Initial Results of Data Collected by the APL D2P Radar Altimeter Over Land and Sea Ice

Carl J. Leuschen and R. Keith Raney

Measuring changes in the cryosphere from satellite-based altimeters has and will continue to provide data that are essential to our understanding of the long-term trends of the Earth's ice cover. Over the past years, APL has played a major role in airborne field activities observing continental ice sheets, outlet glaciers, and sea ice using the delay-Doppler Phase-monopulse (D2P) airborne radar altimeter, designed and built by staff at APL as part of the NASA Instrument Incubator Program. The D2P altimeter has been deployed during field campaigns in both the Arctic (2002 and 2003) and Antarctic (2003 and 2004). During these airborne deployments, radar data were collected along with simultaneous and coincidental laser altimeter measurements. The resulting comparisons show that the two altimeters respond quite differently to the various cryospheric geologies. This article briefly reviews the D2P system and compares radar and laser altimeter data selected from the campaigns.

INTRODUCTION

Over the last decade, the mean sea level has been increasing at an appreciable rate (≈1.8 mm/year).[1] A major source of this rise, other than thermal expansion, is thought to be contributions from the Earth's melting land ice cover. Measurements of the current ice mass and rate of change of the Earth's ice inventory are essential data for predicting climate trends and helping to guide policies aimed at mitigating environmental changes.

Ice sheets and glaciers—mainly those on Antarctica and Greenland—constitute more than 75% of the Earth's total freshwater supply.[2] Their ice cover holds enough water to raise the oceans by ≈80 m.[3] Even a small rise in sea level could have significant effects on human habitation in coastal areas. Substantial increases in fresh water from melting ice sheets are predicted to upset major ocean circulation patterns (e.g., the thermohaline polar–equatorial currents), and declining sea ice coverage facilitates energy loss from the ocean into the atmosphere. Either of these variations would impose major changes on the global climate. Clearly, observing and subsequently understanding trends in land or sea ice cover is of critical long-term importance.

Among the several sensors used to monitor the Earth's cryosphere, airborne- and satellite-based laser

and radar altimeters have played and will continue to play important roles. Measurements made from laser altimeters have exposed regions near the southern coast of Greenland that are experiencing elevation changes exceeding –100 cm/year.[4] Radar altimeter measurements from European Remote Sensing satellites (ERS 1 and 2) showed that the elevation of Antarctica's interior decreased by approximately 0.9 cm/year from 1992 to 1996.[1] The Geoscience Laser Altimeter System (GLAS) aboard the Ice, Cloud, and land Elevation satellite (ICESat), at 1064- and 532-nm optical wavelengths, is currently providing detailed surface elevation data over the ice sheets to enable precise monitoring.[5] The CryoSat mission (part of the European Space Agency's Living Planet Programme), whose payload is the Ku-band (2-cm wavelength) Synthetic Aperture Radar (SAR)/Interferometric Radar Altimeter (SIRAL), was the first of the Earth Explorer Opportunity missions.[6] The objective of CryoSat's 3-year mission was to measure changes in the Earth's inventory of land and sea ice. (The mission experienced a launch failure on 8 October 2005. A replacement mission is being considered.)

OVERVIEW

Ice sheets change slowly, even in response to marked increases in climatic temperature, so an accurate, reliable estimation of the rate of change of ice sheet height requires a measurement record that spans many years. Therefore, the measurement record must be much longer than the length of time during which any one observation platform can reasonably be expected to continue operation. Conventional radar altimeters have been collecting data for more than 25 years. Recent lasers such as GLAS on ICESat eliminate surface-slope–induced errors over continental ice sheets by providing beam-limited measurements. In addition, improved radar altimeters such as the SIRAL on CryoSat are continuing to be developed to focus on the cryosphere. Both laser and radar altimeters offer their own specific benefits in terms of measurement accuracy, resolution, coverage, and lifespan.

Comparisons between the measurements of these two instruments (laser and radar altimeters) are essential for preserving the continuity of altimetry data over snow and ice and also for providing the opportunity to extract additional data products through the combination of those measurements. To make these comparisons, two fundamental questions arise: to what extent, and under what conditions, might ice sheet height measurements from radars and lasers be expected to be comparable? APL has played a major role in early experiments to address these questions.

A radar altimeter's response over ice is not always well understood, especially when there may be snow cover in the measurement footprint. Electromagnetic penetration of dry, cold snow is significant at radar frequencies.[7,8]

More importantly, it is not yet fully understood what aspects of a radar waveform (which responds primarily to interfaces of large dielectric contrast, such as the top of the ice) may be compared to heights measured by a laser (which responds primarily to the upper optical surface at the top of the snow). If snow and ice conditions are well known, then the respective laser- and radar-reflected waveforms can be modeled. The inverse problem is far more difficult: given a radar-reflected waveform, what can be learned about surface conditions? One way to explore this issue is to study data collected by co-located laser and radar altimeters that operate simultaneously. Whereas that would be impractical from space, simultaneous laser and radar altimetry may be collected over a variety of surfaces from an airborne system.

THE D2P INSTRUMENT

In anticipation of CryoSat, which would have been the first implementation of a D2P-class altimeter in space, an airborne proof-of-concept instrument was designed and built by APL. The D2P radar altimeter is a coherent, interferometric Ku-band system.[9] In December 1998, staff at APL began the project, funded under NASA's Instrument Incubator Program, to build this instrument. The D2P development project lasted for 3 years and included a series of flight tests over southern Greenland in June 2000.

