lion depicted in figure 2, had an overall degree of polarization of about 20 percent, but near its inner edge the polarization was considerably less because of the birefringence effect. No change of sign of the polarization was observed in that region.

- The 120° parhelion is in horizontally polarized light about 0.2° higher over the horizon and 0.05° closer to the sun than in vertically polarized light (solar elevation 23°). These values are in agreement with those calculated from the internal reflection laws for birefringent substances for this solar elevation. The vertical shift of that halo in polarized light could be seen visually; the horizontal one not.

The fieldwork has been performed in cooperation with W. Tape. J. H. M. van Lieverloo, KIWA, assisted with the size determinations, and R. S. Le Poole provided assistance in using the Leiden University Astroscan densitometer. J. Tinbergen advised on the polarimetry; the camera was rebuilt by H. Deen, Kapteyn Observatory, Roden. This research was supported by National Science Foundation grant DPP 88-16515 and partly by the Netherlands Organization for Scientific Research.

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Spectral reflectance of antarctic snow: "Ground truth" and spacecraft measurements

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The cold climate of Antarctica is a result of the high reflectance of snow and of the corresponding small amount of energy that is absorbed from the incident sunlight. The energy-absorption rate depends on such variables as grain size, impurities, and incidence angle, as well as on the wavelength of the incident light. In the visible region, ice is highly nonabsorbing, but becomes a strong absorber in the infrared because of molecular vibrational transitions. To understand energy-absorption rates, it is important to investigate the optical properties of antarctic snow over an extended wavelength range—from the ultraviolet to the infrared. Furthermore, for climatological purposes, it is important to understand these properties throughout the antarctic continent. This can only be accomplished by a program of aircraft or satellite remote sensing measurements in conjunction with locally established "ground truth."

In this article, we briefly describe field measurements of the spectral reflectance of snow at two sites, and compare the optically derived snow grain sizes with photographic measurements of the surface grains. These "ground-truth" data are then used to corroborate spacecraft remote-sensing measurements, thereby extending our localized measurements to continental scales.

The field measurements were obtained in December 1989 at the Amundsen-Scott South Pole Station and in December 1991 at the Vostok Station (78° S 107° E). The field instrumentation consists of a portable diffraction-grating spectrometer mounted on a 1-meter-long goniometric arm. This arm swings in a vertical plane, allowing spectral measurements to be obtained over nearly a 180-degree range of emission angles . We obtained complete spectra for nadir viewing with a variety of solar zenith angles. The goniometric measurements were obtained for a variety of individual wavelengths, both inside and outside of water absorption bands. Here we discuss only a few of the spectra and none of the goniometric measurements.

The experimental procedure was used to measure the spectral radiance for a chosen area of snow, which receives sunlight as well as diffuse radiation from the sky. We then block the sunlight and measure the radiance for only incident skylight. The procedure is repeated using calibrated diffuse reflectance standards such as Halon and sulfur surfaces. With this set of measurements, we obtain the bidirectional reflectance of the snow surface and the diffuse-directional reflectance appropriate to skylight. We also find the relative contribution of diffuse skylight to the total radiance, which is appreciable in the ultraviolet and blue regions of the spectrum.

