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Cover: Winter wheat, partially covered with about three centimeters of new snow.

CRREL Report 81-21



*Near-infrared reflectance
of snow-covered substrates*

Harold W. O'Brien and Gary Koh

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NEAR-INFRARED REFLECTANCE OF SNOW-COVERED SUBSTRATES

Harold W. O'Brien and Gary Koh

INTRODUCTION

Large areas of the earth are covered by snow and ice, either perpetually or seasonally, and there is increasing awareness of the importance of the optical properties of snow cover in understanding and predicting hydrological and climatological phenomena. Military applications in camouflage, surveillance and target discrimination in winter have become increasingly significant with the development of advanced electro-optical systems. Optimum utilization of current technology in cold regions requires detailed comprehension of the electro-optical properties of snow cover as a target background.

Significant advances have been made in theoretical modeling of the radiative properties of snow cover, based in part upon laboratory and field measurements of the optical characteristics of snow. There are, however, a great many possible variations in snow conditions such as depth, grain size, crystal configuration and contamination (e.g. dust) which affect the optical properties of a snowpack. Also, the optical appearance of a field of view (or a radiometric measurement) may be considerably altered by the spectral characteristics of substrates beneath optically thin snow covers or by vegetation or other terrain features protruding through

snow cover and occupying a portion of the field of view. These variables require further investigation in the field and increased consideration in modeling concepts.

This program is an extension of previous snow reflectance studies by O'Brien and Munis (1975a, b) and O'Brien (1977) in which spectral scanning techniques were used in a laboratory study of the ultraviolet, red, and near-infrared reflectance characteristics of various snow samples of semi-infinite depth.* The present studies, by contrast, were performed in discrete wavebands between 0.8 and 1.8 μm , under direct solar illumination of natural snow cover in situ. The measurements were made to observe the optical characteristics of various types of snow surfaces and the influence of selected substrates on the overall snowfield reflectance, and included repetitive measurements during snow ablation. Because of interest in satellite applications most of the radiometry was performed with the detector directed vertically downward, on clear days, under direct sunlight.

* Snow of such depth that the influence of any substrate beneath it may be considered negligible, or for which the reflectance at all wavelengths under consideration is within 1% of that for an infinitely thick snowpack

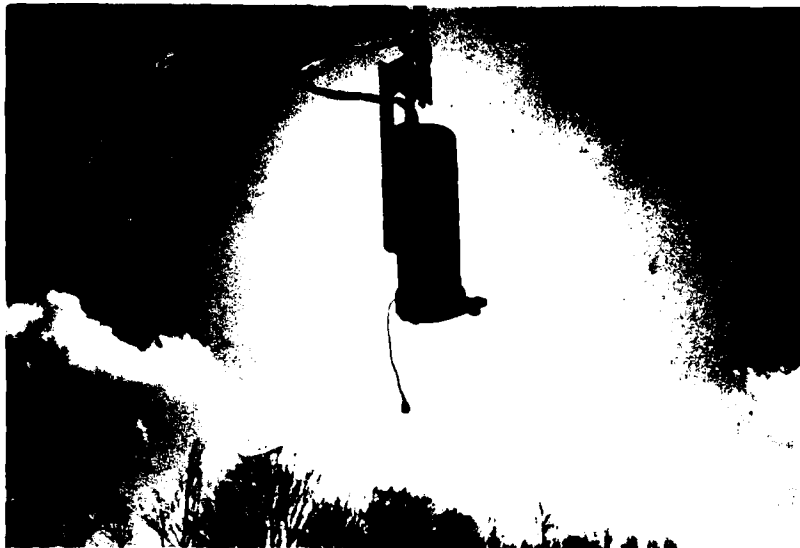


Figure 1. Radiometer head suspended from boom, looking vertically downward.

EXPERIMENTAL METHODS

Substrate preparation

An area of ground approximately 9 m square surrounded by a concrete wall about $\frac{1}{2}$ m high was subdivided into 10 plots, and various crop grasses were planted. At harvest time, the crops were mowed at three different levels, a third at 15 cm, a third at 10 cm, and a third at 5 cm height.

Experimental configuration

A traveling bridge spanned the test site from east to west and could be winched by cable from north to south. A movable tower was mounted on the bridge. Through manipulation of the bridge and the tower, any point within the test area could be reached.

The tower was fitted with a radiometer head mounted on the end of a boom (Fig. 1). When the radiometer was raised, its field of view was directed vertically downward at a distance of approximately 2 m south of the bridge and tower. Another arm at the base of the tower could be swung in or out of the field of view of the radiometer. This arm carried a secondary standard with which the snow substrate reflectance could be compared. The vertical lines of sight from the radiometer to the ground, or to the in-

terposed standard, were approximately 4 and 3 m respectively

A modified research-grade radiometer (Barnes Model 12-511A) equipped with several narrow-pass filters was used for the field measurements. With this instrument, a continuous curve of reflectance vs wavelength could not be obtained. Previous laboratory studies (O'Brien and Munis 1975a, b) had defined the general shape of the spectral reflectance curves for snow in the near-infrared, and it appeared that the more definitive wavelength-dependent features were a dip in the curve near $1.03 \mu\text{m}$, a peak at about 1.10 , a "plateau" around 1.25 to 1.35 , and the slope of a nearly straight-line portion of the curve between 1.50 and 1.80 . (An example of one such curve may be seen in Figure 11b.) Filters selected to define these features had nominal center wavelengths at 0.81 , 1.04 , 1.10 , 1.30 , 1.50 and $1.80 \mu\text{m}$, and nominal band-widths, at half-power points, of approximately $0.05 \mu\text{m}$.

The normal field of view of the radiometer was 0.25 milliradian. Subsequent modification of the radiometer consisted of installing an accessory lens, giving an additional option of a nominal " $10^\circ \times 3^\circ$ " (174.5×52.3 mrad) field of view. Neither of these options was entirely satisfactory. At readily obtainable viewing distances, the 0.25 -mrad field of view was so small as to be

unrepresentative of the heterogeneous scene. For example, the entire field of view at 3 to 4 m could be occupied by a single blade of grass. On the other hand, the 174.5×52.3 mrad (nominal) accessory lens provided a toroidal field of view which was very poorly defined by the viewfinder and did not appear to be very close to 174.5×52.3 mrad in viewing angle.

In either mode, focus was critical. Several sets of measurements had to be discarded because the focusing mirror was found to have shifted downward under its own weight. This problem was subsequently alleviated by restraining the focusing knob with tape so that it could not turn.

Radiometric measurements

Most measurements were made by positioning the boom-mounted radiometer over an appropriate test plot and sequentially comparing the vertical radiance of the snow-covered substrate with that of the secondary standard. This arrangement had two inconvenient limitations: 1) the boom had to be lowered between each set of comparison measurements in order to manually change filters, and 2) it was not possible to monitor the field of view of the radiometer. In some cases the entire sequence of filter measurements was repeated to confirm that the radiometer was returning to the same, or a similar, field of view. It was through this procedure that the drift in focus was discovered. A few measurements were made by mounting the radiometer on a tripod and comparing samples directly with a primary standard.