Conventional radar altimeters are considered "pulse-limited" instruments and, as opposed to their "beam-limited" laser altimeter counterparts, have footprints whose location and size are determined by the surface slope and system resolution, respectively. Simply put, a conventional radar altimeter "sees" the closest reflective surface. Over land ice, the closest surface may not be directly below the altimeter, which imposes an error on the altimeter's height measurement. SIRAL and D2P share system design features that overcome this fundamental limitation.

As shown in Fig. 1a, when the measurement location is assumed to be at nadir over sloped terrain, the radar altimeter height estimate will be incorrect in both value and geophysical location. This error is significant even over ice sheets whose mean slopes are as small as 1° or less. To mitigate slope-induced measurement errors in the across-track direction, the D2P (and SIRAL) design uses two receive channels with their respective antennas separated in the across-track direction by a baseline b, as shown in Fig. 1b. When the two receive channels are combined interferometrically, the phase difference is invertible to estimate across-track surface slope.[10,11] In the along-track direction, slope-induced errors are mitigated by collecting data at a sufficiently high pulse repetition frequency to synthesize a set of beam-limited measurements using the delay-Doppler method,[12,13] as shown in Fig. 2. The delay-Doppler method has been shown to reduce range errors caused by along-track
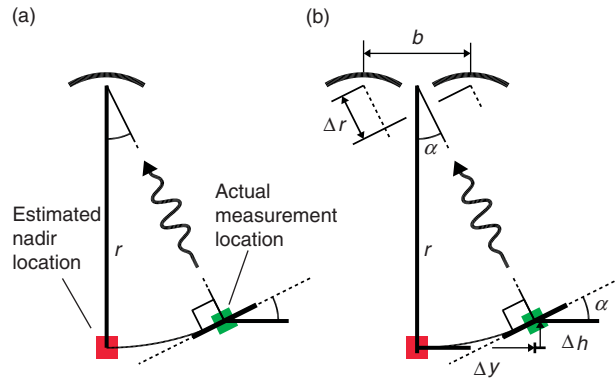
Figure 1. Radar altimeter geometry in the across-track plane. (a) The measurement occurs at a location normal to the surface. When the surface is sloped and the measurement is assumed at nadir, the height estimate will be incorrect. (b) By using two receive channels, with the antennas separated by a baseline, the angle can be determined from the range (phase) difference between the two channels.
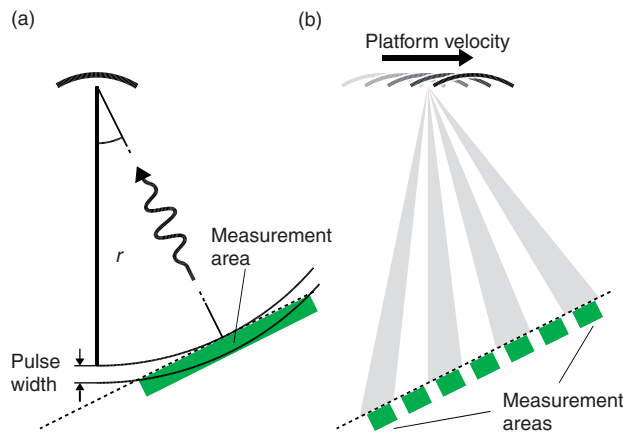

Figure 2. Radar altimeter geometry in the along-track plane. (a) The measurement area of a conventional radar altimeter is pulse limited. (b) Through Doppler processing, a set of synthesized narrow antenna beams is formed to provide beam-limited measurements, which correct the errors in height estimates over a sloped surface.

surface slopes, improve along-track resolution, and provide additional processing gain that in turn reduces measurement error (and lowers transmit power requirements). Since the synthesized measurements are beam limited, the surface slope can be estimated from the peak Doppler bin. Together, these across- and along-track improvements increase surface height measurement accuracy and minimize geophysical location errors that sloping ice sheets induce on measurements from conventional pulse-limited radar altimeters.

The D2P radar system in effect is an airborne prototype for the SIRAL altimeter aboard CryoSat.[14] Both operate at Ku-band, have similar bandwidths, include two receive channels, and produce coherent data that may later be processed by the delay-Doppler algorithm. Table 1 lists the significant parameters and compares the D2P and SIRAL systems. Recognizing these similarities,

the European Space Agency (ESA) co-sponsored the D2P altimeter to participate in several prelaunch CryoSat calibration and validation field activities.[15,16]

The D2P altimeter was designed to accommodate both low and high altitudes, as noted in the table. The 0.2-km minimum altitude has proven to be very useful for simultaneous operation with airborne laser altimeters, which typically must be no more than ≈0.5 km above the surface.

FIELD ACTIVITIES

Arctic

In May 2002, the D2P radar altimeter was flown aboard the NASA P-3 airplane along with the Airborne Topographic Mapper (ATM) laser altimeters in an experiment co-funded by NASA and ESA to collect simultaneous laser and radar altimeter (the LaRA project) measurements over land and sea ice.[15] The principal objective of that experiment was to provide insight into the differences between the estimated height values extracted from coincidental laser (optical) and radar (RF) measurements over various ice and snow surface conditions. The respective height measurements of the two instruments were cross-calibrated to a few centimeters using runway overflights at the NASA Wallops Flight Facility. Primarily because of the tight calibration, the remaining differences in the measured surface heights were attributed to the specific cryospheric characteristics of the scene, such as the loss factors influencing optical or microwave penetration into the snow and ice. Figure 3 shows the radar system and its installation on the NASA P-3 during the LaRA campaign. The upper image shows the aircraft parked in a hanger at Thule, Greenland. The lower left inset is

Table 1. D2P and SIRAL comparison.

