\mathbf{r}}_{\mathrm{A}}^{\mathrm{GPS,LFP}} + \Delta\mathbf{R}_{\mathrm{LS}}\left(\vec{\mathbf{r}}_{\mathrm{L}}^{\mathrm{LFP,S}} + \Delta\vec{\mathbf{r}}_{\mathrm{L}}^{\mathrm{LFP,S}}\right)^{-1}\right] \quad (1)$$

The laser ranger is mounted inside the aircraft pointing basically nadir. The ranger measures the distance between the LFP and the snow surface (S) from points along the flight trajectory ($\vec{\mathbf{r}}_{\mathrm{L}}^{\mathrm{LFP,S}}$). The laser range vector is first corrected for range bias ($\Delta\vec{\mathbf{r}}_{\mathrm{L}}^{\mathrm{LFP,S}}$) and then transformed into a local aircraft reference system (indicated subscript A) centered at the GPS antenna phase center. The transformation is carried out by rotating the laser range vector by the laser mounting bias ($\Delta\mathbf{R}_{\mathrm{LS}}$), which accounts for the misalignment between the laser and aircraft reference frames. The offset vector between the LFP and the GPS antenna is then added ($\vec{\mathbf{r}}_{\mathrm{A}}^{\mathrm{GPS,LFP}}$).

The next rotation uses the INS mounting biases ($\Delta\mathbf{R}_{\mathrm{INS}}$) to transform the laser vector from the local aircraft reference system into the local INS reference frame with axes defined by the roll, pitch and heading axes of the INS. The INS mounting biases account for the angular differences between the aircraft body system and the roll, pitch and yaw axes. This step can also account for the difference between local vertical and the direction perpendicular to the geodetic ellipsoid (WGS84).

The last rotation of this series transforms the laser vector from the INS reference frame to the local-level reference frame using the attitude of the aircraft ($\mathbf{R}_{\mathrm{INS}}$). The local-level reference frame is an Earth-tangential reference system centered at the GPS antenna. The z axis is perpendicular to the WGS84 ellipsoid and points downward. The

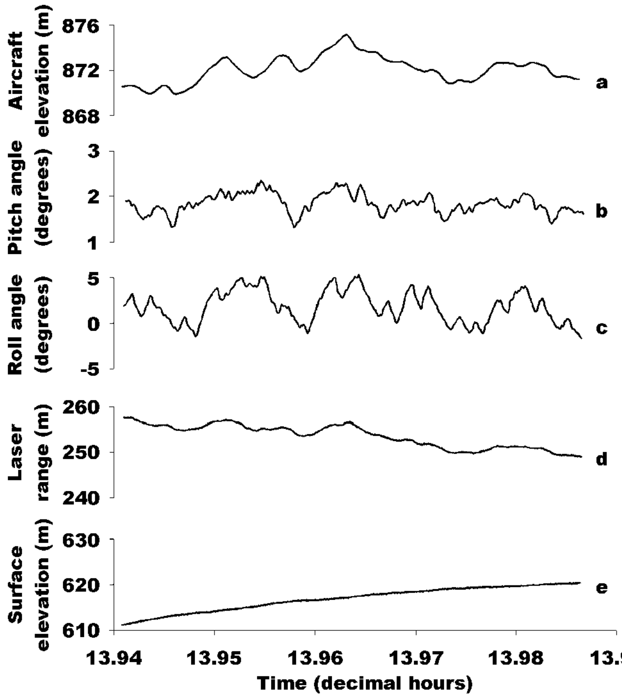

Fig. 4. Plots of the data recorded by each instrument for a laser survey over Siple Dome. (a) Aircraft elevation obtained with GPS. (b, c) Attitude of the aircraft recorded by the INS. (d) Range to the snow surface recorded by the laser altimeter. (e) Resulting elevation profile of the ice-sheet surface.

x axis lies along the intersection of the local GPS meridian and a plane parallel with the tangent plane to the ellipsoid (i.e. points north). The y axis completes the righthand reference system and is positive to the east.

