I. L. THOMAS
A. J. LEWIS*
Department of Scientific and Industrial Research
Lower Hutt, New Zealand
N. P. CHING
New Zealand Forest Service
Wellington, New Zealand

Snowfield Assessment from Landsat

Area measurements are readily possible, and variations in snow density or moisture content may be determined.

ABSTRACT: *The potential use of Landsat MSS data for routine monitoring of the area and condition of a snowfield is explored. Area measurements are readily possible from both the photographic product and the CCT data. The CCT data also may reveal variations in snow density and/or moisture content, and have a spatial resolution equal to, or better than, the photographic product. A non-subjective analysis technique based on the CCT data product is advanced and is used, together with isodensitometric techniques applied to the photographic product, in this snowfield assessment. This study demonstrates that Landsat MSS data have the potential for contributing to rapid assessment and management of snowfield resources, especially if repetitive satellite coverage is obtained.*

Although further work relating actual snow conditions to the recorded radiances is necessary, the importance of using absolute radiance values from CCT data and of considering the effect of topography on recorded snow reflectance is demonstrated.

INTRODUCTION

IN RESPONSE to a request from the New Zealand National Parks Authority, the New Zealand Forest Service and the Remote Sensing Section of the Physics and Engineering Laboratory, Department of Scientific and Industrial Research, initiated a joint study to assess the relative merits of extending an existing skifield (Mt. Robert—41.85°S; 172.80°E) or opening a new area (Six Mile Creek Basin—41.88°S; 172.85°E) for such development.

The Landsat Multispectral Scanner (MSS) records data in four wavelength bands: MSS 4 (0.5-0.6 μm), MSS 5 (0.6-0.7 μm), MSS 6 (0.7-0.8 μm), and MSS 7 (0.8-1.1 μm). It has an effective resolution, derived from the instantaneous field of view, of 56 m (cross track) by 79 m (along track) from a nominal satellite altitude of 920 km. This effective field of view, combined with multispectral sensitivity and potential for sequential coverage, provides a likely source of valuable information for snowfield assessment. The particular questions of access, wind exposure, and general terrain conditions applicable to any skifield assessment are left to the skiing fraternity.

The acquisition of meaningful information on snow cover and snow conditions from Landsat data has been the object of many projects. One NASA publication deals entirely with such observations from satellite data (Rango, 1975). It is repeatedly reported (Rango, 1975, and references cited therein) that the accurate determination of snowline and snow cover area is easily accomplished. However, Bartolucci *et al.*

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* On leave from the Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana.

(1975) have suggested that spectral variations within the snow may not always be readily determined from Landsat data because of detector saturation. Consequently, deductions concerning snowfield parameters such as type, density, surface moisture, etc., are difficult to extract from Landsat data.

In this paper "snow type" is taken as an amalgam of snow crystal size, crystal packing density, and, to a certain extent, temperature and specular reflectance. "Type" thus is taken to range from powder snow through firn to blue ice. In the absence of simultaneous ground truth for the two snowfields, no definitive conclusions as to the actual type of snow in the various regions can be made in this study. Rather, the snow typing side of the study is directed at setting up the analysis techniques to differentiate various snowpack regions without tying these regions to particular snow types.

The overall objective of this study is the development of an analytical package that permits a non-qualitative comparison of the extent of various snow types in two basins. This is accomplished through the subsidiary objectives:

1. To use Landsat data in positioning a transect line in the Six Mile Creek Basin for a continuing series of ground snowpack measurements;
2. To measure the area of different types of snow in the two snowfields;
3. To assess the applicability of Landsat data to differentiating snow types;
4. To develop a repeatable and non-subjective technique for differentiating snow type boundaries from Landsat data;
5. To use Landsat MSS data to fix the topographic boundaries to such snow type regions; and
6. To pose questions for further study as this application of remote sensing develops.

METHODS

The study has been divided into three stages: transect selection, areal planimetry, and analysis of the Computer Compatible Tape (CCT) data for snow type variations. This last stage compares radiance data along three transects within the Six Mile Creek Basin with those along one transect line in the existent ski basin—the Mt. Robert skifield. All stages use the one cloud-free Landsat scene available of the study area (Scene ID no. 2282-21252 recorded on 31 October 1975 (GMT)).

