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RED AND NEAR-INFRARED SPECTRAL REFLECTANCE OF SNOW

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ABSTRACT

The spectral reflectance of snow in the range of 0.60 to 2.50 μm wavelengths was studied in a cold laboratory using natural snow and simulated preparations of snow. A white barium sulfate powder was used as the standard for comparison. The high reflectance (usually nearly 100%) of fresh natural snow in visible wavelengths declines rapidly at wavelengths longer than the visible, as the spectral absorption coefficients of ice increase. Aging snow becomes only somewhat less reflective than fresh snow in the visible region and usually retains a reflectance greater than 80%. In the near infrared, aging snow tends to become considerably less reflective than fresh snow. The rate of decline of near-infrared reflectance due to aging is strongly influenced by the history of the snow during aging. Some of the significant parameters which determine the reflectance of snow are discussed and, where possible, results are presented which illustrate the predominant influences.

INTRODUCTION

This project was initiated in response to engineering problems related to the solar energy reflected from snow covering an underlying structure. Subsequently, interest developed in the application of these studies to problems in environmental satellite technology and in military surveillance and/or camouflage activities.

Although operational environmental satellites have obtained snow data remotely, one problem facing the satellite hydrologist is that of understanding the significance of variations in the spectral reflectance of the snow cover in order to more thoroughly evaluate the remote observations. The problem becomes more complicated because when snow is melting its spectral reflectance can change drastically on a day-to-day basis.

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The purpose of this program was to determine the spectral characteristics of snow in the near infrared (1.00 to 2.50 μm wavelength range) particularly with respect to changes in the spectral reflectance of snow cover during the natural aging process. More recently the scope of the project was expanded to include spectral measurements in the ultraviolet to 0.60 μm wavelength region. Only the spectral reflectance at wavelengths from 0.60 to 2.50 μm are discussed in this paper.

This investigation was conducted principally during the period January 1972 to December 1973 at the U.S. Army Cold Regions Research and Engineering Laboratory, and is discussed in more detail in Reference 1.

PROCEDURE

Spectrophotometric Methods

The physical arrangement of experimental apparatus is depicted in Figure 1. The optical configuration of
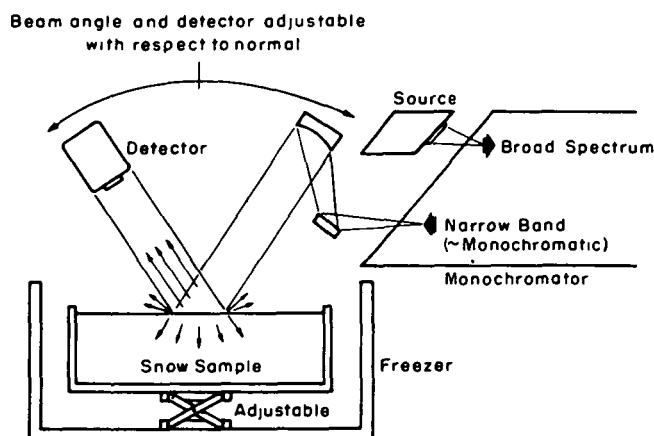

Figure 1. Instrumentation for reflectance measurements.

a Perkin-Elmer Model E-13 spectrometer was altered for utilization as a reflectometer. An open-top commercial freezer display case was used as a cold chamber to maintain snow samples during measurements. Initially the apparatus was set up in a warm laboratory with poorly controlled room temperatures. In November 1972 the equipment was moved to a cold laboratory with good temperature stabilization at 10°C.

Eastman White Reflectance Standard (Lot #201-2) was used as a standard with which to compare the snow reflectance measurements.

Spectral scans were run on the standard and on snow samples for each combination of angles of incidence and reflection desired. To eliminate the necessity of repetition of the terms and to simplify future discussion, abbreviated designations signifying an angle of incidence-hyphen-angle of reflection will be used in this paper. For example, "5°-5°" indicates an angle of incidence of 5° from normal and an equal angle of reflection; "0°-30°" indicates that the source beam was at normal incidence to the reflective surface (standard or snow) and that the reflectance was measured with the detector set at an angle of 30° to the normal. Although more measurements were made at 5°-5° and 0°-30° than at any other angles, several measurements were made at 10°-10°, 0°-15°, 0°-20°, and 0°-25°.

Preliminary tests indicated that reflectance measurements were not detectably influenced by the substrate materials (wood and/or aluminum screening on the bottom of the box) when covered with about 5 or 6 cm of snow. Therefore, all measurements were made with a minimum snow depth of 10 cm.