Snow characterization

Snow density and hardness and the gross particle size were usually measured by standard meteorological methods. In the case of a shallow snow cover (5 cm or less) density and hardness measurements tended to be difficult, if not impossible. Snow temperature measurements were also made—at several depths if the amount of snow accumulation warranted. No attempt was made to measure the liquid water content of the snow.

In the later stages of the study, formvar replicas were made, either by laying a coated microscope slide, formvar side down, on the snow surface or by pressing the slide against the side of a sharply cut "snow pit." In this way we hoped to attain less subjective judgments of snow grain size.

Standard meteorological parameters were recorded at a nearby climatological station manned by a detachment from the U.S. Army At-

mospheric Sciences Laboratory, White Sands, New Mexico.

Reflectance standards

When possible, Eastman White Reflectance Standard, a white barium sulfate powder with excellent reflective qualities, was used as a primary standard with which to compare the snow/substrate measurements. The standard was prepared by filling a milled plexiglass cylindrical container (15 cm inside diameter and 1.25 cm depth) with an amount of the BaSO_4 powder which, when smoothed and compressed, would conform with Eastman Kodak's recommendation on standard density.

For the larger field of view it was necessary to utilize a white cardboard sheet, approximately $\frac{3}{4} \times \frac{1}{2}$ m. This secondary standard was then calibrated (in the laboratory using artificial illumination and in the field under direct solar radiation) by comparison with the Eastman pressed-powder standard.

DATA ANALYSIS

Reflectance measurements

Reflectance measurements contained herein have been converted to absolute values by utilizing the table of absolute reflectance of BaSO_4 , reported by Grum and Luckey (1968).

Snow replica analysis

Although the replication method of snow grain-size analysis was instituted too late in this project to be of great significance to the present study, the replica analysis methodology has considerable potential for future grain size measurements.

A Millipore Particle Measurement Computer (MC) was utilized to determine the size characteristics of the replicated snow granules (Fig. 2). This system incorporates a television camera which converts the image to be analyzed into video signals, and a computer which processes the signals and applies sizing logic.

The television camera was focused on the replicated snow sample with the aid of a 25-mm focal length lens and 10-mm extension ring attachment. A light source positioned incident to the camera side of the sample slide resulted in white snow granules contrasted against a dark background (Fig. 3a). For snow measurement applications this combination provided good magnification and image quality. Shadow-like images of the snow granules can also be achieved

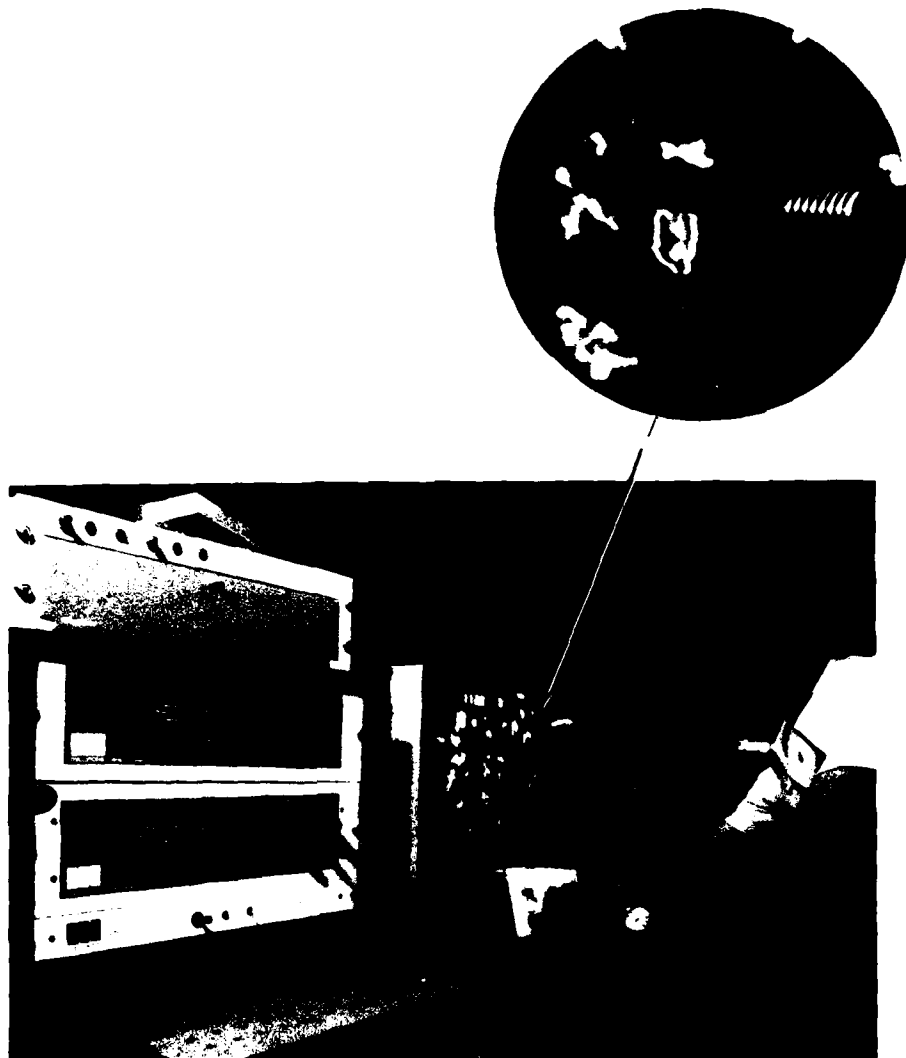
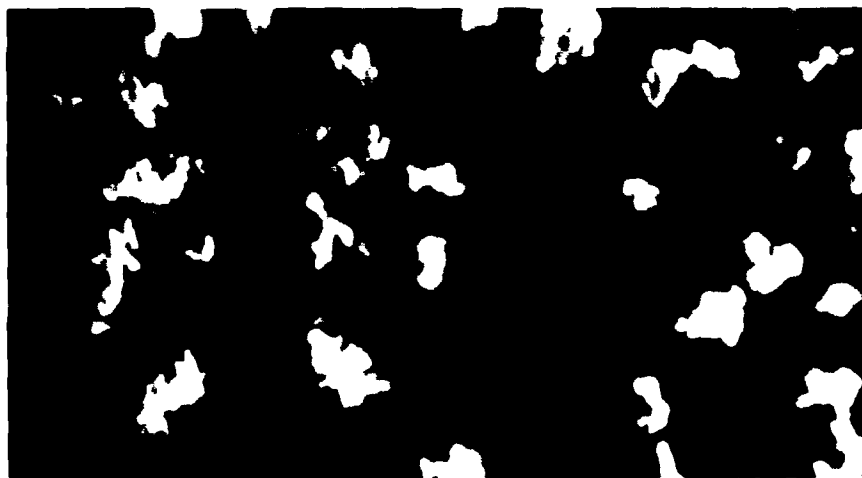


Figure 2. Particle measurement computer (PMC) used in size analysis of some replicas of snow grains.

with the light source placed behind the slide (Fig. 3b). These snow granules, imaged in black against a light background, can also be used for size measurement. Scale lines, shown in Figure 3b but not in 3a, are optional for rough estimation of particle size. The scale lines are fixed approximately 15 mm apart *on the screen* and do not vary with image magnification. In Figure 3b, the distance between lines represents 0.45 mm *on the sample*.

