

CHAPTER VII

IMAGE ANALYSIS

This chapter compares the SAR images from Radarsat and ERS-2 to each other, and to glacier surface measurements. Glaciers, other than the primary study glaciers, and ice-covered lakes in the valley are also examined using SAR imagery. At ASF, the SAR data were converted from decibels to an 8-bit digital number (DN) grayscale so that it can be viewed as an image; pure black is 0 and pure white is 255. Interpretations of the SAR brightness variations to surface characteristics are hypothesized. I anticipated that significant penetration of the radar energy into dry snow would result in an offset of the SAR detected snowline relative to the true snowline. The field measurements collected on Commonwealth and Howard Glaciers are included in Appendixes A and B. Appendix A summarizes the data from the network of stakes measured twice annually to assess the glacier mass balance. The specific data include only those measurements taken in January 1999, close to the date of SAR image acquisition. Appendix B summarizes the data collected along the transect set up between the two reflectors on Commonwealth Glacier.

Surface Brightness Variation.

The standard deviation of surface roughness along the transect on Commonwealth Glacier never exceeded 3.1 cm (Figure 7.1a). The only ablation region that imaged bright (rough) was off the transect, near the terminus, where large melt channels (1-15 m deep) exist and are rougher than the calculated radiometric roughness. No correlation emerged between cover of snow tables or cryoconite holes and SAR brightness (Figure 7.1b,c).

Glacier ice surfaces have less backscatter (darker) than snow surfaces (Figure 7.2). The SAR brightness of four pixels around each sample site (stakes and transect) (Figure 7.3) are averaged, to take into account for errors in geo-location, and compared to SAR brightness. In the ice (ablation) zone, the brightness ranges from DN 141 to 187. The snow (accumulation) zone is brighter, ranging from DN 189 to 249.

As snow depth over ice increases, SAR backscatter increases (Figure 7.4). The linear regression values for both graphs is high $R^2 = 0.75$ and 0.77 . The snow depths in ablation zone are average snow-table or snow patch depths. No linear relationship of brightness to snow depth exists for the ablation zone. This may be due to backscatter dominated by ice surface roughness. The roughness along the transect did not differ significantly yielding a cluster in the ablation brightness points in the snow depth weighted average graph. In the ablation zone the SAR beam is probably specularly reflecting off the buried glacier ice and, to an insignificant extent, volume reflecting in the shallow snow. The brightness linearly increases in the

accumulation zone because the deeper the snow gets, the more it has an opportunity to volume reflect, and less specular reflection off the glacier ice is occurring.

As previously mentioned in chapter five, the precise location of the snowline on Commonwealth Glacier is ambiguous because it is a transition rather than a sharp line. For this analysis, the snowline is where the cover is a minimum of 90%. At T12 and T13, the transition from ice to snow-cover occurs over 100 m; around stake 12 the transition is much longer enlarging the width to 100-250 m. As the snow patches converge, the snow depth increases. At T13, the snow cover was 100% and the average depth 15.3 cm. Along the mass balance stakes the snowline is interpolated to be 485 m below stake 12 (between stakes 11 and 12) ranging from 235-735 m (± 250 m) below stake 12.

Location of the Snowline using SAR. Because T13 is bright in the SAR image and it was just above the actual snowline, it appears that a snow thickness of 15.3 cm can be observed. Both snow tables and snow patches over the ice are likely transparent to the SAR beam. The depths infrequently exceeded 15 cm, averaging 12 cm for snow tables and never exceeding 12 cm on snow patches.

I ran a supervised classification using ENVI to define the SAR snowline (Figure 7.5). The training areas were located on the “dark” ice and “bright” snow zones. Each zone used one training area, consisting of 25-30 pixels each. The snow training area included a four-pixel average of the SAR brightness at T13 (189) to make sure this location was included in the snow class. The snow pixels were assigned the color white, and the dark ice pixels were assigned gray. The SAR

snowline is indicated on the map where the boundary between white and gray occurs and: it is on the glacier, and it is in the approximate location of the snowline (there is a white-gray border at the terminus).

