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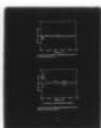
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OBSERVATIONS OF THE ULTRAVIOLET SPECTRAL REFLECTANCE OF SNOW, (U)
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Observations of the ultraviolet spectral reflectance of snow

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Cover: Reflection of solar radiation from an age-hardened snow cover (Shelburne Point, Vt, February 1977). (Photograph by Roy E. Bates.)

CRREL Report 77-27

Observations of the ultraviolet spectral reflectance of snow

Harold W. O'Brien

October 1977

Prepared for

**DIRECTORATE OF FACILITIES ENGINEERING
OFFICE, CHIEF OF ENGINEERS**

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The spectral reflectance of natural snow in the range of 0.20- to about 0.40-μm wavelengths was studied in the laboratory using both continuous spectral scanning and fixed bandpass measurements. White barium sulfate pressed powder was used as a standard for comparison. The reflectance of fresh snow was found to be very high (usually nearly 100%) and only weakly wavelength dependent from 0.24 μm to the visible range. In the 0.20- to 0.24-μm portion of the spectrum, the reflectance was found to be quite erratic. Possible reasons for the irregularities in reflectance measurements are discussed.		

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PREFACE

This report was prepared by Harold W. O'Brien, Research Physicist, Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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The author wishes to thank Dr. Y.C. Yen and Dr. M. Mellor for their critical reviews of the report and for their extremely helpful comments.

Roy E. Bates was very helpful in providing meteorological consultation on snow measurements and observations for this program. The efforts of Dr. Richard H. Munis in maintaining liaison with funding agencies are sincerely appreciated. Dr. Munis also provided several helpful comments and suggestions throughout the course of the project.

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OBSERVATIONS OF THE ULTRAVIOLET SPECTRAL REFLECTANCE OF SNOW

Harold W. O'Brien

INTRODUCTION

The rationale for the instigation and continuation of this research is similar to that which prompted the studies of *Red and Near-Infrared Spectral Reflectance of Snow* by O'Brien and Munis (1975). Briefly, the fact that a large portion of the earth's surface is covered by snow and ice during some portion of the year makes snow a very important factor in hydrological studies and in remote sensing.

This program began in conjunction with the visible red and near-infrared research previously reported and it continued as an extension of that research. The original intention was to relate the spectral reflectance in the ultraviolet and visible ranges to the measurable physical characteristics of a snow cover in a manner similar to that employed in the red and near-infrared ranges, but with close examination of the spectral influence of the crystal microstructure of the snow.

The technical problems encountered in the ultraviolet range so strongly influenced the course of the investigation that it was not possible to provide a complete and definitive description of the ultraviolet reflectance of snow. However, some general results are presented here, together with a description of some of the technical problems encountered, in the hope that they may be of some value and interest to others embarking on similar investigations of the spectral reflectance of snow. Experimental errors have been estimated as quantitatively as possible and have also been evaluated or explained in a partially subjective manner based on several years experience (both good and bad), and on the intuitive impressions that invariably result from close association with repetitive problems.

Many papers have been reviewed and considered during the course of this study. For other literature

relating to the optical properties of snow, the reader is urged to consult the references listed by Mellor (1964, 1965, 1976).

EXPERIMENTAL PROCEDURE

Sample collection, spectrophotometric measurements and data analyses were all very similar to those described by O'Brien and Munis (1975). Salient features and notable differences are described here for ready reference.

Snow collection

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

Observations were made of snow density, hardness and gross particle size using usual meteorological methods. Some samples were also replicated and studied microscopically. At the time of retrieval of snow samples from the field, observations were made in natural snow cover adjacent to the collection boxes to avoid destructive testing of intended samples. (Early tests indicated that the snow collected in these boxes showed no significant differences from the surrounding snow cover outside the boxes.)

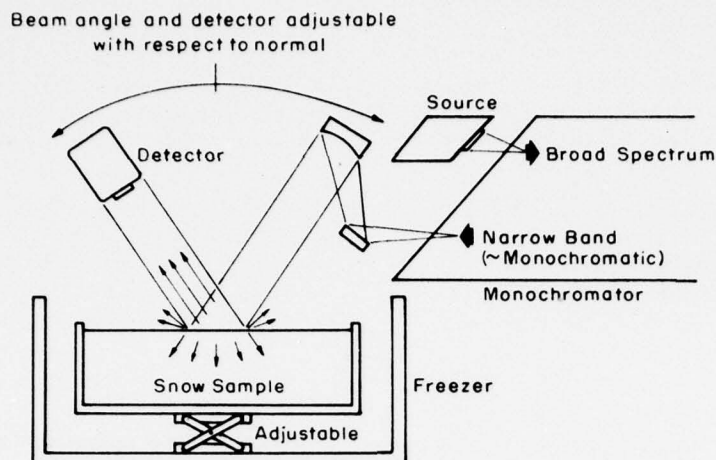


Figure 1. Instrumentation for spectral reflectance measurements.

Spectrophotometric methods

The physical arrangement of experimental apparatus is depicted in Figure 1. The optical configuration of a Perkin-Elmer Model E-13 spectrometer was altered for utilization as a reflectometer.

A deuterium (D_2) source and a 2880-line grating were employed in the 0.200 to 0.400- μm wavelength range, with suitable optical source filters to eliminate higher-order reflections. A few measurements were made in the visible range with a tungsten source and a 1440-line grating. Gold mirrors used for near-infrared measurements were used for a few of the earlier ultraviolet measurements but were subsequently replaced by MgF_2 -coated aluminum mirrors in an attempt to improve the signal-to-noise ratio. The source beam was chopped at 13 Hz for use with a Perkin-Elmer photomultiplier detector. Other measurements were made with a Spectra Pritchard photometer Model 1980 using the same Perkin-Elmer source (unchopped) and monochromator for spectral selection.

Eastman White Reflectance Standard (Lot #201-2), a white barium sulfate (BaSO_4) powder with excellent reflective qualities (Grum and Luckey 1968), was used as a standard against which to compare the snow reflectance measurements. The standard was prepared by filling a milled Plexiglas cylindrical container (0.15-m inside diameter and 0.0127-m depth) with an amount of the BaSO_4 powder which, when smoothed and compressed, would conform with Eastman Kodak's recommendations on standard density.

All reflectance measurements shown in the figures in this report are relative to the BaSO_4 standard. Subsequent to the completion of the draft of this paper,

Franc Grum* (personal communication) was extremely cooperative in providing additional data on the absolute reflectance of the Eastman White Reflectance Standard. This information, together with some of the data provided in his earlier paper (Grum and Luckey 1968), is included in Appendix A. Since there is some disagreement concerning the absolute reflectance values of BaSO_4 (Patterson et al. 1977), no effort was made to convert the curves in this paper to an absolute scale.

A removable platform was inserted at a fixed height, commensurate with the height to which a snow sample could reasonably be raised within the freezer without subjecting the sample to undue drafts and the danger of melting. The incident beam was adjusted to the desired angle and the White Reflectance Standard placed on the platform, such that the beam was centered on the standard powder surface. The detector arm was adjusted for the desired angle of reflectance, with the White Reflectance Standard as close as possible to the center of the detector's field of view. A spectral scan or "run" was then made of the reflectance in the range of the installed grating. Because of some temporal variation of instrument sensitivity, it was found advisable to choose a test wavelength at which to check the recorded signal strength before and after each run.

