SCAR Fellowship Report
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Snow over ice: ground measurements for satellite validation of snow layering over land ice and snow thickness over sea ice around McMurdo Sound, Antarctica

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Abstract. This document is prepared as a final report to the Scientific Committee of Antarctic Research for a fellowship that was awarded in July 2008 and completed in February 2010. The fellowship supported a visit to New Zealand and allow the combination of resources for fieldwork around McMurdo Sound in Antarctica. These projects were awarded to principal investigators Wolfgang Rack and Pat Langhorne for land ice and sea ice work, respectively, by Antarctica New Zealand. In particular, the focus was to employ various techniques (and combinations thereof) to validate snow layering over land ice and snow thickness over sea ice for use in CryoSat retrievals, but also for data reanalysis and process modeling. A description of project background (and support), the objectives and methodologies are presented, as well as indicators that what was proposed have been achieved. Collaborative work is represented by a list of presentations and publications, and some ongoing work is described. Lessons learned in the process are turned into recommendations for future work.

1 Motivation

CryoSat-2, a European Space Agency satellite scheduled to launch in the next month, will carry a radar altimeter that is designed to measure ice elevation on Earth (Wingham et al., 2001) at a higher accuracy than earlier generation instruments, which will facilitate better understanding of how much ice there is and how much this storage is changing to ultimately understand the effects of past climate change and future impacts on sea level rise. There are uncertainties, however, in the retrieved values of ice thickness due to the natural variability in the deposition and distribution of snow over ice. We use two approaches to ground validation by characterizing snow layering over land ice and measuring snow thickness over sea ice. An off-the-shelf digital SLR camera, modified for sensitivity in the near-infrared wavelength range is used for snowpit imaging, and a 1-GHz commercial ground-penetrating radar system is used to collect snow thickness profiles over land-fast first- and multi-year sea ice. Image processing and signal processing techniques are used. Particular differences in the validation approaches between land and sea ice are discussed. Finally, this report includes a brief discussion on how validation results can be used when ground measurements are made non-contemporaneously with satellite overflight and why such efforts are important. The location map included in the original proposal is shown in Fig. 1.

2 Research Programme

The idea for the October-November 2009 fieldwork was to join funded projects supported by Antarctica New Zealand (New Zealand's polar program) through principal investigators Wolfgang Rack of Gateway Antarctica (Event K053), University of Canterbury and Pat Langhorne of the Sea Ice Group, University of Otago (Event K131). The main aim of K053 is to contribute to the validation efforts of the radar altimeter aboard the satellite CryoSat-2 by investigating both land ice and sea ice properties in the region around Scott Base (77°50'51"S 166°45'37"E). Activities include measuring stake heights and locations after being embedded for a year in three sites, see Fig. 2: L1 between White and Black Islands in a zone where a layer of seawater has been found to infiltrate into the shelf ice, L2 on the ice shelf edge in Windless Bight, and L3 along a tributary to the Erebus Ice Tongue. Snow density and layer thickness were measured from snow pits and ice cores. An unmanned aerial vehicle was also flown with a laser profiler and optical camera to record surface roughness.

Event K053 crossed over K131 to share resources to investigate sea ice properties. In particular, K131 wintered-over to study the growth and evolution of platelet ice under land-fast

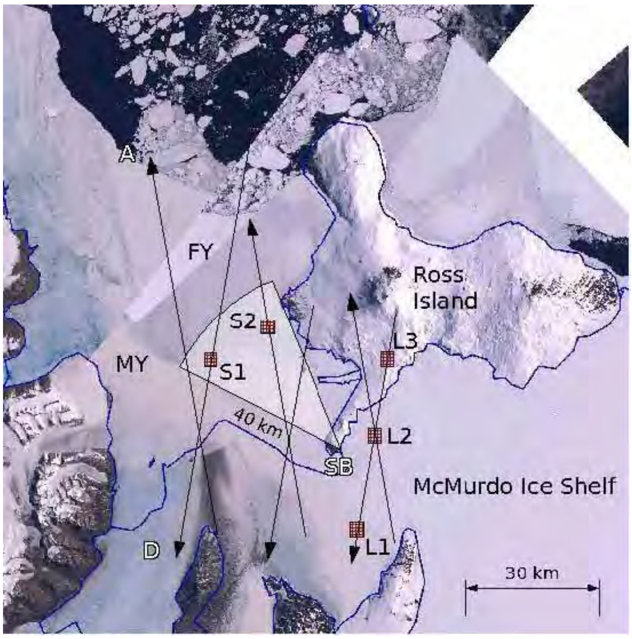

Fig. 1. Image showing Ross Island at the edge of McMurdo Ice Shelf, bounded in the north by open water and sea ice. Scott Base is marked SB and the land sites L1, L2, and L3. This is the image used in the original proposal. Sites S1 and S2 over sea ice have been expanded as transects from east to west over first-year (FY) and multi-year (MY) ice. The airborne lines (black arrows) have been redefined covering more ground than originally planned. Image courtesy of W. Rack.