Snow Sampling Methods

Snow samples were collected by placing open boxes, consisting of a light wood frame covered on five sides with aluminum screen, on the ground in a reasonably level area away from the laboratory buildings and allowing snow to fall naturally into the boxes. Near the end of a fresh snowfall, a precooled, 21-ft^3 home-type deep freeze cabinet was rolled, on casters, outside of the laboratory building and one or more of the snow boxes were carefully lifted and carried to the freezer. The samples were then transported in the freezer into the cold laboratory.

On subsequent days, provided there had been no precipitation in the meantime, other boxes of naturally aged snow from the same snowfall were similarly collected.

Since the investigators had no control over natural aging conditions due to weather, some snow conditions were simulated in the cold laboratory.

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For some series of tests, older snow was ground
in a food mill and allowed to fall loosely into regular
snow sampling boxes. This milled snow appeared to
simulate natural wind-drifted snow quite closely in
density, hardness and texture. Generally, the tempera-
ture of the snow, whether naturally fresh or milled,
was held at about -19°C during storage and measurements.

Aging of snow was simulated by taking fresh snow
or milled snow and allowing various degrees of warming
with the snow sample still in position for reflectance
measurements. Then, sequential spectral reflectance
scans were run while holding the ambient air tempera-
ture as steady as possible at each of several levels:
below, near and above the freezing point.

A sample of artificial snow crust was synthesized
by spraying an ice-water mist on very cold snow.
Although this sample served its purpose in illustrating
a point to be discussed later, it was not considered a
very realistic replica of natural ice crust.

Observations were generally made of the snow
density, hardness and gross particle size using usual
meteorological methods. In addition, occasional
Formvar replicas were made of the snow samples.

DATA ANALYSIS

The strip charts of the spectrophotometer output
were digitized and corrections for drift in signal
strength were formuated. Both standard and snow runs
were corrected for drift and normalized to the same
gain. Each snow run was then compared with the appro-
priate standard run by computing and plotting the
ratio of snow reflectance to standard reflectance
point by point throughout the portion of the spectrum
covered in the run. In addition, some snow runs were
compared with other snow runs by the same method
(i.e., melting and refrozen snow were compared with
the original cold snow samples).

Two experimental discrepancies, not prominently
evident in most figures, appeared in the analyses of
some samples in the form of discontinuities in the
reflectance curves near 1.00 μm and again around
1.75 μm. The nature of these artifacts is discussed in
Reference 1.

When two or more runs were made on the same
sample under essentially constant conditions, the

results were reproducible for the most part within about 1% with occasional deviations of about 3%. Greater possibilities of error occurred at the limits of each monochromator graing (1.00 μm and 2.50 μm) and especially near 2.50 μm where the signal-to-noise ratio deteriorates rapidly.

RESULTS

It is virtually impossible to separate and examine each individual factor which determines the spectral reflectance of snow. An attempt has been made here to discuss some of the significant parameters and, where possible, to present results which may be presumed to illustrate the predominant influences.

A typical example of the spectral reflectance of snow is shown in Figure 2. The overall shape of the reflectance curve is similar for all types of snow examined (except for ice-glazed snow) but the relative magnitudes of various parts of the curve vary with conditions.
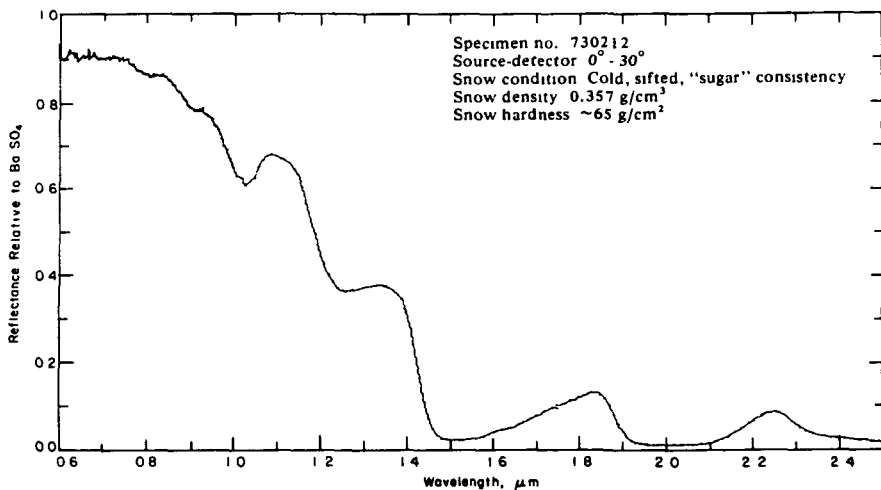

Specimen no. 730212
Source-detector $0° - 30°$
Snow condition Cold, sifted, "sugar" consistency
Snow density 0.357 g/cm^3
Snow hardness ~65 g/cm^2

Figure 2. Typical spectral reflectance curve for snow

Changes in Snow Reflectance Related to Natural Aging

The spectral reflectance of snow in the red and near-infrared regions exhibits rather predictable changes as the snow ages naturally. The history of the snow during aging influences the degree and rate of change of reflectance with wavelength.