Abbreviated designations signifying "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 is at

* F. Grum is with the Analytical Sciences Division, Eastman Kodak Company Research Laboratories, Rochester, N.Y.

normal incidence to the reflective surface (standard or snow) and that the reflectance is measured with the detector set at an angle of 30° to the normal.

When using the Spectra Pritchard photometer, a run consisted of stopping the monochromator scan drive at desired wavelengths (usually every $0.01\ \mu\text{m}$) long enough to record the digital read-out. The spectral slit width, loosely referred to as the "band-pass," was approximately $0.002\ \mu\text{m}$. Because of the physical arrangement of the apparatus, only 0° - 30° measurements were possible with this photometer.

Similar measurements were made on each of the snow samples. The platform holding the standard was removed and the open-top freezer was rolled into position under the mirror system. A screened box containing the snow sample was placed on a "lab-jack" in the freezer, leveled, and raised until the snow surface was in the same location and orientation that the surface of the BaSO_4 standard had previously been in. Spectral scans were run in the same way as on the standard.

In order to avoid unnecessary repetition of description in distinguishing between the two types of measurements, in future discussions the spectral scans utilizing the Perkin-Elmer detector are called "continuous scans" or simply "P-E" scans, whereas the nonscanning spectral bandpass measurements made with the Spectra Pritchard photometer are abbreviated to "S-P" runs or measurements.

Data analysis

Strip charts of the Spectra Pritchard photometer output were digitized and corrections for drift in signal strength were formulated.

A Digital Equipment Corporation Laboratory 8/e computer was utilized to perform the analyses. Both standard and snow runs were corrected for drift and normalized to the same gain. Each snow run was then compared with the appropriate 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. Digital output from the Spectra Pritchard photometer was similarly manipulated using a hand calculator.

Potential sources of error

Numerous potential sources of error were recognized and attempts were made to eliminate or minimize the effects of known problems. Included in this category were electrical noise, stray light, thermal effects and uneven lighting of target areas. Electrical noise seemed to appear intermittently in the strip-chart output. Although the source of this type of

interference was not identified despite repeated attempts, it was usually readily recognized by the fact that the irregularities produced in the reflectance curve were not reproducible in successive runs with the same sample.

Attempts were made to exclude stray light by shrouding the entire optical path and "target" (standard or snow sample) area with black, rubberized cloth.

Thermal influences included not only ambient room temperature but possible effects caused by placing the "deep freeze" case containing the sample within the shroud. The room temperature was well controlled at 10°C . The freezer was placed under the shroud and a flat Plexiglas cover carefully slipped back to expose the sample area, thus minimizing the probability of cold (-19°C) air currents circulating upward from the freezer because of the very slight movement of air from the air conditioning units.

The light beam from the monochromator not only was spectrally dispersed in cross section but was probably not spatially uniform in brightness. This posed no obvious problem when using the Perkin-Elmer detector, as its field of view encompassed the entire light spot. However, the Spectra Pritchard photometer has a narrow field of view (adjustable, but 1° was most commonly used in these measurements). Efforts were made to locate the sample and standard such that the same hot spot in the beam was being viewed in each case.

These, and other possible sources of discrepancies will be reconsidered in the discussion of results.

PRESENTATION OF RESULTS

As many researchers have pointed out, numerous variables are involved in determining the character of a snow surface. O'Brien and Munis (1975) discussed a few of the significant parameters and presented results presumed to illustrate some of the influences predominant in determining the reflectance of snow in the $0.600\text{-}\mu\text{m}$ to $2.50\text{-}\mu\text{m}$ wavelength portion of the spectrum. They were able to present a "typical example" of the reflectance of natural snow and proceed to illustrate changes from the "typical" that occur when various environmental conditions alter the structure and optical characteristics of the snow cover. Unfortunately, the results of the present study do not readily lend themselves to such a presentation.

In attempting to categorize various snow conditions or experimental situations, it is frequently found that there may be more extreme differences within a category than between categories. Also, the measurements

made by using two different methods do not agree particularly well. Some of the variations and disagreements can be explained, at least in part — others cannot. Therefore, the results of this study are rather unnaturally subdivided according to method of measurement.

Continuous-scan measurements

The continuous scan (P-E) measurements, previously described, utilize the continuous-scan feature of the monochromator, together with a chopped deuterium (D_2) source and a synchronized Perkin-Elmer photomultiplier detector.

Figure 2 shows a composite of the reflectance curves made at 0° - 30° . Figure 3 shows the same type of composite of curves made at 5° - 5° . In each case, virtually all of the individual curves fell within the shaded portion of the composite. The extremes of the measurements are shown in dashed lines.

The 0° - 30° reflectance is slightly higher than the 5° - 5° reflectance throughout this spectral region. The shape of the reflectance curves for individual snow samples will be considered later, as will the possibility that these curves tend to represent slightly high values of reflectance.

In the spectral region from about $0.24 \mu m$ in the ultraviolet to $0.45 \mu m$ in the visible, the reflectance seems quite high, regular and fairly flat, whereas the reflectance in the wavelength region from $0.20 \mu m$ to

about $0.24 \mu m$ is much less regular. Most of the 0° - 30° measurements displayed one or more peaks in the latter region. Nearly all of these peaks reached values approaching 2.0 times that of the standard. In general, the 5° - 5° measurements indicated a depression in reflectance in the $0.20\text{-}\mu m$ to $0.24\text{-}\mu m$ spectral region.

Because of the lack of uniformity in the spectral reflectance curves obtained, and the near impossibility of selecting a "typical" reflectance curve, some of the outstandingly nonconforming curves will be presented first (i.e., those that do not fall within the shaded areas in Fig. 2 and 3). Speculation as to the causes for apparent peculiarities will be withheld until the discussion of results.

Figures 2 and 3 show peaks near the $0.22\text{-}\mu m$ wavelength region that exceed the scale limits of the graph. The specific reflectance curves displaying these extremely high peaks represent measurements on the same fresh, unusually light snow and are shown in Figures 4a, b, and c.

The original notes on the snow condition are paraphrased here to give a better idea of the snow type: ~ 2 cm new snow on top of ~ 10 -cm snow from yesterday. Very "feathery" top snow — surface hardness negligible; hardness of deeper layers $\sim 70 \text{ g cm}^{-2}$; density measurements 0.032 and 0.040 g cm^{-3} ; mean surface density 0.036 g cm^{-3} ; the snowflakes were mostly 1 to 2-mm particles.

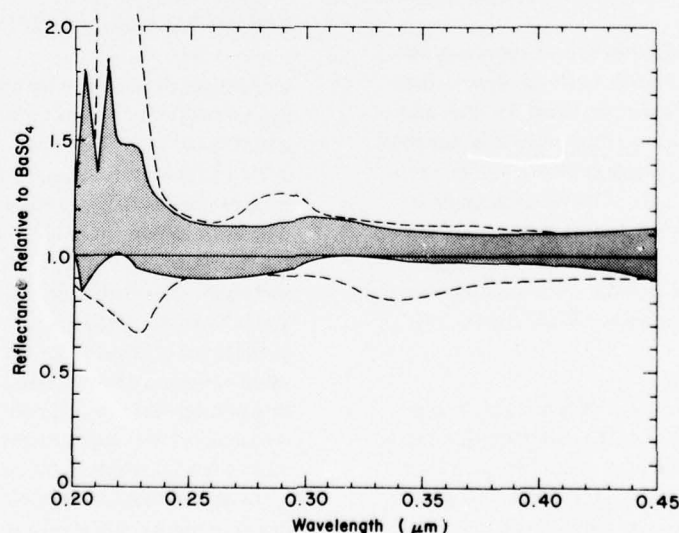


Figure 2. Composite of 0° - 30° reflectance curves.