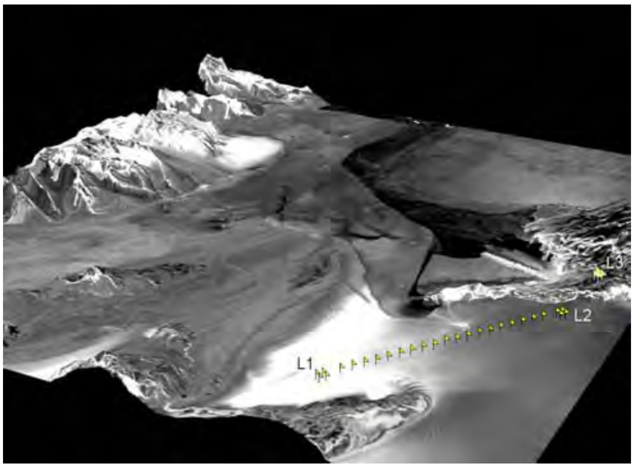

Fig. 2. Oblique radar image showing land ice sites L1, L2, and L3, as well as the transect line between L2 and L3. L3 is on the slopes of Mt. Erebus along a tributary of the Erebus Ice Tongue, visible in the background. Willy Airfield runways are visible as a radiating lines halfway between L2 and L3. White and Black Islands cup L1 that is on a very bright area of the radar image. Image courtesy of W. Rack.

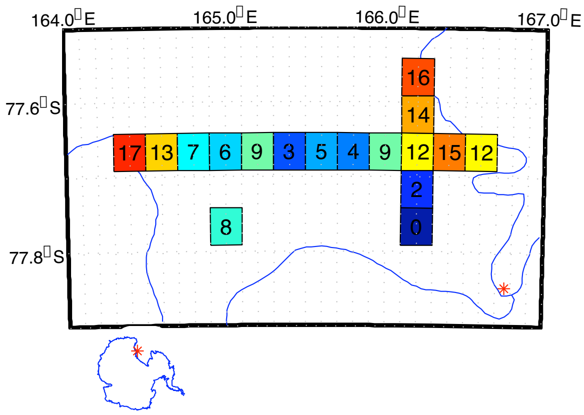

Fig. 3. Average snow thickness in centimeters for quadrants on sea ice where ground-penetrating radar profiles have been made. The red asterisk is the location of Scott Base. The northern east-west transect is mostly over first-year ice, except for the areas close to land. In the south, it becomes predominantly multi-year ice.

ice in the vicinity of Scott Base. Platelet ice is formed by the outflow of low-salinity supercooled seawater from under the ice shelf. They are commonly found under fast ice although they have been observed under floes. Christian Haas of the University of Alberta joins the teams to fly a helicopter-borne inductance meter, known as a HEM bird, over sea ice and the transition region into shelf ice. Almost half of the Antarctic coastline is lined with ice shelves and it is hoped that a better understanding of platelet ice will allow a better picture of how sea ice is formed and sustained to support ice shelf edges in return. Along with the HEM bird a laser altimeter is flown to measure surface roughness. The inductance meter utilizes the high permittivity contrast between ice and water to determine that boundary Holladay et al. (1990). It cannot distinguish snow from ice, thereby providing *total* thickness that includes any snow over ice. However, by using two frequencies, this is the first time the HEM bird has been used to distinguish platelet ice and retrieve its thickness ever since the introduction of electromagnetic induction to Antarctica by Worby et al. (1999).

2.1 Objectives

Errors in the satellite retrievals of the elevation of land ice and the thickness of sea ice are expected to come from the uncertainty in the thickness of any overlying snow. In the case of land ice, repeated measurements at the same exact location is critical to build a time series of the change in elevation at that location. Radar waves from SIRAL, the radar altimeter aboard CryoSat, are expected to penetrate several meters into the snow/firn (e.g., Eisen et al., 2008). Return signals will be complicated by the thickness of the different layers of snow with different densities and morphologies. To complement the snow pit density measurements and the ground-penetrating radar profiles, I use a digital SLR camera, modified to be sensitive in the near-infrared to image the snow layers. Furthermore, we measure permittivity down the snow pit at 2-cm intervals. For land ice, we are interested in the variability of the snow layers that affect the radar scattering by the snowpack. We use the imaging to relate coincident ground-penetrating radar measurements profiled in a grid covering the study site, which will characterize the snowpack in that location.