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Figure 3 illustrates the changes in reflectance of light snow which fell during the evening of 20 January 1972. A fresh sample (curve A) was collected on the morning of the 21st. The weather was generally overcast and below freezing (about -2°C) during the time between snowfall and sample collection. The density of the fresh sample was 0.097 g/cm³.

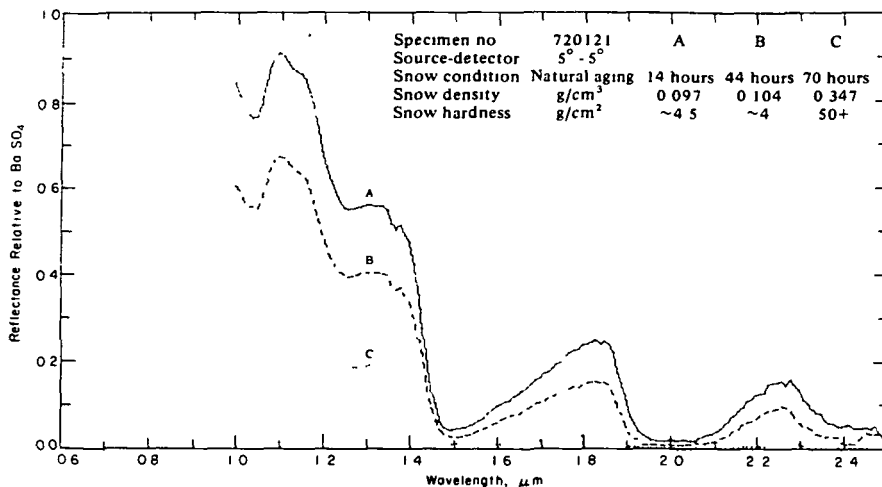| Specimen no	720121	A	B	C
Source-detector	5° - 5°			
Snow condition	Natural aging	14 hours	44 hours	70 hours
Snow density	g/cm³	0 097	0 104	0 347
Snow hardness	g/cm²	~4 5	~4	50+

Figure 3. Changes in snow reflecance with aging.

Thirty hours later, on the afternoon of 22 January, a second sample (curve B) was retrieved from the natural snow cover remaining from the same snowfall. Although the weather was clear and cold (never above freezing and falling to -20.5°C in the night), the measured density had increased slightly to 0.104 g/cm³.

A third sample (curve C) was taken on the afternoon of 23 January, representing nearly three days of natural aging of the same snowfall. This time, however, the ambient air temperature had warmed to about +7°C during the last day of aging and the density of the snow cover was measured as 0.347 g/cm³.

Another illustration of the changes in snow reflectance with aging is shown in Figure 4. Curve A shows the reflectance of freshly fallen snow (22 Dec 1972) and curve B that of snow which had aged naturally for two days with ambient temperatures hovering above and below freezing.

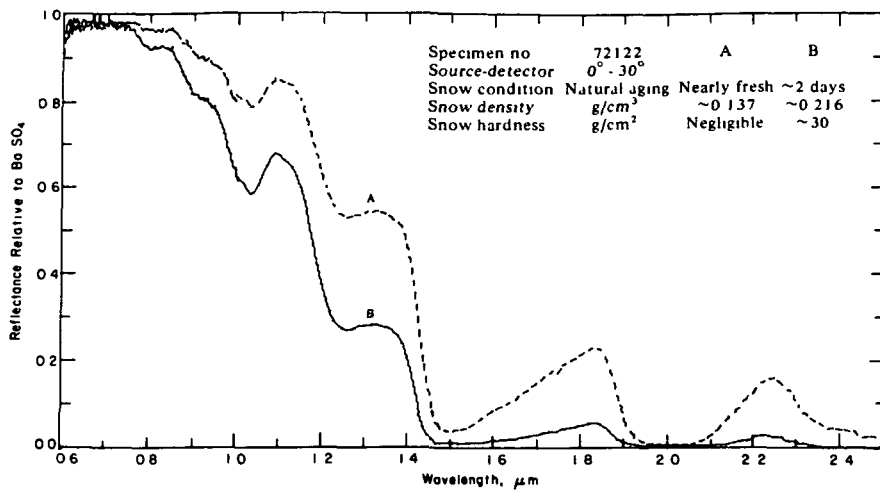|	Specimen no	72122	A	B
	Source-detector	$0°-30°$		
	Snow condition	Natural aging	Nearly fresh	~2 days
	Snow density	g/cm^3	~0 137	~0 216
	Snow hardness	g/cm^2	Negligible	~30

Figure 4. Changes in snow reflectance with aging.

