Variations in Radar Backscatter Across the Great Ice Sheets

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VARIATIONS IN RADAR BACKSCATTER ACROSS THE GREAT ICE SHEETS

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ABSTRACT

Radar backscatter over the great ice sheets is modulated by the near surface properties of polar firn. These properties (grain size, density, stratigraphy, wetness) change in time and from region to region. Information was compiled on the spatial variation in backscatter across selected parts of Antarctica and Greenland from ERS-1 SAR data. This SAR-derived backscatter information is compared to similar data, collected in situ and from the ERS-1 scatterometer, obtained from literature. These results will be used to refine processing schemes for the Radarsat Antarctic Mapping Project.

Histograms of SAR-derived backscatter coefficients (σ^0) were created to determine the backscatter distribution for ESA ERS-1 SAR PRI images over Antarctica and Greenland. Mean backscatter values ($\bar{\sigma}^0$) for the Antarctic interior, near the Antarctic Peninsula, range from -16dB to -7dB. $\bar{\sigma}^0$ for the Greenland interior is about -10dB. These low values of σ^0 are over the interior where volume scattering from individual snow grains dominates. For the Antarctic ice shelf $\bar{\sigma}^0$ range from -6dB to -3dB. $\bar{\sigma}^0$ for the Greenland percolation zone is about -4dB. These high values of σ^0 are over the ice shelf/percolation zone where there are extensive near surface ice lenses from summer melt events.

The SAR-derived backscatter values compared favorably with both the in situ and the ERS-1 scatterometer data obtained from literature. Data collected in situ have vertical resolution between 15 and 24 cm, but regional accessibility is difficult. The ERS-1 scatterometer data have regional coverage and a spatial resolution is 50 km. The SAR-derived data have both regional coverage and good spatial resolution of 25 m. The above comparisons demonstrate the feasibility for using spaceborne SAR to study the physical properties of snow and ice.

VARIATIONS IN RADAR BACKSCATTER ACROSS THE GREAT ICE SHEETS

1.0 INTRODUCTION:

Radar backscatter over the great ice sheets is limited to the near surface properties of polar firn. These properties (grain size, density, stratigraphy, wetness) change in time and from region to region. The purpose of this report is to compile information on the spatial variation in backscatter (σ^0) across selected parts of Antarctica and Greenland and from ERS-1 SAR data. This SAR-derived backscatter information is compared to similar data, collected in situ and from the ERS-1 scatterometer, obtained from literature. Results discussed in this report will be used to refine processing schemes for the Radarsat Antarctic Mapping Project.

2.0 SAR-DERIVED BACKSCATTER DISTRIBUTION FROM ERS-1 SAR PRI DATA OVER ANTARCTICA AND GREENLAND:

Histograms of SAR-derived backscatter coefficients were created to determine the backscatter distribution for ESA ERS-1 SAR PRI (European Space Agency European Remote Sensing (satellite 1) Synthetic Aperture Radar Precision Image) images over Antarctica, near the Antarctic Peninsula, and Greenland.

2.1 Procedure:

The geographic locations (figures 1a - 7a) were obtained from the IDS home page (<http://polestar.mps.ohio-state.edu/ids/ids.html>), the images (figures 1b - 7b) were obtained from D-PAF processed 8 mm tapes (figures 1b - 5b; Antarctica) and UK-PAF processed CCT's (figures 6b - 7b; Greenland). The images were resampled to 50 meter pixel sizes. The histograms (figures 1c - 7c) of the SAR-derived backscatter coefficient (σ^0_{dB}) were created from the 12.5 m resolution PRI data, prior to resampling, and binned at 0.5dB intervals.