A slightly different problem exists for sea ice: snow thickness becomes spatially homogeneous at regional scales but at scales important to higher-resolution airborne and spaceborne sensors, its spatial variability cannot be ignored (see Eisen et al., 2008, and references therein). Surface processes such as wind speed and surrounding terrain will determine snow deposition over sea ice. We know that, on average, snow becomes thicker closer to land and over multi-year sea ice (A. Gough, pers. comm.), but we also want to know is what is the thickness variability in arbitrary sub-regions. The measurements, therefore, are of snow thickness in locations across a region with sampling intervals much smaller than its decorrelation length at distances more than twice the footprint of the HEM bird, which is the satellite footprint. We use a 1-GHz ground-penetrating radar system to collect traces at intervals of 2-5cm across the region of interest.

2.2 Methodology: land ice

Work based on stereology by Matzl and Schneebeli (2006) show that snow reflectance in the near-infrared is related to its surface-to-volume ratio [length^{-1}], also known as its specific surface area:

$$SSA = A \times \exp\left(\frac{r}{t}\right)$$

where r is reflectance [%], and $A = 0.017 \pm 0.009\text{mm}^{-1}$ and $t = 12.222 \pm 0.842$ are empirical constants. It relates to the structure of the snowpack, given an understanding of snow metamorphism, as well as an indication of snow density.

Tape et al. (2010) describe a system that uses an off-the-shelf digital SLR modified to be sensitive in the near-infrared region of the built-in charge-couple device array. Nick Rutter (pers. comm.) of the University of Sheffield provided us with the specifications of the camera system that we duplicated. A description of the setup is as shown on Fig. 4. The pit is imaged from the surface down to the bottom of the pit as far as is possible to dig (4m at the deepest) in sections 75-100cm high. A bubble level on the camera assures that the photos are taken vertically. Matzl (2006) discuss the problem with uneven illumination of the scene. We present a solution by using an optically and physically flat gray reflectance board (see Fig. 5) that is used to cover the region of interest and use it measure the distribution of illumination. The image of the board is taken within minutes of the snow image.

Fig. 4. A tripod is used to situate the camera so that it is centered around the frame and a bubble used to align it parallel to the pit wall. A ruler along the frame provides a reference for scale as well as for camera focus. Reflectance tiles around the frame serve as references for 50% (gray) and 90% (white) reflectance. Photo by W. Rack.

The correction for uneven illumination is crucial for normalizing the brightnesses down the pit as available light decreases. This is apparent in the brightness images shown on Fig. 6. The left panel shows a raw brightness image with a very bright section closer to the top (red) and generally decreasing with depth (blue). After correction, a more realistic brightness profile is presented; see center panel. Only brightness values are recorded by the camera, which need to be converted to reflectance values. This is done by comparing the brightness values of the tiles within the scene to similar values within the scene and linearly interpolating. The same is done for the board. The right panel in the figure shows a reflectance profile that is taken by averaging the image pixel values along each row of the image.

Fig. 5. Sample grayscale image of a section of a snowpit wall. The left image shows an empty frame around a snow face and the right image shows the reflectance board inserted into the frame to cover the snow face. The board is used as a reference to measure the distribution of illumination throughout the region within the frame.

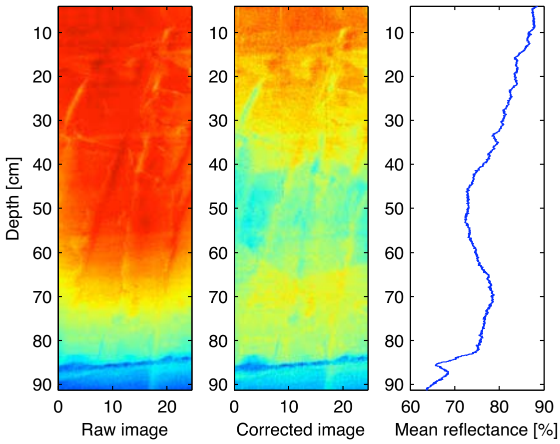

Fig. 6. Only the section within the black boundary on Fig. 5 is used to calculate reflectance. The left panel shows an uncorrected image while the center panel is corrected. Once corrected, the brightness values can then be converted to reflectance (right panel).

From the empirical equation found by Matzl and Schneebeli (2006), reflectance is converted into specific surface area (see Fig. 7, center panel). The left and right panels compare independent measurements of density (blue line) and permittivity (red line), respectively, down the pit. Circles on the left panel are the permittivity values converted into density values. The blue horizontal line on the right panel show an ice layer while the black line is the suspected last summer melt layer.

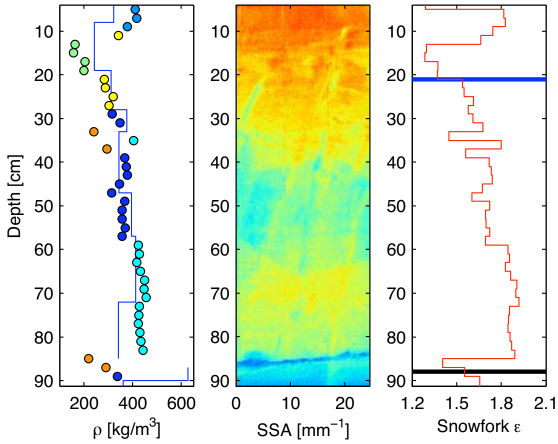

Fig. 7. The center panel show specific surface area varying down the profile. Independent measurements of density ρ (left panel, blue line) and permittivity ε (right panel, red line) were also made. The circles on the left panel are the permittivity values converted to density. Horizontal lines on the right panel indicate ice layers: blue for a strong melt and black for what is suspected as the last summer melt layer.