The significance of these graphs will be more apparent after a discussion of the spectral reflectance of artificially melted and refrozen snow.

Effect of Melting and Refreezing on Snow Reflectance

Several experiments were performed to determine the effect of melting and refreezing on the spectral reflectance of snow. Since the only snow readily available at the time was somewhat aged and crusty, snow samples were prepared by sifting the old snow through a food mill. The resulting snow was very similar in appearance, texture, and physical properties to naturally windblown snow. The series of runs at $5°$ $-5°$ shown in Figure 5 depicts the sequence of events which followed. The first run was made with freshly milled snow continuously cold [about $-19°C$ (curve A)]. The ambient temperature was then raised to near melting and the snow temperature held around -1.5 to -0.5°C during the next run (curve B). The sample temperature was then returned to $-19°C$ and the reflectance rechecked (curve C). It is obvious from the proximity of these curves that temperature changes below melting have little effect on the spectral reflectance. During the fourth run (curve D) a draft of warm air was wafted across the surface of the snow causing slight surface melting, with no visible dimin- ution of snow volume but giving the appearance of a "glistening wet" surface. The ambient air temperature varied between $+2.5°C$ and $10°C$ during the run. With
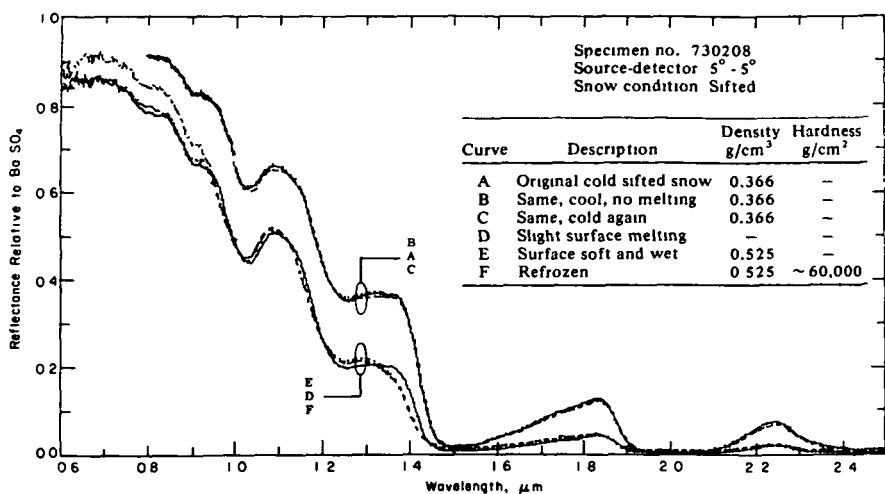
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Figure 5. Effects of temperature snow reflectance.

the onset of surface melting, the near infrared reflectance decreased drastically.

By the fifth run (curve E), the surface of the snow was soft and wet to a depth of about 1/8 in. The ambient temperature was about $+6^{\circ}C$ without the warm air blower. The snow was then refrozen and another run (curve F) made with the ambient temperature about $-5^{\circ}C$.

A comparison of the reflectance of cold, melting and refrozen snow are shown in Figure 6. In this case, the original cold snow was used as the reference. The ratios of the spectral reflectances of melting and refrozen snow to cold snow were then computed.