Parameter	D2P	SIRAL
Operating frequency (GHz)	13.900	13.575
System bandwidth (MHz)	360	320
Pulse waveform	Linear FM	Linear FM
Pulse length (μm)	0.3–3.0	51.0
Pulse repetition frequency (kHz)	1.00–1.75	1.97–17.80
Range resolution (m)	0.42	0.47
Peak power output (W)	5	25
Antenna (deg)		
Along-track	4.0	1.0
Across-track	8.0	1.2
Antenna baseline (m)	0.15	1.20
Operational altitudes (km)	0.2–10.0	720.0
Platform velocity (km/s)	0.15	7.00

Figure 3. D2P installation on the NASA P-3 aircraft: (clockwise from top) aircraft, D2P equipment racks, and bomb bay–mounted antenna.

an enlarged view of the instrument bay where the D2P antenna can be seen in the forward starboard portion. The lower right inset shows the two D2P equipment racks installed side by side inside the aircraft.

The field geometry is illustrated in Fig. 4. The laser and radar collected both coincidental and simultaneous measurements. Depending on the aircraft altitude, the D2P footprint ranged from 5 to 20 m in the along track and 30 to 100 m in the across track, while the conical scanning laser swath sufficiently covered the entire D2P footprint with many laser shots of an approximately 1-m radius.
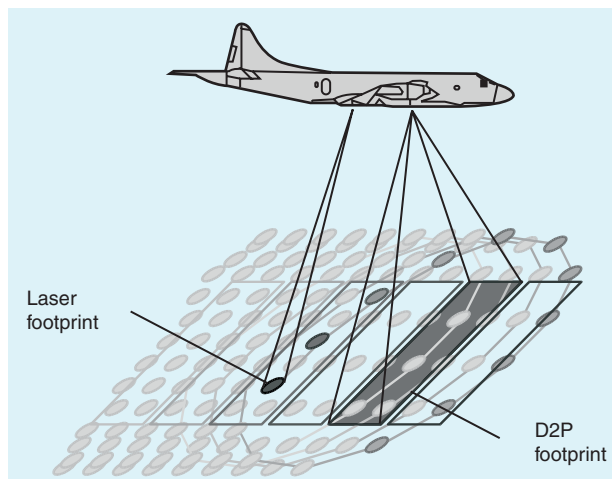

Figure 4. Field geometry. The scanning laser covers a wider swath than the D2P footprint. Each D2P footprint encompasses a number of laser measurements.

As a follow-on to the LaRA campaign, the D2P system was flown again in 2003 under joint NASA and ESA sponsorship as part of the CryoSat Validation Experiment (CryoVEx) field campaign. As in 2002, simultaneous laser and radar altimeter measurements were collected in the Arctic.[16] In addition to data collection, the CryoVEx mission was an experimental "test run" to exercise procedures planned for future calibration and validation activities to be conducted by ESA in support of CryoSat. CryoVEx was a major multi-agency enterprise. *In situ* snow and ice measurements as well as helicopter-based electromagnetic induction ice thickness soundings were collected by researchers aboard the Alfred Wegner Institute *Polarstern* icebreaker research vessel from Germany.

Figure 5 shows some images of the system installed on the Greenland Air Twin Otter during the CryoVEx campaign. The upper left inset shows the interior installation. The extra fuel tank can be seen on the left, the D2P racks on the right placed front to back, and the laser rack in the background behind the fuel tank. The upper right inset is a bottom view of the aircraft. The D2P antenna appears as the brownish square just behind the rear wheels and before the rear wing. The bottom image is the aircraft parked at Svalbard in northern Norway. The D2P antenna can just be seen behind the ladder and below the open door. Figure 6 shows the coverage of the LaRA campaign in red and CryoVEx in blue.

Antarctic

In late summer 2003, the D2P radar altimeter was deployed again on the NASA P-3 during the Antarctic AMSR-E Sea Ice (AASI) calibration and validation field campaign. The AMSR-E (Earth Observing System Advanced Microwave Scanning Radiometer) instrument aboard the Aqua satellite retrieved sea ice concentration data using passive radiometric temperature measurements over a variety of microwave frequency bands. The role of the D2P altimeter during this campaign was to provide additional estimates of sea ice concentration, freeboard, and possible snow cover from the precision height measurements. Unfortunately, the 2003 campaign was canceled after aircraft difficulties occurred during the first data flight. The AASI campaign was completed in 2004 on a Naval Research Laboratory P-3. Figure 7 shows the flight tracks during both the 2003 and 2004 AASI campaigns.