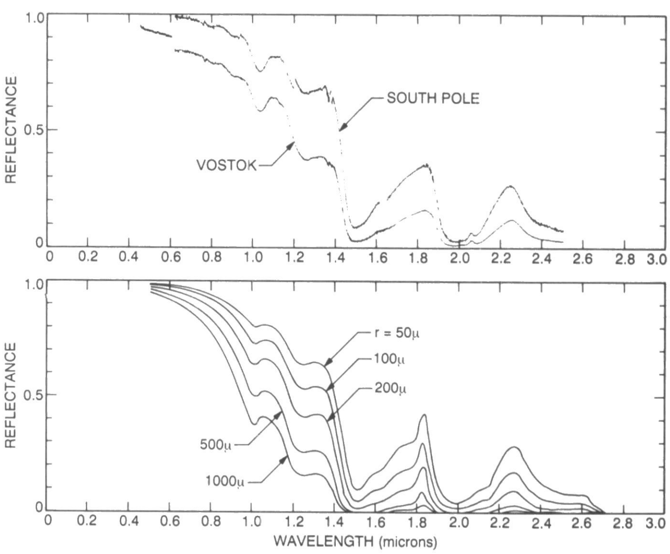

Figure 1. Spectral reflectance of snow. The upper panel is directional-directional reflectance spectra measured at the South Pole and Vostok stations. For both sites, the incidence angle was about 68 degrees and the emission angle was zero, relative to the vertical. The lower panel shows theoretical directional (60 degree)-hemispherical reflectances, computed for varying grain radii by Wiscombe and Warren (1981). A comparison indicates that snow particles at South Pole and Vostok are about 50 and 200 microns in radius, respectively.

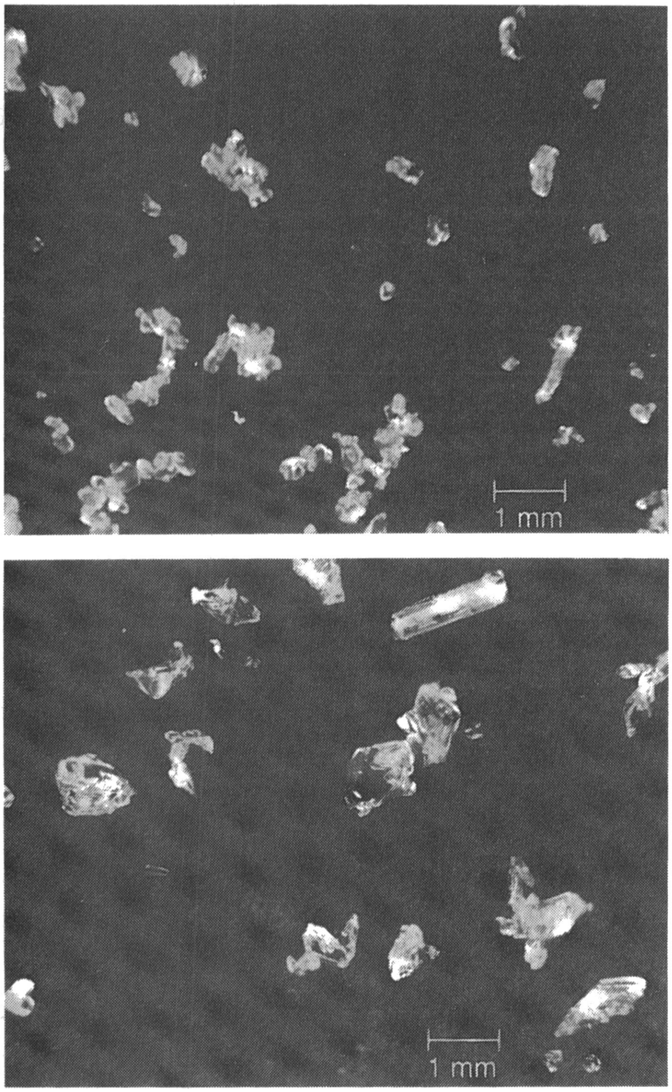

Figure 2. Photographs of surface snow grains. The upper panel shows a representative sample found at the South Pole December 1989, while the lower panel is for Vostok, December 1991. The Vostok grains are several times larger than those of the South Pole, in agreement with their spectra.

Spectra obtained at South Pole and Vostok are shown in figure 1. The well-known water-ice absorption features occurring at 0.81, 0.90, 1.04, 1.25, 1.50, 1.65, and 2.0 microns are quite evident. All of these absorption features are stronger in the Vostok spectrum than for South Pole. This can be explained as longer path lengths for light passing through the absorbing ice grains, i.e., the snow particles at Vostok are larger than those at South Pole.

We can quantify the differences in grain size by comparing the observed spectra with the theoretical reflectance spectra computed by Wiscombe and Warren (1981), which are shown in the bottom panel of figure 1. Comparing the observed and theoretical spectra, we estimate that the mean grain radius at South Pole is roughly 50 microns, while Vostok snow grains possess a mean radius of about 200 microns.

These spectroscopic radii are in good agreement with direct measurements. Representative photographs of surface snow grain samples are shown in figure 2. At the South Pole, a mean photographically derived radius of 75 microns is found and is somewhat larger than the above spectroscopic value of 50 microns. At Vostok, a 200-micron radius was found for both the photographic and spectral measurements.