I also ran a second “isodata” unsupervised classification (Duda and Hart, 1973) using ENVI with two classes across the Commonwealth Glacier area (Figure 7.5) (including some non-glacier areas). In an isodata classification technique, initial class means are calculated in each training area and then the pixels are clustered into the nearest class using the minimum distance. The result is similar to the supervised classification (Table 7.1). The unsupervised classification snowline is 0-60 m higher than the supervised classification.

Table 7.1: Supervised and unsupervised SAR classification categories.

Color	Category	Supervised classification (DN)	Unsupervised classification (DN)
Gray	Ice	0-188	0-198
White	Snow	189-255	199-255

Although done quite differently, the two classifications yielded results quite similar. This is part because the analysis was binary. If only the glacier surfaces were used, the similarity would not be too surprising; the rapid change of brightness would separate out in the middle. However, the fact that the unsupervised classification, including substantial areas outside Commonwealth Glacier, closely mapped the snowline is surprising. This fact that an unsupervised (isodata) binary classification

determined the snowline to within 60 m indicates that large areas could be snowline mapped with some accuracy without surface verification.

The SAR snowlines determined by the classification routines compare well with the snowline seen on oblique photographs taken from a helicopter (300-500' above ground level) at the same time as the data collection (Figure 5.5). Only the upper reflector and the meteorological station (near stake 11) are identifiable for ground reference location (the original photographs are slides and these features are difficult to pick out in the reproductions in this thesis). The general shape of the west-side snowline matches the shape and location in the SAR image. On the east side the approximate position and shape of the snowlines in the photograph and the SAR image appear to correspond. Because of the difficulties of comparing a georectified overhead view to a low-altitude oblique photo, the comparisons are only estimated to be good within 200 m. Comparisons between the apparent shapes of the snowlines are within 50 m.

A Landsat 6 image (band 4, near infrared, 0.76-0.90 μm) acquired from United States Geological Survey (USGS) and taken on January 6, 1993 (Figure 7.6a) was utilized to further define the snowline. Although the image was acquired six years prior to the SAR imagery, the shape and location of the snowline, including the ice patch correspond. This suggests some stability in the year-to-year snowline in this region. The SAR snowline also compares well with overhead aerial photographs (INSTAAR MCM LTER website, 2000) taken six years previously (November 1993) (Figure 7.6c). Again, the shape and location of the snowlines, including the ice patch

correspond closely. Both of these images are out of date with the field measurements and SAR images, however, since they both appear to correspond to each other and to the SAR image, the snowline in 1993 was likely vary near to its 1999 shape and location. As mentioned in Chapter III, maximum estimated penetration of SAR into dry snow is 21.7 m (Rott et al., 1993). On Figure 7.6c is a best estimate of where the SAR snowline would be if 10 m of snow were transparent (ten meters was used to include the round-trip path). The location of the estimated SAR penetrated snowline (Figure 7.6c) and the SAR snowline (Figure 7.6b) shows a significant theoretical displacement.

The measured snow data from the transect and stake data is used to compare the accuracy of the two classification snowline results. The supervised classification accurately crossed just below T13, where the snow cover was 100% and the depth was 15 cm, and just above stake 12, where the snowline was patchier and measured 27 cm deep. T13 maps just above the snowline in the supervised classification, since it was used as the lowest brightness for the snow class. The SAR snowline surrounds stake 12 on three sides, forming a cul-de-sac of ice. Using the range of the actual snowline estimated for this region (235 to 735 m below stake 12), the SAR snowline matches the actual snowline. The unsupervised classification snowline crosses T13, 60 m too high and stake 12, 335-585 m too high. The snowline for T13 is within the 100 m transition zone for this area and stake 12 has an arm of the snowline below it that falls within the range of the snowline estimate for the area. Although both

classification schemes identify similar SAR snowlines, the supervised classification seems more accurate.

A problem with the classifications is the misclassification of a dark region near in the upper accumulation zone where no exposed or near-surface ice exists (this region is discussed in more detail later). Anomalies such as this, and areas outside the glacier (which are undefined in this analysis) all require an operator to supervise the classification. The SAR determined snowline in the rest of this analysis will be that resulting from the supervised classification and referred to as the “SAR snowline” (Figure 7.7).

Why Did the SAR Snowline Match the Actual Snowline?