Finally the expression of the laser vector from the GPS antenna to the laser spot on the snow surface is transformed into the WGS84 global Cartesian system. Rotations for the latitude and longitude of the aircraft are performed to align the local-level reference frame axes with the WGS84 axes. Latitude and longitude values are recorded by the GPS on board the aircraft. The position of the laser footprint is computed by adding the laser vector in the WGS84 system to the vector recorded by the GPS on board the aircraft ($\vec{\mathbf{P}}_{\mathrm{W}}^{\mathrm{GPS}}$).

3. CALIBRATING THE LASER SYSTEM

To compute the precise location of the laser footprint, the systematic biases of the laser system (range bias and laser/INS mounting bias) must be removed. For example, the laser ranger is not perfectly aligned with the aircraft's roll and pitch axes, as defined by the INS. Also, the roll and pitch axes defined by the INS do not run directly along the center line of the aircraft and along the wings. The offset vector between the LFP and the GPS antenna phase center should also be estimated. A combination of ground and in-flight calibration procedures are usually used for determining these parameters. This section describes the procedures applied for calibration of the system and summarizes the estimated parameters.

3.1. Ground calibration

The offset vector between the LFP and GPS antenna phase center was measured by traditional surveying methods using a theodolite and tape measure. Several symmetrical "hard"

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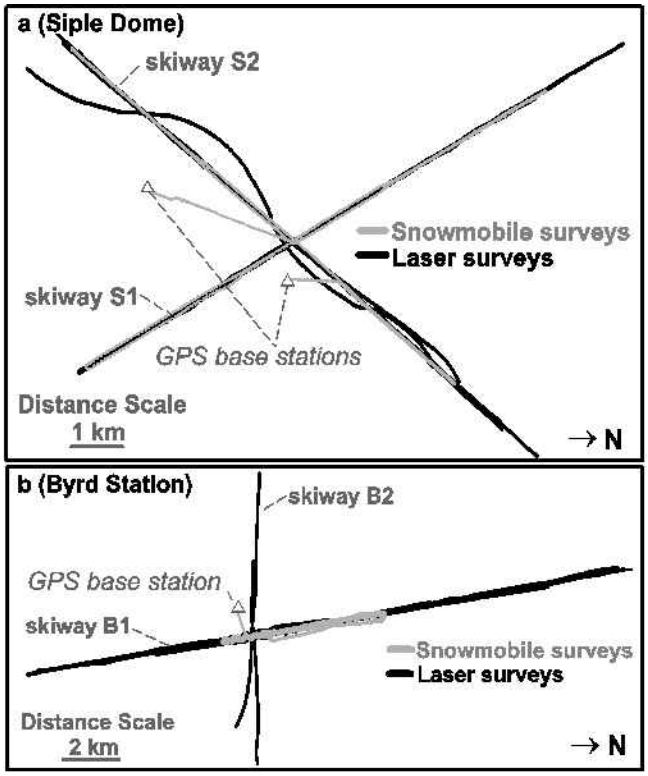

Fig. 5. Laser-altimetry calibration surveys and snowmobile GPS surveys at (a) Siple Dome in December 1997 and (b) Byrd Station in December 1999.

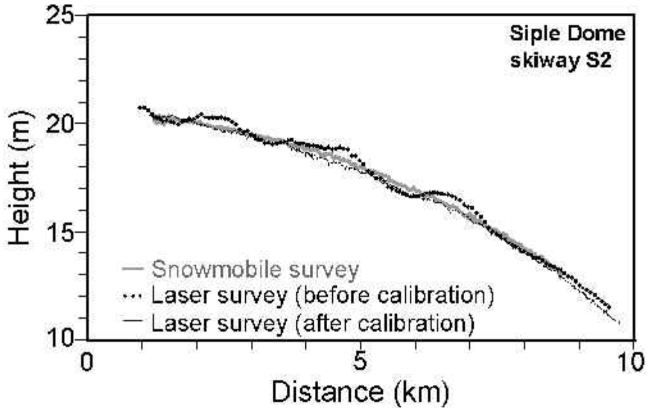

Fig. 6. Two laser profiles derived from the same survey along skiway S2 at Siple Dome before and after the removal of instrument range and mounting biases. Gray line is the reference snow surface derived from snowmobile-mounted GPS surveys.