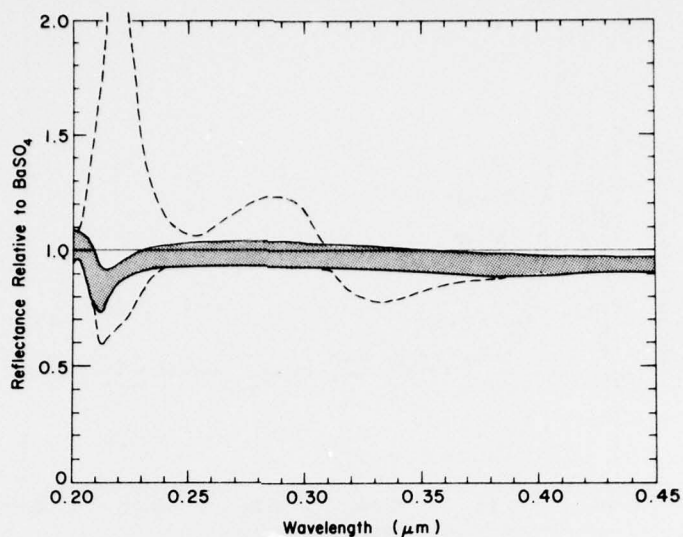
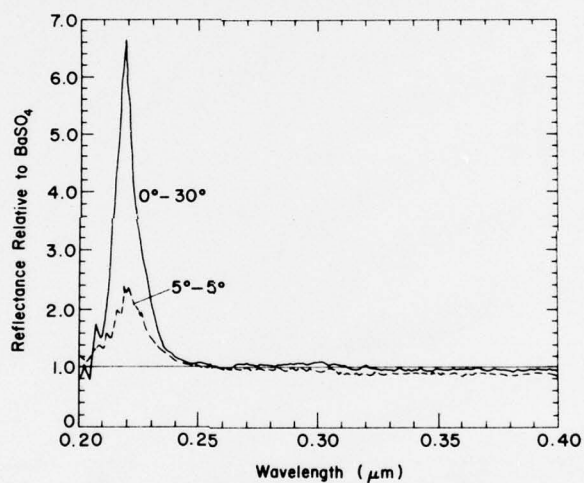


Figure 3. Composite of 5°-5° reflectance curves.



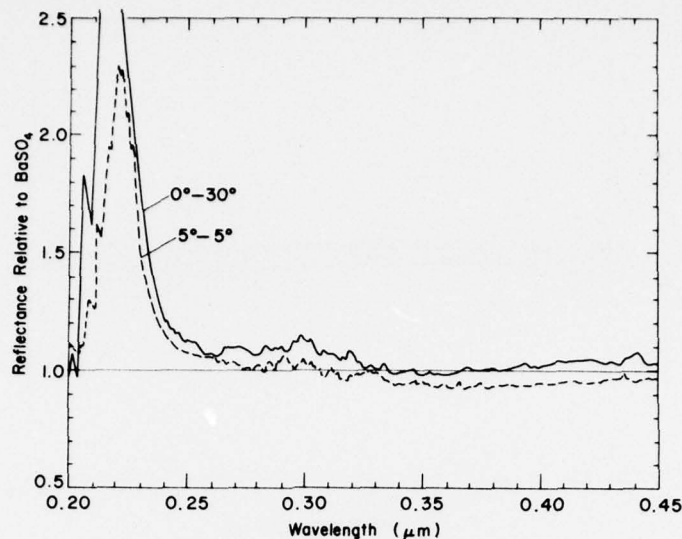
a. Comparison of 0°-30° and 5°-5° measurements.

Figure 4. Unusual case of reflectance from fresh very light, feathery snow.

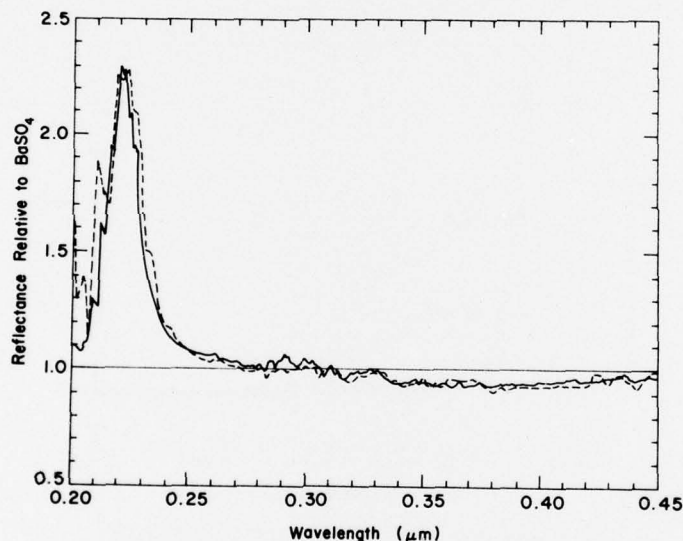
Microscopically (by replication) the snow crystals were identified as primarily dendritic types, probably mostly spatial dendritics with exceedingly fine branches. The 0°-30° curve is distinctive in the magnitude of the peak at about 0.216 μm , reaching a reflectance value nearly 7 times that of the standard. The 5°-5° curve is exceptional in that it is the only 5°-5° curve displaying a notable peak: most of the 5°-5° curves exhibited a

depression of reflectance in the same spectral region. The 5°-5° peak occurred at about 0.218 μm wavelength.

Figures 4a and 4b incorporate both the 0°-30° and 5°-5° runs for easy comparison. Figure 4b is similar to Figure 4a except in scale and illustrates the apparently higher reflectance at 0°-30° than at 5°-5°. Figure 4c portrays two separate reflectance scans (5°-5°) of the same snow, made about 15 minutes apart, indicating



b. Comparison of 0°-30° and 5°-5° measurements (larger scale than in Fig. 4a).



c. Comparison of two separate 5°-5° runs.

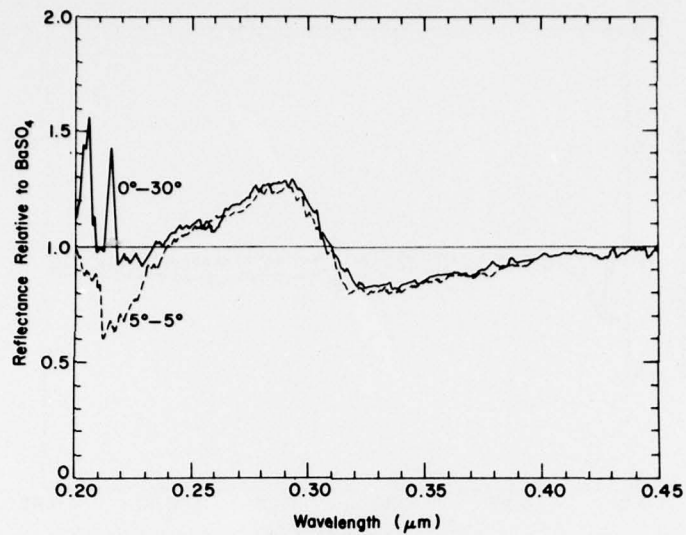
Figure 4 (cont'd). Unusual case of reflectance from fresh, very light, feathery snow.

that the apparently anomalous high peak was not due to any transient influence. However, it would be less than honest not to admit that such close agreement between two successive runs is not *always* attainable.