One unexpected result was the match between the SAR snowline and actual snowline. The SAR snowline was anticipated to be displaced up-glacier due to radar penetration through the thin snow layer to glacier ice and reflect away from the sensor. The SAR snowline would be displaced up glacier to a point where the volume reflection of the snow would be sufficient to scatter energy back to the sensor. For example, with a small mass balance gradient with altitude (typical of polar glaciers), and 10 m penetration (10 m in and 10 m out adding to 20 m, the distance that was estimated for full penetration in homogeneous snow by Rott and Mätzler (1987), and Ulaby, et al. (1981)), roughly a 2 km shift would occur in the apparent snowline for a glacier with a 5° slope. This did not occur: the SAR snowline matched the actual

snowline. Three factors are offered to explain this: temperature, sub-surface roughness, and enhanced volume backscattering.

Temperature. Ulaby et al. (1981), pointed out the moisture content of snow greatly affects its reflectivity and small changes in temperature near 0° C have the greatest effect on how the snow scatters. The ice surface might have slightly greater moisture content than the snow because of the albedo differences between the two. Air temperatures during the fieldwork and image acquisition averaged -3° to -4° C (Table 7.2) with a good wind. High sublimation rates are common in the valley, cooling and drying the surface significantly (Lewis et al., 1995). If the ice surface was wetter than the snow, the image should exhibit a broad transition zone between the ice and snow because the patchy snow and ice would present a mixture for the SAR pixels, changing in tone with the changing snow cover. This was not apparent in the image.

Table 7.2: Temperatures at the Commonwealth Meteorological Station.

Date	Average Temperature (° C)	High temp. (° C)	Low temp. (° C)
1/15/1999	-3.41	0.31	-7.86
1/19/1999	-4.51	-2.22	-4.51

Subsurface Roughness. The standard deviation of the subsurface roughness along the transect never exceeded 3.1 cm. The only ablation region that imaged bright due to roughness is near the terminus, where large melt channels (1-5 m deep) exist. It was not noted in any snow pits, nor is it likely that processes are operating on the

smooth snow surface that would cause differential melting and re-freezing of layers that would surpass the wavelength of the SAR (5.66 cm), which is the minimum radiometric roughness.

Enhanced Volume Backscatter. Layers of different density in snow act as a specular reflective surface (Mätzler and Schanda, 1984; Tsang et al. 1985; Ulaby et al., 1981) in which part of the beam is reflected and part transmitted (Figure 7.8). I hypothesize that in thin, dry snowpacks, reflection off multiple internal layers increases the total path length of the beam and enhances the opportunity for volume scattering. Most of the energy would be scattered by the near surface layers because the deeper layers receive less energy and contribute a diminishing portion to volume scattering (Forster et al., 1991; Ulaby et al., 1981).

The snow pits dug on Commonwealth Glacier display multiple snow layers (Figure 7.9). As mentioned previously, the snowline was located only 5 m down glacier from site T13 and 235-745 m below stake 12. The depth of snow at T13 was 15.3 cm, with a brightness of DN 191, and the depth at stake 12 was 27 cm with a brightness of 192. One snow layer was identified at T13 and 5 layers were identified at stake 12. Probing of the snow at T13 revealed at least one layer and perhaps a snow pit would have revealed more.

For enhanced volume backscatter to exist, layers must reflect the radar, causing the beam to volume-interact with the snow at a shallow depth. The volume reflection is then able to escape the snowpack with little attenuation of radar strength. The propagation of radar energy through snow is governed by the snow's relative

dielectric constant (Glen and Paren, 1975; Hall, 1998; Ulaby et al., 1981). For SAR frequencies, the dielectric constant for dry snow is directly related to density (Glen and Paren, 1975),

$$\epsilon = (1 + 0.51\rho_s)^3 \quad (7-1)$$

where ϵ is the relative dielectric constant of dry snow, and ρ_s is the density of snow in g cm^{-3} . An electromagnetic wave passing from a medium with one dielectric to a medium with a different dielectric is reflected and/or refracted. The magnitude of the reflection coefficient is given by

$$\Gamma = \frac{\frac{1}{\epsilon_2^2} - \frac{1}{\epsilon_1^2}}{\frac{1}{\epsilon_2^2} + \frac{1}{\epsilon_1^2}} \quad (7-2)$$

where Γ is the reflection coefficient, ϵ_1 is the dielectric of the first layer, and ϵ_2 is the dielectric of the second layer (Forster et al., 1991).