points on the aircraft (joists, flap indicators and seats) were used to define the aircraft reference system. One axis runs the length of the aircraft between symmetric points. A second axis is perpendicular to the first axis and is aligned with the aircraft wings. The third axis is vertical and perpendicular to the other two. The offset vector of [−1.378 m, 0.411 m, 1.696 m] was measured in 1996. The alignments of the INS and laser ranger were measured by electronic level to estimate the instrument mounting biases. Since the angular measurements over short distance can result in large errors, these mounting bias estimates have been refined by in-flight calibration.

3.2. In-flight calibration

Previously used calibration techniques require surveys of large, smooth, flat surfaces (e.g. lakes, ocean, runways) to resolve the misalignment between the INS and the laser (e.g. Krabill and others, 1995; Hofton and others, 2000). Since flat, horizontal surfaces are not found in the interior of the West Antarctic ice sheet (WAIS) a new calibration algorithm has been developed, which facilitates calibration over arbitrary, natural surfaces (Filin and Csathó, 2002). The core of the procedure is an analytical approach that combines Equation (1) with an analytical approximation of the surface. The calibration parameters are determined by least-squares adjustment.

To calibrate the system, skiways next to the Siple Dome and Byrd Station base camps were surveyed using both snowmobile-mounted GPS and laser altimetry (Fig. 5). For a more convenient analysis of the results, the data were converted into a local coordinate system. Conversion to a local frame consists of a constant translation of the origin, usually into a surveyed point within the site. In this case, the antenna phase center of the base-station GPS is used. The x axis of the local system points to true north, the z axis points toward the center of the Earth, and the y axis completes a righthand reference system.

Analysis of the recoverability of the systematic errors shows that not all systematic errors can be recovered for a nadir-looking, laser profiling system (Filin, 2001). The effect of a heading bias is absorbed in the pitch and roll biases, and the INS and laser mounting biases cannot be separated. Therefore we combine the INS and laser mounting biases into laser-system pitch and roll mounting biases. The recovered biases also include the range bias of the laser. Pitch and roll maneuvers were performed over the calibration site to obtain a more robust solution for the mounting biases.

The difference between the ice-sheet surface reconstructed from non-calibrated and calibrated laser data and the reference surface at Byrd Station is shown in Figure 6. After the system calibration the mean of the residual is zero and its standard deviation is 0.06 m. The estimated instrument biases are −1.6° pitch, −0.1° roll and 0.12 m in range during the 1997/98 field season and −1.9° pitch, −0.2° roll and 0.6 m in range for the 1999/2000 season. In both seasons, the pitch and roll mounting biases determined by in-flight calibration agree well with the combined laser and INS mounting biases measured on the ground. The large range bias in the second season might be caused by problems related to the saturation of the return signal. Changes in atmospheric conditions such as temperature and humidity could also contribute to this error, because they affect the speed and refraction of light, which reduces measured laser ranges through the atmosphere (Marini and Murray, 1973). Some users of airborne laser altimetry use an atmospheric correction, based on the measured temperature and humidity at the LFP and at the target (Vaughn and others, 1996; Ridgway and others, 1997). In Antarctica, however, there are too few meteorological stations located on the ice surface to effectively utilize this technique. Instead, any effects that the atmosphere may have on the laser range are considered in the range bias along with other possible range errors. Once determined, the range bias is assumed to be unchanging throughout a season and is added to each range measurement from that season.