EXAMPLE DATA

Some example data gathered over a northern section of the Greenland ice sheet are presented in Fig. 8. The horizontal axis represents geophysical location, and the vertical axis contains the radar profiles relative to the World Geodetic System 1984 (WGS84) reference frame. The profile waveforms are coded into the range window using a hue-saturation-value color scheme. The radar power is mapped into the *value* and the cross-channel phase is mapped into the *hue*. Cross-channel phase is a measure of the incident angle, shown by the color bar. The image is fully saturated. In areas where the aircraft is rolling, the image shows a broader range of hues since, under those anomalous conditions, the antenna is illuminating a larger and range-varying swath on the
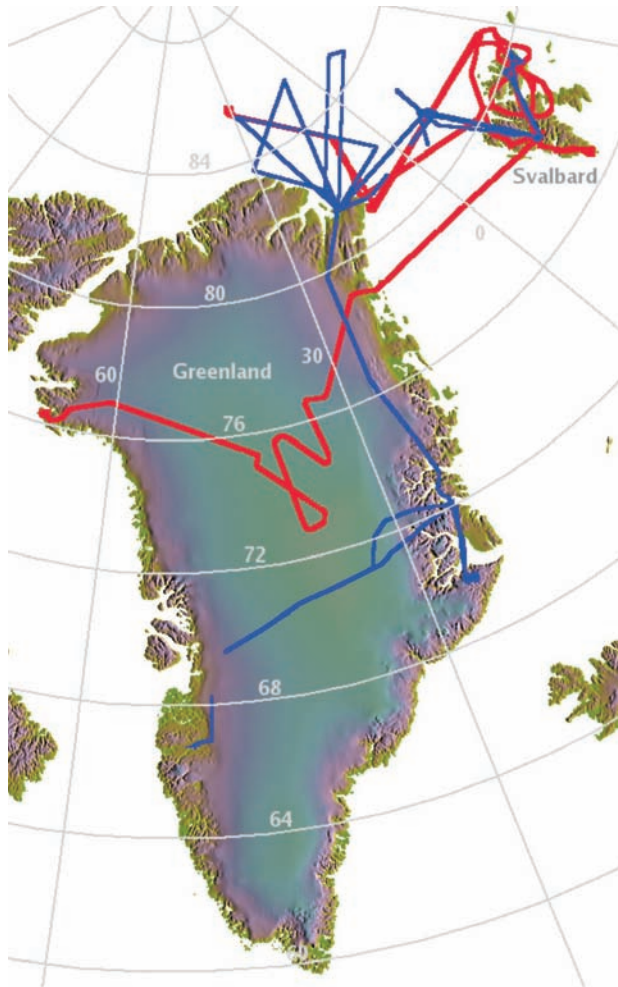

Figure 5. D2P installation on the Greenland Air Twin Otter aircraft: (clockwise from bottom) aircraft, D2P equipment racks, and bottom view of aircraft showing the antenna just aft of the rear wheels.

Figure 6. Flight tracks during the LaRA campaign (red) and CryoVEx (blue).
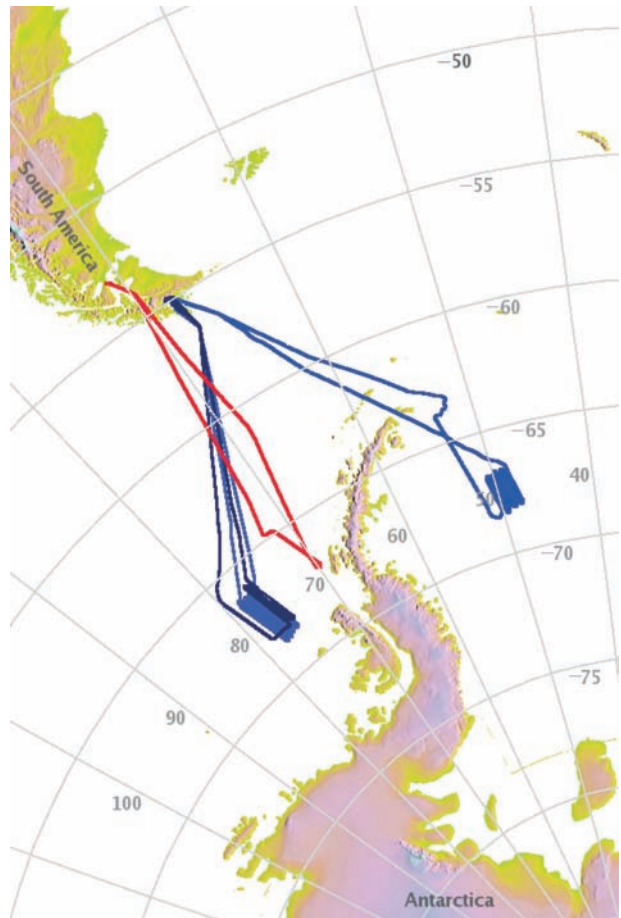

Figure 7. Flight tracks during the AASI campaign in 2003 (red) and 2004 (blue).
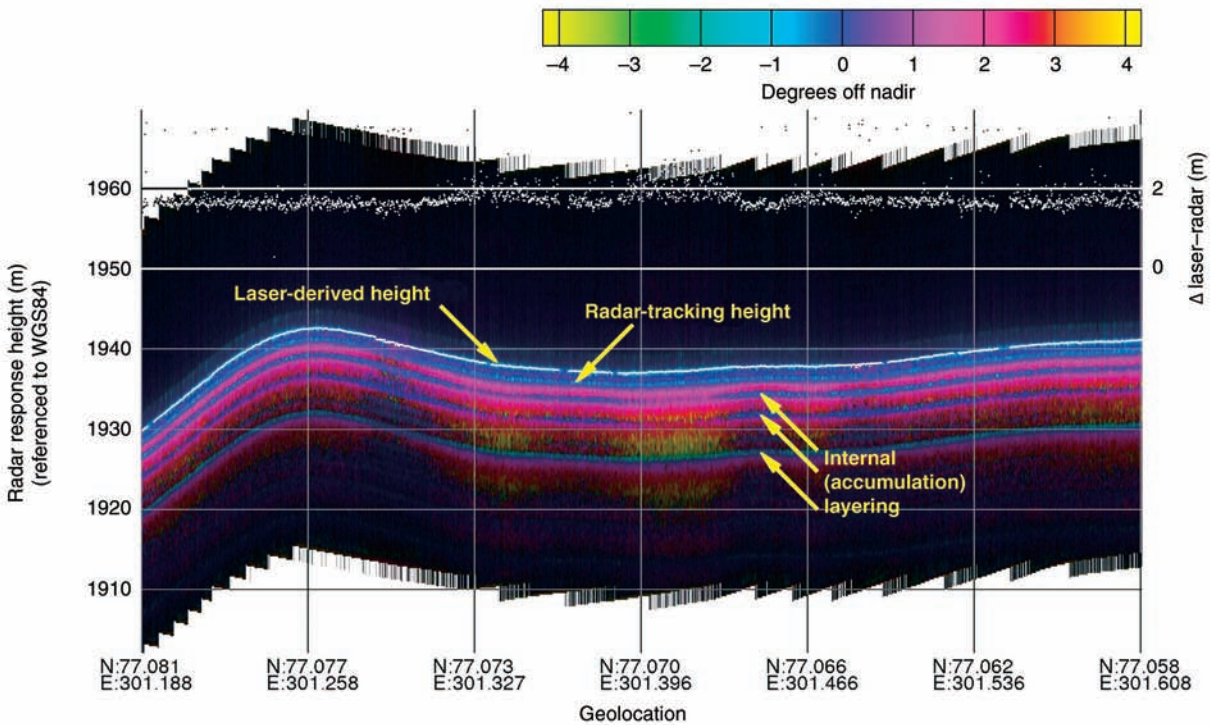
Figure 8. Example data over the northern Greenland ice sheet. A profile of the radar waveforms is shown in color as a function of height (left axis) and geolocation. The light blue line labeled laser-derived height shows the laser measurement overlaid on the radar profile. The radar-tracking height is the blue contour just below the laser height. Internal layering is also annotated. The white plot near the top (right) shows the difference between the laser and radar measurements using the scale on the right.