For our purposes here, specific surface area (SSA) is defined as the surface-area-to-volume ratio of snow particles *as a collection*, as opposed to considered individually. As separate particles, snow becomes more rounded as it decomposes; the particles become more "compact", i.e., their surface area is small compared with volume. But shape and size alone do not characterize the structure of a snowpack. By considering snow as a collection of particles in a given volume, specifically as they are naturally deposited, SSA facilitates a characterization that is based on porosity (a different sense of compactness) of the snow volume. In particular, it is a description of the structure of the snow/ice-air matrix. Furthermore, Grenfell and Warren (1999) argue that SSA is more strongly related to the electromagnetic properties of snow, which is what we are interested in because any radar scattering will be dependent on the arrangement of snow/ice particles in an "air" volume. For a discussion of the difference between effective optical particle diameter and the traditionally measured grain size, see Langlois et al. (2010).

Our definition of SSA, strictly speaking, is a function that is independent of density. Imagine snow in a volume with high specific surface area. This probably means that the particles have been compacted in the volume but does not imply that the density is high. Conversely, a low specific surface area represents loose snow but is not an indication of the density of the individual particles. Not all decomposition will increase specific surface area, but we can expect densification from decomposition as well as compaction. In Fig. 8 is shown a plot of density against specific surface area. Notice the spread of points. If we cluster the points and plot them along the profile (exactly as on the left panel of Fig. 7), a pattern emerges in terms of the layers that can be "retrieved" from the image. The colors in the circles denote the same clusters on both panels. We see high specific surface area on the top layer; this coincides with a light snow event with strong winds that compacted the surface. Below it is depth hoar, with high SSA but very low density. Density generally increases with depth but structure is indicated by a change in SSA.

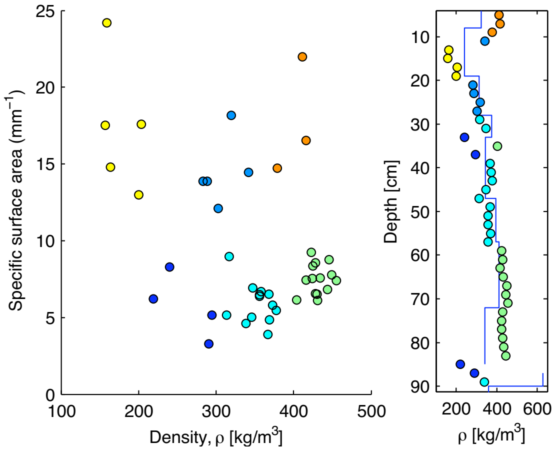

Fig. 8. Scatter plot of density against specific surface area of the top section of a snow pit on site L3 (dry snow zone), left panel. The same points indicated by color plotted as density as it changes with depth is on the right panel. The blue line on the right panel are the density measurements taken by layer from weighing snow samples. Cluster analysis made on the left plot indicate layering on the right plot. It is interesting to note that very thin layers are effectively missed by any of the traditional sampling except in notes from hardness tests or irretrievable samples.

2.3 Methodology: sea ice

Isostatic equilibrium can be understood in terms of bouyancy. When ice (less dense than water) floats in water, a certain proportion of its mass is "displaced" above the water surface. The remaining volume (or thickness) below the surface will have a volume (or thickness) equal to the water that displaces the top, i.e.,

$$\rho_w z_d = \rho_s z_s + \rho_i z_i$$

where the density of water is ρ_w, snow ρ_s, and ice, ρ_i, with corresponding thicknesses z. The equivalent volume (or thickness) of water is called the draft, z_d. A diagram is shown on Fig. 9.

Airborne or spaceborne altimeters can cover wider areas allowing a snapshot of the larger system and allows a time

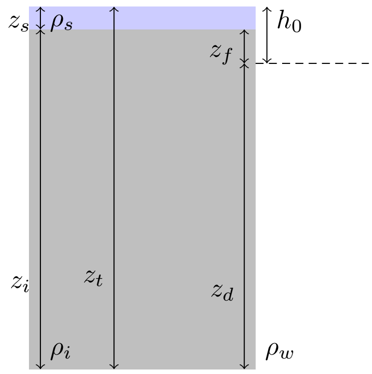

Fig. 9. An idealized block of ice floating in water is shown with a layer of snow on it. The thickness of the snow is z_s and that of ice is z_i. The total thickness of this pack is $z_t = z_s + z_i$. There will be an amount of ice–and the overlying snow–that is displaced above the surface of the water and its height is h_0. When open water is present, a laser altimeter will be able to take two measurements, one on the snow/ice surface and another on the water surface, and by differentiating retrieve the value h_0. However, it is the ice thickness, without the snow, that we are interested in. With a radar altimeter, it is possible to measure the elevation of the ice surface because radar will penetrate through snow. That way, we get a measure of the ice(-only) *freeboard*, the height of the ice above the water surface. Combining the laser and radar measurements allows the retrieval of the ice *draft*, the thickness of the ice that is submerged. Ice thickness, without the snow, is just $z_f + z_d$.

