UNUSUAL RADAR ECHOES FROM THE GREENLAND ICE SHEET

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1. INTRODUCTION

In June 1991, the NASA/Jet Propulsion Laboratory airborne synthetic-aperture radar (AIRSAR) instrument collected the first calibrated data set of multifrequency, polarimetric, radar observations of the Greenland ice sheet (Rignot et al., 1993). At the time of the AIRSAR overflight, ground teams recorded the snow and firn (old snow) stratigraphy, grain size, density, and temperature (Jezek and Gogineni, 1992) at ice camps in three of the four snow zones identified by glaciologists to characterize four different degrees of summer melting of the Greenland ice sheet (Benson, 1962). The four snow zones are: 1) the dry-snow zone, at high elevation, where melting rarely occurs; 2) the percolation zone, where summer melting generates water that percolates down through the cold, porous, dry snow and then refreezes in place to form massive layers and pipes of solid ice; 3) the soaked-snow zone where melting saturates the snow with liquid water and forms standing lakes; and 4) the ablation zone, at the lowest elevations, where melting is vigorous enough to remove the seasonal snow cover and ablate the glacier ice. There is interest in mapping the spatial extent and temporal variability of these different snow zones repeatedly by using remote sensing techniques. The objectives of the 1991 experiment were to study changes in radar scattering properties across the different melting zones of the Greenland ice sheet, and relate the radar properties of the ice sheet to the snow and firn physical properties via relevant scattering mechanisms. Here, we present an analysis of the unusual radar echoes measured from the percolation zone.

2. EXPERIMENTAL RESULTS

Figure 1 shows average values of the radar reflectivity σ^0_{RL} (i.e., receiving right-circular polarized signals and transmitting left-circular polarized signals) obtained by averaging the radar measurements recorded by AIRSAR at the Crawford Point site in the percolation zone along the flight path as a function of the incidence angle of the radar illumination θ. At 5.6 and 24 cm, σ^0_{RL} is higher than unity at 18°, and decreases toward higher incidence angles. At 68 cm, σ^0_{RL} is ten times lower, and shows kilometer-scale spatial variations. Figure 1 also shows the circular polarization ratio, $\mu_C = \sigma^0_{RR}/\sigma^0_{RL}$, and the linear polarization ratio $\mu_L = \sigma^0_{HV}/\sigma^0_{HH}$ obtained at the Crawford Point site. These ratios of echo power in orthogonal senses are defined to be equal to zero for specular backreflection from a perfectly smooth dielectric surface. μ_C is larger than unity at 5.6 and 24 cm for incidence angles larger than 30° and 45°, respectively, increasing to 1.6 and 1.4 at 66°. At 68 cm, μ_C is everywhere less than 0.8 and drops as low as 0.1 in some places, with kilometer-scale spatial variations negatively correlated with those observed in the radar reflectivity images. μ_L is as large as 0.46 at 5.6 cm and 0.22 at 24 cm, but remains less than 0.1 at 68 cm.

In the AIRSAR scenes of the Swiss camp and the GISP II sites, at all three wavelengths, σ^0_{RL} are 10 to 30 times lower than at Crawford Point; μ_C is less than 0.4, and μ_L is less than 0.1. To the best of our knowledge, no natural terrestrial surface other than the Greenland percolation zone shows strong echoes with $\mu_C > 1$ and $\mu_L > 0.3$ (see Figure 1 caption). However, strong echoes with large values of μ_C and μ_L have been reported for the icy Galilean satellites since the

1970's (Ostro et al., 1992). More recently, radar observations of the Mars residual south polar ice cap (Muhleman et al., 1991), portions of Titan (Muhleman et al., 1990), and polar caps on Mercury (Slade et al., 1992) have revealed that surfaces with high radar reflectivity and $\mu_C > 1$ exist elsewhere in the solar system. Figure 1 shows that the mean values of disk-integrated radar reflectivities σ^0_{OC} and circular and linear polarization ratios μ_C and μ_L for Europa, Ganymede, and Callisto at 3.5 and 13 cm resemble those of the percolation zone at 5.6 and 24 cm, and dwarf the values reported for other terrestrial surfaces. Yet, Greenland's average values at 24 cm are several tens of a percent lower than at 5.6 cm, and $\mu_C < 1$ at 68 cm, indicating a change in the scattering process at the longer wavelengths, whereas 70-cm estimates of μ_C for the icy satellites apparently exceed unity (Campbell et al., unpublished data). Also, μ_C for the percolation zone decreases significantly from 66° to 18°, whereas no such difference has been noticed for the icy satellites (Ostro et al., 1992); and σ^0_{RL} is a much stronger function of the incidence angle than in the case of the icy satellites (Ostro et al., 1992).