The Antarctic images (figures 1b - 5b) are July, 1992 D-PAF PRI products processed after September 1, 1992. The SAR-derived backscatter coefficient was calculated by the following relationship:

$$\sigma_{dB} = \langle I \rangle_{dB} - K_{dB} + \beta_{dB},$$

where,

$\langle I \rangle_{dB} = 10 \log_{10} (DN^2)$, where I is the pixel intensity and DN is the digital number of a given pixel,

$K_{dB} = 10 \log_{10} K$, where K is the calibration constant equal to 58.24dB for D-PAF processed after September 1, 1992,

$\beta_{dB} = 10 \log_{10} [\sin \theta / \sin \theta_{ref}]$, where β is the incidence angle correction factor, θ ranges from 19.5° at near range to 26.6° at far range, and $\theta_{ref} = 23^\circ$,

(Laur, 1992).

The Greenland images (figures 6b - 7b) were obtained on October, 1991 and March, 1992, respectively. They are UK-PAF PRI products processed prior to September 1, 1992. The SAR-derived backscatter coefficient was calculated by the following relationship:

$$\sigma_{dB} = \langle I \rangle_{dB} - K_{dB} + \beta_{dB} - G^2_{dB}$$

where,

$\langle I \rangle_{dB} = 10 \log_{10} (DN^2)$, where I is the pixel intensity and DN is the digital number of a given pixel,

$K_{dB} = 10 \log_{10} K$, where K is the calibration constant equal to 59.49dB for UK-PAF processed prior to September 1, 1992,

$\beta_{dB} = 10 \log_{10} [\sin \theta / \sin \theta_{ref}]$, where β is the incidence angle correction factor, θ ranges from 19.5° at near range to 26.6° at far range, and $\theta_{ref} = 23^\circ$,

$G^2_{dB} = 10 \log_{10} (g^2(\alpha))$, where G^2 is the in-flight antenna pattern correction factor and α is the look angle

(Laur, 1992).

2.2 Discussion:

Histograms of SAR-derived backscatter coefficients were created to determine the backscatter distribution over Antarctica and Greenland. SAR-derived backscatter values for the Antarctic interior ice sheet (figures 1c and 2c) range from -33dB to +5dB with an approximate mean σ^0 ranging between -7dB and -16dB. SAR-derived backscatter values for the Greenland interior ice sheet (figures 7c) range from -22dB to -2dB with an approximate mean σ^0 of -10dB. These low values of σ^0 are over the interior where volume scattering from individual snow grains dominates.

SAR-derived backscatter values for the Antarctic ice shelves (figures 3c and 4c) range from -20dB to +5dB with an approximate mean σ^0 ranging between -3dB and -6dB. SAR-derived backscatter values for the Greenland percolation zone (figures 6c) range from -18dB to +5dB with an approximate mean σ^0 of -4dB. These high values of σ^0 are over the ice shelf/percolation zone where there are extensive near surface ice lenses from summer melt events.

SAR-derived backscatter values for a combination of the Antarctic Peninsula and Larsen ice shelf (figures 5c) range from -30dB to +5dB. This distribution is bimodal with mean σ^0 of approximately -6dB and -17dB. These values match well with the ice shelf and interior ice sheet values quoted above.

The SAR-derived backscattered values discussed thus far are summarized in Table 1:

Table 1		SAR-DERIVED BACKSCATTER VALUES (Winter)		
SITE		MIN	MEAN	MAX
Fig. 1	(Antarctic interior)	-25	-7	5
Fig. 2	(Antarctic interior)	-33	-16	3
Fig. 3	(Antarctic ice shelf)	-20	- 6	1
Fig. 4	(Antarctic ice shelf)	-16	- 3	5
Fig. 5	(Antarctica bimodal)	-30	-17 & -6	5
Fig. 6	(Greenland percolation)	-18	- 4	5
Fig. 7	(Greenland interior)	-22	-10	-2

A summary of derived backscatter values in dB for incidence angle ranging from 19.5 to 26.6°, C-band, ERS-1 SAR data.

3.0 A SUMMATION OF BACKSCATTER CHARACTERISTICS FROM LITERATURE

A summation of backscatter data, collected in situ and from the ERS-1 scatterometer, for Antarctica and Greenland including azimuthal anisotropy of backscatter for two sites in Antarctica follows.