series at scales appropriate for cryospheric process studies. However, there is an uncertainty in the thickness of the snow over the sea ice that distorts the retrieved values of ice thickness Maksym and Markus (e.g., 2008). It is caused by the variability in the density of the snow and its thickness that may distort the return signal from the snow-ice interface. We will ignore snow density (although sensitivity analysis show it to significantly contribute to the overall uncertainty) and concentrate instead on measuring the *natural* variability of the snow thickness over a region.

The approach we employ is to use a 1-GHz ground-penetrating radar system that is commercially available (it is the pulseEKKO system supplied by Sensors and Software in Canada). It is towed behind a snow machine and collects traces at intervals of 2-5cm. A grid is drawn across McMurdo Sound and at crossings probe measurements of snow thickness were taken alongside ground-penetrating radar transects. Fig. 10 shows a sample 150-m line above first-year sea ice in the west of the sound. A weighting algorithm is used to semi-automatically pick the peaks in the signal and connect a reflecting "horizon" across the radargram. The permittivity contrast between snow and ice make the snow-ice interface a strong reflector and thus facilitate our picks. Probe measurements are included in the plot and are indicated by the red asterisks. It was difficult to align the manual measurements with the radar tracks and so we allow for a horizontal error of up to 10m. Furthermore, traces have been "skipped" when the odometer is "jumped" or when the snow-machine is moving too fast to properly record a full trace. These are indicated by black crosses at the bottom of the radargram. The picking algorithm ignores these traces and continues with the next closest pick and interpolates for the missed value.

We arbitrarily collect the snow thickness values into quadrants across McMurdo Sound, as shown in Fig. 3. Histograms of the collections are shown on Fig. 11. The (red) vertical lines are the mean values at each quadrant. At this point in the discussion, the locations of the quadrants are irrelevant, so they are not indicated on the plots. What is important to notice is the bimodal character of the plots where there is an average snow thickness greater than 0m. The mode close to 0m tells us that there is a patchiness in the snow cover, i.e., that bare ice is likely to be found on the surface. What is the spatial extent of this patchiness? For an area the size of the footprint of an airborne or spaceborne sensor, is this patchiness significant? In particular, we want to know whether or not assuming an average snow thickness over a certain region can be improved on?

Apart from the variation around the mean that are shown by the histograms in Fig. 11, there is *spatial* information gathered by taking profiles with sampling intervals that are smaller than the *spatial* variability of the parameter of interest, in this case snow thickness. By taking the distances of sample points in a profile and plotting them against the autocorrelation of snow thickness values, we get what is shown on Fig. 12. What this plot says is that the correlation of the values between paris of points decreases as the distance between them increases. It also says that any correlation is lost when the points are 20m apart (i.e., zero correlation, horizontal broken line). Furthermore, it says that there is some repeating pattern at around 10m (red vertical broken line showing an increasing correlation after decreasing).

3 Non-contemporaneous ground measurements

A question that comes up in discussions about CryoSat validation is "How do ground measurements contribute to validation when they are made without contemporaneous satellite overflight?" Well, we mentioned that there is uncertainty in the "retrieved" ice elevation from the satellite altimeter caused by the properties of overlying snow. By using techniques in optimal interpolation, we can decrease the uncertainty by providing complementary information. Following is a simplified example, where there is only one variable and the weighting function is linear.

Say we have an estimate of snow thickness z_{s1} from a weather station close to a region of interest. We can use this information by "averaging" the satellite value for snow thickness z_{s0}, to get an improved estimate:

$$\hat{z}_s = w z_{s_0} + (1-w) z_{s_1}$$

where $0 \leq w \leq 1$ is some weighting function. The variance of this estimate would be

$$\hat{\sigma}_s^2 = w^2 {\sigma_{s_0}}^2 + (1-w)^2 {\sigma_{s_1}}^2$$

where σ_{s0} and σ_{s1} are the standard deviations of the retrieved value and the initial estimate of snow thickness, respectively, and which are determined by the measurement uncertainty and natural variability of the parameter.

The objective would be find w that minimizes the estimate of the variance. For this example, the higher the variance of z_{s0} the smaller will be its weight in the averaging and vice versa. It will be critical to understand the uncertainty in point measurements to know how that might affect a regional average (either of point measurements or of scattering from a sensor footprint).