The area of the individual snow granules was measured automatically with the use of a light

pen (Fig. 2). Pointing the light pen at the image of each snow granule to be measured caused a white outline to appear around the image. Depressing the pen against the TV monitor caused a calibrated measurement of the desired particle parameter (area, maximum length or other parameters) to be displayed on the monitor and printed out on paper tape. Area measurements could then be converted mathematically to a "projected" grain diameter (the diameter of a circle of equal area) if desired.



a. Reflected illumination.



b. Transmitted illumination.

Figure 3. μ MC images of snow particles. The distance between the dark lines represents 0.45 mm on the sample.

DISCUSSION OF RESULTS

A number of variables interrelate to determine the spectral reflectance of snow and snow-covered substrates. Some of these were discussed by O'Brien and Munis (1975a, b), others by Bohren and Barkstrom (1974), and Choudhury and Chang (1979) * Warren and Wiscombe (1980)

* No attempt is made here to present an extended bibliography on snow or substrate reflectance, only a few papers of immediate cognizance which illustrate points of interest are mentioned.

have carefully considered many of the important parameters which may exert significant influences on the spectral albedo of snow.

In addition, when snow-covered substrates are being considered, the spectral characteristics of the substrates themselves must not be overlooked. Tucker (1977), Tucker and Miller (1977), and Rao et al (1979) discussed vegetation canopy variables and soil spectrum contributions to reflectance. Gausman et al. (1976) presented data on the reflectance of dead compared with live vegetation, which also has some bearing on the present study.

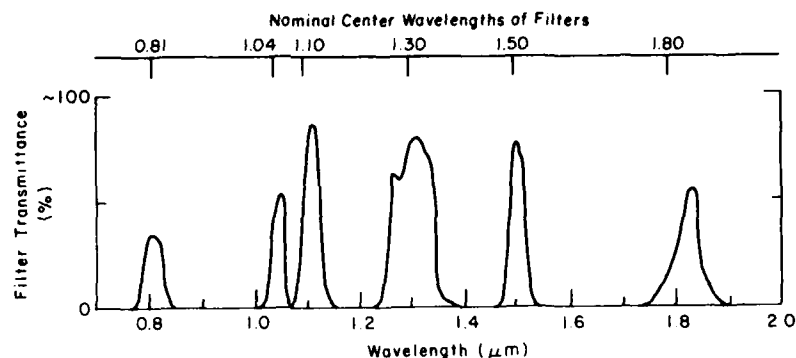


Figure 4. Transmission curves of filters used in measurements.

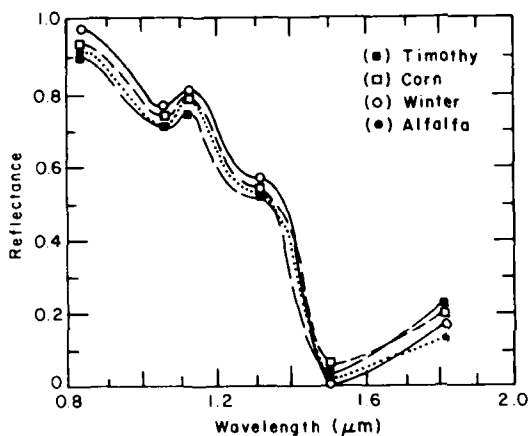


Figure 5. Reflectance of snow-covered crop grasses.

In the presentation of reflectance measurements which follows, each individual radiometric measurement is shown by a mark indicating the nominal peak transmission wavelength of the filter. In order to make the data presentation more coherent and easier to compare with previous experimental and theoretical results, curves have been interpolated based on the measured data points and on prior knowledge of the general shape of snow reflectance curves.

Because some of the results appeared to be slightly anomalous in the light of theoretical expectations and previous laboratory results, the actual wavelength pass-bands of the filters were measured on a Perkin-Elmer E-14 Spectrometer. These are shown in Figure 4. It will be noted that there are slight discrepancies between measured and nominal values.

After fall rains and early wet snow the three

levels of crop grass height were hardly distinguishable. Sturdier stalks remained upright while many of the broader blades were beaten down. Consequently, no attempt was made to make sequential measurements based on crop height. Substrates are described or shown in photographs on an individual basis in the discussion which follows.

Comparative reflectance of various substrates under snow

Figure 5 illustrates measurements of several crop grasses covered with a rather complex snow-ice cover (Fig. 6). Because of the structure of the snow cover, this might also be considered to represent an old snow substrate beneath a layer of light, new snow. Earlier snow melt, refrozen, produced a layer of solid ice at ground level, with grass sprigs frozen in at what appeared to be random orientations. Above the ice was an 8-cm layer of old icy snow (hardness index about 95,000 g cm⁻²). On top of this layer was a less hard, but still rather crusty 6-cm snow layer (hardness about 70 g cm⁻²). At the top surface lay a very light layer of snow about 1 cm thick (aged about 1½ days at subfreezing temperatures), whose hardness was too slight to measure. The total snow cover was about 15 to 18 cm thick. During the measurement period the air temperature increased from -3.5°C to 0°C. Temperature profiles of the snow remained essentially constant: -0.5°C at 1 cm depth, -1.0°C from 3 to 8 cm depth, and -1.5°C below 10 cm depth.

Snow density (which in routine measurements requires a minimum snow depth of 5 cm) taken near the top of the snow cover included a significant portion of the lighter crusty layer and measured 0.182 Mg m⁻³. It is almost certain that the



a. Snow surface.



b. Stratification of snow cover (15 cm rule).