surface. The radar surface and other internal reflections are labeled in the image.

The features in this image can be explained by considering the waveform generated from a layered medium. Figure 9 illustrates a simple scenario consisting of three interfaces (layers). Here, the beam pattern of the D2P antenna points at approximately 2.5° starboard, and the color spectrum of the incident angles corresponds to the color bar in Fig. 8. The surface response consists of a
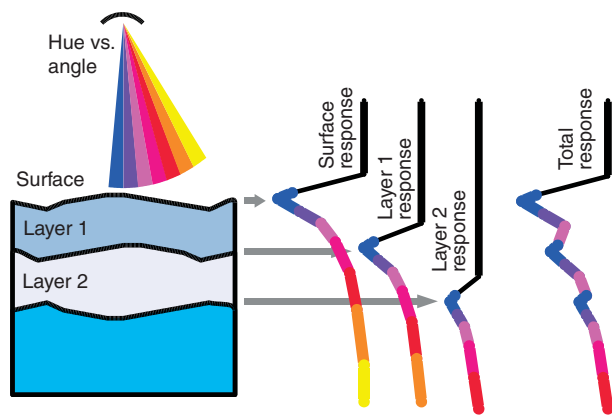

Figure 9. D2P waveform over a layered medium (not to scale). The response of a single interface shows a blue peak tapering off in amplitude and progressing in color according to the angle of incidence. The superposition of many interfaces (layers) is indicated by the plot on the right.

peak value at nadir, which has a blue hue corresponding to 0.0°. The angle on the surface increases with receiver delay, causing the amplitude of the surface response to decrease and the colors to progress through the spectrum. The response for the other two layers is similar except that they are lower in amplitude and delayed. The total response is the combination of the three waveforms, where the color of the largest amplitude at a specific delay tends to dominate. In the example, the colors of the total response vary between blue and magenta, similar to those illustrated by the waveforms in Fig. 8. This simple example shows how the blue hues in Fig. 8 are the initial response of the surface and consecutive layer interfaces, while the magenta and other hues are due to off-nadir backscatter from these interfaces.

Referring again to Fig. 8, the white line near the uppermost signal return is the laser height derived for each radar footprint. The white-on-black plot near the top of the range window displays the magnified difference between the laser and radar tracking heights. To make meaningful comparisons between the two instruments, their respective measurements must be mapped into similar footprints and resolutions. The higher-resolution laser shots are mapped into the radar footprint by taking an average of all the laser height estimates within the radar footprint weighted by the radar antenna pattern. As shown in Fig. 4, each circular laser footprint is much smaller than the radar footprint;

however, the conical scan of the laser instrument covers a wider swath than the footprint of the radar. The radar footprint is a rectangle limited in the along-track plane by the delay-Doppler processing and pulse limited in the across-track plane.

Penetration into the surface by the radar 2-cm wavelength radiation is evident by the many near-surface accumulation layers that stand out in the profile. The ≈1.8-m difference between the laser and radar measurements most likely corresponds to the overlying layer of snow and is in agreement with the annual water equivalent accumulation (≈500 mm/year) in this area estimated from ice cores, firn cores, and additional observations.[17] This measurement difference implies that the "surface height" detected by the radar is not actually the air/snow surface, as defined by the laser, but more likely the interface between the recently accumulated snow and the ice. This is a typical occurrence for a radar operating over dry snow.[8] (Ground truth sufficient to justify this interpretation is not available at this location.) In addition, such differences will be regionally and seasonally variable. Understanding these changes is essential if long-term data records from laser and radar measurements are to be compared.