TRANSECT SELECTION

The first stage was the selection of a suitable transect line within the Six Mile Creek Basin for a continuing program of ground measurements on snow depth/type. This transect line was located on the basis of an analysis of the MSS 4 positive transparency, using a Datacolor 703 isodensitometer, and the topographic data from the basin. The processed Landsat MSS 4 data, as shown in Plate 1, readily allowed the snow/bush line to be delineated. The extent of this snow cover over suitable skiing terrain led to the selection of the ground transect as indicated in Figure 1. (Because the currently available topographic mapping of the area is expressed in Imperial units, topographic references are retained in these units throughout this work.)

Field inspection of snow depth and type over this transect commenced at the end of the 1976 Southern Hemisphere ski season. New Zealand Forest Service staff now also routinely overfly the color coded depth markers and assess basic snowfield parameters.

PLANIMETRY AND SNOW AREA MEASUREMENTS

The second stage of the study used the color-coded isodensitometer product, obtained from the MSS 4 positive transparency, to derive the area covered by each of the three highest differentiable radiance ranges recorded on the photographic product. Whereas the wavelength region 0.6-0.7 μm is usually preferred to that used here, 0.5-0.6 μm, on the grounds of lesser atmospheric scattering, the contrast differentiation within the snowfield in the supplied MSS 4 product was superior in this case to that of the MSS 5 transparency.

Photographically enlarged and contrast enhanced transparencies were then prepared of the MSS 4 sub-image, raised on the Datacolor 703 color isodensitometer, and color slides were taken of the output. These were then projected onto a base map. Suitable orientation of this map/projector system compensated for scale differences and small distortions introduced in photographing the isodensitometer screen.

The three highest "radiance" ranges were discontinuously separated by some 5 CCT levels from the adjacent lower radiance region. Consequently, they were advanced as representing the snowfield, with the lower radiance region being associated with the bare ground and bush-covered terrain. These higher radiance regions in the two basins are denoted by purple, white, and yellow in Plate 1.

After transferral of the three highest regions, standard planimetric techniques led to the deduced percentage areas presented in Table 1. The regions chosen in each basin