3.3. Testing calibration values

After correction of range and angular biases, the SOAR

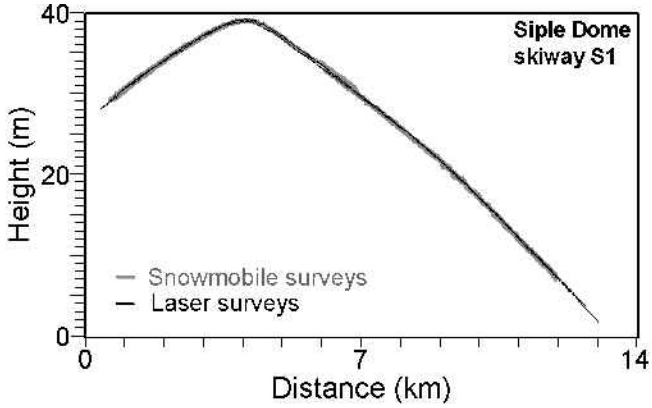

Fig. 7. Surfaces derived from repeat laser altimetry (black lines) and snowmobile-mounted GPS (grey lines) along skiway S1 at Siple Dome.

system performed well over short distances (~10 km) from the base stations at Siple Dome. Repeat flights over Siple Dome's skiway S1 show a 2.8 cm bias with a rms of 10.3 cm. The bias is attributed to surface slope, because the repeat flight-lines were usually about 25 m apart. The rms difference may be a true measurement of surface roughness caused by sastrugi. Sub-decimeter accuracy was also found when laser-derived elevations were compared to elevations measured with the snowmobile surveys (Fig. 7).

4. CROSSOVER ANALYSIS

Laser surveys that cross nearly perpendicularly to one another are evaluated to determine the repeatability of the procedure over long baselines. Crosses are evaluated by comparing laser measurements within a 10 m radius of the crossover point (Fig. 8). The crossover point is the average of three to four measurements from each survey transect, as shown by the black and white crosses in Figure 8. An error

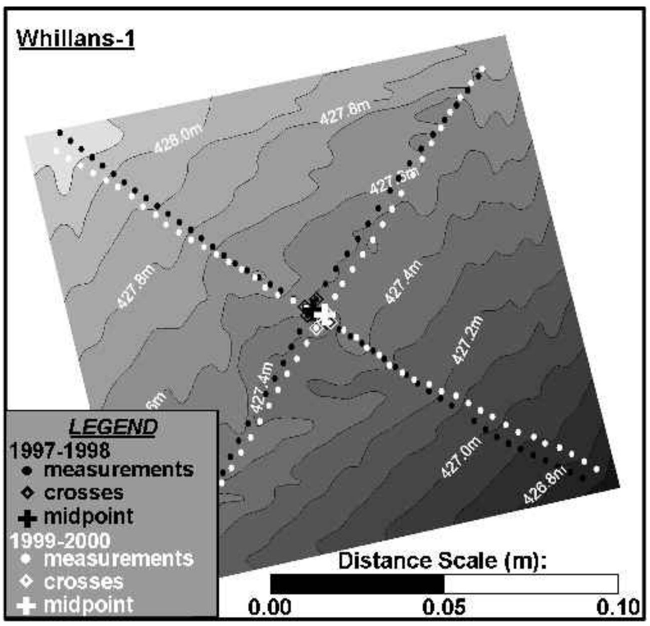

Fig. 8. Laser measurements around calculated crossover points at crossover No. 8 on Whillans-1 (see Fig. 10 for location of this crossover). Only the laser measurements within 10 m of the approximated crossover point are used for comparison. Contours created using laser measurements from 1999/2000 surveys.