Figure 10 shows a radar waveform corresponding to the geolocation in Fig. 8 at N:77.066, E:301.466. The green amplitude plot of the cross-channel power uses the linear scale on the right, the black power plot uses the logarithmic (dB) scale on the left, and the red line is the surface height as measured by the laser. The peak power at approximately 1935.95 m is at a lower surface height than the laser estimate (1937.74 m). This discrepancy corresponds to the 1.8-m difference illustrated in Fig. 8. There is a weaker peak just before the maximum power that is less in amplitude by about 50% (or 3 dB). This earlier radar response coincides well with the laser-measured height. The amplitude difference is consistent
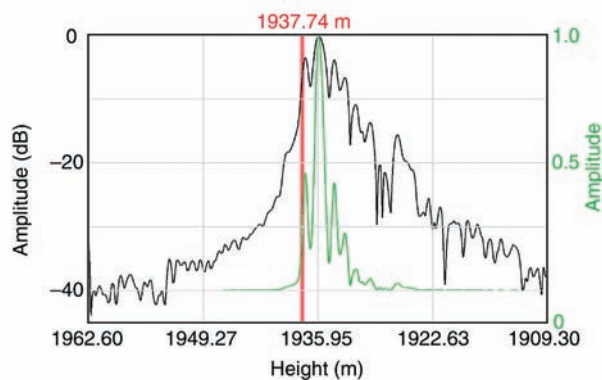
with the reflection coefficients of air/snow and snow/ice interfaces calculated using appropriate mixing formulas for snow and ice.[18] This plot reaffirms the interpretation that the positive laser–radar difference indicates snow cover. These measurements also suggest that a detailed analysis of radar waveforms may (under appropriate circumstances) be inverted to provide surface height data that would be consistent with data from lasers.

Figure 11 shows data from sea ice collected at low altitude (≈250 m) over a horizontal extent of about 1 km. The white profile near the top shows a profile of the sea ice derived from the laser and radar height values. The labels between the radar response and the sea ice profile divide regions of the image into new ice, open water, and sea ice. New ice is identified by a specular waveform and level tracking. For a typical quasi-rough surface, radar energy is backscattered at all angles, but the surface of new ice within a lead is so smooth and level that only near-perfect vertical reflections are generated from the radar's illumination. The resulting specular response consists of the nadir reflection (blue hue), but lacks the usual off-nadir components apparent at later time delays observed in other waveforms. The specular interpretation is also reinforced by a much larger signal power (not apparent in this data format in which all waveforms have been normalized). Open water is identified by a rougher waveform (broader range of hues) and a slightly lower height compared to the new ice. Sea ice is identified by varying waveform roughness and height values. The sea ice also appears to be highly fractured by many smaller leads.

The ice profile near the top also shows a comparison between the laser height (red) and the radar height (green). In regions where the laser value is higher, the gap between the two values is blue, while in regions where the radar is higher, the hue tends toward yellow. The blue regions are explained to be snow cover as was illustrated in the previous example. An explanation of the yellow regions is more problematic; a need for more comprehensive geophysical descriptions of the local snow and ice is indicated.

Figure 12 shows two radar waveforms corresponding to the lead in Fig. 11 at N:–67.690, E:283.730. The top waveform shows the radar response to be "specular," having very low off-nadir response, indicative of smooth new ice. The linear-scale waveform consists of a single peak matching the laser height. The decibel-scale waveform shows subtle sidelobes associated with the windowing function used during the processing and also exposes minor nonlinearities in the system response. The bottom waveform illustrates the radar response over open water. This response shows a slight roll off on the trailing edge of the main peak as a result of the rougher surface of the water compared to the new ice. The small –30-dB peak near the end of the waveforms is the result of a slight DC bias in the analog-to-digital converter.