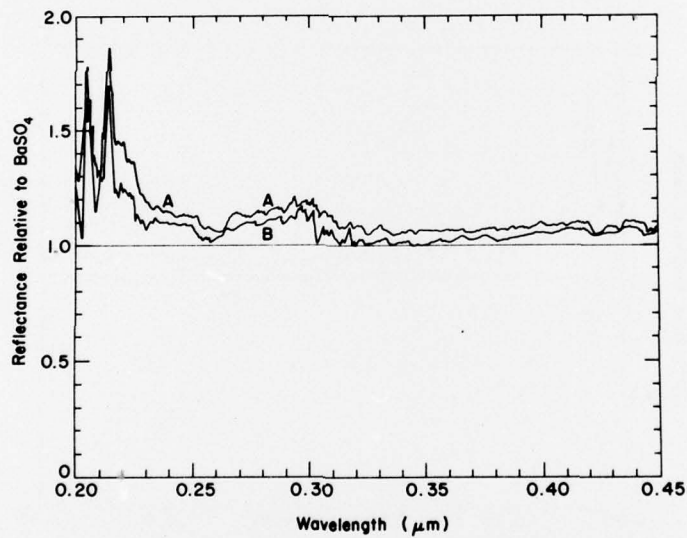
Figures 5a-5e illustrate the changes that appeared in the spectral reflectance measurements on two snow

samples over a period of a few days. For simplicity in discussion, these samples are referred to as A and B.

Sample A consisted of approximately 14 cm of new snow, freshly fallen upon a base consisting of about 6 cm of old granular snow. The density of the new snow was 0.137 g cm⁻³; its hardness was negligible in the top

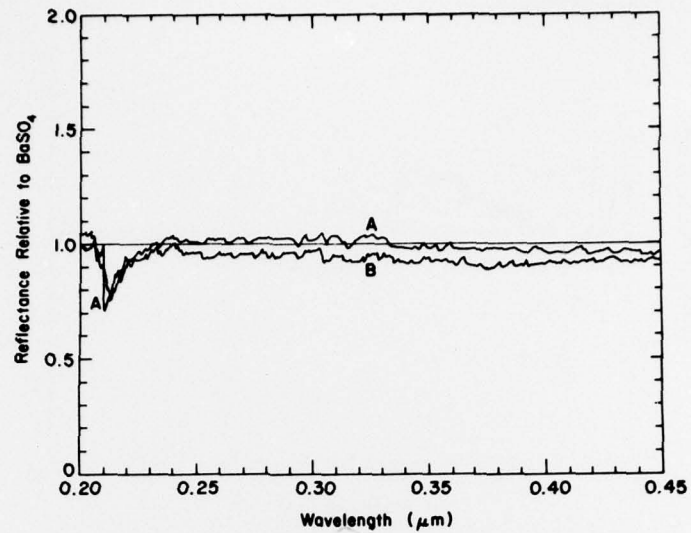


a. Fresh snow (sample A).

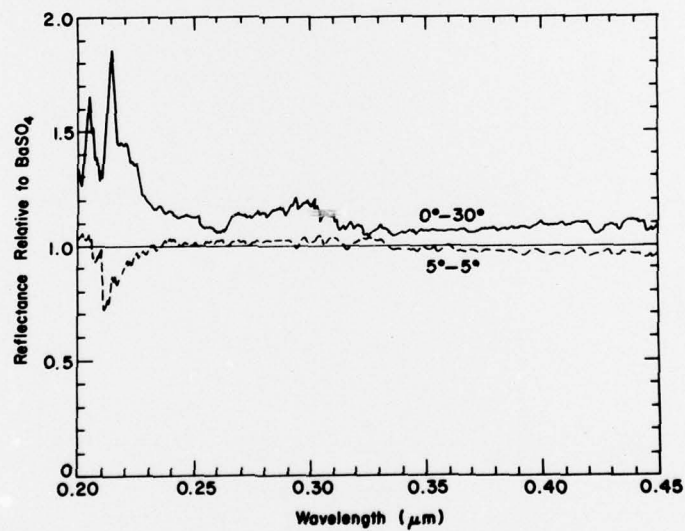


b. Nearly fresh snow (sample A) compared with snow aged in-situ for 2 days (sample B) at 0°-30°.

Figure 5. Spectral reflectance measurements of two snow samples over a period of a few days.

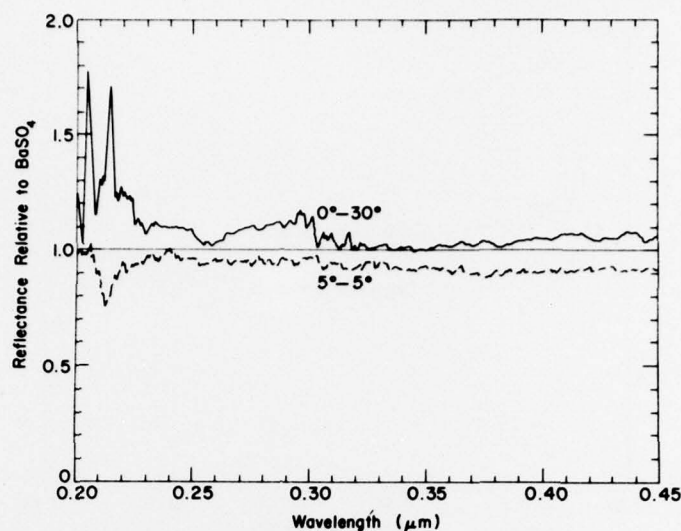


c. Nearly fresh snow (sample A) compared with snow aged in-situ for 2 days (sample B) at 5°-5°.



d. Comparison of angular measurements of sample A.

Figure 5 (cont'd). Spectral reflectance measurements of two snow samples over a period of a few days.



e. Comparison of angular measurements of sample B.

Figure 5 (cont'd).

centimeter or so, and about 11 g cm^{-2} below that. The snow particles were mixed in size: many small dendritic crystals ($< 1 \text{ mm}$), some aggregates of 2-3-mm diameter. Visually, these aggregates gave the appearance of clusters of plates and columns, but subsequent microscopic examination of replicas revealed a predominance of a very fine structural network of what appeared to be fern-like dendritics.

Sample B was derived from the same snowfall as sample A, but was allowed to age naturally in-situ for 2 days before being transferred to the freezer. During the 2-day aging period, ambient temperatures exceeded 0°C for several hours, ranging up to about $+3^\circ\text{C}$. The measured snow density was 0.245 g cm^{-3} at the surface and 0.216 g cm^{-3} in deeper layers; hardness was variable but was approximately 30 g cm^{-2} . The sample appeared slightly "crusty." Formvar replication was not entirely satisfactory, with few particles clearly defined. Those that could be reasonably identified appeared to be fragments of dendrites, many partially melted and having a sleet-like appearance (no sleet is known to have fallen between the collection times of samples A and B).

Figure 5a compares the reflectance of the freshly collected sample A at $0^\circ\text{-}30^\circ$ with that at $5^\circ\text{-}5^\circ$. The previously mentioned differences in reflectance between $0.20\text{-}\mu\text{m}$ and $0.24\text{-}\mu\text{m}$ wavelengths are again evident in these curves. Beyond $0.24 \mu\text{m}$, the curves are close together, with the $0^\circ\text{-}30^\circ$ reflectance being slightly higher than that at $5^\circ\text{-}5^\circ$. The anomalous part

of the curve (if that is a satisfactory expression to describe those measurements falling outside the apparent normal range) lies in the broad, low peak or "hump" in the reflectance curve around $0.26\text{-}0.30\text{-}\mu\text{m}$ wavelengths, and in somewhat "subnormal" values in the $0.31\text{-}0.38\text{-}\mu\text{m}$ range of wavelengths.