Figure 6. Snow-covered winter wheat.

density of the top centimeter of snow was considerably less than the composite measurement of 0.182 Mg m^{-3} . Relative humidity was about 30%; wind was variable at about 3.5 knots at 030°. The solar altitude during this series of measurements was approximately 40° . Snow particle grains near the surface were noted

(grossly) to be generally around 1 mm in diameter, with some as large as about 3 mm. Formvar replication of the surface snow was not sufficiently successful for utilizing the nMC analysis, so that size distribution measurements are not available. Microscopic examination of the replicas was possible, and revealed the presence of

numerous ice crystal aggregates whose size range confirmed the macroscopic observations. The aggregates appeared to be principally assemblages of hexagonal planes, the plate-like components of which were approximately 75 μm in diameter and very thin in cross section. Although it was difficult to observe and measure the thickness of the planes, those which could be seen clearly were estimated to be from 15 to 50 μm thick (based upon comparison with 25- μm glass spheres which were sprinkled on the replica). In addition, there appeared to be some particles in the 25- to 50- μm -diameter range. It could not be established with certainty whether these were replicas of ice crystal fragments or other artifacts. These curves closely resemble the theoretical curves of Wiscombe and Warren for snow having an effective grain size of about 0.15 mm diameter. Curve D in Figure 16a of O'Brien and Munis (1975a) for snow of 0.170 Mg m^{-3} density also appears to approximate our curves here.

It would appear, then, that at this snow depth, with very little substrate protruding above the snow surface, the contribution of surface and subsurface crop grasses to overall reflectance is extremely small. Apparent differences between the crop types, particularly near 1.8 μm , may have some physical significance, possibly indicating variations in the amount of protruding crop grass.

These measurements compare favorably to theoretical predictions for snow with a grain size of about 150 μm diameter. That particular dimension (150 μm) was not evident in any measurement or observation of the surface snow crystal replicas. It is probable that in relatively fresh, light snow it will be necessary to revise current thinking that revolves around particle size. The grain size used in theoretical calculations may be an elusive parameter to measure in real snow. The beauty and variability of individual snow crystals have been well documented by Bentley and Humphreys (1931), Nakaya (1954) and others. The rather extensive snow classification system of Magono and Lee (1966) also illustrates some combined crystal forms. When snowflakes are observed through a binocular microscope the three-dimensional complexity of the various crystal combinations can readily be appreciated. A snowflake that appears to be about a millimeter in diameter may in fact be one (a graupel pellet, for example), or it may be a myriad of crystal components such as the surface snow described above. What, then, is the particle diameter? The overall aggregate (snow-

flake) diameter of 1 mm? The breadth of the plate-like branches (say 75 μm)? The thickness of the branches (maybe 25 μm)? Obviously, gross "eyeball" estimations will not suffice. Furthermore, until "snowflakes" lose their type-identifiable structure, i.e. until plate-like crystals or appendages have become more equilateral through melting, sublimation or fragmentation, it is highly likely that a new method will have to be devised for approximating the "equivalent grain size" of a fresh snowpack. What determines whether a snowpack is "fresh"? It is generally assumed that the metamorphosis of snow begins quite soon after deposition, resulting in a granular crystal form which may be readily assigned a measurable diameter. This is undoubtedly true, particularly in the presence of wind, high temperature, low humidity or strong direct solar radiation. However, under certain conditions new snow can retain much of its structural detail for a considerable period of time. We have observed definite fine structure in a snow cover after several days of cold, windless weather, and after months in a deep-freeze at -19°C .

In this series of measurements, it is apparent that a close examination of the crystal nature of the deeper snow layer(s) would have been appropriate. Just as the density of the top layer of new snow was surely less than that of underlying layers, so the crystal size and shape of the new snow would have been different from that of the older layer beneath. This would have had an effect, particularly at the shorter wavelengths where radiation penetration of snow is greatest. The light, 1-cm surface layer, with crystal components having dimensions of 75 μm or less, combined with underlying older snow of unknown but presumably considerably larger grain size may have resulted in an "effective" grain size of 150 μm for the snow cover as a whole.

Ablation of a snow cover

Figure 7 illustrates one example of radiation changes during the ablation of a snow cover in late spring. The snow fell on 9 April 1979, and since on 10 April it was too overcast for measuring the reflectance of direct solar radiation, the measurements were made on 11 April. The snow did not seem to have deteriorated appreciably in the interim.

Since the objective of this set of measurements was to follow the reflectance changes of the snow cover to vanishing depth, it was imperative that the field of view be quite accurately known and, in the final stages, kept small

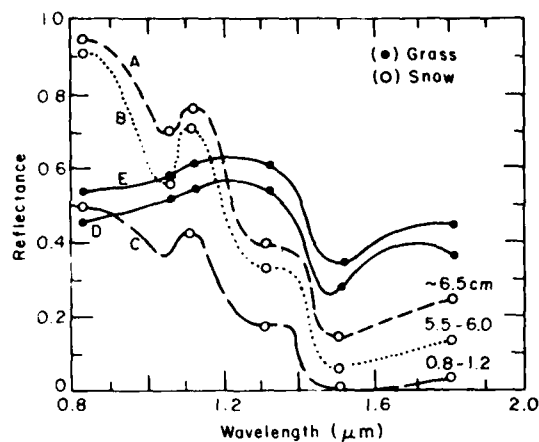


Figure 7. Reflectance changes during ablation of a snow cover.

enough to be contained within a single patch of snow. For this reason these measurements were made with the radiometer mounted vertically on a tripod, approximately 1 m above the target area so that the field of view could be visually monitored through the optical system. Alternate measurements were made of the BaSO_4 pressed-powder standard. Table 1 gives conditions at the times of measurement.

Curves A and B resemble the theoretical curves of Wiscombe and Warren (1980) and Choudhury (1979) for snow particles of approximately $200 \mu\text{m}$ (curve A) and $300 \mu\text{m}$ (curve B) diameter at 0.81 -, 1.04 -, 1.10 -, and 1.81 - μm wavebands. However, in the 1.3 - μm passband the measured values are considerably lower than

those predicted by theory, whereas near 1.5 - μm wavelengths the reverse seems to be true. Curve C closely approximates theoretical curves for snow grain diameters of about 1.5 mm , except for the extremely low measured value in the 0.81 - μm wavelength region. Curves D and E, representing interpolated data points for the substrate described in Table 1, are included only for comparison. The interpolation between crop grass data points is approximate, based upon curves of stacked leaf spectral reflectance of corn (Gausman et al. 1976).

There are several possible explanations which may, separately or collectively, account for the differences between measured and theoretical values of the snow-cover reflectances.

Based on considerations discussed by Wiscombe and Warren (1980) it is unlikely that a snowpack (as in curves A and B) of approximately 0.3 Mg m^{-3} density, depth of 5 - 6 cm , and assumed particle diameter of 200 to $300 \mu\text{m}$ would show significant differences in reflectance from an infinite snowpack, particularly at wavelengths of $1.0 \mu\text{m}$ or longer.

Although in our tests the winter wheat had been largely beaten down by fall rains and winter snowfalls, some of the dead leaves might still have extended close enough to the snow surface that the snow cover over them did not approximate a semi-infinite thickness. If this situation had prevailed one would expect, based on the data points shown in curves D and E, that the overall influence of the leaves would have been to decrease the effective reflectance at wavelengths shorter than about $1.2 \mu\text{m}$ and increase it at longer wavelengths. It would also be expected

Table 1. Weather and snow conditions for reflectance measurements presented in Figure 7.