4 Achievements

A way of observing snow stratigraphy for deep (> 1m) pits has been used and compared with density and permittivity measurements. The near-infrared imaging allows records of dipping profiles as well as roughnesses between layers. The primary contribution of the work is in providing a way to correct for uneven illumination, which is crucial to properly converting brightness values to reflectance. Snow pit measurements will help validate surface-based ground-penetrating radar profiles that cover an area the size of a satellite footprint. The validation will contribute to CryoSat Calibration and Validation Retrieval Team (CVRT) as well as past reanalysis and future retrievals (see discussion on Sec. 3).

The snow thickness measurements derived from ground-penetrating radar profiles conducted in November 2009 provide spatial information about its distribution over first- and multi-year sea ice. Although the measurements are only a snapshot in time of snow thickness, it contributes to our knowledge of the spatial variability in subregions within McMurdo Sound and are useful as validation data for similar climatologies in the area for the CryoSat CVRT. Furthermore, the same data provide validation for the snow thickness retrievals made from measurements by the HEM bird with its laser altimeter. Because the HEM is an airborne instrument, it is more promising as access to larger areas and inaccessible regions.

5 Continuing Work

The SCAR fellowship has bridged the opportunity to conduct fieldwork, collect and analyze the data as well as present some results. It has also allowed for continuing collaboration and data sharing.