Figures 5b and c show the differences between the reflectance of an originally fresh snow (sample A) and that of a snow that has experienced 2 days of natural aging (sample B). At this time, sample A had been in the freezer at -19°C for 11 days, and sample B for 9 days. Previous experience had indicated no significant reflectance changes in snow samples during freezer storage (over periods of 2 weeks or more) as long as the sliding Plexiglas cover was kept on the freezer and no obvious hoar frost occurred on the snow surface. The density of sample A had increased very slightly (from 0.137 to 0.140 g cm^{-3}), presumably because of natural settling. The hardness did not perceptibly change. Sample B remained unchanged.

In Figure 5b, the rather drastic changes in the shape of the measured reflectance curve of sample A (at $0^\circ\text{-}30^\circ$) that occurred over the 11-day period since the previous measurements are immediately obvious. The previous "hump" around $0.29 \mu\text{m}$ (Fig. 5a) has decreased considerably, while the reflectance appears much higher than before in the spectral region beyond $0.31 \mu\text{m}$. Figure 5c, showing the same sample conditions as Figure 5b but measured at $5^\circ\text{-}5^\circ$, indicates an even more drastic change in the spectral reflectance of

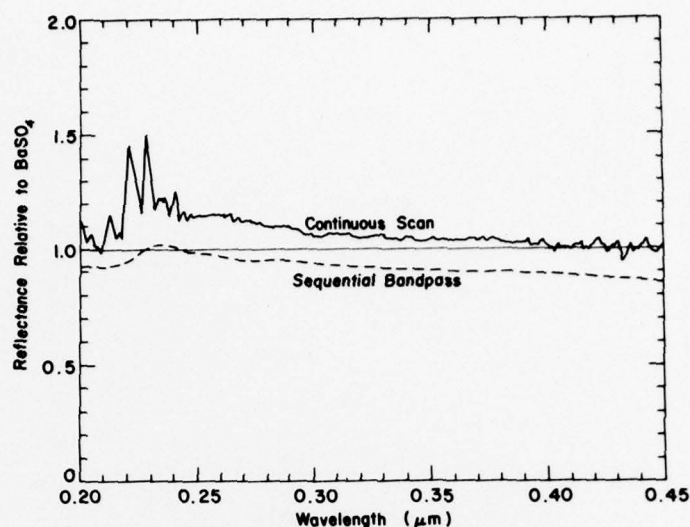


Figure 6. Comparison of continuous-scan vs sequential bandpass measurements on fresh snow.

sample A than that at 0° - 30° : both the "hump" near $0.29 \mu\text{m}$ and the depression around $0.30 \mu\text{m}$ to $0.38 \mu\text{m}$ seem to have disappeared. Sample B displays a spectral shape very similar to that of sample A, in both figures, but the naturally aged snow of sample B does appear to be somewhat lower in reflectance, across the spectrum, than the more nearly fresh snow of sample A. Figures 5d and 5e show the same reflectance runs as Figures 5b and 5c but are rearranged for easy comparison of the differences between the angular reflectance at 0° - 30° and 5° - 5° of samples A and B respectively.

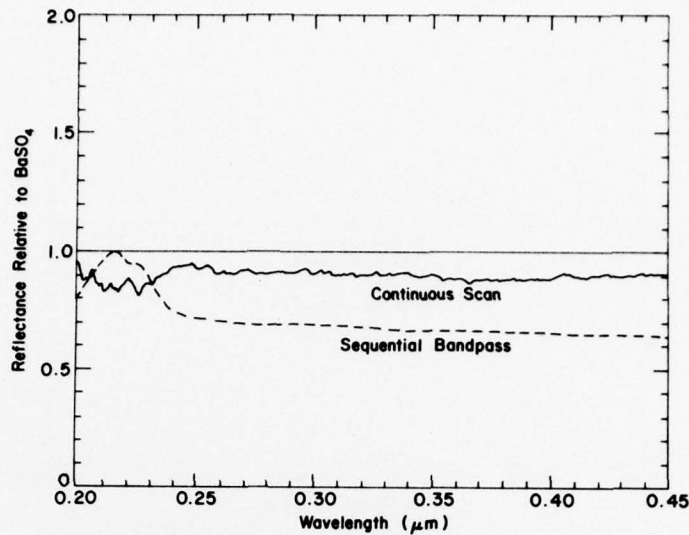
Comparison of sequential bandpass and continuous-scan measurements

The sequential bandpass measurements are those made with the monochromator set at specific center wavelengths with a bandpass of approximately $0.002 \mu\text{m}$ (the same spectral slit width as in scanning measurements) and using the Spectra Pritchard photometer detector.

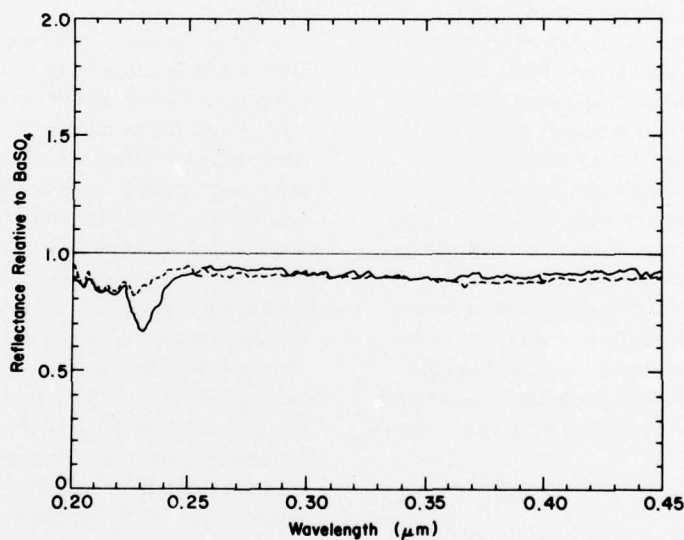
Preference would have dictated that comparative runs with the sequential bandpass (S-P) and continuous-scan (P-E) methods be made on numerous snow samples. However, the time and effort involved in changing back and forth between the two configurations prohibited frequent use of this procedure. Also, because of the arrangement of the fixed-bandpass apparatus, only 0° - 30° measurements were practical with this method.

A few examples showing the comparative results in reflectance measurements made by the two methods are displayed in the following figures. Figure 6 shows measurements of the snow collected fresh during a continuing snowfall (over 20-cm depth had accumulated). The snow density was measured as 0.0985 g cm^{-3} , and the hardness as 2 g cm^{-2} . The snow particle size was visually estimated to be mostly in the range of 0.25 mm to 0.50 mm in diameter, with a few particles ranging to about 1 mm in diameter. Subsequent microscopic examination of replicas revealed that the predominant snowflake type consisted of aggregates of "bullets" and spatial assemblages of aggregates of "bullets." Note the similarity in the shapes of the two curves in Figure 6 despite the discrepancy in the amplitude of the reflectance measurements. Both curves seem to verify the previous inference of relatively high reflectance at wavelengths near 0.22 or $0.23 \mu\text{m}$ (at 0° - 30°).