Using equation 7-2 and snow density data, the reflective behavior of the SAR beam for each layer can be estimated. Density profiles exist for only two pits on Commonwealth Glacier, dug to glacier ice at stakes 12 and 14. The dielectric of air is 1.00, ice is 3.17 for frequencies from 1 MHz to well above the microwave region (Lide, 1999), and the dielectric for snow was calculated using equation (1) and reflection coefficients calculated using equation (2). The densities and reflection coefficients for the layers are shown in Table 7.3. Absolute values were used because the sign of the reflection coefficient only indicates whether the reflected wave is in phase with the incident wave (Alonso and Finn, 1967) and is not important in this

study. Surface layers of snow were too thin (~ 1 cm) to measure at stakes 11 and 12 and densities were inferred from surface layers at the nearest stakes (10 and 14, respectively).

Table 7.3: Reflection coefficients for the layers at Stakes 12 and 14.

Thickness (cm)	Density (g cm^{-3})	Dielectric	Reflection Coefficient for boundary layer below
Stake 12			
surface		1.00	0.06
2	0.15	1.25	0.03
8	0.23	1.39	0.04
5	0.36	1.66	0.04
8	0.24	1.41	0.02
6	0.31	1.55	0.18
glacier ice	0.89	3.17	
Stake 14			
surface		1.00	0.09
1	0.25	1.43	0.01
8	0.29	1.51	0.05
7	0.45	1.86	0.05
26	0.30	1.53	0.04
24	0.19	1.32	0.21
glacier ice	0.89	3.17	

Figure 7.10 shows a hypothetical radar beam path for stake 12. The magnitude of the reflection coefficient was used to scale the width of the radar beam to show relative magnitudes of transmission and reflection. In comparison to the total path length of a snowpack without layers, the five layers in at stake 12 increase the path length by a factor of 1.8. Because the coefficient of reflection is low, only one reflection per layer is shown and the attenuation of the refraction is negligible. Based

on this first order analysis, the 29 cm snow thickness has an effective thickness of 52.2 cm.

Down-glacier from the actual snowline, the snow patches seem to be transparent to the SAR beam, yet their depth, roughly 12 cm, is close to the 15 cm depth of the SAR snowline. Stratigraphic observations indicate that these patches did not contain layers and therefore enhanced volume reflection is minimal. In addition, the patchiness itself reduces the backscatter because of the intervening areas of clear ice. The speckle observed in the ablation zone may be due to large but infrequent patches of snow, although other explanations (e.g. roughness) exist. Resolution of this question requires more field data.

Results from snowline mapping using SAR on Howard Glacier are inconsistent with the results from Commonwealth Glacier. The glacier only appeared on the Radarsat image because the ERS-2 scene did not cover that part of the valley. The aspect and slope of Howard Glacier faced away from the SAR beam at a sharp incident angle of about 10-23°. The entire glacier imaged dark with some tonal variation to indicate the transition from the snow to ice surfaces. However, the terrain correction degraded the resolution of the image sufficiently that it was nearly impossible to use. Because of this, the unprocessed image was used. These poor characteristics are probably attributed to the high incidence angle of the beam.

Enhanced Volume Backscatter is the best hypothesis explaining the shallow volume reflection seen on Commonwealth Glacier. More field data is required to specifically tie SAR brightness to snow depth, layering and density. Also needed is a

range of incidence angles that work for the Taylor Valley snow type, as noted on Howard Glacier the snowline was not accurately mapped, most likely due to excessive incidence angle.

Comparison Between Radarsat and ERS-2.

Figure 7.11 shows that the brightness variations along the transect for each satellite correspond closely with a correlation coefficient of 0.76. The SAR transect was taken from the cliff-edge of the glacier, through the reflectors, to the steep slope on the far edge of the glacier (Figure 7.12). Surface measurements were only collected from the lower reflector to 1 km up glacier from the upper reflector. The glacier margin faced the SAR platform and due to its steep slope was very bright and easily identified on all SAR images. The ridgeline to the north of the glacier, where the SAR transect terminates is mostly bare rock with thin snow at the base.