Figure 10. Waveform at N:77.066, E:301.466 (see Fig. 8). Heights are relative to the WGS84 reference frame. The logarithmic (dB) scale is in black, the linear scale in green, and the laser height in red. The radar measurement is offset about 1.8 m from the laser measurement.
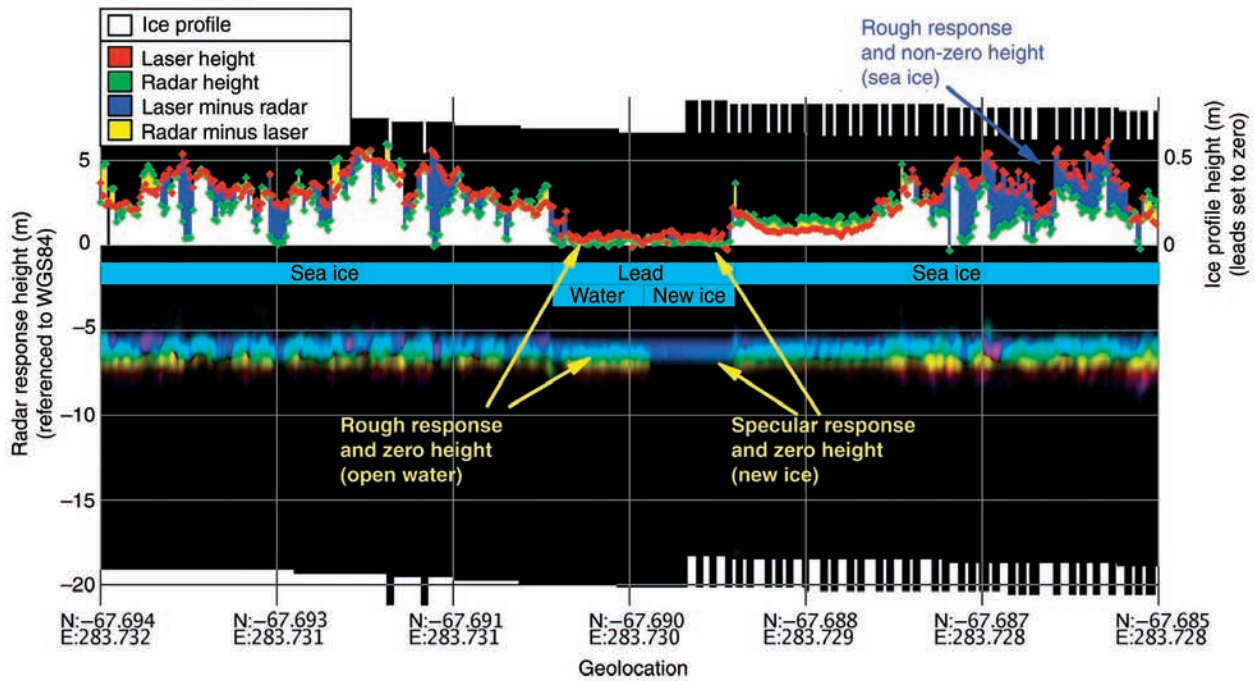
Figure 11. Example data over Antarctic sea ice. A profile of the radar waveforms is shown as a function of height (left axis) and geolocation. The image is separated into zones corresponding to sea ice, open water, and new ice. A profile of the ice (derived from the LaRA measurements) is displayed near the top using the scale on the right. Regions where the laser is higher than the radar indicate snow cover.
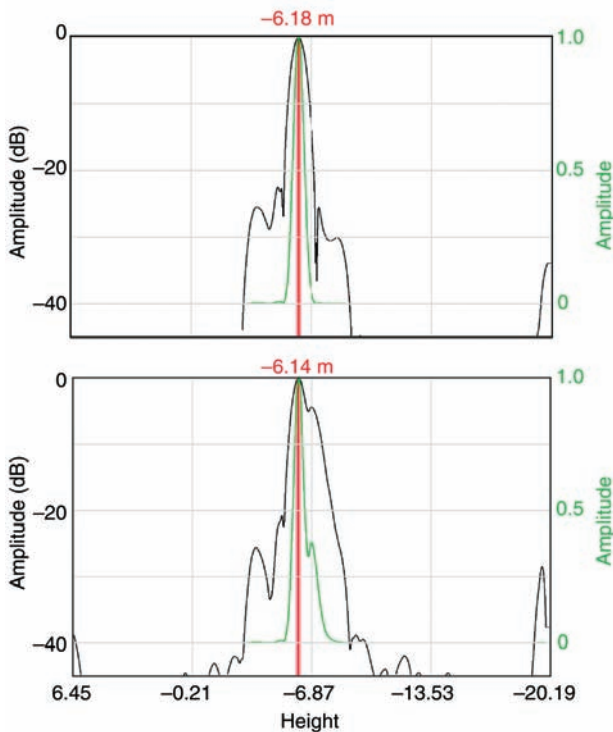

Figure 12. Waveforms at N:–67.690, E:283.730. Heights are relative to the WGS84 reference frame. The logarithmic scale is in black, the linear scale in green, and the laser height in red. The laser and radar show minimal offset. Top: Specular response over newly formed ice. Bottom: rougher response over open water.

CONCLUSIONS

The airborne APL D2P radar altimeter, when flown in company with a co-located laser altimeter over a variety of ice sheets, has collected data that illustrate the frequent occurrence of differentials between surface heights measured by the two types of instruments. These differences are due largely to the penetration of the radar pulse through the snow cover to the ice surface, in contrast to the laser which responds primarily to the top of the snow. The examples presented here have shown that in regions where microwave penetration is low, such as open water, or where sea ice or ice sheets have minimal snow cover, the laser- and radar-derived heights agree. Conversely, the results differ in areas where penetration is significant, such as ice sheets covered by relatively deep, dry snow. These interpretations are further complicated in regions where the laser seems to show penetration with respect to the radar. Close examination of waveforms over deeper snow shows a small peak before the main peak in the radar waveform that often corresponds to the snow surface height observed by the laser. The generalizability of this signal, and its applicability to surface height measurements from space, will be the subject of future investigations.

The results obtained from the D2P instrument over the last few years have provided some initial insight into the nature of the radar waveform over varying cryospheric scenes, but a more robust interpretation of the

results would require in-depth knowledge of local snow and ice characteristics. Additional calibration and validation activities are currently being planned to acquire this much-needed knowledge of the coincidental *in situ* snow properties. The D2P instrument has already provided valuable data and should play a significant role in future field seasons.

REFERENCES

[1]Wingham, D. J., Ridout, A. J., Scharroo, R., Arthern, R. J., and Schum, C. K., "Antarctic Elevation Change from 1992 to 1996," *Science* **282**, 456–458 (1998).

[2]Evans, D. L., Apel, J., Arvidson, R., Bindschadler, R., Carsey, R., et al., *Spaceborne Synthetic Aperture Radar: Current Status and Future Directions*, Technical Memorandum 4679, NASA (1995); http://southport.jpl.nasa.gov/nrc/.

[3]Drewry, D., Jordan, S. R., and Jankowski, E., "Measured Properties of the Antarctic Ice Sheet: Surface Configuration, Ice Thickness, Volume and Bedrock Characteristics," *Ann. Glaciol.* **3**, 83–91 (1982).

[4]Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., et al., "Rapid Thinning of Parts of the Southern Greenland Ice Sheet," *Science* **283**, 1522–1524 (1999).

[5]Zwally, H. J., Schutz, B., Abdalati, W., Abshire, J., Bentley, C., et al., "ICESat's Laser Measurements of Polar Ice, Atmosphere, Ocean, and Land," *J. Geodynamics* **34**, 405–445 (2002).

[6]Drinkwater, M. R., Ratier, R. F. G., and Wingham, D. J., "The European Space Agency's Earth Explorer Mission CryoSat: Measuring Variability in the Cryosphere," *Ann. Glaciol.* **39**, 313–320 (2004).