Table 1. Crossover results for all ice streams

Crossover No.	*rms error* 1997/98 m	1999/2000 m	*Crossover occurrence*	*rms error by occurrence* m
Whillans-1				
1	0.24^{i}	0.07^{s}	All flights	0.08
2	0.13^{s}	0.06^{i}	$^{(s)}$Same flight	0.07
3	0.06^{s}	0.06^{i}	$^{(i)}$Independent flight	0.09
4	0.07^{i}	0.11^{s}		
5	0.02^{s}	0.04^{i}		
6	0.07^{s}	0.17^{i}		
7	0.08^{i}	0.08^{s}		
8	0.02^{s}	0.05^{i}		
9	0.06^{s}	0.05^{i}		
Whillans-2				
1	–	0.14^{i}	All flights	0.20
2	0.34^{i}	0.16^{i}	$^{(s)}$Same flight	0.17
3	0.12^{s}	0.16^{s}	$^{(i)}$Independent flight	0.22
4	–	0.21^{i}		
5	0.24^{s}	0.14^{s}		
6	0.18^{i}	0.14^{i}		
7	–	0.32^{s}		
8	0.31^{i}	0.28^{i}		
9	0.06^{s}	0.19^{i}		
ISC				
1	0.26^{i}	0.10^{i}	All flights	0.10
2	–	0.03^{i}	$^{(s)}$Same flight	0.08
3	0.12^{i}	0.03^{i}	$^{(i)}$Independent flight	0.11
4	–	0.07^{i}		
5	0.04^{s}	–		
6	0.16^{i}	0.07^{i}		
7	–	0.08^{i}		
8	0.19^{i}	0.04^{i}		
9	–	0.04^{i}		
10	0.02^{s}	–		
11	–	0.11^{s}		
12	–	0.08^{s}		
13	–	0.4^{i}		
14	–	0.06^{i}		
15	–	–		
16	0.13^{s}	0.06^{i}		
17	–	0.05^{i}		
18	0.17^{i}	0.04^{i}		
19	–	0.04^{i}		
20	0.12^{i}	–		
ISE				
1	–	0.28^{i}	All flights	0.28*
2	–	0.06^{i}	$^{(s)}$Same flight	0.35*
3	–	0.12^{s}	$^{(i)}$Independent flight	0.21*
4	22.22^{i}	0.73^{s}		
5	–	0.21^{s}		
6	–	0.30^{i}		
7	11.97^{s}	–		
8	–	–		
9	–	–		

* 1997/98 data not included.

for each crossover is calculated using the elevation difference of individual measurements from the mean. The results from crossover analysis for each ice stream are shown in Table 1. In most cases, the crossover errors are < 0.32 m (Fig. 9), though GPS solutions were very poor (up to 80 m errors) for the 1997/98 ISE surveys. This resulted in the large crossover errors shown in Table 1, and therefore these data are not used for further analysis. All crossover locations are presented in Figure 10.

The agreement between surveys conducted during the same flight (indicated by superscript s in Table 1) is a measure

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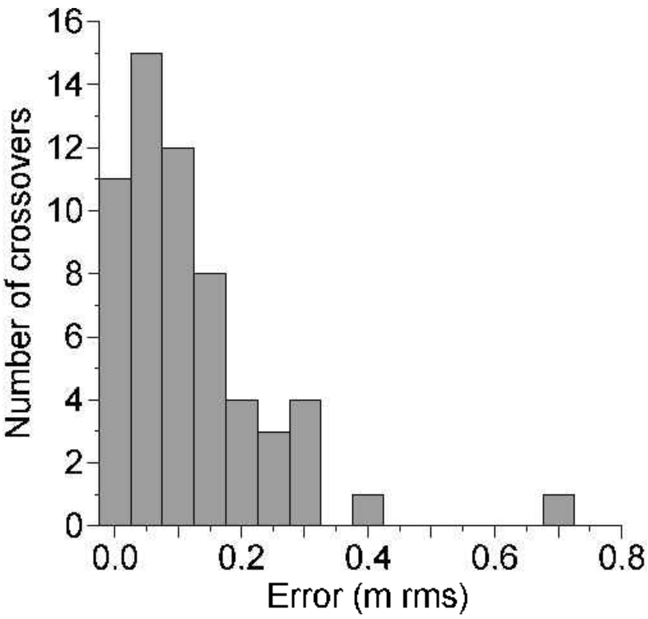