The ERS-2 image, the lines are offset from each other but exhibit similar patterns (Figure 7.13). This is due to the radiometric correction used in Terrcorr. The difference in magnitude between the two sensors is largest in the ablation zone and smallest in the accumulation zone of the glacier. In the ablation zone, the brightness (except for the reflectors) is rather flat. Farther away from the reflectors the correlation is less because of differences due to projection. The difference between the corrected distance and the uncorrected is almost 1000 m, this occurs because the corrected image is rectified to a DEM and the uncorrected image is still in a reference plane relative to the satellite and not georeferenced. The geometric differences

between these two images effects varying distance measurements. Some of these differences can be seen when comparing the corrected and uncorrected shape of Commonwealth Glacier in Figure 6.11.

The Radarsat corrected and uncorrected brightness values are similar (Figure 7.13) with a correlation coefficient of 0.64. Between the reflectors, they are extremely close with a correlation coefficient 0.91. In the lower half of the snow zone, the values are similar, but in the upper half the reflector brightness comparisons become more ambiguous. Once again, because of projection differences, the uncorrected line terminates 500 m shorter than the corrected line.

The comparison between the two corrected images (Figure 7.14) show that the brightness generally parallels one another ($R^2 = 0.84$). The Radarsat image has two spikes in the brightest part of the snow zone that is absent in the ERS data. The cause of the two spikes is unknown, but the main difference between the SARs is polarization. HH polarization (Radarsat) is sensitive to horizontal features; perhaps there is a buried layer feature the horizontal polarization is efficiently backscattering. The difference in magnitudes between the two transects is that different radiometric corrections were used; however the patterns of brightness (as indicated in the high correlation) is very similar.

The transect crosses the snowline soon after passing the upper reflector and the brightness values gradually increase to the maximum data value (255) and subsequently decreases. The area in the upper snow zone near stake 19, 21, 22, 23 (Figure 7.3) are darker than the surrounding snow areas. The aspect of the stakes is

flat (stakes 20, 21) and northeast (stakes 19, 22, 23). The slope for the whole area is mostly flat with a few areas reaching 11° . Nearby at stakes 17, and 18 the backscatter is very bright and has a northeast (stake 18) or southeast (stake 17) slope. It seems unlikely that orientation to the SAR beam is causing the darker areas; a more likely cause is that there are snow conditions that are reducing the backscatter. Thomas Nylen investigated the area for hard layers around the area of stakes 19 and 21 in November of 2000. The snow surface of the area is covered patches of hard, 3 cm thick wind crust with snow in between (Appendix D). Most of the buried hard layers were fairly thin, some of the ones that could not be punched through, the layer sounded hollow. The snow between the hard layers was soft and easy to pass the probe rod through. The average depth the probe rod could be passed to was 165 cm (35-290 cm). Layers were encountered between 25-180 cm deep. The area is in a gully running from the west-northwest to east-southeast. The region is a depression likely formed by winds draining from higher elevations (Nylen, personal communication). The mass balance at stake 21 is frequently a lower positive balance (hence less snow at the surface) than the neighboring stake 20. Although this observation is made a year and a half after the SAR images were taken, the processes and surface conditions could very well be similar. If this is true, the SAR might be specular reflecting off the hard crusty layer on the surface, or near surface, and not allowing penetration and volume reflection.

The lengths of the corrected SAR transects differ by 300 m (Figure 7.14). This difference could be due to errors in plotting the ends of the transect on the SAR

images, differences in SAR look angle, and random errors unique to each sensor (i.e. accuracy of the precision processor, and spacecraft location error). Were it not for the two spike anomalies and the differences in the overall distances, the two curves would be very close in pattern.

Howard Glacier.

Howard Glacier is only visible on the Radarsat image because the ERS-2 image does not include that part of Taylor Valley. As described in Chapter VI, Howard Glacier slopes to the north at slopes ranging from 10° to 23° creating a local incidence angle of the Radarsat beam of 34° - 47° . Given these geometric characteristics, severe distortions were created in the corrected image and I found the uncorrected image easier to interpret.