3.1 Antarctica:

Measurements were made by Rott and others (1993) in the summer of 1989-90 with a dual frequency scatterometer/radiometer suspended 3.5 meters above the surface. Figure 8 compares C-band (5.3 GHz) and X-band (10.3 GHz) backscattering coefficients (σ°) at polarizations VV ($\square$), HH (+), VH (x), and HV ($\diamond$) versus incidence angle (θ), measured at three sites in Antarctica. For VV and HH polarizations at incidence angle of 20° , the backscattering coefficients range from -5dB to -12dB for C-band and 0dB to -7dB for X-band, from site to site. Between incidence angle of 10° and 50° the σ° decrease by about 15dB for C-band and 15dB to 20dB for X-band, however, the variation between VV and HH polarizations remains constant.

Rack (1995) presents the averaged backscatter coefficients for full coverage of Antarctica for latitudes below 78.8°S . Figure 9 shows the ranges of averaged backscatter coefficients ($-4 < \sigma^\circ < -16$) from the ERS-1 scatterometer for April 5-30, 1993, with incidence angles between 30° and 40° . Figures 10 a, b, and c compare the range of averaged σ° for the periods of (a) July 1-August 4, 1992, (b) December 1-January 1, 1993, and (c) April 5-30, 1993 for continental Antarctica, the Antarctic ice shelves and sea ice. Ice shelf σ° values for winter (figures 10 a and c) range from -4dB to -7dB and for summer (figure 10b) range from -13dB to -16dB. The interior ice sheet σ° values appear to change little and range from -4dB to -13dB. Notice that the most pronounced change in σ° from winter (figures 10 a and c) to summer

(figure 10b) occurs along the Antarctic Peninsula where σ^0 decreases from a range of -4dB to -7dB in austral winter to a range of -13dB to -16dB in austral summer. This 10dB change is presumably associated with summer melts.

3.2 Greenland:

In 1992, Jezek and others (1994), performed surface-based microwave radar measurements at 5.3 GHz and 13.3 GHz with VV polarization on the western flank of the Greenland Ice Sheet. A bandwidth of 700 MHz was employed resulting in a resolution of around 24 cm. Figures 11 a and b show the volume backscatter coefficient (σ_v^0) of the glacial surface (values representative of the interior ice sheet) and ice layer (values representative of the percolation zone) at 5.3 GHz (C-band) and 13.3 GHz (Ku-band) over a range of incidence angle from 0° to 50°. Note that σ_v^0 is related to the surface backscatter coefficient (σ_s^0) by $\sigma_v^0 - 7\text{dB} = \sigma_s^0$, and a higher σ_v^0 is expected at 13.5 GHz since a shorter wavelength leads to more scattering from large snow grains and the rough surfaces of the ice layers. At incidence angle of 25° the glacier surface has σ_v^0 of -12dB at 5.3 GHz, and -9dB at 13.3 GHz (figure 11). At incidence angle of 25° the ice layer has σ_v^0 of -4dB at 5.3 GHz, and +3dB at 13.3 GHz (figure 11). As the incidence angle increases from 20° to 50°, σ_v^0 for the glacier surface decreases by about 10dB for both frequencies. Figure 11c shows the total surface backscatter coefficient, σ^0 , of the glacial surface at 5.3 GHz and 13.3 GHz over a range of incidence angles from 0° to 50°. At incidence angle of 25°, σ^0 is approximately -3dB at 5.3 GHz, and approximately +1dB at 13.3 GHz. Between incidence angle of 20° and 50° the σ^0 decrease by 4dB at 5.3 GHz and 3dB at 13.3 GHz.

Zabel and others (1995), obtained an evolving radar signature from high-resolution radar measurements of summer surface melting and refreezing of meltwater in the percolation zone of the Greenland ice sheet. Observations were made on four consecutive days, June 23, 24, 25, 26, 1993. It is important to note a progressive decline in the mean air temperature from +1.5 °C on 23 June to -3 °C on 26 June.

