Reflectance of Snow as Measured In Situ and from Space in Sub-Arctic areas in Canada and Alaska

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Abstract—**Quantitative measurement of snow reflectance from space has been possible since the launch of the Landsat Thematic Mapper (TM) in 1982. Efforts to validate the accuracy of Landsat derived reflectances are ongoing to enable mapping global snow reflectance, and eventually snow albedo, using data from future satellite sensors. Visible and near-infrared measurements of clean snow and dirty snow (both actively melting) were acquired near Yellowknife, N.W.T., Canada, in May 1990 using a portable spectrometer, and the Landsat TM. Similar measurements were also acquired over snow covered glaciers in Alaska in August 1987. The *in situ* reflectance at nadir of the dirty snow was approximately 30% lower in the visible part of the spectrum than was the reflectance of the cleaner snow near Yellowknife. The shapes of the reflectance curves are also different, the curves for the dirty snow being flatter than the curves for the clean snow. The shape of the reflectance curves of actively melting snow near Yellowknife versus fresh snow as measured in Alaska, was similar in the visible region of the spectrum, but diverged in the near-infrared region, with the reflectance of the melting snow decreasing moreso than for fresh snow. In Alaska, the off-nadir look angle measurements of snow consistently exceeded 1.0 because of enhanced forward scattering from the snow at off-nadir angles when the sensor is facing the Sun. TM-derived reflectances acquired near Yellowknife are not directly comparable with *in situ* measurements because a mixture of cover types is included within each 30 × 30 m pixel. Because the variability in solar zenith angle causes major differences in absolute reflectance, the shape of the reflectance curves and the anisotropic reflectance properties are found more useful in differentiating snow type and moisture state than are actual reflectances.**

I. Introduction

Snow cover is a highly variable material in terms of its extent, thickness, and reflectance. These parameters change as snow ages and metamorphoses, and are important to global energy balance because the thermal and reflective properties of snow influence its duration and the heat flux between the atmosphere and the ground. Snow reflectance is highly variable over large areas, especially since it is influenced by ground cover. At present, satellites can be used to measure reflectance at near-nadir viewing angles using the Landsat Thematic Mapper (TM) sensors on board Landsats 4 and 5, launched in 1982 and 1984, respectively. In the future, the Moderate Resolution Imaging Spectrometer (MODIS) on board the Earth Observing System (EOS) will be capable of measuring snow reflectance globally. The present work has been undertaken in order to measure snow reflectance under different snow and surface conditions, and ultimately to improve our ability to measure snow reflectance over large regions from space.

Field and Landsat satellite measurements of actively melting snow near Yellowknife, N.W.T., Canada were acquired in early May 1990. Reflectance was measured using a hand-held spectrometer, and radiance data from the TM on board the Landsat satellite was used along with ancillary information and an atmospheric correction program to calculate reflectance from space. The reflectance of actively melting snow as measured *in situ* near Yellowknife is shown to differ from drier (fresh) snow as measured in a similar manner on August 2, 1987 in the Wrangell Mountains, Alaska, both in terms of its absolute reflectance, and its anisotropic reflectance properties. In addition, the shape of the reflectance curves are different. Though not directly comparable to the *in situ* measurements, reflectances of snow and of lake ice acquired near Yellowknife on May 1, 1990 are also shown and some of the problems relating to validation of TM-derived reflectance using *in situ* measurements are discussed.

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II. Background

Much literature is available regarding measurement of snow reflectance [1]. In general, the reflectance of snow decreases with increasing grain size and with age of snow [2], [3] and is only weakly dependent on snow density when the grain size is constant [4]. In the near-infrared, the reflectance of aging snow decreases considerably as melting and associated grain size increases [1], [2], [5], [6]. Snow, like all natural surfaces, is an anisotropic reflecting surface, and the anisotropic reflectance properties vary with snow type and wetness.

The calculation of snow reflectance using Landsat satellite data has also received attention [5], [7]–[11]. Snow reflectance derived from Landsat TM sensors has been compared with reflectance acquired *in situ*. Results have demonstrated that, at least under certain conditions, there is good correspondence between snow reflectance as calculated using Landsat TM data (after atmospheric corrections have been applied) and *in situ* reflectance over targets of pure snow [11].

Detailed measurements of snow reflectance at off-nadir angles have been acquired and have demonstrated the importance of hemispheric reflectance measurements for use in calculating snow albedo [12], [13]. The anisotropic reflectance is most pronounced when the sensor viewing direction is facing the Sun. Additionally, Steffen [14] showed that the anisotropic reflectance properties are increasingly pronounced as snow grain size increased from 0.15–3 mm in radius for all solar zenith angles studied. Since grain size increases with age of snow, older snow displays greater anisotropy than does fresher snow.