3. INTERPRETATION

Zwally (1977) suggested that ice inclusions could explain low emissivities measured for the percolation zone by spaceborne microwave radiometers. Since then, surface-based radio sounding experiments, and airborne active and passive microwave measurements (Swift et al., 1985), have supported the hypothesis that volume scattering from subsurface ice layers and ice pipes is the major influence on the radar returns. Recent surface-based radar observations conducted at Crawford Point (Jezek and Gogineni, 1992) at 5.4 and 2.2 cm provided clear evidence that, at incidence angles between 10° and 70°, most of the scattering takes place in the most recent annual layer of buried ice bodies. Studies of the snow stratigraphy at Crawford Point at the time of the radar flight indicate that the ice inclusions from the previous summer melt were at 1.8 m below the surface. Ice layers and ice lenses, a millimeter to a few centimeters thick, extend at least several tens of centimeters across, parallel to the firn strata. Ice pipes, several centimeters thick and several tens of centimeters long, are vertically extended masses reminiscent of the percolation channels that conduct meltwater down through the snow during summer, feeding ice layers. The fact that radar returns measured at 68 cm are significantly weaker and have lower polarization ratios than those at 5.6 and 24 cm suggests that the discrete scatterers responsible for the radar echoes are of typical dimension less than a few tens of centimeters, similar to the scales of the solid-ice inclusions. The 68-cm echoes probably are dominated by single reflections from deeply buried layers of denser firn or concentrated ice bodies, whereas the 5.6- and 24-cm echoes probably are dominated by multiple scattering from the ice layers and pipes in the most recent annual layer. The relatively sharp decrease in μ_C and μ_L for θ less than 40° perhaps reveals the presence of a strong, specular reflection from the ice layers at small incidence angles, which is also suggested by the strong dependence of radar reflectivity on incidence angle. Ice layers and pipes also form in the soaked zone, but the snow there is so saturated with liquid water that the radar signals are strongly attenuated, cannot interact with the buried ice formations, and hence yield echoes with low reflectivities and polarization ratios. In the dry-snow zone, the snow is dry, cold, porous, clean, and therefore very transparent at microwave frequencies, but does not contain solid-ice scatterers that could interact with the radar signals.

For the satellites, no in-situ measurements exist, but theoretical interpretations favor subsurface coherent volume scattering as the source of the radar signatures (Hapke, 1990), a phenomenon also known as weak localization (see van Albada et al., 1990 for a review). Coherent backscattering can theoretically produce strong echoes with $\mu_C > 1$ (the helicity of the incident polarization is preserved through multiple forward scattering) and $\mu_L \approx 0.5$, provided that (i) the scattering heterogeneities are comparable to or larger than the wavelength (Peters, 1992), and (ii) the relative refractive index of the discrete, wavelength-sized scatterers is smaller than 1.6 (Mishchenko, 1992). As noted by Ostro and Shoemaker (1990), prolonged impact cratering of the satellites probably has led to the development of regoliths similar in structure and particle-size distribution to the lunar regolith, but the high radar transparency of ice compared with that of silicates permits longer photon path lengths, and higher-order scattering. Hence coherent backscatter can dominate the echoes from Europa, Ganymede, and Callisto, but contributes negligibly to lunar echoes. Similarly, the upper few meters of the Greenland percolation zone are relatively transparent (unlike the soaked zone) and, unlike the dry-snow zone, contain an abundance of solid-ice scatterers at least as large as the radar wavelength, with a relative refractive index of about 1.3, so coherent backscatter also can dominate the echoes there. However, the detailed subsurface configurations of the satellite regoliths, where heterogeneities are the product of meteoroid bombardment, are unlikely to resemble that within the Greenland percolation zone, where heterogeneities are the product of seasonal melting and freezing.