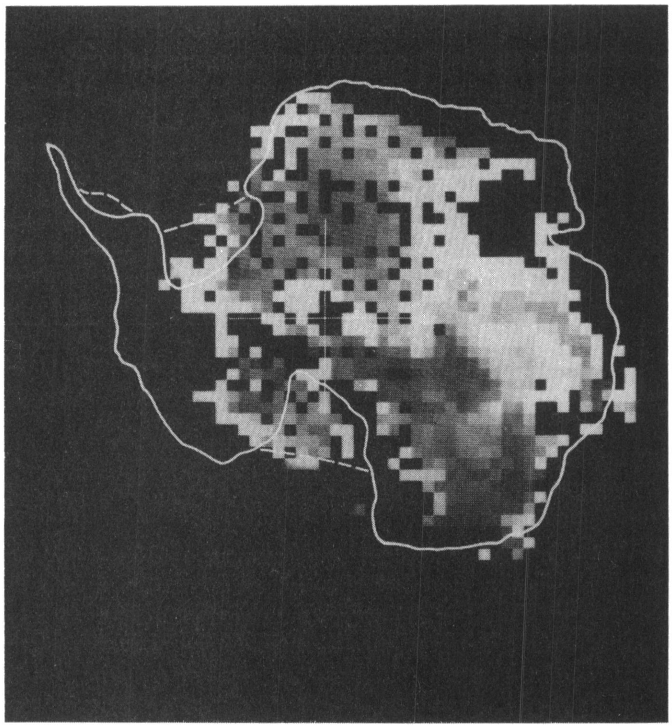

Figure 3. Snow grain-size distribution over Antarctica. The map was derived from Galileo spacecraft flyby data, using the ratio of intensities at 1.5 and 1.7 microns. Bright pixels correspond to approximately 50 micron radius particles, while dark gray pixels represent grains of about 200 micron radius.

Encouraged by the good agreement between the spectrally derived radii and the directly measured values, we examined spectra taken by the Near-Infrared Mapping Spectrometer (NIMS) experiment (Carlson et al. 1992). These data were obtained from the Galileo spacecraft during the 8 December 1990 flyby of the earth. Spatially resolved spectra were obtained in the 0.7 to 5.2 micron region and arise from reflected sunlight and thermal emission.

In this initial attempt to map the grain-size distribution across Antarctica, we focus on the region of characteristic water ice absorption features, in particular, the region extending from 1.5 microns to 2.5 microns (see figure 1). Both theoretical and observed spectra show that the ratios of reflectivity at peaks and valleys varies with grain size. For the map shown here, we use the ratio of signals at 1.5 and 1.7 microns. At these wavelengths, atmospheric gases such as H_20 vapor, are fairly transparent, particularly for the dry atmosphere over the polar plateau. It is also possible, in this wavelength range, to distinguish between thick clouds and snow, due to the high reflectivity of the cloud particles compared with snow. The presence of thin clouds, however, influences our results, so cloudy regions occuring near the coast and ice shelves must be regarded with special caution. Using the ratio of intensities provides a measure that is independent of sastrugi and other geometric effects, at least to a first approximation.

The results are shown in figure 3. Bright pixels represent high values of the ratios of 1.5 and 1.7 micron intensities, which correspond to small particles. It is gratifying that this map, albeit preliminary, is consistent with our South Pole and Vostok field data. Near the South Pole, the NIMS data indicate small particles of order 50 microns in radius, with grains at Vostok three to four times larger. This map shows similarity with a microwave gradient map derived by Fily and Beniost (1991), which is related to near-surface grain size (Surdyk and Fily 1991).

The mean grain size appears to vary across the continent, but the observed distribution shows no immediately obvious correlation with topographical or meteorological parameters. It is clear that there are large variations in grain sizes. Because the rate of solar-energy absorption depends upon grain size, this spatial variability must be considered in climatological estimates of the net albedo of Antarctica.

Continuing analyses of the field measurements will lead to refined algorithms with which to analyze the remote-sensing data. Additional spacecraft data will be obtained during the second, and last, Galileo earth flyby, occurring in December 1992.

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