Albedo of both dry and wet snow increases with solar zenith angle [1], [15]–[18]. Dubreuil and Woo [15] report that for most observations, snow albedo varies inversely with solar elevation on clear days and may be caused by variation in the specular reflection component with low Sun angle. Absolute reflectance is influenced greatly by solar zenith angle.

Snow reflectance is relatively insensitive to grain size, but sensitive to contamination by dust and soot in the visible part of the electromagnetic spectrum. But in the near-infrared, the reverse is true [5]. Reductions in reflectance in the visible part of the spectrum by a few percent can be caused by about 0.1 parts per million by weight (ppmw) of carbon soot [19]. Soot may be the dominant absorber in arctic snow and is present in concentrations that should affect snow albedo appreciably [20], [21].

Reflectance of freshwater lake ice is generally lower in the visible part of the spectrum than is the reflectance of snow, and the reflectance does not decrease as much into the near infrared wavelengths as it does with snow [6], [22]. Experimental evidence suggests that scattering by a particular ice sample depends, in part, on age, temperature, and vapor bubble content [23]. The reflectance of freshwater ice is highly dependent upon the amount of snow or slush that is incorporated into the ice [22], [24], [25], and the size distribution of air bubbles [26].

Leshkevich *et al.* [27] measured the bidirectional reflectance of refrozen slush ice in the visible and near-infrared bands. They found that bidirectional reflectance varied throughout the day and that the anisotropy increases with increasing solar zenith angle, the effect being more pronounced in the near infrared than in the visible region of the spectrum.

III. Study Area and Methodology

Reflectance measurements were acquired northeast of Yellowknife, Northwest Territories, Canada at approximately 62° 30' N, 114° 00' W where the terrain consists of extensive and numerous bedrock outcrops from the Canadian Shield rock. In Alaska, reflectance measurements were acquired of snow over glacier ice in the Wrangell Mountains at approximately 62°06'N, 144°09'W.

There were two sites near Yellowknife, both near the northern boundary of the boreal forest, where stunted conifers are interspersed in the landscape. On May 1, 1990, the snow was actively melting and patchy in coverage. At site 1, snow depth varied from 12 to 18 cm, the snow surface was hummocky and the air temperature was 4°C. Snow crystal size was measured using a magnifying lens which has a scale inside so that the crystal size can be measured visually by a person looking through the lens. Using this method it was estimated that most of the snow crystals measured at site 1 were 1–2 mm in diameter. At the time of the field measurements (14:45 local time) the solar zenith angle was 58.06°. At site 2, the snow surface was visibly dirty and there was about 1 cm of slush overlying solid ice that formed from melted snow. (Snow crystal size was not measurable in the slush.) Because the snow was thin, reflectance properties from the ice below are likely to influence the reflectance. At 15:30 local time the solar zenith angle was 62.69° at site 2.

On August 2, 1987 the snow over glacier ice was moist (air temperature 12°C) but fresh, probably <24 h old snow at the time (12:00 local time) of the *in situ* measurements. The snow surface was flat and the average snow crystal size was about 0.5 mm in diameter. Though the snow on the surface had apparently experienced some melting and refreezing [11], meltwater was not visible as it was in the snow near Yellowknife.

In situ measurements were acquired using an SE-590 spectrometer that measures radiance from 350–1100 nm in 252 discrete steps. (Because of the characteristics of the silicon detectors in the sensor, the signal-to-noise ratio (SNR) is small beyond about 900 nm, therefore, those data are not shown in the results section of this paper.) The field of view of the sensor is 1° and for the measurements shown herein represents approximately 3 cm^2 on the ground.

A reference panel containing powdered, pressed halon was used as a standard from which to compare the radiance measurements of snow. Halon has been found to be an excellent standard of diffuse reflectance [28]. However, measurement of the reflectance properties of our reference panel show that it is an anisotropic reflecting surface when measured at off-nadir look angles in the viewing direction facing the Sun, and the anisotropy increases at high (> 50°) off-nadir look angles.

Immediately prior to and following the acquisition of each set of snow scans, the halon reference panel was measured in a nadir-viewing direction. Using the ratio of the snow scan to a reference panel scan or average of several scans, reflectance factors may be calculated and plotted to generate reflectance curves.

