The Cryosphere Discuss., 2, S528–S531, 2009
www.the-cryosphere-discuss.net/2/S528/2009/

The Cryosphere Discussions

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Interactive Comment

Interactive comment on "Comparison of airborne radar altimeter and ground-based Ku-band radar measurements on the ice cap Austfonna, Svalbard" *by* O. Brandt et al.

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Received and published: 5 March 2009

Summary: The paper compares results from an airborne altimeter with data obtained with a very high bandwidth (VHB) surface radar, and with surface glaciological data from snow pits. All the data were collected from the Austfonna Ice Cap on Svalbard in April-May 2007. The airborne altimeter, referred to as the ASIRAS, is a simulator for the satellite altimeter SIRAL to be flown on the ESA CRYOSAT satellite. The emphasis in the paper is on understanding the time domain waveforms so that ultimately better use can be made of airborne and satellite altimeters.

General Comments: The paper is well written, contains significant results, and is a useful contribution to understanding nadir-looking radar signatures from various ice regimes. The emphasis has been placed on comparing the airborne and surface data, and includes the conclusion that the high bandwidth surface data can help in understanding the airborne results, and ultimately be useful as a validation tool for satellite data. While this is reasonable there are circumstances in which results from the new generation of satellite and airborne altimeters (which use along-track focusing based on pulse-to-pulse coherence) will differ from the traditional altimeters which use footprints defined by pulse- or beam-limited operation. The ground-based VHB radar used in this work does not utilize along-track coherent processing but the ASIRAS does.

Results are also presented in the paper which demonstrate that thin crust layers in the winter snow pack, which are relic surfaces and are often coupled with hoar frost layers, do create strong backscatter signatures. This mirrors our unpublished results from the Devon Ice Cap (with the same radars, but with significantly less yearly accumulation), and is potentially significant not only to the interpretation of vertical radar returns (altimetry) but also to off-nadir (SAR) imagery of cold polar firn. Further, the work under review shows that the last summer melt layer in the wet snow and superimposed ice-to-firn transition zone often exhibits a stronger return than the surface layer. These results, together with the associated snow pit data, are significant in helping to plan algorithms for the CRYOSAT-2 satellite to be launched later this year. The results complement other work in Greenland, and our work on the Devon Ice Cap, by providing information from the wet snow and superimposed ice zones. I leave it to the discretion of the authors and the editor whether any of the comments below should lead to changes in the published paper.

Specific Comments: Processing ASIRAS data coherently leads to a footprint size of a few meters along-track by around 30 m across-track (-6 dB), when the aircraft altitude is 700 m. This means that the off-nadir surface to each side of the sub-aircraft track for a flat snow surface is ambiguous in range with the snow at a depth of around 10 cm in the nadir direction. Below a depth of about 30 cm the volume from which the returns are integrated is around 30 m wide, a few meters along-track (dependent on the averaging used), around 12 cm in depth, and the volume is closer to the surface at the cross-track edges than in the middle. The important influence of the footprint size and shape can be shown by processing raw ASIRAS data both with and without the along-track focusing stage. This was done using our processor (equivalent to the ESA L1B processor) on data from near the summit of the Devon Ice Cap (weak percolation zone). One section of raw ASIRAS data was processed normally and averaged over an along-track distance of 50 m. The first peak in this profile represented the surface, the next stronger return corresponded to the previous years melt, and the subsequent weaker peaks appeared to track earlier annual melt layers. These results are comparable to published results (Hawley et al., 2006) for the dry snow zone in Greenland. If the focusing stage is left out the individual footprints to be averaged are now much larger and extend fore and aft of the nadir direction as well as side-to-side. In this case there is a significant influence on the average return with depth; the peaks are broader and the deeper layers virtually disappear.

The explanation is straightforward if one considers the radar return signal as a combination of specular reflections from flat facets together with a random cloud of individual scattering centers. The specular reflection is more likely to be in the direction perpendicular to the surface and will be more readily visible if the footprint volume is as small as possible about that direction. The increased scattering volume in the no-along-track focusing case effectively reduces the contribution of the specular component to the point that the deeper layers are now difficult to discern. Note, as explained below, that this effect is dependent on the depth of the specular layer.

The situation is even worse for the VHB radar which uses antennas that have much smaller apertures than ASIRAS, and consequently much broader beam widths. When the VHB antennas are around 1 m above the snow surface the curved shell-like volume contributing to one range bin will extend in all directions, not just in the across-track direction as with ASIRAS. When the range bin is just beneath the snow surface the

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returns will be pulse limited and from a limited angular range, not defined by the broad antenna beam width. But the returns for deeper layers will be beam limited and will include returns from a volume which could include a number of layers and the off-nadir surface. Again, the detection of near-horizontal interfaces with a significant dielectric discontinuity (related to density transitions) will depend on the existence of reflecting facets of a size smaller than the first Fresnel zone. Whether these returns are visible or not will depend on their strength in relation to the integrated returns from the total volume of the particular range bin. Consequently, it is clear that layering will be more readily observable in the near surface layers when the VHB radar is pulse limited than for deeper layers when the range bin potentially includes a number of layers. This reflects our experience with the VHB radar on the Devon Ice Cap; we can readily see even subtle layering in the winter accumulation but have more difficulty seeing returns from deeper ice layers. To summarize, the returns from the same area with a wide beam-width surface radar can differ from an along-track focused altimeter like ASIRAS or the SIRAL instrument on CRYOSAT. This will be true even if the centre frequency and bandwidths are matched.

While I don't disagree with the conclusion that the VHB surface radar can be used to validate airborne (ASIRAS) and even spaceborne (CRYOSAT) altimeters, consideration should be taken of the facts that the volume over which the returns are integrated can be very different, the wave front curvature (related to the size of the first Fresnel zone) is very different, and that these differences can lead to different 'signatures' and a differing ability to resolve layering in the large ice caps.

Interactive comment on The Cryosphere Discuss., 2, 777, 2008.

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