Examination of the spatial pattern of tonal differences on Howard Glacier reveals veins running down the axis of the glacier with some dark lines far up into the accumulation zone. The ablation zone is characteristically dark. I determined the SAR snowline on the glacier using the same unsupervised isodata classification procedures previously described. The unsupervised classification was used because the uncorrected image was used for analysis and exact location of snow sample sites cannot be accurately located. Comparing the SAR snow line with observations in the field (Figure 7.15) indicate that that there is uphill displacement of the SAR snowline relative to the snow line, however the locations of the snow survey and transect sample sites is extremely difficult to plot. Examining the snowline from the January

6, 1993 Landsat 6 image shows a snowline that is lower on the glacier than the SAR snowline. The Landsat image is six years out of date, however, the Landsat snowline crosses the mass balance stakes just above stake 30, which corresponds with the field observations. At stake 30, the SAR snowline is displaced up-glacier from the actual (and Landsat) snowline (Figure 7.16). The displacement is caused by the local incidence angle of the beam being large. This causes more specular reflection off all density interfaces than was occurring on Commonwealth Glacier. Volume reflection is occurring within the snow mass, however the snow/air and buried density interfaces specularly reflect higher percentages of the total SAR energy than was occurring on Commonwealth Glacier. The increase in specular reflection off the air/snow surface and shallow snow density interfaces sends more of the SAR energy out of the snowpack leaving little to interact with the snow mass and result in a significant reduction in volume reflection.

Analysis of Other Features of the Valley.

This section compares glaciological features that are identified on SAR images from 1996 and 1999. Four persistent features are noted: “veins, hook, and channeling” on Canada Glacier, and “ripples” near the top of the ablation area on Taylor Glacier. A SAR transect up the centerline on Taylor Glacier is compared to a Landsat 6 image. Finally a comparison between two Taylor Valley lakes shows a dramatic change in backscatter by season.

Persistent Features. Several persistent features are noted on Canada Glacier (veins, hook and channeling) and one on Taylor Glacier (ripples). There are veins of brighter backscatter extending along the axis of the glacier on the east side of Commonwealth Glacier (Table 7.4, Figure 7.17). Judging from other satellite-visible imagery, it appears that more snow has been blown onto the east side of the glacier (Figure 7.6), and indeed, helicopter over flights over the east neck corroborate this observation. The veins were not measured for depth or layering but like T13 and T14, they are likely at least 15 cm deep and have different density layers yielding enhanced volume backscatter.

Table 7.4: Comparison of SAR features.

	Veins (Figure 7.17)	Hook (Figure 7.17)	Channel (Figure 7.18)	Ripples (Figure 7.21)
2/1/1996 Radarsat	Three.	Faint.	Dense and very distinct.	Bright.
3/5/1996 ERS-1	One.	Faint.	Channeling not as apparent as 2/1/1996.	
10/23/1996 Radarsat	Three.	Visible.	Channeling is distinct.	Bright.
10/30/1996 ERS-2	Three.	Visible.	Dense and very distinct.	One ripple.
1/15/1999 ERS-2	Three.	Faint.		
1/19/1999 Radarsat ScanSAR	Indistinct.	Very faint.	Indistinct.	Bright.

The hook on Commonwealth Glacier is a radar feature that appears brighter in the early spring (October), and is barely visible in late summer and fall (January-March) (Table 7.4, Figure 7.17). Air photos taken November 1993 and Landsat in January 1993 show no visible signs of the hook (Figure 7.6). Three mass balance

stakes are within the hook area and data is available for 11/1993 and 1/1996. For 1/12/1996 snow depths range up to 8.5 cm, and 11/11/1996 a snow depths up to 4.0 cm (2/3 of the stakes without snow). Because the depths are so shallow, it is unlikely the hook has anything to do with a thin surface snow layer.