The measurements made on another snowfall are shown in Figures 7a and b. This snow is rather difficult to describe. During the snowfall, there were occasions when there seemed to be rain mixed with the snow, resulting in snow densities of 0.25 g cm^{-3} to 0.27 g cm^{-3} beneath the surface. Some drier snow fell near the end of the snowfall, but this layer was of indeterminate depth and this made it very difficult to obtain meaningful density and hardness measurements relating to the ill-defined depth of optical influence. The top layer (perhaps 1 cm) had a density of about 0.08 g cm^{-3} , but the underlying snow, with a density of about 0.25



a. Continuous-scan and sequential-pass measurements.



b. Two continuous-scan measurements.

Figure 7. Comparison of continuous-scan and sequential-pass measurements on inhomogeneously layered snow.

g cm^{-3} , undoubtedly exerted a strong influence on the measurements.

In Figure 7a, the S-P measurements indicate a much lower reflectance than the P-E scan values throughout most of the spectral region. Note, however, that although the S-P measurements display the expected

peak in the 0.21- μm to 0.23- μm wavelength region, the P-E scan does not. Subsequent comparison of that scan with another made the same day, on the same snow (Fig. 7b), repeated the apparent dip in the reflectance measurements.

Figure 8 depicts S-P measurements on another light,

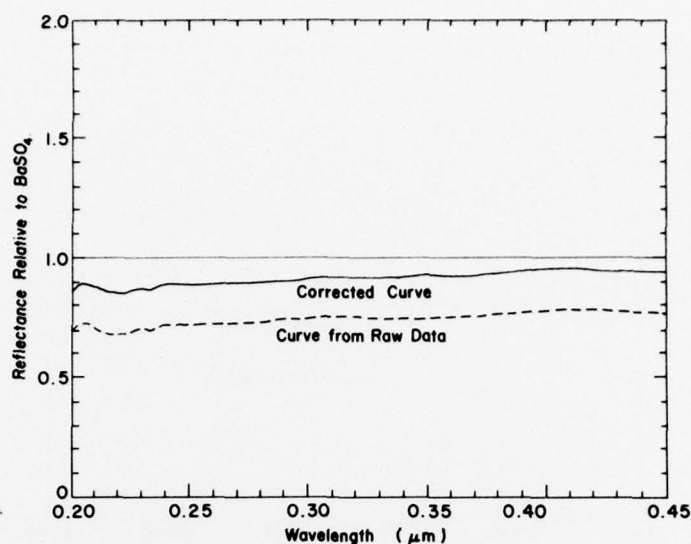


Figure 8. Sequential-pass measurement on light, fluffy snow.

fluffy snowfall, which had been very slightly wind-blown. The snow density was 0.085 g cm^{-3} ; the hardness was about 5 g cm^{-2} in the top 10 cm of snow, and about 20 g cm^{-2} in deeper layers. Microscopic examination of replicas revealed an apparent predominance of dendritic snowflakes so heavily stippled with cloud droplets as to obscure all fine detail in the dendritic branches. This sample did not display any significant peaks or depression in the $0.20\text{-}\mu\text{m}$ to $0.24\text{-}\mu\text{m}$ region. The spectral measurements throughout the range considered indicate unusually low values of reflectance in the raw data (dashed line). Review and analysis of the data indicated the probability of an unusually large experimental error caused by stray light. (This problem is more fully discussed later.) Correction for the error resulted in the solid line which more nearly agrees with P-E results.

Theoretical calculations

Dunkle and Bevans (1956) described a method for calculating the solar reflectance and transmittance of a snow cover. The theory treats the snow cover as a diffusing medium which, in the special case of a deep snow cover, is irradiated from one side only. Since the calculations reported by Dunkle and Bevans included only the $0.3\text{-}\mu\text{m}$ to $1.3\text{-}\mu\text{m}$ wavelength range, their equations were employed to determine the theoretical curve from $1.3 \mu\text{m}$ to $2.5 \mu\text{m}$ by Gregor Fellers of CRREL (personal communication). The theoretical results obtained by the method of Dunkle and Bevans were in quite good agreement with the

experimental data later obtained by O'Brien and Munis (1975).

Since the present work consists principally of measurements in the ultraviolet, it was also desirable to extrapolate the calculations of Dunkle and Bevans (1956) to $0.20 \mu\text{m}$. Munis (1976) states (personal communication) that he had a great deal of difficulty in finding reported values of ultraviolet absorption coefficients. His assessment of data from a paper by Browell and Anderson (1965) indicated: "The upper limit for the absorption coefficient of hexagonal ice at $0.1400 \mu\text{m}$ was approximately $2 \times 10^5 \text{ cm}^{-1}$." Using this value and the coefficient at $0.31 \mu\text{m}$ given by Dunkle and Bevans, he drew an exponential curve connecting the two points. It is highly speculative, and it is perhaps doubtful, that the absorption coefficient increases exponentially from a value of 10^{-3} cm^{-1} at $0.31 \mu\text{m}$ to $2 \times 10^5 \text{ cm}^{-1}$ at $0.1490 \mu\text{m}$. However, in the absence of more accurate values, this was used by Munis to obtain a very rough approximation to the reflectance values in the $0.2\text{-}\mu\text{m}$ to $0.3\text{-}\mu\text{m}$ spectral region.

Figure 9 shows the spectral values of reflectance calculated for three different particle sizes (solid-line curves). The top curve represents the calculated reflection from snow particles of approximately the smallest size generally found in snow covers. The bottom curve indicates a large snowflake size for comparison. These curves are superimposed on the shaded portion of the curve from Figure 3.

Although there are several good theoretical papers

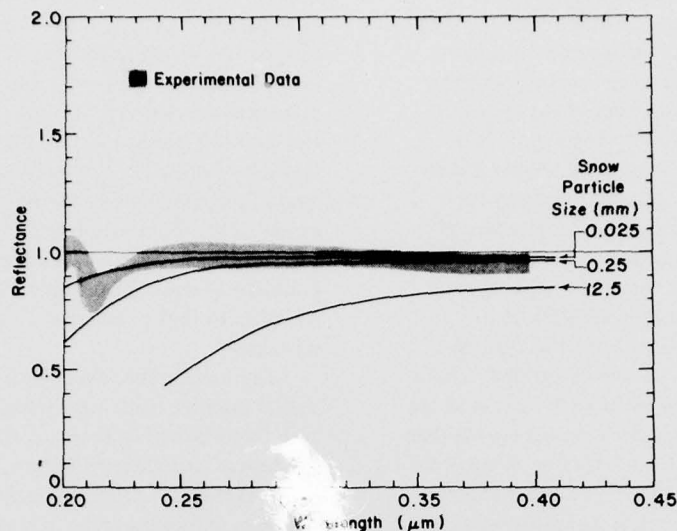


Figure 9. Theoretical reflectance curves (solid lines) (after Munis 1976).

on the transmittance, reflectance, and absorption of light by snow, only the paper cited by Dunkle and Bevans was used for comparison because of its availability at the time and its ready adaptability to these studies.

DISCUSSION OF RESULTS

Several difficult questions are addressed here. For example, why do snows of apparently similar physical characteristics show such variety in the amplitude and shape of their reflectance curves? Why do the measurements made by one method indicate generally lower reflectances than those made by another method on the same snow? What is true spectral reflectance of snow in the ultraviolet region?