The radar used was a 13.5 GHz FMCW radar with a 2 GHz bandwidth allowing for an 11 cm resolution in snow. To compensate for spatial resolution differences between the ERS-1 SAR (5.3 GHz) and the radar used for these measurements, a total equivalent backscatter coefficient was computed by assuming a return effectively coming from the surface but with power integrated over the contributions at depth. However, an absolute comparison of σ° is not possible due to the different frequencies. Table 2 depicts the σ° in dB for three incidence angles on four consecutive days.

Table 2: BACKSCATTER VALUES (Summer & 13.5 GHz)

DATE	$\theta = 0^\circ$	$\theta = 20^\circ$	$\theta = 40^\circ$
23 June 1993	11.9	-10.7	-12.2
24 June 1993	13.7	-0.2	-10.0
25 June 1993	11.1	2.4	2.2
26 June 1993	14.3	1.0	2.7

Total equivalent surface backscatter coefficient for three angles of incidence (θ) on four consecutive dates (note an associated decrease in temperature). Higher backscatter is expected at 13.5 GHz, since a shorter wavelength leads to more scattering from large snow grains and the rough surfaces of the ice layers (Zabel et. al., 1995).

The variation of σ° at θ of 20° and VV polarization ranges from -10.7dB on 23 June to -0.2dB, 2.4dB and 1.0dB on the 24, 25 and 26 June, respectively. The low total σ° on 23 June is believed to be a result of low penetration due to snow surface wetness. The higher backscatter values on 24, 25, and 26 June are due to the snow freezing.

3.3 Azimuthal Anisotropy (Antarctica):

Rott and Rack (1995) present the azimuthal anisotropy of backscattering over Antarctica based on scatterometer measurements of ERS-1, operating at 5.3 GHz and VV polarization for the period extending from April 5-30, 1993. The angular dependence of σ° in the range of incidence angle $19^\circ \leq \theta \leq 59^\circ$ is given by:

$$\sigma^\circ(\theta) = A + B(40-\theta) + C(40-\theta)^3 [dB].$$

The values of the empirical parameters A, B, and C for a particular site are specified in figures 12a and b. Figure 12a shows little azimuthal anisotropy (φ) of σ° near the Siple Station, located at an elevation 1054 m. This area experiences high accumulation, permanently dry snow, and little wind. Values for σ° decrease with increasing incidence angle by approximately 12dB. Figure 12b shows pronounced azimuthal anisotropy of σ° for an area in Princess Elizabeth Land, located at an elevation 2500 m. This area experiences strong katabatic winds. The curves are plotted for the φ -ranges of 180° to 200° and 260° to 280° . At incidence angle of 25° the total range of σ° for different azimuth angles is about 13dB. This range of σ° decreases with increasing incidence angle to about 8dB.

3.4 Discussion:

The SAR-derived backscatter values, discussed earlier, compare favorably with both the in situ and the ERS-1 scatterometer data obtained from literature. Data collected in situ have free-space resolution between 15 and 24 cm, but regional accessibility is difficult. The ERS-1 scatterometer data have regional coverage and spatial resolution of 50 km. The SAR-derived data has the advantage of both regional coverage and good spatial resolution of 25 m. These comparisons demonstrate the feasibility and some of the advantages for using spaceborne SAR to study the physical properties of snow and ice.

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APPENDIX

GEOGRAPHICAL LOCATION

Figure 1.a.

ORBIT-FRAME: 05192-05211
CENTER LATITUDE: 75.440 S
CENTER LONGITUDE: 286.423

Figure 1.b. Antarctic interior ice sheet (near Antarctic Peninsula).

BACKSCATTER COEFFICIENT HISTOGRAMS

Showing backscatter values (dB) for the full image

Minimum: -58.8926 dB

Maximum: 24.4408 dB

Figure 1.c.

GEOGRAPHICAL LOCATION

Figure 2.a.

ORBIT-FRAME: 05407-05805
CENTER LATITUDE: 70.840 S
CENTER LONGITUDE: 294.512

Figure 2.b. Antarctic interior ice sheet (near Antarctic Peninsula).

BACKSCATTER COEFFICIENT HISTOGRAMS

Showing backscatter values (dB) for the full image

Minimum: -46.3172 dB

Maximum: 16.7177 dB

Figure 2.c.