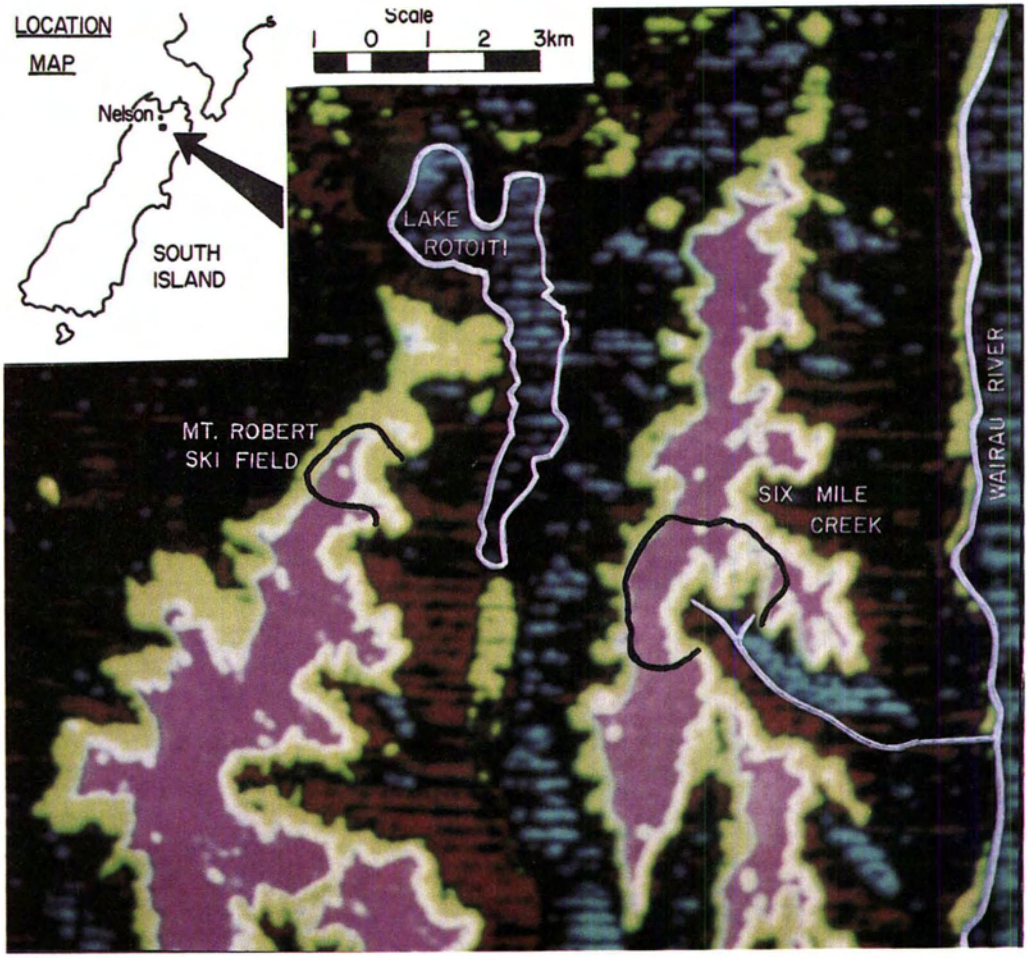

PLATE 1. Color-coded isodensitometer image of the MSS 4 positive transparency of part of scene 2282-21252 that was used in assessing the area of snow in the two basins and selecting the location of the transect. Inset: location map for the study. (The color coding used in the two basins is discussed in the text and summarized in Table 1.)

for this area assessment were bounded on three sides by ridge lines. The fourth side, closing the area, was a line drawn between the lateral spurs to the basin (see Plate 1 and Figure 1), with the bare ground and bush covered terrain being excluded. Comparison with the CCT product led to the deduced radiance ranges given in Table 1.

ANALYSIS OF THE CCT DATA

Snow of all types has MSS radiances that usually place it in a region of compressed dynamic range on the non-linear photographic "scene-radiance/film-density" curve. Linear CCT data is thus more appropriate for achieving the objectives (3) to (6) outlined previously.

PRODUCTION OF CODED PRINTOUTS FROM THE CCT DATA

In order to relate the picture element (pixel) radiance data to ground topography, a 47 character set was linearly allocated to the O-127 CCT level range. This enabled subimages to be output onto a lineprinter from an IBM 370/168 computer for each MSS band in turn in such a way that the ground topography could be recognized. The radiance level for each pixel was then deduced from the non-overprinted character set.

The computer user has no control over the column or row spacing, or over the character size used in the lineprinter output. Consequently, mapping distortions are present in the lineprinter products, particularly when sampling is oblique to the Landsat scan lines. To overcome this distortion, control points were established by measuring direction and distance either parallel to or perpendicular to scan lines from identified locations. As a consequence a positional

TABLE 1. Percentage of the Total Area in Each Radiance Category, from the Color Coding of Plate 1, for the Mt. Robert and Six Mile Creek Basins

Radiance Category in Plate 1	Approximate radiance intensity range[3] (mw ster^{-1} cm^{-2} bandwidth^{-1})	Percent of total area studied	
		Mt. Robert	Six Mile Creek
I Purple[1]	Above 1.0	26%	43%
II White[1]	0.6 – 1.0	36%	30%
III Yellow[1]	0.2 – 0.6	35%	19%
IV Unclassified[2]	Less than 0.2	2%	7%
Total Area (hectare)		193.9 (ha)	498.4 (ha)

Source: MSS band 4 positive, Scene No. 2282-21252

[1] The colors are those portrayed in Plate 1 (see also Probine *et al.*, 1976).

[2] This "Unclassified" category falls between those regions exhibiting the high radiances of snow and the low radiances of the bare and bush-covered terrain (see text).

[3] The radiance intensity ranges were derived from the CCT data and have an associated tolerance of ±0.2 mw ster^{-1} cm^{-2} integrated over the channel bandwidth. (This was derived from the spread in the MSS 4 CCT values along the "iso-color" contours in each basin.)

accuracy of ±1 pixel may be ascribed to the relationship between a ground feature and its location on the coded printout.

CCT TRANSECT LINE SELECTION AND DEDUCED RADIANCE PROFILES

Four transect lines were selected for study, one approximately along the existent Mt. Robert skifield towline and three in the Six Mile Creek Basin (Figure 1). Transect (D-A) was placed along the previously determined New Zealand Forest Service snow sampling line. Transect (D-C) was established to approximate the sun illumina-