In general, melting lowers the spectral reflectance of snow. At some wavelengths, part of the reflectance lost by melting may be regained by refreezing, particularly with source-detector angles of 0° -30°. In the spectral region from about 1.9 to 2.1 μm wavelength, the reflectance of melting and refrozen snows appears to be about the same as or greater than that of loose cold snow. This occurs in a region of high energy absorption by water, and even greater absorption by ice. Since this portion of the spectrum is one of generally low reflectance for snow, and the curves therefore represent the ratio of two relatively small numbers, caution must be observed in interpreting the significance of specific details.
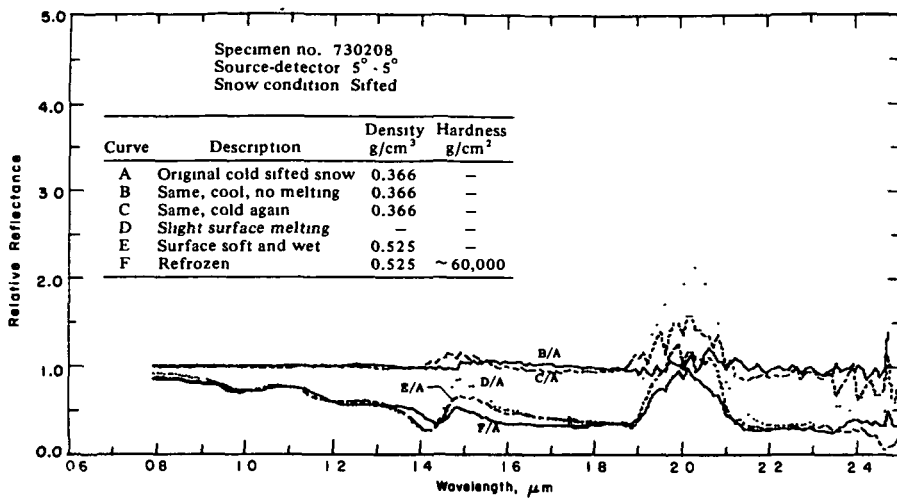
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Figure 6. Ratio of curves from Figure 5.

However, there is little question that increased reflectance of slightly melting snow may occur in this region.

Reflectance of Ice-Glazed Snow

On 8 December 1972, a light snowstorm changed to freezing rain causing an extremely hard smooth ice glaze on top of the snow. A sample was taken at night at just about the time the freezing rain ended. The snow under the crust had a density of 0.148 g/cm³. The ice-glazed crust, approximately 1/4 in. thick, had a measured density of 0.903 g/cm³. The following morning the undisturbed snow cover was subjectively observed to have a very high specular reflectance in the visible range. The spectral reflectance measured in the near infrared at 5° -5° is shown in Figure 7. In the range of wavelengths from 1.00 to 1.40 μm, the reflectance of the crust is qualitatively similar to that of other snow, particularly aged and/or refrozen samples. However, beyond 1.4 μm, the spectral reflectance of this ice crusted snow bears little resemblance to that of other snow samples studied.

Effect of Drifting and Wind-Compaction on Snow Reflectance

Approximately 8 in. of snow fell during the period of 1700 hours on 15 December and 0930 hours on 16 December 1972. A sample of this snow was collected about 2 hours after cessation of the snowstorm and
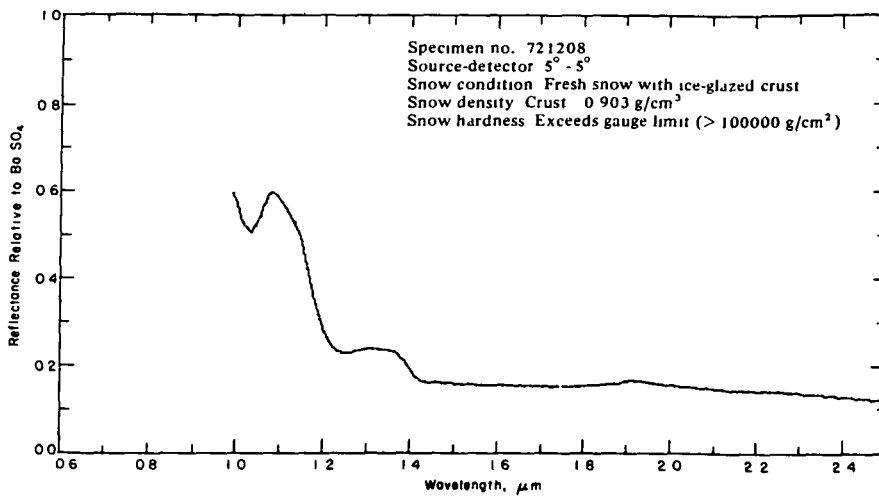
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Figure 7. Reflectance of ice-glazed snow crust.