Using the SE-590 spectrometer, scan sets were acquired over snow targets. Each set consisted of measurements at nadir (0°), and 15°, 30°, and 45° off-nadir, facing the Sun. A similar set of measurements was acquired facing 90° away from the Sun. The SE-590 was hand-held and an inclinometer on the sensor was used to determine the off-nadir viewing angle. The solar and atmospheric conditions were considered to be stable during the fast (<1 s) integration time of the sensor.

IV. Results

In Fig. 1 the maximum reflectance factor at Yellowknife site 1 is about 0.95 at 400 nm with a sensor viewing angle of 45° off-nadir and a viewing direction facing the Sun. The reflectance factor at nadir is about 0.78. This represents about a 0.17 increase in reflectance from nadir to 45° off-nadir. Due to the directional reflectance characteristics of snow, the difference between reflectance factors acquired at different angles is greater in the viewing direction facing the Sun (Fig. 1) than when measuring the same snow facing 90° away from the Sun where the increase in reflectance from nadir to 45° is only 0.09 at 400 nm (Fig. 2). Thus, anisotropy is greatest in the viewing direction toward the Sun. Reflectance increases with viewing angle even when viewing at 90° away from the Sun, although not nearly as much as when measurements are acquired facing the Sun. This is because some specular reflection still occurs, but not as much as occurs when the sensor is facing the Sun [12], [13].

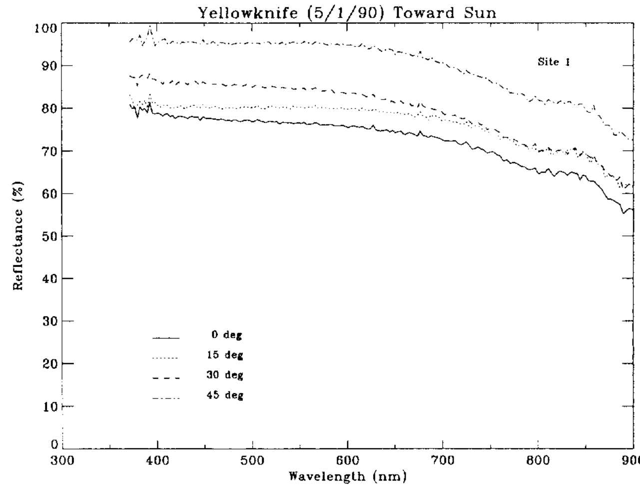

Fig. 1. Reflectance curves obtained when facing the Sun, for snow at site 1 near Yellowknife, N. W. T. on May 1, 1990.

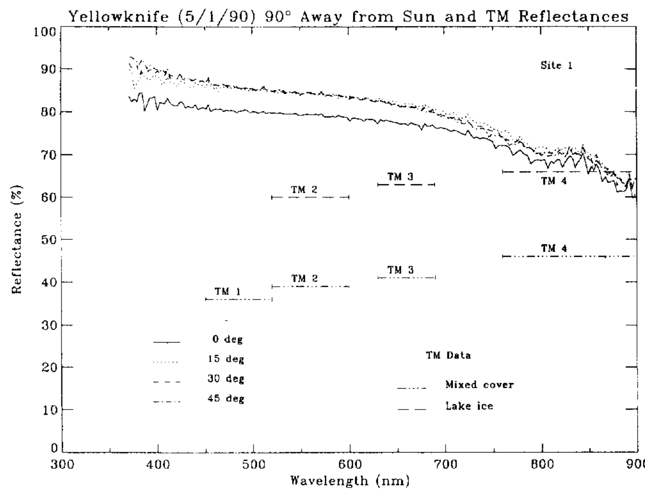

Fig. 2. Reflectance curves obtained when facing 90° away from the Sun, for snow at site 1 near Yellowknife, N. W. T. on May 1, 1990. Also shown are Landsat-derived, atmospherically-corrected reflectances in nonsaturated TM bands acquired on May 1, 1990 (TM scene I. D. # 5225218112).

For the Yellowknife study area, site 2, which consisted of a thin layer of dirty, actively melting snow over ice, reflectances were lower than at site 1. The anisotropic reflectance was stronger than at site 1, with a minimum measured reflectance at 400 nm of about 0.50 at nadir and a maximum reflectance of about 0.80 at 45° off-nadir (Fig. 3). In addition to the fact that the reflectance factors are lower at site 2, the shape of the reflectance curves are different. The reflectance curves plotted for site 2 are flatter than those plotted for site 1 (cleaner snow).