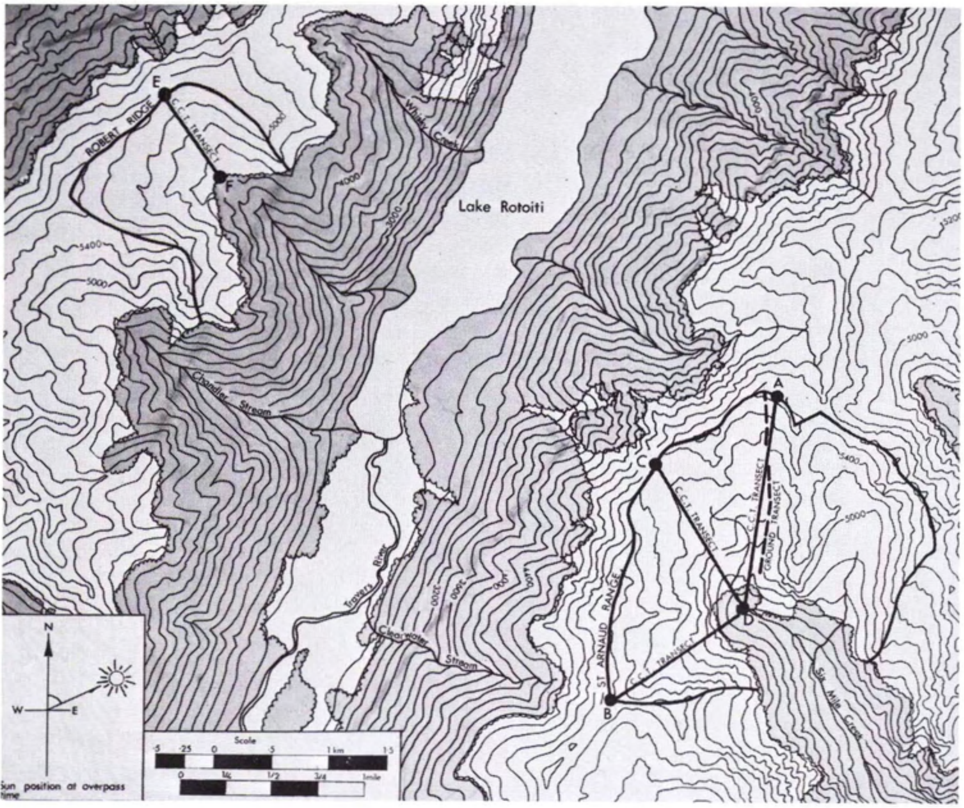

Fig. 1. The location of transect lines for CCT radiance comparisons in the Mt. Robert and Six Mile Creek Basins. The shaded area signifies bush, and the solid circles, marking the ends of the transects, indicate also the positional uncertainty of ±1 pixel in the use of the CCT product.

tion angle on the Mt. Robert transect (F-E), and transect (D-B) was set up on the predominantly sunward slope approximately opposite the (D-A) transect. These transect lines were then located on the printouts and the radiance profile, in each band, was deduced from the relation between the coded characters and the CCT levels.

These CCT level data were now converted to radiance data (in milliwatt per steradian per square centimeter integrated over the channel bandwidth) for the following reasons:

1. Small variations in spectral radiance could signify different melt/freeze histories or density regimes in the snow (O'Brien and Munis, 1975). For these variations to be assessed and inter-related, it is desirable for the recorded radiances to be expressed in common units.
2. The low-gain mode in three of the four MSS channels has approximately the same full-scale radiance response, but such is not the case for MSS 7.
3. The CCT data for MSS 4, 5, and 6 are decompressed (range 0-127), whereas the MSS 7 data are in the linear mode (range 0-63).
4. The spectral bandwidths of MSS 4, 5, and 6 are all nominally the same at 100 nm, but that for MSS 7 is nominally 300 nm.
5. Radiance is often expressed as "mw ster^{-1} cm^{-2} nm^{-1}." The use of such terminology here would require knowledge of the sensors' spectral response and the spectral transmission characteristics of each channel's optical filter. Neither data are readily available. Consequently the radiance recorded in each band is expressed as being "integrated over the channel bandwidth" (abbreviated to "bandwidth^{-1}").

The pixel radiance values were plotted together with the topographic elevation profile and are presented in Figures 2, 3, 4, and 5. (The uncertainties in the four MSS band radiances are ±0.03 (mw ster^{-1} cm^{-2} bandwidth^{-1}) for MSS 4, ±0.02 for MSS 5; ±0.02 for MSS 6, and ±0.09 for MSS 7, derived from ±½ the CCT level range used in the coded printouts).