before significant wind occurred. The ambient tempera-
ture during snowfall and up to the time of collection
did not exceed $-6^{\circ}C$. The snow density was 0.121 g/cm^3
and the hardness almost negligible (<2 g/cm^2). Due to
equipment problems, the sample was stored in a closed
deep-freeze at $-19^{\circ}C$, for about 30 hours before reflec-
tance measurements were made. The density and hardness
remained essentially unchanged. The reflectance of
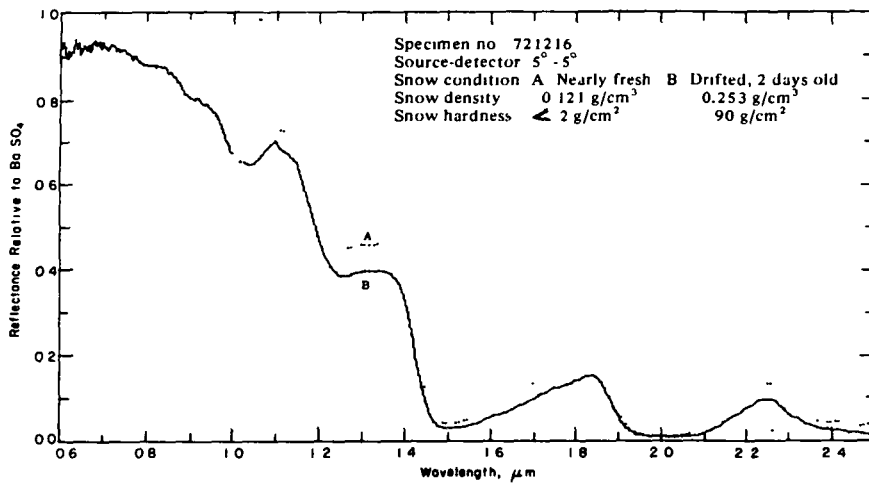this snow is shown by curve A in Figure 8. On 17

Figure 8. Effect of snow drifting on snow reflectance.

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December, at about 1530 hours, another snow sample was
retrieved. The weather had been cold (not above -1°C)
and windy (10 to 18 knots) on the 16th and 17th of
December so that the snow had drifted considerably and
had compacted somewhat. The density and hardness of
the drifted snow were 0.253 g/cm^3 and 90 g/cm^2 respec-
tively. The reflectance of this drifted snow sample is
shown by curve B in Figure 8.

Note that the drifted snow exhibits a lower re-
flectance than fresh snow. However, snow (particularly
at the peaks near 1.8-μm and 2.2-μm wavelengths) re-
tains more of its reflectance during two days of wind
compaction, even with the additional aging at cold
temperatures, than snow which has aged naturally and
increased commensurately in density without drifting.

Snow Reflectance at Various Angles

In the present study, the reflectance curves for
a given snow are generally very similar for a variety
of angles, indicating agreement with the popularly held
concept of near-perfect diffusivity of snow. There is,
however, lack of consistency between samples in the
relative magnitudes of measured reflectances at dif-
ferent angles. From the earlier data, many of which
are not shown in the illustrations, the tentative
conclusion was that the reflectance of snow seems to be
about the same at 5° -5° and 0° -30°, with perhaps
slightly greater reflectance at 0° -30°.

On the night of 21 March 1974, a fairly heavy
snowstorm occurred at Hanover, New Hampshire, pre-
senting an opportunity to recheck the angular reflec-
tance of a fresh snow. A fresh sample was obtained at
2100 hours. The density was 0.170 g/cm^3 and the
hardness was approximately 8 g/cm^2. Between 2100 hours
and 0419 hours the following morning, spectral scans
were made at several angles, as shown in Figure 9.
For that particular snow, at least, the relative re-
flectance was greatest at 0° -30°, decreased succes-
sively at 0° -25°, 0° -20°, and 0° -15°, and was even
less at 5° -5° and 10° -10°.

Other illustrations of snow reflectance at various
angles may be seen in Figures 10a and 10b. These
figures are presented in a later section because of
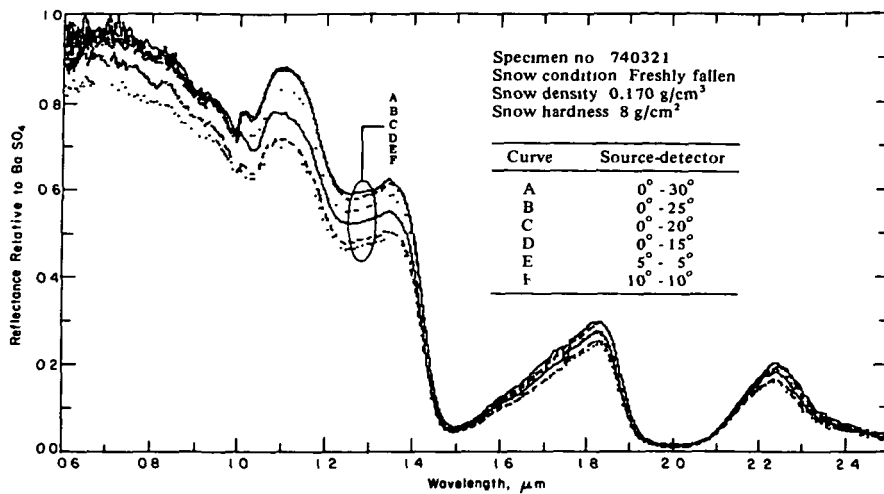their pertinence to another discussion.