Fig. 9. Bar graph illustrates the range of errors for all crossovers. 1997/98 ISE data are not included in this graph.

of the precision of the laser altimetry system, and it indicates if the GPS solution remained fixed for the entire flight. Table 1 also shows how elevations compare if crossing laser surveys occurred during independent flights (superscript i). A GPS phase length is approximately 23 cm, so a rms error on the order of 23 cm indicates that the phase integers were not fixed for the entire flight. This appears to have occurred on at least one flight each season on Whillans-2 and ISE, as indicated by the errors in Table 1. Minimal errors of 0.07 and 0.08 m on Whillans-1 and ISC, respectively, indicate that it is possible to improve on the expected 0.10 m errors associated with GPS positioning of a moving aircraft (Shi and Cannon, 1995).

The agreement between surveys conducted during independent flights is a measure of the accuracy of the laser altimeter system. Table 1 shows that the accuracy of this procedure is generally in the range 0.09–0.22 m (excludes data from 1997/98 ISE). This is similar to the 0.09–0.37 m accuracy range reported by Blankenship and others (2001) who used the same SOAR system and an independent processing scheme.

5. IMPROVED MAPS OF ICE STREAMS

The topographic maps in Figure 10 were produced after combining laser-altimetry data with the RAMP DEM (Liu and others, 2000). The DEM is used to fill in the gaps between laser survey lines and outside of the laser survey grids. The accuracy of the contours in Figure 10 changes with distance from the laser surveys. Near laser survey lines, contours are influenced mostly by laser data and are accurate to better than ±0.22 m in most cases (Table 1). Away from the laser