CRITERIA FOR BOUNDARY SELECTION

Three criteria were now advanced through which regions containing different types of snow could be repeatably discriminated. The first, or "radiance gradient," criterion rests on the sympathetic positive or negative response in all MSS channels to different snow types (from O'Brien and Munis, 1975). The second, or "radiance block," criterion relies on each snow type having a different spectral signature. The higher probability regions within the radiance level occurrence frequency plot for each MSS channel yield the preferred "radiance blocks" for each snow type for each MSS band. The third criterion relies on various snow types occurring within a common altitude range over a restricted area. This last criterion is used to check the boundaries suggested by the first two criteria.

"Radiance gradient" criterion. The first criterion relies on all four MSS channels responding in sympathy as the sampling proceeds over pixel areas containing different snow types. If this trend were maintained in this analysis over all channels for at least two pixels, a ,"radiance gradient" boundary was allocated to that position along the transect.

"Radiance Block" Criterion. The second criterion involved (1) plotting the frequency of occurrence of radiance values within selected intervals for each MSS band (Figure 6), (2) noting the groupings of increased frequency of radiance occurrence ("radiance blocks"), and (3) determining the boundaries to these blocks.

Data from all four transects were used in these plots so that the "radiance block" criterion would apply to both the Mt. Robert Basin and the adjacent Six Mile Creek Basin. A three-point running mean of the frequency data for each band was then plotted. Boundaries were selected at the minimum value on the lower radiance side of the maxima. A range of at least one radiance sampling interval was assigned to each boundary about the minimum, greater ranges being given to minima having greater radii of curvature. These boundaries are presented in Table 2.

On the basis of Skylab S192 scanner data, Barnes and Smallwood (1975) concluded that the reflectance of snow decreased with increasing wavelength. Consequently, MSS 4 is expected to reveal more variations in the snowpack than MSS 7 due to the greater snowpack radiance dynamic range being reflected in MSS 4. Acting against such an expanded radiance dynamic range for MSS 4 over MSS 7 is the increased atmospheric scattering present in the shorter wavelength channels. It was decided to examine the frequency of occurrence plot (Figure 6) of the *linear* radiance values derived from the CCT product to determine which channel, MSS 4 or 5, showed the more evident maxima to minima ratios. On both counts—greater radiance dynamic range and more

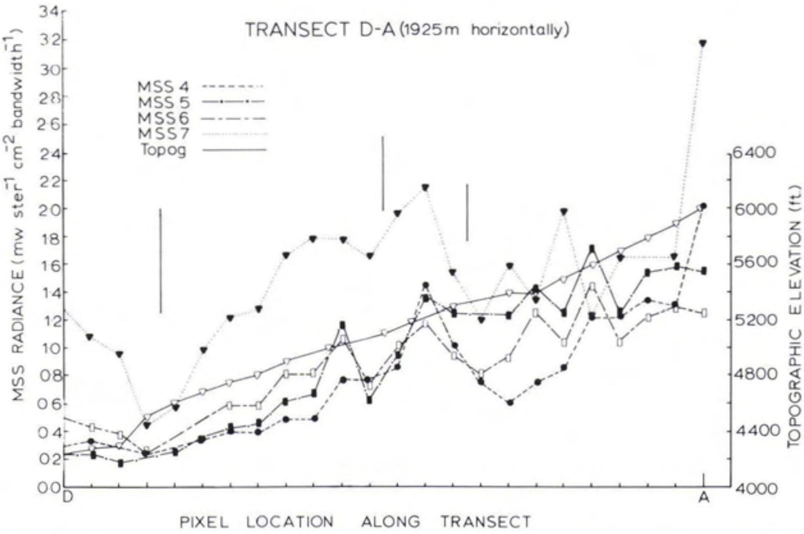

FIG. 2. The variation in MSS radiance along the D-A transect, and the ground topography profile. Suggested snow region boundaries marked by vertical bars.

evident maxima to minima ratios—the MSS 4 channel was superior for such snowpack studies in the Six Mile Creek/Mt. Robert area for scene 2282-21252. Accordingly, the boundaries advanced in Table 2, in particular those from MSS 4, were combined with the first criterion for boundary selection.

Criterion based on a common topographic altitude for similar snowpack states. The Six Mile Creek Basin contained three transect lines spanning a range of sun irradiance aspect angles under essentially similar climatic conditions. Within this "control" basin a "similar" altitude would be expected for the boundary to each class of snow. Upon inspection of the Six Mile Creek Basin topography, and comparing snowpack distributions in subsequent years, this "similarity" was taken to be: 'general agreement within ±150 feet in altitude.'