	Curve (See Fig 7)				
	A	B	C	D	E
Time	1040	1113	1400	1445	1455
Approx solar altitude	50°	53°	44°	35°	35°
Air temp ($^\circ\text{C}$)	+5.9	+5.5	+7.5	+8.0	+8.0
Relative humidity	30%	29%	26%	26%	26%
Wind direction	010°	350°	010°	010°	010°
Wind speed (m s^{-1})	3.5	3.0	2.5	3.0	3.0
Snow depth (cm)	6.5	5.5-6	0.8-1.2	0	0
Snow temp ($^\circ\text{C}$)	-1.0	-0.5	0	n a	n a
Snow density (Mg m^{-3})	0.28*	~ 3*	~ 4-5*	n a	n a
Snow hardness	.	.	.	n a	n a
Snow condition	Slight surface melting	Soft, moist (good for snowballs)	More granular and wet	Winter wheat dead, brown, damp but drying fast, i.e. E probably dryer than D. Some bare dirt in field of view	

*Snow depth insufficient for accurate measurements

that such a situation would have affected the shorter wavelengths more than the longer. This does not appear to have been the case in this situation.

The low measurement at 1.30 μm (nominal) wavelength may have been due to the fact that in all of the other passbands measured the absorption coefficient of water is lower than that of ice (Irvine and Pollack 1968). Strictly speaking, at 1.30 μm this also seems to be true. But at wavelengths between approximately 1.3 and 1.47 μm , the absorption coefficient of water is greater than that of ice. When the area under the filter transmission curve (Fig. 4) is integrated it appears that more than half of the radiant energy transmitted by the so-called 1.3- μm filter falls in the region of greater absorption coefficients of water. This could mean that the reflected radiation in this passband was noticeably reduced by increased absorption in the slightly melting snow. This idea receives some support from the laboratory results of O'Brien and Munis (1975b), who measured the reflectance of slightly melting snow and wet melting snow, repeating the measurements after refreezing the same snow. They report that: "Refreezing may, however, cause an increase of reflectance relative to that of melting snow at wavelengths near 1.4 μm ." In some of their results there was a slight but definite increase in reflectance in the 1.3- and 1.47- μm wavelength regions upon refreezing. In other measurements the effect is not so apparent. Since the refreezing of soft, wet snow in the laboratory required a short but finite time, it is logical to suppose that grain growth continued during the freezing process, thus tending to lower the reflectance of the refrozen snow and possibly biasing, to a small extent, the comparison of wet vs frozen snow in the laboratory studies.

The relatively high measurements at 1.5 μm may be due to experimental error, since the measurements of samples and standard were usually quite small, with lower than usual signal-to-noise ratios. The ratios of pairs of small radiances, then, were susceptible to increased error. It is probably more important to note, however, that the absorption coefficient of water is considerably less than that of ice in this passband. It seems reasonable to assume that the *effective* absorption coefficient for a wet snow cover lies somewhere between those of ice and water. From Wiscombe and Warren's discussion of the "sensitivity of albedo calculation to error in absorption coefficient" and their accompanying

Figure 15, and assuming that the effective absorption coefficient of the snow cover was decreased by nearly 50% (at 1.5- μm wavelength) due to the presence of water, then the reflectance at 1.5 μm would be more than doubled, resulting in much closer agreement between theory and our measurement. Whether the slight wetness of the snow could have the observed effect has not been determined although, quoting O'Brien and Munis (1975a), "There is also an indication that the reflectivity of snow at wavelengths near 1.5 μm is not greatly reduced by melting and refreezing, and may in some cases increase."

The condition of the snow cover at the time may explain the shape of curve C quite well. If the assumption is made, quite reasonably, that during the ablation of the snow from 6 cm to 1 cm the effective grain size increased considerably, say to about 1.5 mm diameter, the curve fits nicely to theoretical predictions at wavelengths longer than 1 μm . In the region beyond 1 μm wavelength even the small depth of snow cover present (0.8–1.2 cm) probably approximates a semi-infinite cover. However, in the 0.81- μm passband, with approximately 1.5 mm diameter effective grain size, the effect of finite thickness (Wiscombe and Warren 1980) would be significant and the resultant measurement would be lowered considerably due to the influence of the relatively absorptive substrate. It is also possible that the measured reflectance in this passband could have been further decreased by concentration of dust accumulations in the melting snow (Warren and Wiscombe 1980). There was, however, no visual evidence of such an occurrence. The effects of melting, if correctly postulated in the case of curves A and B, are not obvious in curve C in comparison to the effects resulting from increased grain size and decreased snow depth. With some reservations because of the assumptions required, we feel that curve C is quite complementary to the theory of Wiscombe and Warren regarding finite thicknesses of snow cover.

Reflectance from a very light, fresh snow cover

Figure 8 gives a series of measurements not immediately amenable to interpretation. The measurements were made on the day following a January snowfall of about 3.5 to 4 cm of very light snow. Temperatures remained well below 0°C and the snow was still very fresh and light. Several measurements had to be discontinued

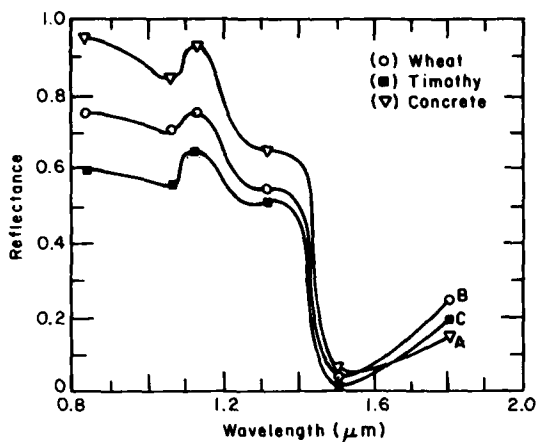


Figure 8. Reflectance from a very light, fresh snow cover over winter wheat (~1300 hr, solar altitude ~23°), timothy (~1130 hr, solar altitude ~24°), and concrete pavement (~1400 hr, solar altitude ~20°).