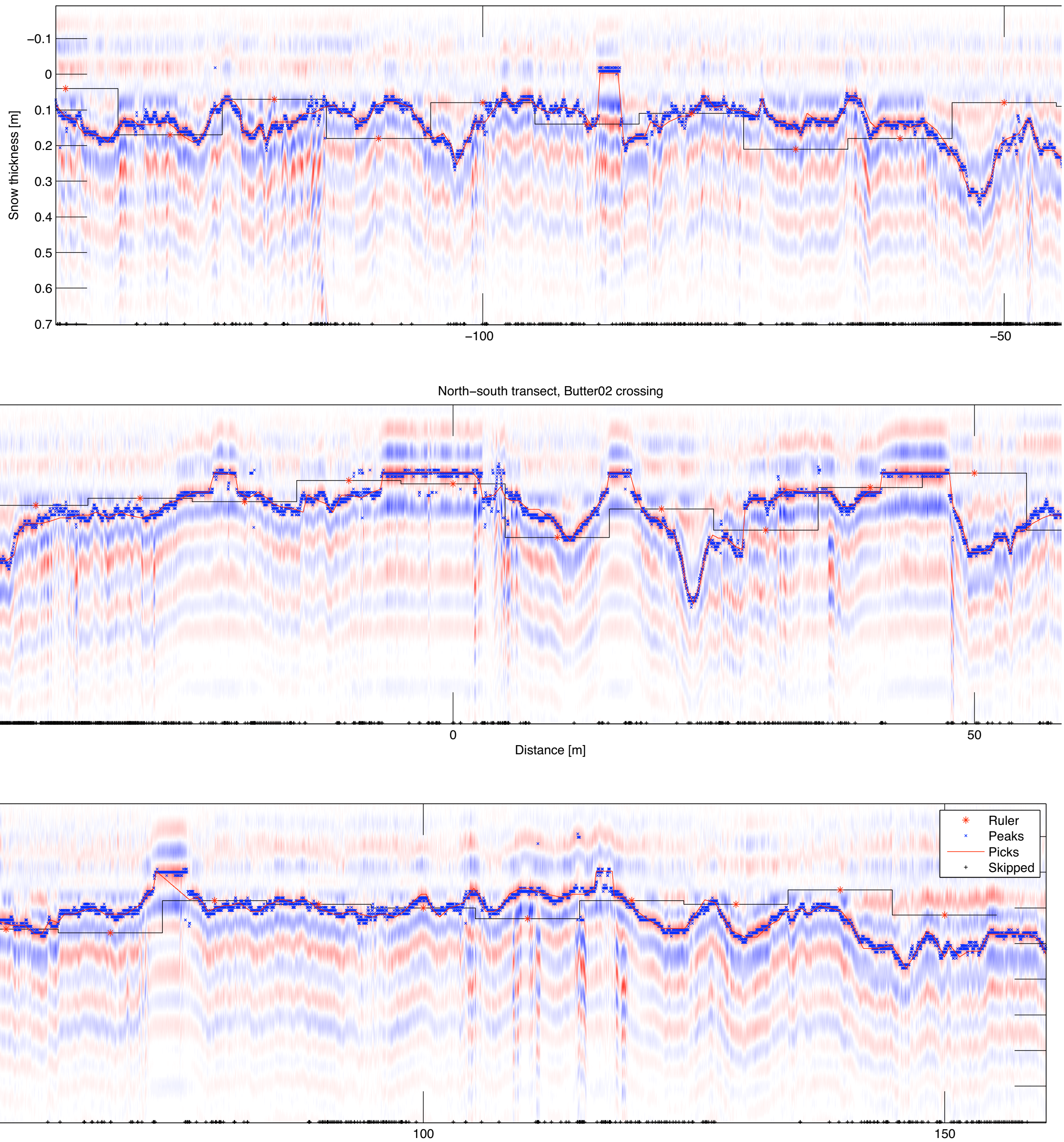

Fig. 10. A sample radargram of a 150-m line on the western part of McMurdo Sound. It shows the reflecting horizon–indicating snow thickness–that is "picked" across the plot by utilizing the strong permittivity contrast between snow and ice that produces a peak in each trace. The peaks are connected using a weighting algorithm that also interpolates for missed values caused by the system skipping recording. Manual probe measurements of snow thickness were taken at 10-m intervals and are shown here as red asterisks. The measurements were difficult to align producing a horizontal error of the order of about 10m.

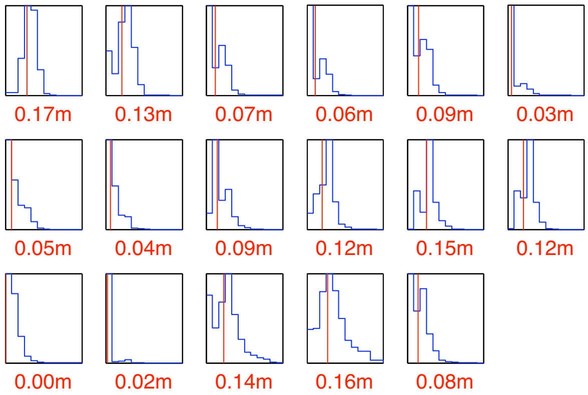

Fig. 11. Histograms of snow thickness collected from arbitrary quadrants across McMurdo Sound. Mean values are represented by the (red) vertical lines. Their locations are not indicated on the panels because they are not important for the current discussion. What is significant is the bimodal character of the histograms with mean thicknesses greater than 0m, which suggests that there is a patchiness in space of the snow thickness–that there is bare ice and the areas are not entirely covered with snow.

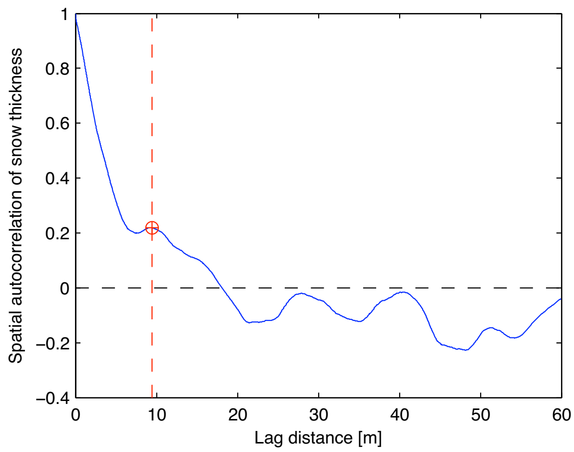

Fig. 12. A spatial autocorrelation plot shows how the correlation of snow thickness values decreases as distance between two points increase, i.e., points that are close to each other are "more related" than are points farther apart. By measuring at intervals much smaller than the spatial variability of snow thickness (2-5cm), information about the decorrelation length and any periodicity emerges. For this example from a profile over first-year ice toward the western end of fast ice in McMurdo Sound early in the spring (November 2009), the decorrelation length is close to 20m (zero decorrelation is represented by the horizontal black broken line). The plot also tells us that some pattern repeats at distances around 10m, which matches our rough observations of snow mounds separated by ice patches of about 4m.

5.1 Radar investigations

Some forward-modeling using the permittivity data and the layering information from the near-infrared photography are in process (not shown here). So are the ground-penetrating radar profiles over the snowpits that were dug. Nikolai Krützmann, who is currently working on a Ph.D. with Wolfgang Rack at the University of Canterbury, is currently processing the data. Information on the snow layers and the roughness of the layer boundaries will be crucial data to compare with what can be gathered from the imaging. Matching of the layer properties will be where wavelet analysis techniques are going to be applied.

5.2 HEM comparisons

Snow thickness retrievals from the HEM bird are still in process. The ground-penetrating radar data will be used to validate the retrieved values and help to determine whether the HEM retrievals are good enough to stand alone without any ground validation of snow thickness.

5.3 Data sharing

Data will be catalogued on `http://polardata.ca/` and made available through the National Snow and Ice Data Center (`http://ipydis.org/data/`).

Snow layer information will be sent to the CryoSat CVRT and be made available through Christian Haas.

Snow thickness histograms, east-west and north-south profiles, as well as spatial autocorrelation data will be uploaded onto the Antarctic Sea ice Processes and Climate (ASPeCt) data archive at `http://www.aspect.aq/data.html`. ASPeCt falls under the auspices of the Antarctica and Global Climate System (AGCS) programme of SCAR. The data will contribute to the determination of long-term, continent-wide distribution of snow on ice by providing in situ snow thickness observations Rignot and Thomas (see 2002).