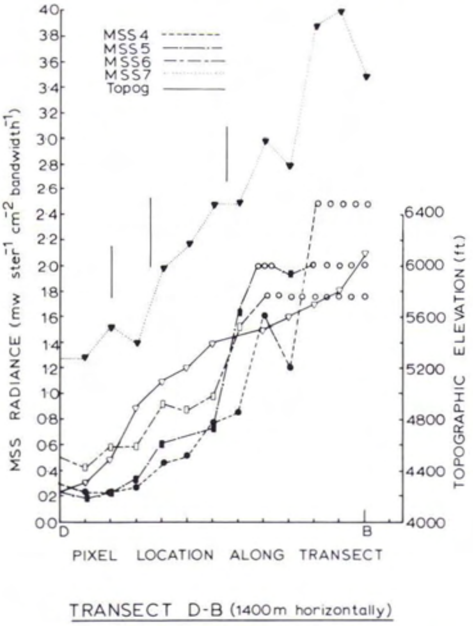

FIG. 3. As for Figure 2 for transect D-B. Regions of detector saturation shown as ooooooooo.

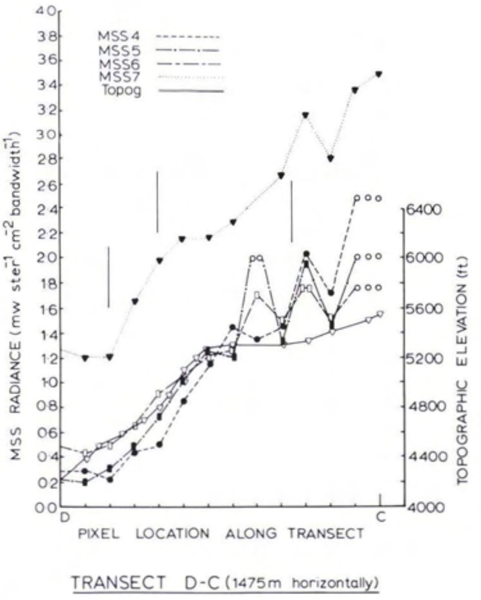

FIG. 4. As for Figure 3 for transect D-C.

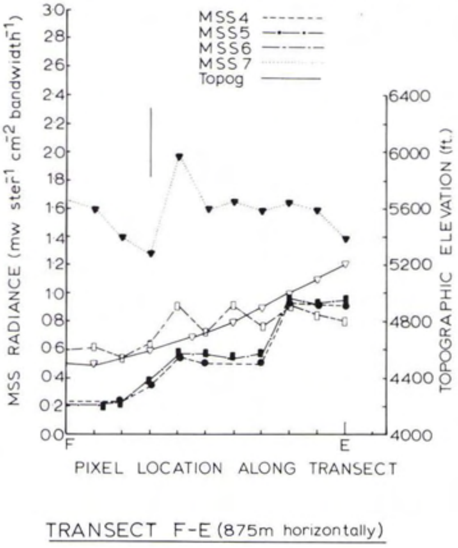

FIG. 5. As for Figure 2 for transect F-E.

BOUNDARY SELECTION

The "radiance gradient" criterion was used first to indicate the likely location of the boundaries between different snow types along each transect. If the MSS 4 radiance values at these possible locations fell within the previously determined "radiance block" boundary ranges and, in general terms, satisfied the MSS 5, 6, and 7 "radiance block" ranges, the locations were suggested as marking the boundaries between regions of differing snowpack. The topographic altitudes of these suggested boundaries were now intercompared within the Six Mile Creek Basin (transects D-A, D-B, D-C). If "similarity" was found between these altitudes, the locations were regarded as the snowpack boundaries and were marked by vertical bars in Figures 2, 3, 4, and 5. The topographic altitudes of these boundaries are presented in Table 3 (with the associated tolerances arising from the positional accuracy of ±1 pixel).

COMPARISON OF THE SUGGESTED SINGLE BAND (COLOR ISODENSITOMETER) AND FOUR BAND (CCT) DERIVED BOUNDARIES

Plate 1 presents the three highest MSS 4 radiance ranges for the two basins. The topographic altitudes of each colour coded MSS 4 photographic density region were found from this analysis and are presented in Table 4.