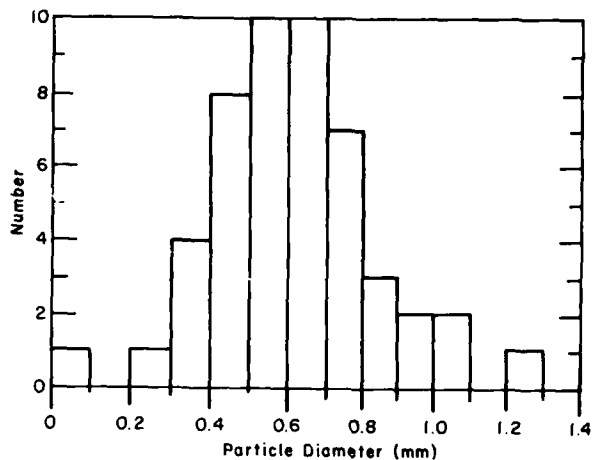


Figure 9. nMC snow particle size distribution of a light, fresh snow cover. The possibility of a greatly increased peak between 0 and 0.1 mm diameters is discussed in the text.

because of fluctuating radiometer readings caused by clouds of ice crystals blowing between the sun and the sample area, even though the average wind speed did not generally exceed 2 m s^{-1} . The photograph in Figure 1 was taken in an attempt to capture the sparkle of the "diamond dust." Although the desired effect is not apparent in the photograph, it was visually obvious that the light crystals were transported high in the air from the treetops seen in the photograph.

The density of the snow on the ground was between 0.03 and 0.07 Mg m^{-3} prior to the radiometric measurements. Because of the continued low temperature (the highest reading of ambient air temperature, in the sunlight, was -2.5°C) it is doubtful that the density and/or grain size changed significantly during the measurement period. The temperature within the snow cover during this period was -2°C , slightly higher than the ambient air.

This series of measurements was one of the few in which the grain size distribution was measured using the replica/nMC method previously discussed. The size distribution as measured is shown in Figure 9. Other pertinent data are provided in the caption of Figure 8.

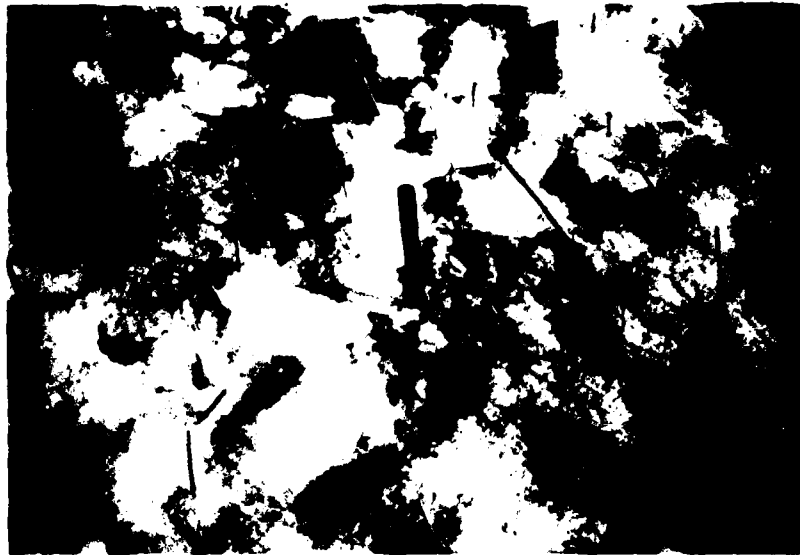
The curves shown in Figure 8 are quite dissimilar from the previously illustrated snow reflectance measurements. The most obvious disparities are the differences between the curves for the three substrates, and the lack of agreement

with theoretical predictions of reflectance at the measured snow grain size. Theoretically, one would expect that the snow cover represented by these reflectance measurements would have a much smaller grain size than the 0.62-mm "projected" mean grain diameter. Curve C, for example, would be expected to result from snow particles of less than $50 \mu\text{m}$ radius!

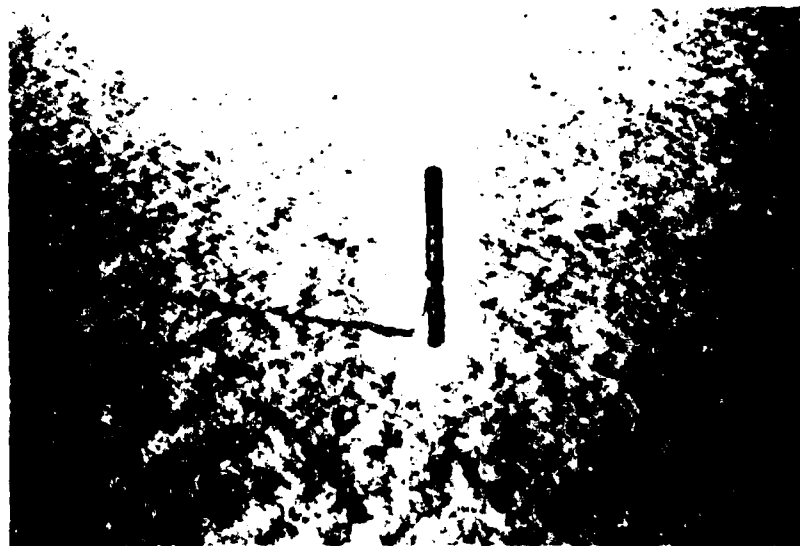
Microscopic examination of the replicas made during this series of measurements revealed that the snow crystals were predominantly dendritic (plane and spatial) and spatial assemblages of hexagonal planes. The planar portions of these crystals appeared to be on the order of $100 \mu\text{m}$ in breadth and generally thinner than glass beads of $25 \mu\text{m}$ diameter.

It was mentioned in connection with the comparison of reflectance of various snow-covered crop grasses that some particles on the replicas were found to have dimensions of about 25 to $50 \mu\text{m}$. In the microscopic examination of the replicas made in this series of measurements, it was also found that a rather large number of very small particles (15 – $25 \mu\text{m}$) were evident. As in the previous case, positive identification of most of these particles as replicated ice crystals was impossible. They were therefore not included in the nMC size distribution analysis.

If we assume that the extremely high values shown in curve C of Figure 8 are the result of inappropriate determination or specification of effective grain size, then we must explain why



a. Wheat.



b. Concrete.

Figure 10. Light, fresh snow cover over winter wheat and concrete pavement.

curves A and B are so much lower in the 0.81- to 1.30- μm wavelength region. A photograph of the test plots containing snow-covered winter wheat (Fig. 10a) illustrates one probable contribution to the lower reflectances measured over the crop-grass plots. Note the sprigs of vegetation protruding through the snow surface, the irregularity of the snow surface and the shadowing effect

in some areas. Upon close examination of the snow cover, cavities were discernible beneath the snow surface where snow had bridged over blades of crop grass. This effect would make the effective snow depth very hard to judge. The cover photo, although of a different snowstorm, more clearly illustrates a similar condition.

Figure 10b shows the snow surface over the

concrete area. Although this surface also shows some irregularity and shadowing, it is considerably smoother than that over the crop grasses. The originals of both photographs (Fig. 10a, b) give some evidence of sparkle (specular reflection from individual snow crystal surfaces). With the radiometer head mounted on the boom as described, there was no way to determine the exact field of view of the radiometer. Thus, the portions of the fields of view which contained exposed grass vs snow, or direct sunlight vs shadow, are not known. The low solar altitudes at the times of measurement not only increased the shadowing of the nonplanar surfaces, but in shadowed areas diffuse radiation would have an increased influence compared to direct sunlight. As shown by Wiscombe and Warren, at low solar altitudes (high zenith angle), increasing the ratio of diffuse to direct illumination lowers the total reflected radiance.