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Figure 9. Comparison of angular reflectances of snow.

Relationship of Snow Reflectance to Snow Density

As previously mentioned, the reflectance of snow depends a great deal upon its history. Whatever the subsequent history of a freshly fallen snow, there is a tendency toward densification of that snow. Thus, natural aging over a period of time, even at sub-freezing temperatures, results in changes in the physical (and optical) characteristics of the snow caused by settling, sintering, and sublimation. Mechanical working of the snow, such as occurs during blowing and drifting snow, causes densification by settling and wind compaction. Melting of snow, even when slight, not only tends to increase the effective mean grain size and density by melting the smaller particles (such as dendritic branches) first but also produces free water in the snow. Densification of snow, by whatever means, is accompanied by a reduction of the reflectance of the snow - less noticeably in the visible red region but more and more significantly in the near-infrared region.

As a matter of interest, a survey was made of snows of several densities, disregarding history, and relating the reflectance at various wavelengths to the density of the snow. Wavelengths used were 1.0, 1.1, 1.3, 1.8 and 2.24 µm. In each case, the decrease in reflectance with density showed a simple correlation of about 0.8 at the 0.01 confidence level.

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Dunkle and Bevans (Reference 2) calculated the theoretical spectral reflectance (0.3 to 1.3 µm) of a snow cover "for particle sizes of 0.001, 0.01 and 0.1 in. ..." Their theory ".... indicates that, as snow ages and the snow crystals grow, the albedo should tend to decrease from the initial high values." It would therefore be anticipated that a reduction in the spectral reflectance would result from the combination of densification and increased particle size which occurs with aging. This expectation is confirmed by experimental measurements.

Although drifted snow observed immediately after being wind-blown has a greater density, due to wind compaction, than undrifted snow, the drifted snow would be expected to have a smaller size distribution and more rounded ice particles than snow which has aged by other processes due to mechanical working of the snow crystals (Reference 3). In the previous discussions of drifted snow, it was noted that drifted snow has a slightly higher reflectance, particularly at some wavelengths, than other snow samples which have otherwise "aged" to approximately the same density, thereby indicating the probably influence of the smaller particle size on the resultant reflectance.

Evidence that the spectral reflectance of snow may be preferentially affected by rather slight changes in the crystal structure of the snow may be inferred from Figures 10a and 10b. The reflectance of a freshly fallen snow (composed predominantly of spatial dendritic crystals with plate-like branches) is shown in Figure 10a. Figure 10b shows the reflectance of the same snow after slight aging was revealed microscopically by some loss of crystal detail. From a comparison of the two figures, it appears that, although the reflectance decreased at all angles, the diffuse reflectance deteriorated considerably more than did the specular component.