On comparing these single band results (Table 4) with those obtained from the four MSS channels (Table 3), good agreement is noted for the boundaries between the postulated snow types 1/2 and 2/3 within the Six Mile Creek Basin. The "ground/snow type 1" boundary shows less close agreement between Tables 3 and 4. This is suggested as being principally due to the regions with a high contrast ratio on the photographic product less faithfully following the actual

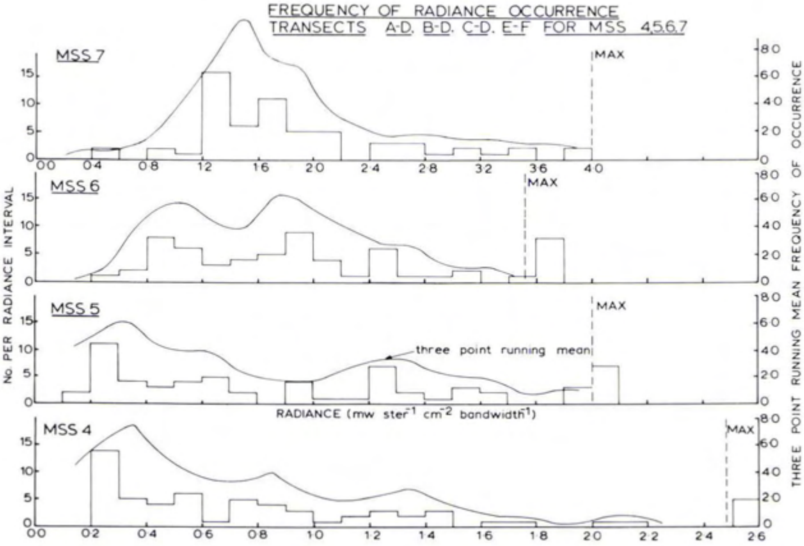

FIG. 6. The differential and three-point running mean of radiance occurrence for each of the MSS bands. (This plot includes the data from all four transects D-A, D-B, D-C, F-E.) (Those radiance values leading to sensor saturation are plotted immediately above the maximum sensor response level—indicated on the plots.)

TABLE 2. SNOWFIELD "RADIANCE BLOCK" BOUNDARIES FROM FIGURE 6

MSS 4	MSS 5	MSS 6	MSS 7
0.1 − 0.3	0.1 − 0.3	0.2 − 0.4	0.4 − 1.2
0.6 − 0.8	0.8 − 1.1	0.6 − 0.8	
1.0 − 1.2			

Units are all (mw $ster^{-1}$ cm^{-2} $bandwidth^{-1}$)

radiance region boundary as recorded on the CCT product, due to the flare and chemical adjacency effects present in the photographic emulsions. In general a "migration" of the apparent lower radiance region into areas of higher radiance would be expected when using positive photographic transparencies. Consequently, a general trend for the boundary to the "ground/snow type 1" regions to progress towards higher altitudes could be expected. This trend is seen in comparing Tables 3 and 4, but further studies of this migration effect are necessary.

Inspection of the radiance profile for the F-E transect (Figure 5) led to the rejection of the two boundaries at 4800 and 4900 ft., suggested by the single band analysis which led to Table 4, as neither fully satisfied the "radiance gradient" nor "radiance block" criteria. The use of four band CCT based analysis consequently refines the general snowfield classification procedure, as could be expected. In particular, the pixel-by-pixel analysis, made possible by the CCT product, avoids any of the spatial integration effects present in the photographic product.

COMPARISON OF SNOWPACK CONDITIONS IN THE BASINS UNDER SIMILAR CLIMATIC CONDITIONS TO THOSE THAT EXISTED FOR SCENE 2282-21252

In the absence of simultaneous ground truth for scene 2282-21252, comparative aircraft and ground assessments of snowpack conditions were made under similar climatic conditions in late October 1976.

Monthly summaries of temperature and precipitation for the Lake Rotoiti station (located between the two basins) indicate that there was little difference between the two years 1975 and 1976. Monthly mean temperature differences were less than 1°C and monthly precipitation differences were less than 4 mm. The snowfall record for the Lake Rotoiti station indicates that, at the times of both the overpass and the overflight, conditions were similar. One week before, in each case, fresh snow fell to the same altitude (2500 ft).

Whereas such a retrospective survey cannot categorically confirm the snowpack assessments deduced from the CCT data, the similarity was such that these assessments are believed to represent the general conditions prevailing at the time of the Landsat overpass on 31 October 1975.

CONCLUSIONS

Conclusions from this study fall into two categories: those related to the application of Landsat to this monitoring role and those conclusions that can be drawn about the actual differences between the Mt. Robert and Six Mile Creek snowfields.