Another possible contributing factor which should be considered here is the effect of finite thickness. Again referring to Wiscombe and Warren (1980), the effects of finite thickness for a snow cover of 3.5 to 4 cm depth, having a density between 0.03 and 0.07 Mg m⁻³ (about 1 to 3 mm water equivalent), depend strongly upon the effective size distribution of the snow particles. For a snowpack of finite thickness, measurements would, of course, have some degree of dependence upon the optical characteristics of the substrate. The reflectance of crop grass and concrete substrates is discussed briefly in a subsequent section. The effect of finite thickness is probably present to a significant degree in these measurements, particularly in the case of those blades of crop grass with a lesser but undeterminable depth of snow cover. Absorptance by subsurface grass would have a greater effect than absorptance by the deeper concrete and would produce the same trend of departure from theoretical values as is seen here. However, because of the uncertainty of the effective size distribution of this snow cover, and the unknown depth distribution of grass spears, it is probably not judicious or productive to speculate in detail as to the quantitative effect of substrate reflectance in this case.

In addition to the effects of protruding substrate, finite thickness, nonplanarity of the snow surface and low solar altitude, one other factor might be considered, although its effect is believed to be insignificant in this case. This is the possibility of changes in the snow cover during the series of measurements. It was noted earlier

that because of continued low temperatures, deterioration of the snow was not anticipated during the measurements. It was also mentioned that ice crystals were occasionally observed in the air. It is possible that an increasing number of small ice crystals or fragments were deposited on the sample area, resulting in increased scattering and consequently contributing to a temporally increasing reflectance. The probability of this occurrence producing a significant effect seems rather remote, however.

Measurements at angles other than vertical

A few measurements were made with the detector set at angles other than vertical. In these cases, the detector was tripod-mounted and the accessory lens removed so that a 0.25-milliradian field of view was obtained which could be approximately defined visually through the radiometer viewing lens. The azimuth of the detector was approximately toward the sun.

Figure 11a, curve A, shows measurements made with the radiometer at an angle of 73° from the normal (solar altitude 41°) on coarse, wet (melting), granular snow about 15 cm deep. Snow grain size was grossly estimated to be about 1 mm in diameter. Ambient air temperature was about +15.5°C. The reflectance appears unusually high for the assumed particle diameter. In addition, the measured reflectance at 1.04 μm wavelength is higher than that at 1.1 μm, an anomaly not seen in other reflectance measurements. Curve B represents measurements on the same snow, about 1½ hours later, at an angle of 45° from normal with solar elevation 33° and snow depth decreased to about 3 cm. The ambient air temperature had increased to about +17°C. The snow grain size appeared to have increased (perhaps to about 2 mm in diameter). Snow density at this time was measured as 0.368 Mg m⁻³. Also shown are the data points for subsequent measurements made on the substrate: dead grass with a few green blades and some dirt. These will be discussed briefly in the following section.

The curve in Figure 11b represents laboratory measurements on a cold, "sugar consistency" snow of approximately the same density (0.357 Mg m⁻³) with source and detector angles of 0° and 30°, respectively. Unfortunately, grain size was not measured. The data points shown by circles are the same as for Curve B in Figure 11a. Even considering the similarity of snow density in these two cases, the resemblance of the two

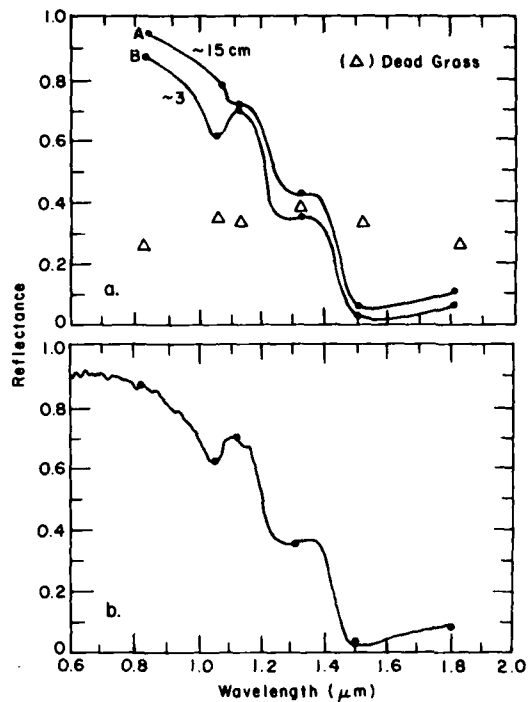


Figure 11. Reflectance measurements on snow, with detector at non-vertical angles.
 a) Measurements during current experiment.
 b) Laboratory measurement (O'Brien and Munis 1975a,b). Points are data of curve B above.

sets of data is surprising since the *in situ* snow was melting, the laboratory sample was frozen (-10°C), and the particle sizes of the laboratory sample are believed to have been considerably smaller than those of the snow *in situ*. Agreement with theoretical predictions would require that the *in situ* snow have a much smaller mean diameter than those reported. The question again arises as to the validity of gross visual observations of particle size. In this case, due to the high temperatures involved and the fact that there had been light rain the night before, it seems indisputable that fine structure in the snow would have been obliterated. It is probable that visual estimation of the mean grain size of the snow was badly overestimated. It seems unlikely, however, that the actual effective grain size was small enough to account for the high measurements in the 0.8- to 1.1- μm wavelength range. Unfortunately, no replicas were made at the time of these measurements and no microscopic verification of crystal condition is available

It seems probable that the high reflectances of curves A and B are the result of partial specular reflection (or increased scatter in the direction of the radiometer) at these angles of incidence and detection.

Reflectance from substrates

In some of the results discussed previously, reference was made to the potential effect of substrate reflectance in cases where the snow could not be considered optically semi-infinite in depth. In some of the figures, substrate reflectance data were included for reference.

In Figure 12 a few substrate measurements are presented, together with some spectral measurements of Gausman et al. (1976). Because our intent is to show qualitative relationships rather than to make precise quantitative comparisons, the reproduction of Gausman's curves may be somewhat approximate. Figure 12a compares curves of Gausman et al. for the reflectance of individual corn leaves with our laboratory measurements on standing winter wheat which appeared to be essentially dead. The wheat, and the ground in which it grew, had been frozen solidly at -19°C for several days, then thawed, refrozen and rethawed and allowed to set for several days at room temperature. The wheat had turned a dead-looking brown color. In general, the magnitude of the reflectance of this wheat appears to be in the range of Gausman's measurements on corn leaves. However, our wheat was not desiccated, and this probably accounts for the tendency of our data to be influenced by water absorption bands, so that the wheat resembles green corn leaves more than dried leaves in the regions of increased water absorption. Tucker (1977) points out that Gausman's term "dead leaves" probably applies to leaves which have been dead or dormant for some time but that "the processes are gradual." Apparently the chemical processes in our sample had not proceeded to the extent required to produce the spectral appearance of "dead leaves."