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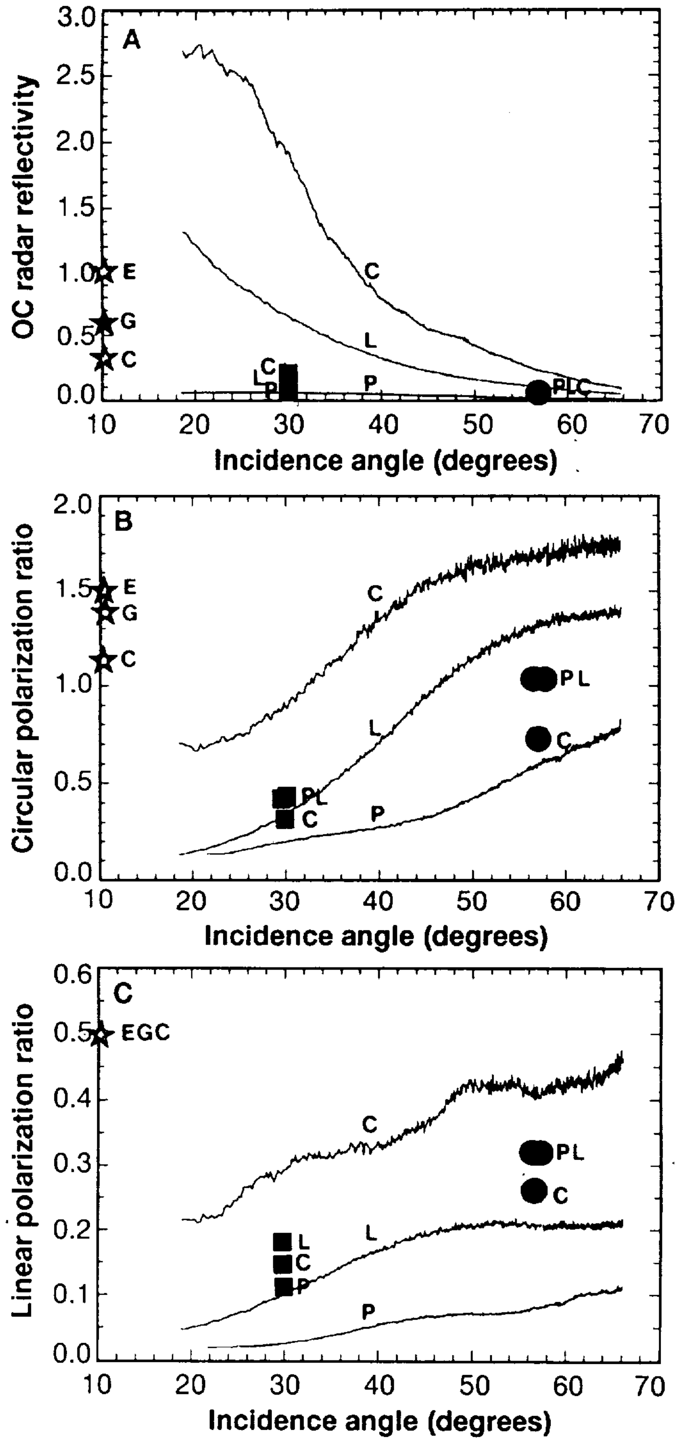

Figure 1. Average values of the (A) OC radar reflectivity σ^0_{RL}, (B) circular polarization ratio $\mu_C = \sigma^0_{RR}/\sigma^0_{RL}$, and (C) linear polarization ratio $\mu_L = \sigma^0_{HV}/\sigma^0_{HH}$ for the Greenland percolation zone obtained by averaging the radar measurements recorded by AIRSAR at Crawford Point along the flight path, at 5.6 (C-), 24 (L-), and 68 cm wavelength (P-), as a function of the incidence angle of the radar illumination. Radar backscatter values and polarization ratios measured from wavelength-sized roughness on a surface of lava (black squares) (J. J. van Zyl, C. F. Burnette, and T. G. Farr, *Geophys. Res. Lett.* **18**, 1787 (1991)) and from tropical rain forest (black dots) (A. Freeman, S. Durden, and R. Zimmerman, Proc. of the Int. Geos. Rem. Sens. Symp., Houston, Texas, May 26-29, IEEE New York Pub., 1686 (1992)) are also shown in the Figure. The values indicated for the icy satellites Europa (E), Ganymede (G), and Callisto (C) are disk-integrated average measurements at 3.5 and 13 cm wavelengths (Ostro et al., 1992).