[7]Rignot, E., Echelmeyer, K., and Krabill, W., "Penetration Depth of Interferometric Synthetic Aperture Radar Signals in Snow and Ice," *Geophys. Res. Lett.* **28**(18), 3501–3504 (2001).

[8]Laxon, S., Peacock, N., and Smith, D., "High Interannual Variability of Sea Ice Thickness in the Arctic Region," *Nature* **425**, 947–950 (2003).

[9]Raney, R. K., and Jensen, J. R., *The New Generation of Radar Altimeters: Proof of Concept. NASA Instrument Incubator Program (IIP) Final Report*, SRO-01-16, JHU/APL, Laurel, MD (2001).

[10]Jensen, J. R., "Design and Performance Analysis of a Phase-Monopulse Radar Altimeter for Continental Ice Sheet Monitoring," in *IEEE Int. Geoscience and Remote Sensing Symp. Proc.* **2**, Florence, Italy, pp. 865–867 (1995).

[11]Jensen, J. R., "Angle Measurement with a Phase Monopulse Radar Altimeter," *IEEE Trans. Antennas Propagat.* **47**, 715–724 (1999).

[12]Raney, R. K., "A Delay/Doppler Radar Altimeter for Ice Sheet Monitoring," in *IEEE Int. Geoscience and Remote Sensing Symp. Proc.* **2**, Florence, Italy, pp. 862–864 (1995).

[13]Raney, R. K., "The Delay/Doppler Radar Altimeter," *IEEE Trans. Geosci. Remote Sens.* **36**, 1578–1588 (1998).

[14]Raney, R. K., and Jensen, J. R., "An Airborne CryoSat Prototype: The D2P Radar Altimeter," in *IEEE Int. Geoscience and Remote Sensing Symp. Proc.* **3**, Toronto, Canada, pp. 1765–1767 (2002).

[15]Raney, R. K., and Leuschen, C., *Technical Support for the Deployment of Radar and Laser Altimeters During LaRA 2002. Final Report*, SRO-03M-09, JHU/APL, Laurel, MD (2003).

[16]Raney, R. K., and Leuschen, C., "Simultaneous Laser and Radar Altimeter Measurements over Land and Sea Ice," in *IEEE Int. Geoscience and Remote Sensing Symp. Proc.* **1**, Anchorage, AK, pp. 676–678 (2004).

[17]Dethloff, K., Schwager, M., Christensen, J. H., Kiilsholm, S., Rinke, A., et al., "Recent Greenland Accumulation Estimated from Regional Climate Model Simulations and Ice Core Analysis," *J. Climate* **15**, 2821–2832 (2002).

[18]Ulaby, F. T., Moore, R. K., and Fung, A. K., *Microwave Remote Sensing: Active and Passive, Vol. 3: From Theory to Applications*, Artech House, Inc., Norwood, MA (1986).

THE AUTHORS

Carl J. Leuschen is a Senior Professional Staff member of the Space Department's Ocean Remote Sensing Group of APL. Dr. Leuschen's interests include radar altimetry, radar sounding, and ground-penetrating radar. He is currently a participating scientist for the MARSIS radar sounder aboard the European Space Agency's Mars Express mission and is also contributing to the SHARAD sounder aboard the NASA Mars Reconnaissance Orbiter. In 2002, he received a NASA New Investigator Award to investigate signal processing algorithms for ice sounding radars. He has the primary role for the deployment of the APL D2P airborne radar altimeter and has participated in numerous field experiments at polar regions. Before joining APL, Dr. Leuschen was a graduate student at the University of Kansas Radar Systems and Remote Sensing Laboratory. In 1997, he received a NASA Graduate Student Research Fellowship to develop a ground-penetrating radar for Mars. He graduated with highest distinction for his B.S. in 1995 and with honors for his Ph.D. in 2001, for which he received the Richard and Wilma Moore Thesis Award. He is a member of the IEEE and the Tau Beta Pi Engineering Honor Society. **R. Keith Raney** is the Assistant Supervisor of the Ocean Remote Sensing Group of APL. Currently, Dr. Raney is developing advanced radar altimeter and radar ice sounding concepts and is on the Science Advisory Group for ESA's CryoSat radar altimeter Earth Explorer project. He is a Guest Member of the Lunar Radar Orbiter Science Working Group, representing the Mini-RF radar imager, a technical demonstration instrument for the mission. While with the Canada Centre for Remote Sensing (1976–1994), Dr. Raney helped to initiate the Radarsat mission. As the Radarsat Project Scientist, he was responsible for the conceptual design of the SAR system. He contributed to the design of NASA's Magellan Venus mapping radar, the ESA's ERS-1 SAR, and the Shuttle Imaging Radar SIR-C. He also served on the Europa Orbiter Radar Sounder Team (NASA/JPL). Dr. Raney is the principal inventor for the U.S. patent on the chirp scaling SAR processing algorithm, holds the patent on the delay/Doppler radar altimeter, and has a patent on an ice sounding radar. He was on the founding Board of Associate Editors for the *International Journal of Remote Sensing* and serves as an Associate Editor (radar) for the *IEEE Transactions on Geoscience and Remote Sensing*. His many awards include a Group Achievement Award for the Magellan Radar Science Team, the Gold Medal of the Canadian Remote Sensing Society, and the Millennium Medal 2000 from the IEEE, of which he is a Fellow. For further information on topics covered in this article, contact Dr. Leuschen at carl.leuschen@jhuapl.edu.

Carl J. Leuschen

R. Keith Raney