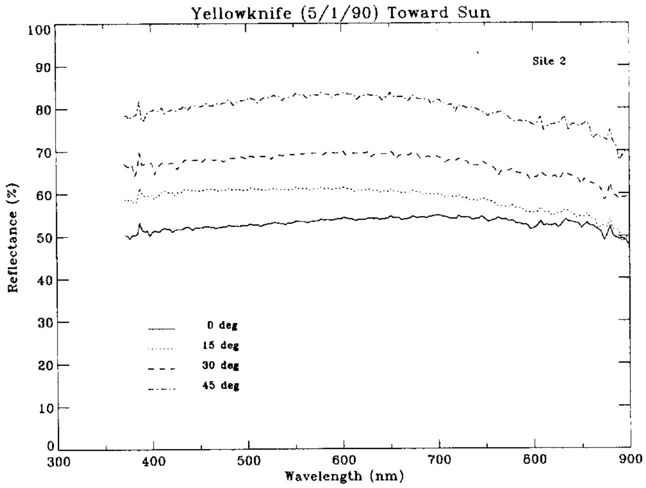

Fig. 3. Reflectance curves obtained when facing the Sun, for dirty snow at site 2 near Yellowknife, N. W. T. on May 1, 1990.

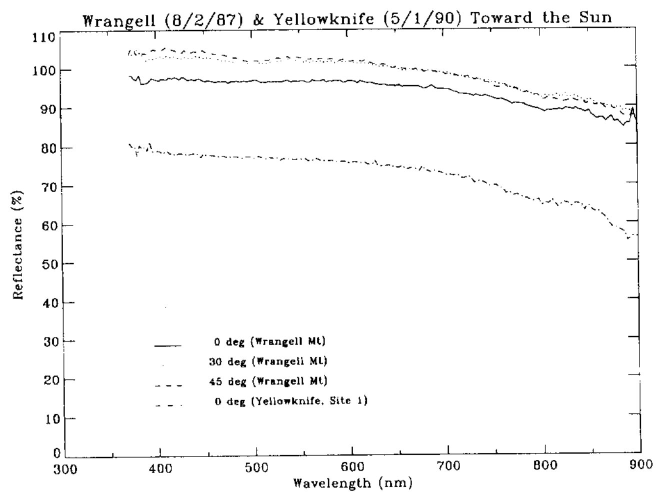

Fig. 4. Reflectance curve (0° viewing direction (nadir)) measured near Yellowknife (site 1) on May 1, 1990 and reflectance curves (0°,30°, and 45° off nadir) acquired at the test site in the Wrangell Mountains on August 2, 1987.

The actively melting snow at sites 1 and 2 near Yellowknife displays reflectance factors that are considerably lower than those measured by us elsewhere. For example, on August 2, 1987 in the Wrangell Mountains, Alaska, nadir reflectance factors of about 0.97 were measured (the solar zenith angle was 46.96°) (Fig. 4). Reflectance factors >1.0 have been observed over fresh snow targets as seen in the Wrangell Mountains data (Fig. 4). Because snow crystals can reflect light specularly, more light may be reflected than is incident upon the snow in a particular viewing direction. This effect is greatest when the sensor is facing the Sun. The actively melting snow near Yellowknife never displayed reflectance factors greater than 1.0 according to our measurements. Reflectance factors that exceed 1.0 are quite common in drier snow and have been observed by us repeatedly in various snowpacks.

The shape of the reflectance curves is similar in the actively melting snow (Yellowknife), and in the drier snow (Wrangell Mountains) (Fig. 4). However, beyond about 700 nm, the reflectance of the melting snow from Yellowknife decreases moreso than it does for drier snow in the Wrangell Mountains consistent with theory and previous observations [1], [5].

The snowpack near Yellowknife had attained a maximum depth of approximately 48 cm during the 1989–1990 winter. By May 1, 1990, the depth was about 12–18 cm. Impurities from various sources, mostly atmospheric, collect in the snow as it falls and while on the ground. As a snowpack melts, these impurities build up in the remaining snow. The presence of impurities lowers the reflectance [3], [20], [22], [29]. The impurity content of the snow was not measured in the Wrangell Mountains, or in the snow near Yellowknife; however, in the case of the snow in the Wrangell Mountains, there had been recent snowfalls, thus the impurity content of the surface layers of snow was probably quite low. The (assumed) greater impurity content of the snow at site 1 near Yellowknife on May 1, 1990 relative to the snow in the Wrangell Mountains on August 2, 1987, may contribute to the lowering of the measured reflectance relative to the reflectance measured in the fresh snow.