Figure 3.a.

GEOGRAPHICAL LOCATION

ORBIT-FRAME: 05350-05085
CENTER LATITUDE: 70.842 S
CENTER LONGITUDE: 288.043

Figure 3.b. Antarctic ice shelf (Antarctic Peninsula).

BACKSCATTER COEFFICIENT HISTOGRAMS

Showing backscatter values (dB) for the full image

Minimum: -45.9349 dB

Maximum: 19.0807 dB

Figure 3.c-1.

BACKSCATTER COEFFICIENT HISTOGRAMS

Showing backscatter values (dB) for partial image (less sea ice portion)

Minimum: -34.4663 dB

Maximum: 19.0807 dB

Figure 3.c-2.

GEOGRAPHICAL LOCATION

Figure 4.a.

ORBIT-FRAME: 05035-05013
CENTER LATITUDE: 67.896 S
CENTER LONGITUDE: 295.958

Figure 4.b. Antarctic ice shelf (Antarctic Peninsula).

BACKSCATTER COEFFICIENT HISTOGRAMS

Showing backscatter values (dB) for the full image

Minimum: -33.3836 dB

Maximum: 22.1891 dB

Figure 4.c.

GEOGRAPHICAL LOCATION

Figure 5.a.

ORBIT-FRAME: 05350-04995
CENTER LATITUDE: 67.079 S
CENTER LONGITUDE: 295.138

Figure 5.b. Antarctic Peninsula and Larsen ice shelf.

BACKSCATTER COEFFICIENT HISTOGRAMS

Showing backscatter values (dB) for the full image

Minimum: -58.8860 dB

Maximum: 23.1089 dB

Figure 5.c.

GEOGRAPHIC LOCATION

Figure 6.a.

ORBIT-FRAME:	01111-02169
CENTER LATITUDE:	70.689 N
CENTER LONGITUDE:	313.715

Figure 6.b. Greenland percolation zone (ice shelf).

BACKSCATTER COEFFICIENT HISTOGRAM

Showing bckscatter values (dB) for the full image

Minimum: -35.559761

Maximum: 7.550394

Figure 6.c.

GEOGRAPHIC LOCATION

Figure 7.a.

ORBIT-FRAME:	03304-02064
CENTER LATITUDE:	75.687 N
CENTER LONGITUDE:	319.023

Figure 7.b. Greenland interior ice sheet.

BACKSCATTER COEFFICIENT HISTOGRAM

Showing bckscatter values (dB) for the full image

Minimum: -38.540985

Maximum: 1.761467

Figure 7.c.

Figure 8. C-band (top row) and X-band (bottom row) backscattering coefficients at the polarizations VV ($\square$), HH (+), VH ($\times$), HV ($\diamond$) versus incidence angle, measured at sites Veststraumen, Base Camp, and Amundsen Ice, Antarctica (Rott et al., 1993).

Figure 11a.b.c. (a) and (b) give the angular variation of the volume backscatter coefficient from the glacial surface (representative of the interior) and from the ice layer (representative of the percolation zone). (c) gives the total surface backscatter coefficient as a function of incidence angle: Greenland (Jezek, et. al., 1994).

Figure 12. (a) Shows little azimuthal anisotropy (φ) of backscatter (σ°) near Siple Station, Antarctica. This area experiences high accumulation, permanently dry snow, and little wind (Rott and Rack, 1995). (b) Shows pronounced azimuthal anisotropy (φ) of backscatter (σ°) for an area in Princess Elizabeth Land, Antarctica. This area experiences strong katabatic winds (Rott and Rack, 1995).

Figure 9. Averaged backscatter coefficients from ERS-1 scatterometer for April 5-30, 1993, with incidence angle between 30° and 40° for continental Antarctica (Rack, 1995).

Figure 10 a.b.c. Compares the range of averaged backscatter coefficients for the periods of July 1-August 4, 1992 (a), December 1 - January 1, 1993 (b), and April 5-30, 1993 (c) for continental Antarctica, the Antarctic ice shelves, and sea ice (Rack, 1995).