Figure 12b compares the substrate of Figure 11a with Gausman's curves. This curve of grass, *in-situ*, agrees quite well with Gausman's curve for a dead corn leaf at wavelengths between 0.8 and 1.3 μm . At longer wavelengths, it seems to approach the values for a green corn leaf. It might be noted that this grass was probably still damp from the recently melted snow cover.

The substrate reflectance measurements of winter wheat previously shown in Figure 7 are compared with curves of Gausman et al. for the

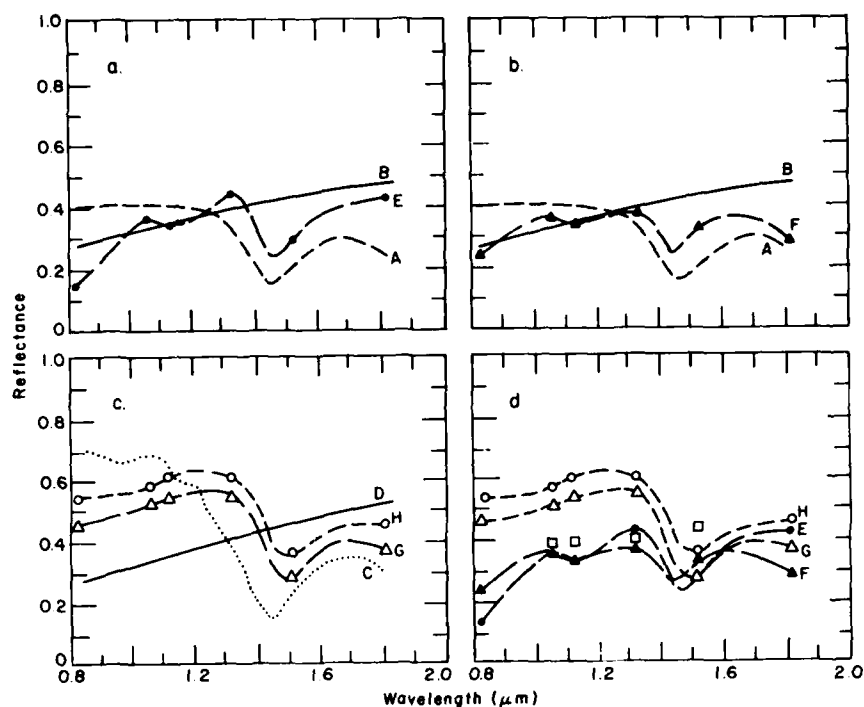


Figure 12. Reflectance from substrates.

- A— Individual green corn leaf (after Gausman et al. 1976).
- B— Individual dried corn leaf (after Gausman et al. 1976).
- C— Stacked green corn leaves (after Gausman et al. 1976).
- D— Stacked dried corn leaves (after Gausman et al. 1976).
- E— Laboratory measurements on winter wheat.
- F— Dead grass in-situ (from Fig. 11a).
- G, H— In-situ measurements on winter wheat (from Fig. 7, Curves D, E respectively).
- Data points of bare, dry concrete.

reflectance of stacked layers of corn leaves (Fig. 12c) and with our laboratory measurements on winter wheat and in-situ measurements of grass (Fig. 12d). Compared to Gausman's curves, the wheat reflectance seems to increase from 0.8 to 1.3 μm , as does that of stacked dry leaves, but it then decreases abruptly to assume characteristics more akin to those of stacked live leaves. Although wintered-over and apparently quite dead, the winter wheat in situ exhibits the same trends as the laboratory wheat. In this case, however, the reflectance is somewhat higher and is probably due to "residual greenness" as well as to dampness of the dead wheat. The higher reflectance of the in-situ wheat may also be related to specular reflectance from the randomly oriented damp grass.

Also included in Figure 12d are measurements of the reflectance of concrete pavement. Al-

though these were not made at the same time as the reflectance measurements of Figure 8, they may have some usefulness in considering the potential effect of finite snow thickness on the reflectance shown in Figure 8.

CONCLUDING OBSERVATIONS

Reasonable agreement between in-situ field measurements of snow reflectance and theoretical predictions of snow albedo has been demonstrated in a qualitative sense, but quantitative agreement requires rationalization of individual measurement conditions. The reasonable though not formally substantiated assumptions required to achieve compatibility between theory and measurements may provide an important key to physical parameters which need more detailed

consideration in theory and/or field measurement programs.

The crystalline structure of the snow should be more thoroughly characterized. For new snow, at least, a new size parameter needs to be defined in order to provide a closer link between a field-measurable dimension and the optical character of the snow. We feel that the appropriate size parameter is more closely related to the individual crystal components than to measurements of aggregates and, unfortunately, the latter are generally approximated in the grain sizes reported from visual estimates.

Fresh snow cover consisting of dendritic crystals, assemblages of planes, and other combinations of thin, plate-like crystals may require consideration of a bi-modal size distribution because of fragmentation of fragile structures. We hope to resolve this question by future detailed microscope/MC size distribution analyses of new snow covers.

Layered snow cover should be carefully characterized as to crystal types (microscopically identified), size distribution and the thickness of each layer, from the surface down deep enough to ensure approximation of a semi-infinite snow depth for the wavelength(s) being considered. Eventually, models will be required which not only account for snow layering but for other substrates, including vegetation, minerals and ice, which may be present at less than semi-infinite depths.

There are indications that, in modeling melting or rain-soaked snow, it is important to account for the wet surfaces of the snow grains by inclusion of terms involving the complex index of refraction of water as well as ice, particularly in spectral regions where the absorption coefficient of liquid water is substantially different from that of ice. Current methodology for field measurements of the liquid water content in snow (hot/cold calorimetry, dielectric probe measurements, etc.) may need to be improved or replaced in order to provide adequate accuracy for validating such a model.

The measurements made in this study are not sufficiently comprehensive to conclusively verify the theoretical evaluation, presented by Wiscombe and Warren (1980), of the depth at which a snowpack becomes effectively semi-infinite. However, the snow conditions (density, depth, etc.) that show indications of substrate influence on the reflectance measurements seem to agree with Wiscombe and Warren's predictions. Still, it could be that some adjustment to the theory

may be required for wet snow in spectral regions of greatly differing ice/water absorption coefficients.

Wiscombe and Warren (1980) have stated the hope that their model will eventually be able to predict snow albedo as a function of age and temperature, rather than grain radius. We deem this a commendable aim, provided that the "age" of the snow is expressed in terms of some function of the history of temperature, wind, and relative humidity.

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