V. Landsat Thematic Mapper — Derived Reflectances

There was a Landsat overpass at 12:11 local time on May 1, 1990 over the Yellowknife test sites and, at that time, the solar zenith angle was approximately 49.62°. Reflectances derived from Landsat TM data and corrected for atmospheric effects were calculated for the May 1 data acquired over Yellowknife according to formulation discussed in Markham and Barker [30]. First, the at-satellite reflectances in the six TM reflective bands (TM1: 0.45–0.52 μm, TM2: 0.52–0.60 μm, TM3: 0.63–0.69 μm, TM4: 0.76–0.90 μm, TM5: 1.55–1.75 μm and TM7: 2.08–2.35 μm) were calculated except in cases where sensor saturation occurred. (Saturation is quite common over snow in TM bands 1–3.) Then, the Simulation of the Satellite Signal in the Solar Spectrum (5S) atmospheric correction program [31] was run to calculate the correction for atmospheric effects. A look-up table was developed so that corrected reflectances could be derived easily from the at-satellite reflectances calculated from the TM scene. Using the 5S code, we selected a standard atmosphere, subarctic summer, in lieu of detailed atmospheric profile measurements which were not available.

Reflectance factors measured at nadir using the SE-590 on May 1, 1990 at site 1 are shown in Fig. 2 along with the Landsat-derived, corrected reflectances of lake ice and mixed cover centered over site 1. The TM and *in situ* measurements are not directly comparable because the 100 × 100 pixel subscene that was selected included nonsnow features (i.e., rock outcrops, scattered trees, and other vegetation) as well as snow. And the reflectance of the nonsnow features is considerably less than the reflectance of snow. However, in the Wrangell Mountains, Landsat TM band 4 data acquired simultaneous with the *in situ* measurements provided the same reflectance as measured on the ground [11]. In that case, pure and homogeneous snow targets were measured *in situ* and by the TM and were thus directly comparable.

Also in Fig. 2, the Landsat-derived, corrected reflectance values are plotted for lake ice near Yellowknife. The lake ice surface consisted of cracks and slush ice on May 1. The surface of the lake ice was not snow covered. Unfortunately, the reflectances of the lake ice we measured using the spectrometer are not available because the tape recording device on our sensor failed, therefore a comparison of the satellite and in-situ values for the lake ice is not possible.

VI. Discussion and Conclusion

Actively melting snow has quite different reflectance properties than does dry snow in terms of its absolute reflectance, shape of the reflectance curve and its anisotropic reflectance properties. The actively melting snow measured near Yellowknife at site 1 gave reflectance factors that were considerably lower than those of drier snow measured by us elsewhere. This is attributed to the larger average grain size of the snow near Yellowknife, and an assumption that the impurity content of the snow was quite high relative to fresher snow targets. The visibly dirty snow overlying solid ice near Yellowknife at site 2 gave still lower reflectance factors and a flatter reflectance curve than did the cleaner snow at site 1 or the fresh snow in the Wrangell Mountains. The dirty snow measured at site 2, displayed the greatest anisotropy of the three snow types studied (Yellowknife site 1, site 2, and the snow in the Wrangell Mountains) (Figs. 1, 3, and 4). This is consistent with previous observations which show that old snow displays greater anisotropy than does fresh snow [14].

Landsat-derived reflectances of actively melting pure snow targets could not be measured directly because areas of pure snow were below the resolution element of the sensor on May 1, 1990 near Yellowknife. A subscene covering a variety of cover types, including snow, gave an average reflectance of 0.36 in TM band 1 (0.45–0.52 μm) (Fig. 2), for example. At site 1 the reflectance factor within the wavelength region of TM band 1 was about 0.77 for actively melting snow as measured *in situ* at nadir. Lake ice with some slush on top gave TM-derived reflectances that were similar to actively melting snow (site 1) in the TM band 4 wavelength regions (0.76–0.90 μm) but lower than those in the TM band 2 and 3 wavelength regions. The TM-derived reflectances of the lake ice are greater than the nadir reflectances measured *in situ* over dirty snow near Yellowknife at site 2 (Figs. 2 and 3). Furthermore, the TM reflectances are shown to increase with wavelength in TM bands 1–4 which is opposite from what we find in the *in situ* data, where the reflectance often begins to decrease between 600–700 nm.

Future sensors like the EOS/MODIS should enable identification and quantitative measurement of the reflectance of snow including delineation between dry and actively melting snow over large areas. The 19 reflective bands on the MODIS will permit an improved measurement of snow reflectance (relative to TM) throughout the visible part of the electromagnetic spectrum. This is because sensor saturation should not occur in all of the visible channels of MODIS, and the greater number of bands will permit a better knowledge of the reflectance curve. This is important for identification of snow wetness condition as seen in the in-situ measurements near Yellowknife and in the Wrangell Mountains, as well as at other sites.

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