CONCLUSIONS ON THIS APPLICATION OF LANDSAT DATA

The *potential* use of Landsat data in assessing the type and area of different regions in a snowfield has been established. A repeatable analysis system has been advanced and fills the analysis requirements for further studies.

Several general observations have been made from the data that should help future interpretation of MSS radiance values from snow-covered areas. The most important of these is the effect on the recorded snowpack radiance from local slope angles and orientation along an altitude contour line. This enhanced specular reflection effect is evident in a comparison of transects D-A (Figure 2), a south-facing slope directed away from the sun, and D-B (Figure 3), a north-facing slope directed towards the sun. Higher radiance values, and even detector

TABLE 3. TOPOGRAPHIC ALTITUDE OF THE VARIOUS BOUNDARIES TO THE SNOWPACK REGIONS (MSS SENSOR SATURATION OBSCURED ANY POSSIBLE FURTHER REGIONS ABOVE SNOW TYPE 3 FOR TRANSECTS D-B, D-C)

Transect	D-A (ft.)	D-B (ft.)	D-C (ft.)	F-E (ft.)
Ground/Snow Type 1	4550 ± 50	4500 ± 200	$4550 {}^{+100}_{-200}$	4600 ± 50
Snow Type 1/Snow Type 2	5100 ± 50	$5000 {}^{+100}_{-200}$	4900 ± 150	
Snow Type 2/Snow Type 3	5300 ± 50	5450 ± 50	5300 ± 50	

TABLE 4. THE TOPOGRAPHIC ALTITUDE OF THE BOUNDARY TO EACH OF THE THREE HIGHEST MSS 4 RADIANCE REGIONS, DEDUCED FROM THE COLOR CODED PHOTOGRAPHIC DENSITY REGIONS PRESENTED IN PLATE 1, ALONG THE TRANSECTS USED IN THE CCT ANALYSIS IN THE SIX MILE CREEK AND MT. ROBERT BASINS.

Radiance Category in Plate 1	D-A (ft.)	D-B (ft.)	D-C (ft.)	F-E (ft.)
IV Unclassified/III Yellow	4700 ± 50[1]	5000 ± 100	4600 ± 100	4500 ± 100
III Yellow/II White	5000 ± 50	5150 ± 50	5100 ± 100	4800 ± 50
II White/I Purple	5300 ± 100	5450 ± 50	5300 ± 50	4900 ± 50

[1] These altitude tolerances are derived from the range in altitude along the iso-color boundary in the vicinity of the intersection with the transect.

saturation in three bands, were recorded for the sunward slope.

It has also become apparent that coordinated ground—satellite data collection is necessary for further progress to be made in relating snow type to recorded Landsat radiances. Such ground data should be on an areal scale compatible with the Landsat pixel resolution and should include data on snow age, density, temperature, moisture content, type, depth, and crustal hardness.

Greater use, too, should be made of the CCT data in snowpack monitoring.

CONCLUSIONS ON COMPARING THE SNOWPACK IN THE TWO BASINS

The MSS 4 data readily yeilds the area of a snowfield. From Table 1 the area of each of the three higher radiance regions may be deduced and, hence, total snowpack area may be inferred. The Six Mile Creek Basin is thus concluded to have contained a greater extent of snow at overpass time on 31 October 1975 (GMT). This is reinforced by the "patchiness" suggested as being present in the Mt. Robert Basin on comparing the radiance profiles derived in the multi-band analysis.

Comparison of MSS CCT radiance values along the transects from Six Mile Creek (Figure 4) and Mt. Robert (Figure 5) suggests that there were other differences between the snowpack in the two basins. The Six Mile Creek Basin transect (D-C) has similar radiance values below 4600 ft, slightly higher values between 4600 and 5000 ft, and much higher radiance values above 5000 ft than the Mt. Robert Basin transect (F-E). Over 50 percent of the transect in Six Mile Creek Basin has radiance values higher than the maximum radiance values in the Mt. Robert Basin.

The general increase in radiance values in the three Six Mile Creek Basin transects strongly suggests that the snow is fresher and drier as the altitude increases. Such a relationship of snow radiance and the condition of the snow was reported by O'Brien and Munis (1975). It has acted as the basis for the classification procedures used here to divide the radiance profiles along each transect into four regions. The two higher levels are interpreted to be potentially skiable snow; the two lower levels are probably non-skiable with the lowest radiance region in each basin being below the snowline.

ACKNOWLEDGMENTS

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