Canada Glacier has deep surface channels near its terminus that are radiometrically rough (Table 7.4, Figure 7.18). No channels are seen on the (c) and the (d) images. The 1/15/1999 image (c) is on the edge of the SAR scene. Because the incidence angle at the near edge is small (16-20°), both sides of the channel are close to being uniformly illuminated and are returning similar backscatter. When the incidence angle is larger, there is more differential SAR illumination of the sides of the channels (and perhaps some shadowing) and the backscatter difference effects a linear channel on the SAR image. A similar effect is happening with the channel in (d). This time the image is not near the edge of the image but the look direction is more perpendicular to the axis of the channels. The difference of illumination of the sides of the channels is small and they do not stand out in the image. Because of the look direction, the shadowing is also greater on the terminus cliff face to the northeast.

A very shallow but long flow-line depression is visible on the (b), (d) and (e) images. This depression does not show on the graphic representations of the DEM (probably due to its 30 m resolution), but the November 1993 air photo confirms its existence (Figure 7.19). On the (f) image this feature is not visible because of the

large pixel size. The fact that it is visible on three out of four of the (non-ScanSAR) images, testifies to the high vertical resolution of the SAR sensors.

The ripples on the upper Taylor Glacier (Figure 7.20) are persistent and are very similar year-to-year (Table 7.4, Figure 7.21). The original hypothesis was that the bright areas were snow accumulations drifted in persistent topographical patterns. Comparing the ripples to the Landsat image reveals only vague similarities to surface snow on the glacier. The lower, right side of the second, and middle of the third ripple corresponds with lines going across the glacier. The lines may be an abrupt slope change, but they do not appear in the contour lines derived from the DEM. The exact nature of what causes these ripples is unknown.

The terminus of Taylor Glacier is consistent in all the SAR images (Figure 7.22). The smooth ice surface specularly reflects the radar yielding a dark gray to black backscatter. The radiometrically rough terminus channels are visible in all the images.

Taylor Glacier Transect. I plotted a transect on the SAR image from the terminus of the Taylor Glacier following the centerline and into the East Antarctic Ice Sheet at the edge of the SAR image. The uncorrected Radarsat image was used because the corrected image did not include much of the upper Taylor due to the border being clipped to the DEM. Four regions are noted: the first three with flat linear trend lines (Figure 7.23). Comparing the SAR image with a Landsat 6 Satellite image (band 4) (Figure 7.20) reveals areas on the SAR image that are likely channels, and ice. The Landsat ice areas are dark to light gray in tone in the SAR image. Three

very bright (SAR) spikes on the graphed transect correspond to the (SAR) “ripples” mentioned previously. The Landsat image shows these areas to *generally* correspond to snowfields, but as mentioned previously detailed boundaries do not line up. The SAR backscatter in these snowfields (ripples) is much brighter than the snow zone further up the glacier. Because the area all through the snowfields is a very low slope ($<3^\circ$) there is no dominating aspect. The reason for the brighter backscatter in this area is unknown, but may have exceptionally efficient volume backscattering enhancement due to snow layering. The satellite image does not cover beyond 116 km on the transect, so the surface characteristics represented by “light dappled” and “dark dappled” areas are not known. The progressively darker backscatter along this upper transect, is consistent with Partington's (1998) SAR image of the highlands of Greenland. Perhaps the dappled areas are hard-packed sastrugi (sharp, irregular ridges formed on a snow surface by wind erosion and deposition) with specular reflection characteristics. Or they could be areas of exposed ice.

Lakes. A comparison of the lakes (Fryxell, and Bonney) in Taylor Valley showed no correlation with satellite polarization. There was, however, a seasonal change. In the austral spring, the lakes are very bright and even in tone; in the summer and fall they become darker and speckled in tone (Figure 7.24). This is likely due to changing melt water on the surface of the lake ice (Fritsen, 1998). The surface of the lake ice is very rough, reaching 1.5 m in amplitude. By January melt-pools fill the hollows with liquid water, slush, and thinly iced-over ponds. The liquid water on the surface of the lake ice is likely absorbing the radar beam and causing the lower

backscatter. Table 7.5 compares the brightness of Lakes Fryxell and Bonney to the nearest glacier ablation area. There is a small brightness difference in the summer and fall and a large difference in the spring.

$$ratio = \frac{glacier_brightness}{lake_brightness} \quad (7-3)$$

The numbers are ratios of an average of 10 random pixels of a lake and an average of 10 random pixels of a nearby glacier (Lake Fryxell used Commonwealth Glacier, and Lake Bonney used Taylor Glacier). Bold indicates data from austral spring.