5.4 Publications and presentations

Recent presentations related to the work that has been done include

– Clavano, W. R., Sharp, M., and Rack, W. "Correcting for uneven illumination in near-infrared images of snow layers in a dry zone, Ross Island, Antarctica." *Sea Ice Symposium*, Dunedin, New Zealand, 18–19 February 2010.

– Clavano, W. R., Haas, C. and Rack, W. "Snow thickness variations over first- and multi-year sea ice using ground penetrating radar." *Snow and Ice Research Group Annual Workshop*, Queenstown, New Zealand, 15–17 February 2010.

I have also been invited to speak locally at the university, at a progressive homeschool class, at an elderly home, as well as the public library, about what it is like to work in Antarctica.

Other upcoming presentations will be at conferences this summer:

- Rack, W., Haas, C., Krützmann, N., Clavano, W., Pinchin, J., Gough, A., and Langhorne, P. "CryoSat-2 validation on land and sea ice in the western Ross Sea Region, Antarctica, based on near-surface remote sensing methods." *Geophysical Research Abstracts* (**12**), EGU General Assembly 2010, Vienna, Austria, 02–07 May 2010.

- Haas, C., Langhorne, P., Gough, A., Clavano, W., Rack, W., and Haskell, T. "Remote detection of the loose platelet layer at the base of a sea ice cover by helicopter-borne electromagnetic induction measurements." *International Symposium on Sea Ice in the Physical and Biogeochemical System*, Tromsø, Norway, 31 May–04 June 2010.

The fellowship has also allowed two papers to be prepared, which are tentatively:

- Clavano, W. R., Rack, W., and Sharp, M. "Using near-infrared images of snow layers to validate ground-penetrating radar profiles".

- Clavano, W. R., Haas, C., and Rack, W. "Thickness distributions of spring snow over land-fast sea ice in McMurdo Sound, Antarctica".

6 Recommendations for Future Work

6.1 Land ice

The only way to validate measurements of coincident ground-penetrating radar profiles is to dig a snowpit and observe the snow properties as they change with depth. A visual inspection should be done and if time and resources allow, density measurements should be taken. Setup for the near-infrared photography is tricky when the pit is small and/or deep. The pit face needs to be properly prepared so that it is as flat as possible with respect to the camera frame; any other touches could potentially affect the arrangement of the crystals and distort the SSA measurement. Furthermore, any uneven illumination needs to be corrected for to be able to convert brightness into appropriate reflectance equivalents. Finally, there is suspicion that transmitted light from within the pack (behind the face) and/or from incident sunlight on the surface behind the pit affects the scattered light from the face. This will need to be investigated in the future.

For snow over land ice, we need to measure the natural variability of the properties of the snow layers at the same point at different times to create a time series at that point. For process studies, this needs to be made at annual scales, so revisiting the site every year during the maximum expected storage would be beneficial.

6.2 Sea ice

For snow over sea ice, because we know very little compared with land ice, measurements of snow thickness need to be made at different times of the year and in different areas: we understand little about how a certain climatology affects snow distribution for different storms and how much is deposited across a subregion.

Sensitivity analysis of the isostatic equilibrium equation will show that because the range of snow density values is large it will contribute significantly to the overall uncertainty of the retrievals. With this in mind, it is will be important to measure the variability in the snow density if and when resources permit.

Towing a radar system behind a snow machine over sea ice is too inhospitable for the equipment (I actually managed to destroyed the system this way). Even, relatively flat sea ice is too hard and irregular for a flat belly antennae system. Besides, extreme conditions like ridges are missed from the profiling. Increased surface roughness over land fast multi-year sea ice make the going very rough and dangerous. Mounting the radar on the side of a snow machine or even alongside the laser altimeter on airborne platforms is being considered.

Finally, as more spatial information becomes available to have an idea of the decorrelation lengths of snow thicknesses over a given area from a type of storm, simple probe measurements can be designed so that the sampling intervals are smaller than any recurring pattern (e.g., bare ice patches). Probe measurements are very reliable and if efficiently conducted, can cover more ground in a shorter time without the need of post-processing the data collected.

7 Conclusions

Near-infrared photography of snowpits facilitates the gathering of information of snow layering over land ice that includes stratigraphy that is made relevant to its electromagnetic properties. The imaging is way of collecting snow data that leaves the samples in their natural state.

Ground-penetrating radar can be used to measure snow thickness over flat areas of land fast sea ice. Valuable spatial information can be gathered from point measurements taken at 5cm intervals. Knowledge of this natural variability can be used to improve the retrievals of snow thickness from airborne and spaceborne sensors. Comparisons with HEM retrievals, in particular, will determine the validity of the instrument as it is or whether mounting a radar system to collect coincident measurements will remove the uncertainty.

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