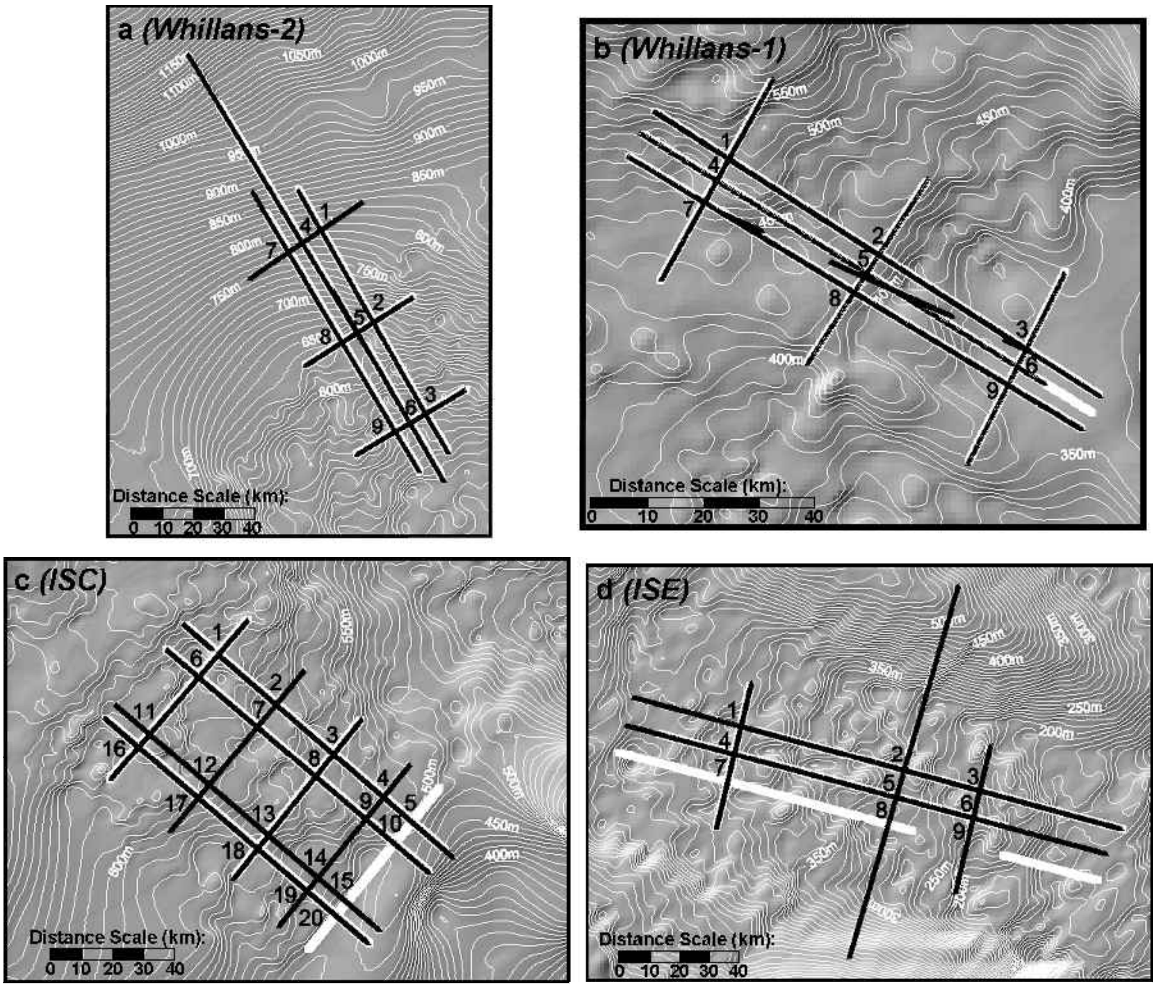

Fig. 10. 1997/98 (white lines) and 1999/2000 (black lines) laser surveys covering Whillans-2 (a), Whillans-1 (b), ISC (c) and ISE (d). Crossover points are numbered according to Table 1. Laser-altimeter surveys are superimposed on a shaded relief version of the RAMP DEM (Liu and others, 2000).

surveys, contours are created solely from the DEM and therefore subject to the ±10 m errors associated with that dataset (Liu and others, 2000). Laser-derived elevations typically differ from the DEM by 5–10 m. This is partly a signal of the errors in the DEM, but because the two datasets were not taken concurrently, some of the difference may be attributed to changes in surface elevations with time.

6. CONCLUSIONS

A technique for processing SOAR laser-altimetry data has been presented. The procedure includes a scheme for processing differential GPS data used to precisely geolocate the position of the aircraft. Methods used to combine the GPS, INS and laser range data to produce the three-dimensional location of the illuminated laser spot on the snow surface are also presented.

Skiways at Siple Dome and Byrd Station in West Antarctica were used as calibration and validation sites for the current study. The skiways were mapped with GPS mounted on a snowmobile to produce a reliable surface for comparison. The same skiways were also surveyed repeatedly with laser altimetry. By comparing the surfaces, a laser range bias and instrument mounting biases were quantified and included in the processing scheme.

Validation of the procedure over long distances was evaluated at crossover points. Large uncertainties were expected to come from the GPS solutions because orbiting GPS satellites are visible from Antarctica only at low angles, making it difficult to resolve errors in the vertical. GPS proved to be more robust than expected when a rigorous data-processing scheme was applied. Use of the carefully determined calibration values also greatly reduced errors. The accuracy of the system is shown to be in the range 0.09–0.22 m, based on the error of laser-derived elevations at crossover points.

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REFERENCES

Aðalgeirsdóttir, G., K. A. Echelmeyer and W. D. Harrison. 1998. Elevation and volume changes on the Harding Icefield, Alaska. *J. Glaciol.*, **44**(148), 570–582.

Bell, R., V. Childers, R. Arko, D. Blankenship and J. Brozena. 1999. Airborne gravity and precise positioning for geologic applications. *J. Geophys. Res.*, **104**(B7), 15,281–15,292.