SUMMARY

Many factors influence the red and near-infrared spectral reflectance of snow. The principal parameters affecting the spectral reflectance, particularly in a natural meteorological environment, are so interrelated as to defy precise definition of the role of individual factors.
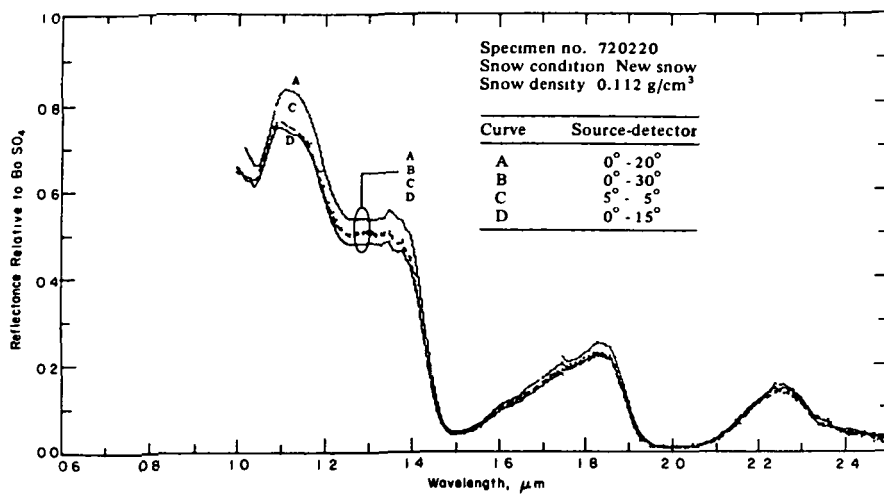
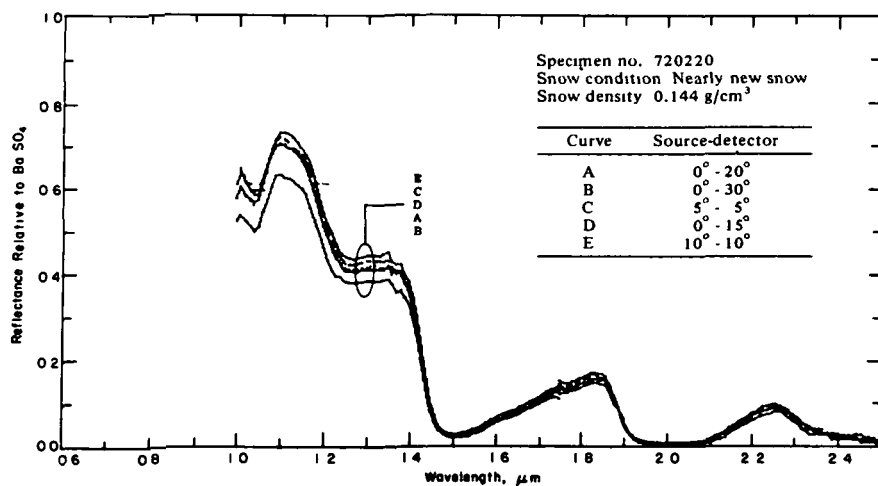**Figure 10a.** Comparison of angular reflectances of snow.

Figure 10b. Comparison of angular·reflectances of snow.

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Because of the polydisperse crystal shapes, sizes, and orientations which occur in a natural fresh snowfall, together with the innumerable possible sequences of natural aging to which the snow may be subjected, it is much simpler (and perhaps as valuable from a practical standpoint) to formulate some general conclusions concerning the spectral reflectance of fresh snow and the reflectance changes that take place during several types of natural aging.

1. Fresh snow has a very high reflectance in the visible red region. The spectral reflectance falls off sharply in the near-infrared wavelengths and is strongly related, inversely, to the spectral absorption coefficients of ice (Fig. 3, curve A).

2. Snow which has aged under cold conditions, with normal settling and densification, shows a slight decrease in red reflectance and moderate decreases in infrared reflectance (Fig. 3, curve B).

3. Snow which has drifted under cold conditions, and become densified to some degree by wind-compaction, also exhibits a slight decrease in red reflectance and moderate decreases in infrared reflectance (Fig. 15). However, compared with cold aged snow which has not been wind-blown but which has achieved equivalent densification by natural settling, the drifted snow tends to have a slightly higher reflectance, particularly near 1.8-μm and 2.2-μm wavelengths (compare Fig. 3 and 8).

4. Snow which is even slightly melting, when compared with nearly fresh cold snow, has a distinctly lower reflectance in the red region and an even more pronounced decrease in infrared reflectance generally. There is an exception, however, in that the reflectance may stay nearly the same as that of fresh snow (or even increase slightly) in the 1.9 to 2.0-μm wavelength region (Fig. 5,6).

5. Refreezing of snow which has previously been exposed to melting temperatures has a relatively minor effect, resulting in a reflectance curve generally resembling that of the melting snow. Refreezing may, however, cause an increase of reflectance relative to that of melting snow at wavelengths near 1.4 μm and 2.1 μm (Fig. 6,5).

6. The specular reflectance of ice-glazed crust
is spectrally similar to that of refrozen snow in the
1.00 to 1.40-μm range. The ice glaze reflects fairly
uniformly from 1.00 to 2.50 μm with gradual diminution
of reflectance and just the suggestion of a minor peak
in reflectance around 1.9 μm (Fig. 7). Unfortunately,
the diffuse component of reflection from the ice-
glazed crust was not studied.

7. Measurements of snow reflectance at various
angles indicate that for light fresh snows, with the
source normal to the snow surface, the spectral reflec-
tance generally increases slightly with increasing
detector angles between 15 and 30°. The reflectance
at 5° -5° and 10° -10° is slightly less (Fig. 9-10b).
For aging snow, results are erratic, presumably due to
the variety of microstructural changes involved in the
aging process.

8. The red and infrared spectral reflectance has
a significant inverse correlation to snow density.
Since densification is the result of many of the
natural aging phenomena, it is probable that this
correlation is the result of many concomitant influ-
ences.

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