In attempting to reply to the first two questions, it must be admitted that one possibility is that of experimental error. Most of the potential sources of error have been mentioned briefly in a previous section of this paper, and as already stated, "Attempts were made to eliminate or minimize the effects of known problems." However, viewing the results as a whole, there remains some suspicion that a few of the adverse influences were reduced but not entirely eliminated.

Assuming that the apparent anomalies in the reflectance curves have a physical basis relating to the optical characteristics of the particular snow cover,

the explanation of possible phenomena causing the anomalies is seriously hampered by such factors as the lack of reliable information on the ultraviolet absorption coefficients of ice, the ill-defined role of snow-grain size distribution and crystal orientation in determining ultraviolet reflectance, and the possible presence of contaminants (absorptive, reflective, or even fluorescent) in the snow cover.

Differences in amplitude of reflectance measurements

Numerous measurements, including many of those shown in the preceding figures, indicate that the spectral reflectance of snow in the 0.20- to 0.40-μm range generally decreases with aging (or increasing density).

Although only two combinations of angles of incidence and reflection were measured, the reflectance was observed to be rather consistently greater at 0°-30° than at 5°-5°.

The reduction in reflectance due to aging and the apparent dependence of reflectance upon the angle of measurement are believed to be qualitatively valid. Quantitatively, however, there is some room for skepticism as to the actual magnitude of the reflectance curves.

The P-E scans generally seem to indicate higher reflectances than do the S-P measurements. Several possible reasons for this situation are described in the following paragraphs.

The P-E detector was located entirely within the black rubberized shroud (used to minimize stray light), whereas the S-P photometer was located outside the shroud with only its viewing lens mount penetrating the shroud. (To do otherwise would have meant extensive remodification of the equipment.) It is therefore possible that when the snow sample was in place, the P-E detector (photomultiplier) may have been cooled slightly, thereby giving incorrectly high readings. Because of the arrangement of the sample freezer, it had been thought that circulation of cool air to the detector area would be insignificant.

Another possible effect is that of stray light, although this was believed to be well controlled. There was a slightly greater possibility of stray light entering the measurement area during snow measurements than during standard runs, because it was more difficult to get the shroud fitted snugly with the freezer in place. In an effort to avoid such an occurrence, indicator lights on the electronics control panels were painted nearly opaque red, room lights were turned off during measurements, and a very small, shielded "pen-light" was used only intermittently as necessary to record data. If, in spite of this, light leaks did occur during snow measurements, they would tend to increase readings on the S-P, whereas they would decrease readings on the P-E (since the P-E responds to synchronized chopped light). Thus, this situation would produce discrepancies opposite to those actually found.

Light leaks during runs on the standard (which seem less likely) could produce the type of differential found in comparing P-E to S-P measurements. Ordinarily, readings were checked with lights off and on to determine the approximate degree of light leakage. When significant differences were found, the shrouding was checked and efforts were made to close any gaps that might permit light leakage before further measurements were made. Thus, erroneous readings due to stray light should not normally have influenced results by more than 2-3%. One glaring exception is noted in Figure 8. On that occasion, the operator apparently did not note the discrepancy until after completion of the standard run and then found a light leak that had contributed an apparent increase in gain of approximately 17% over the correct reflectance readings.

Still another problem in comparing measurements from the two detectors is that of the difference between their respective fields of view. The P-E has a wide angle field of view, encompassing an area considerably larger than the illuminated target area. The S-P has several optional apertures, but most measurements were made with a one-degree viewing angle, giving a field of view of approximately 1 cm at the

target. The irradiated target area was several centimeters in width and length; and the source beam, after passing through the monochromator, was spectrally distributed in width and not uniformly distributed in intensity. In making measurements with the (S-P) instrument, the standard target was inserted, the illuminated target area found by setting the monochromator to a visible wavelength, and the photometer directed at a spot near the center of the illuminated area. The monochromator was then readjusted to pass ultraviolet light, and the photometer was adjusted very slightly in azimuth and elevation to find a "hot spot." (This was, perhaps, a mistake.)

After making spectral measurements on the standard, similar measurements were made on the snow sample with its surface as close as possible to the previous location of the standard surface. In retrospect, because of the extreme multiple scattering of the monochromator beam within the snow, it may be presumed that the photometer would then see a composite brightness representing the reflectance of an area somewhat larger than that of the actual field of view. This composite brightness might well be expected to give a lower reading on the photometer than the hot spot measured on the standard.

So, it is probably a combination of slightly high P-E readings (producing many readings over 100% compared to the standard) due to detector cooling, and S-P readings artificially lowered by dissimilarities in irradiation of sample and standard, that accounts for most of the discrepancies between the amplitudes of the reflectances measured by the two methods.

At one time, the question arose as to whether the P-E measurements might appear to be too high (i.e., greater than those of the standard) because of some sort of "fringe effect." Since the P-E detector's field of view exceeds the irradiated target area, when viewing the standard the P-E "sees" an illuminated area equal only to that of the incident beam, but when viewing a snow sample, it "sees" an illuminated area considerably larger (because of multiple scattering within the snow). Numerous experimental measurements were made in an attempt to determine whether there was such an effect and, if so, to evaluate it. Black matte paper, with a measured ultraviolet absorption of nearly 100%, was used to cover the standard and snow samples. Various covers were used, each having a different-size hole: 1 cm², 2 cm², 4 cm², 8 cm², 16 cm². The covers were laid flat on the reflecting surface, thus determining the size of the reflecting spot seen by the detector. Unfortunately, the results of these tests were erratic and uninformative, presumably because of the uneven distribution of irradiation within the field(s) of view.

Irregularities in the shape of spectral reflectance curves

Obviously, the reflectance characteristics of snow depend strongly upon the spectral complex index of refraction of ice. Unfortunately, the spectral values for the ultraviolet wavelengths between 0.2 and 0.3 μm are not well known or at least are not apparent in the literature. It is, therefore, not feasible to speculate at great length on the probable effects of this parameter on the shape of the ultraviolet spectral reflectance curves. The interpolation employed in Figure 9 permits only a rough assessment of the amplitude of reflectance appropriate to certain ice grain sizes. Whether or not there are peculiarities in the complex index of refraction of ice to account for the irregularities in reflectance observed in the 0.20- μm to 0.24- μm wavelength range is a moot point.

Researchers involved in the study of radiative transfer in snow are acutely aware that the "grain sizes" of the particles composing the snow cover exert an important influence upon the albedo of the snow. However, there seems to be some disagreement as to the nature of this influence on the spectral reflectance in the ultraviolet and visible ranges. Mellor (1964) gives a good account of "grain sizes for deposited snow." But, what is grain size in an optical sense? Bentley and Humphreys (1931) illustrated many of the beautiful and complex shapes of naturally occurring snow crystals. Nakaya (1954) measured the approximate range of dimensions of snowflakes that may be anticipated in freshly fallen snow. He measured dendritic crystals, for example, which were several millimeters in diameter or "largest dimension," but which were only 9 or 10 μm in thickness. With a little breeze to tumble and shatter such crystals, ice fragments having a volume measurable in cubic micrometers are possible. On the other hand, aggregates of snow crystals, or snowflakes, may reach sizes of several centimeters — each snowflake composed of a myriad of tiny ice particles of indeterminate "optical" size. Also, as Mellor (1976) points out, "Wetting or thawing can produce grains several millimetres in diameter...."