Blankenship, D. D. *and 9 others*. 2001. Geologic controls on the initiation of rapid basal motion for West Antarctic ice streams: a geophysical perspective including new airborne radar sounding and laser altimetry results. *In* Alley, R. B. and R. A. Bindschadler, *eds. The West Antarctic ice sheet: behavior and environment*. Washington, DC, American Geophysical Union, 105–121. (Antarctic Research Series 77.)

Christensen, E. L., N. Reeh, R. Forsberg, J. H. Jörgensen, N. Skou and K. Woelders. 2000. A low-cost glacier-mapping system. *J. Glaciol.*, **46**(154), 531–537.

Csathó, B., T. Schenk, R. Thomas and W. Krabill. 1996. Remote sensing of polar regions using laser altimetry. *Int. Arch. Photogramm. Remote Sensing*, **31**(B1), 42–47.

Echelmeyer, K. A. *and 8 others*. 1996. Airborne surface profiling of glaciers: a case-study in Alaska. *J. Glaciol.*, **42**(142), 538–547.

Filin, S. 2001. Calibration of airborne and spaceborne laser altimeters using natural surfaces. (Ph.D. thesis, Ohio State University.)

Filin, S. and B. Csathó. 2002. Improvement of elevation accuracy for mass-balance monitoring using in-flight laser calibration. *Ann. Glaciol.*, **34**, 330–334.

Garvin, J. B. and R. S. Williams, Jr. 1993. Geodetic airborne laser altimetry of Breiðamerkurjökull and Skeiðarárjökull, Iceland, and Jakobshavns Isbræ, West Greenland. *Ann. Glaciol.*, **17**, 379–385.

Hofton, M. *and 6 others*. 2000. An airborne laser altimetry survey of Long Valley, California. *Int. J. Remote Sensing*, **21**(12), 2413–2437.

Krabill, W. B., R. H. Thomas, C. F. Martin, R. N. Swift and E. B. Frederick. 1995. Accuracy of airborne laser altimetry over the Greenland ice sheet. *Int. J. Remote Sensing*, **16**(7), 1211–1222.

Krabill, W. *and 8 others*. 1999. Rapid thinning of parts of the southern Greenland ice sheet. *Science*, **283**(5407), 1522–1524.

Lindenberger, J. 1993. Laser-Profilmessungen zur topographischen Geländeaufnahme. (Ph.D. thesis, Universität Stuttgart. Verlag der Bayerischen Akademie der Wissenschaften.)

Liu, H., K. C. Jezek and B. Li. 2000. *RADARSAT Antarctic Mapping Project digital elevation model*. Boulder, CO, National Snow and Ice Data Center. (Data available by FTP.)

Marini, J. and C. Murray. 1973. Correction of laser range tracking data for atmospheric refraction at elevation angles above 10°. *U.S. Nat. Aeron. Space Admin. Tech. Rep.* X-591-73-351.

Ridgway, J. R., J. B. Minster, N. Williams, J. L. Bufton and W. B. Krabill. 1997. Airborne laser altimetry survey of Long Valley, California. *Int. J. Geophys.*, **131**(21), 267–280.

Shi, J. and M. Cannon. 1995. Critical error effects and analysis in airborne DGPS positioning over large areas. *Manuscr. Geod.* 69, 261–273.

Spikes, B., B. Csathó and I. Whillans. 1999. Airborne laser profiling of Antarctic ice streams for change detection. *Int. Arch. Photogramm. Remote Sensing*, **32**(3-W14), 169–175.

Spikes, V. B., B. M. Csathó, G. S. Hamilton and I. M. Whillans. 2003. Thickness changes on Whillans Ice Stream and Ice Stream C, West Antarctica, derived from laser altimeter measurements. *J. Glaciol.*, **49**(165), 223–230.

Vaughn, C. R., J. L. Bufton, W. B. Krabill and D. L. Rabine. 1996. Georeferencing of airborne laser altimeter measurements. *Int. J. Remote Sensing*, **17**(11), 2185–2200.

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