Table 7.5: Brightness comparison of lake ice and nearby glacier ice.

	Lake Fryxell	Lake Bonney
10/23/1996	0.29	0.34
10/30/1996	0.32	0.22
2/1/1996	1.06	0.62
3/5/1996	0.71	0.80
1/19/1999	0.95	0.72

A comparison between average weekly (the week prior to the SAR image) air temperatures between the lakes and the nearest glacier metrological station strengthens the melt-pool hypothesis (Table 7.5). The air over the lakes is warmer than over the nearest glacier. In the austral fall there would be no liquid water on the glaciers or lakes. In the austral summer and fall, however, the temperatures indicate that lake surface ice melt is probable, and less likely on the glaciers. On both glaciers, the melt water is confined to the bottoms of some cryoconite holes and the bottoms of some large channels, both of which do not cover a large surface area. The temperatures for 3/5/1996 are low enough that any liquid water is unlikely, and the

Lake Fryxell image shows a medium backscatter (Figure 7.24). Perhaps there is still pooled water under a thin cap of ice on the lake ice surface and part of the SAR is penetrating the thin ice cap and being absorbed in the liquid water. Later in the year when this pooled water freezes, the backscatter maximizes reacting to the very rough lake ice surface.

Table 7.5: Average weekly temperature comparison between lake and glacier (°C).

	Austral spring		Austral summer and fall		
	10/23/1996	10/30/1996	1/19/1999	2/1/1996	3/5/1996
Lake Bonney	-22.3	-17.2	-1.9	1.0	-10.7
Taylor Glacier	-22.0	-19.0	-4.2	-1.6	-13.0
Lake Fryxell	-24.5	-19.6	-2.3	0.0	-12.1
Commonwealth Glacier	-23.1	-20.5	-5.2	-2.1	-11.7

Summary.

Glacier surfaces in Taylor Valley are generally radiometrically smooth and appear dark in the SAR image over most of the ablation zone. The snow zone images brighter because of the volume reflection from the entire depth of snow penetrated by the SAR beam. Because of the known penetration characteristics of SAR in dry snow, I expected a displacement of the SAR inferred snowline. In contrast, the SAR inferred and actual snowlines were very close to each other. This correspondence is due to enhanced volume reflection and can reveal the presence of snow depths of only 15 cm deep. Enhanced volume reflection results from layers of different densities acting as a specular reflective surfaces (Mätzler and Schanda, 1984; Tsang

et al., 1985; Ulaby et al., 1981). Reflection off internal layers increases the path length the beam travels (Ulaby et al., 1981), creates more opportunity to scatter in the snow, and increases total reflection. Therefore thin, dry snowpacks with no internal layers will not be visible in SAR imagery.

The corner reflectors worked very well, precisely locating the transect, adding scale, and two known points to the SAR image. The reflectors were placed on smooth glacial ice and the contrast of the dark backscatter of the ice to the brilliant reflection of the reflectors left no doubt to their locations on the image.

SAR can map snowlines in dry snow and be a useful instrument for tracking snowline changes over broad regions. Problems were encountered with a glacier sloping steeply away from the SAR platform, but that condition is readily visible on the image.

Curious and persistent features are compared in 1996 and 1999 SAR images. The Commonwealth Glacier “hook” (Figure 7.17) may be seasonal feature or fading from 1996, but is not visible in any other (non SAR) imagery. SAR imaging of the channeling at the terminus of Canada Glacier is not visible on one image because it is on the near edge of the SAR scene and the incidence angle is very high. This fact illustrates how detailed analysis must take into consideration the location of the SAR when the image is captured.

The time of year is another important consideration to interpreting SAR images. For instance the backscatter of lake surfaces varies dramatically by season. The lake surfaces are three times the minimum radiometric roughness determined in

equation 3-1. In the spring, when no liquid water exists on the lake ice, the rough surface backscatters brightly (Figure 7.24). Later in the year, melt on the surface of the lake ice and pools of liquid water develop on the lake surface (and near-surface). Despite the lake ice rough surfaces, the radar is absorbed and the backscatter is greatly reduced.