The preferential directional diffraction of light by nonrandom distribution in ice crystal orientation is known to occur in natural atmospheric conditions producing sun pillars, parhelia, and occasionally sun crosses. The bright cross sometimes seen emanating from a street light on a cold night is similar to a sun cross and is caused by the preferential vertical and horizontal scattering of the light from the plane surfaces and edges of plane (usually hexagonal) ice crystals drifting downward with their principal axes horizontally oriented, in a manner similar to that in which

a falling leaf flutters to earth. When a freshly fallen snow cover that is "sparkling like diamonds" in a bright light is closely examined, the sparkle is usually found to be reflected light from plane crystals (hexagonal plates or plane dendritic crystals) lying on the surface of the fresh snow. It is thus possible that a specular component of reflection from numerous snow crystals having similar orientations could significantly influence measurements such as those made in this study.

Whether or not the irregularities observed in reflectance between 0.20- μm and 0.24- μm wavelengths could be an optical phenomenon related to ice particles of extremely small optical size or to preferential scattering caused by nonrandom crystal orientation is not known. The largest "spikes" in reflectance did occur in measurements of extremely light, feathery snow. It is probable that the controversy in the past as to whether the relatively flat portion of the spectral reflectance curve (from about 0.30- μm wavelength out to the visible) increases or decreases in magnitude with increasing wavelength may well be due to differences in the optical grain size and size distributions of particles making up the surface layer of the snow cover.

Another peculiarity worthy of discussion is that shown in Figures 5a-c. The spectral reflectance curve for this snow, when freshly fallen, exhibited a hump in the 0.28- μm to 0.30- μm wavelength range and somewhat lower than usual values in the 0.31- μm to 0.35- μm spectral region (Fig. 5a). After several days storage in a freezer at -19°C (one sample also experienced two days of natural aging), the hump as well as the depression had diminished substantially at 0° - 30° and had virtually disappeared at 5° - 5° (Fig. 5c). This phenomenon suggests the possibility of a volatile contaminant in the falling snow that gradually diffused out of the surface layer of the snow. It is also possible that the snow particles had changed shape because of molecular diffusion, although changes in snow structure over a period of a few days at -19°C are difficult to detect microscopically.

The true spectral reflectance of snow in the ultraviolet region

The third question posed in the beginning of this discussion of results, as to the *true* spectral reflectance of snow in the ultraviolet region, cannot be unequivocally (if even satisfactorily) answered at this time. Interpretation of the results of this study leaves considerable room for conjecture. The author's conclusions are presented in the next section.

Figure 10 shows a partial overlay of Figures 2 and 3 illustrating the overlapping of the measurements of the

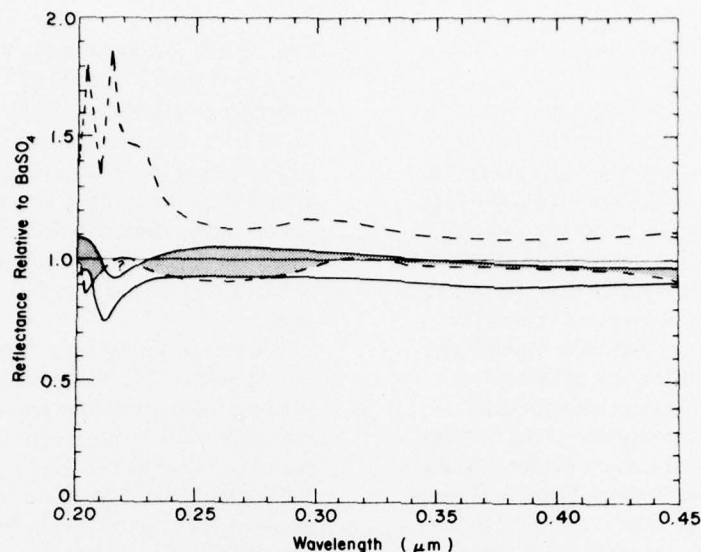


Figure 10. Most frequently occurring reflectance measurements.

most frequent occurrence for all spectral scanning measurements including both 0°-30° (dashed lines) and 5°-5° (solid lines) runs. The area of overlap is shaded in Figure 10. The unshaded area with the "?" represents a region of no overlap. In other words, very few reflectance values from either 0°-30° or 5°-5° scans fell within this "?" area; the 0°-30° measured reflectance values were generally higher and the 5°-5° generally lower than values within this region.

CONCLUSIONS

The principal parameters affecting the spectral reflectance of snow, particularly in a natural meteorological environment, are diverse, yet so interrelated as to defy precise definition of the role of individual factors.

It is to be expected that the spectral absorption of ice plays an important part in determining the overall shape of the reflectance curve of any snow cover. In the ultraviolet range, the spectral absorption coefficients are not well known. When melting occurs, the spectral absorption of water and water vapor modify the measured reflectance accordingly.

The crystal size and microstructure of the snow also constitute quantitatively significant and spectrally variable factors.

Many combinations of polydisperse crystal shapes, sizes, and orientations may occur in a naturally fresh snowfall. The snow may then be subjected to innumerable possible sequences of natural aging. These factors,

together with the possible presence of contaminants (reflective, absorptive or fluorescent; volatile or persistent) make precise description of the ultraviolet spectral reflectance of snow extremely difficult. For this reason, only a few rather general conclusions will be attempted here. These conclusions are based upon the number of measurements exhibiting similar tendencies and the types of experimental error possible and their probable degree of influence.

1. Snow has a very high reflectance throughout the ultraviolet region. The shaded portion of Figure 10 probably provides a fair representation of the shape of the reflectance curve for the region represented. Estimates of possible experimental error lead to the conclusion that the magnitude of the measurements represented by the shaded area of Figure 10 is probably about 3% to 8% high.

2. The ultraviolet reflectance is only weakly related to snow surface density measurements, showing a very slight but inconsistent tendency toward an inverse relationship. Part of the reason for this inconsistency is the unpredictable influence of inhomogeneous density distribution below the surface layer of the snow.

3. The snow reflectance at 0°-30° is almost invariably higher, throughout the ultraviolet range, than that at 5°-5°.

4. Snow reflectance in the spectral region from 0.24 μm to the visible is only slightly dependent on wavelength, showing a slight net decrease in reflectance toward the visible end of the range. Within this range, however, the reflectance curves for some samples show a small degree of "waviness" with very weak maxima

and minima, and tending toward a gradual but slight increase in reflectance toward the visible end of the range. Maxima and minima of more than a few (4 or 5) percent are thought to be the result of atmospheric contaminants precipitated with the snowfall (Fig. 7-9).

5. In the 0.20- μ m to 0.24- μ m spectral range, the reflectance measurements were very erratic. Generally, these measurements indicated high peaks in the 0°-30° measurements and somewhat of a depression in the 5°-5° measurements. Unbelievably high peaks in reflectance were observed in this region when extremely light snow was being measured, particularly at 0°-30° and on one occasion at 5°-5°. Although the possibility of some type of fluorescent phenomenon has not been ruled out, these phenomena are presumed to be due either to peculiarities in the relatively unknown absorption characteristics in this portion of the spectrum or to effects created by the extremely fine structure of the snow crystals found in this type of snow.

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APPENDIX A. ABSOLUTE REFLECTANCE VALUES OF PRESSED BaSO₄ POWDER.*

<i>Wavelength (nm)</i>	<i>Absolute reflectance</i>
200	0.912
210	0.920
220	0.923
225	0.923
250	0.939
275	0.979
300	0.987
325	0.980
350	0.985
375	0.992
400	0.995

* From Grum and Luckey (1968)
and Franc Grum (personal communication).