# MAPPING NEW ZEALAND AND ANTARCTIC SNOWPACK FROM LANDSAT

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## ABSTRACT

Computer mapping, based on the Landsat digital data, can aid the efficient management of one of New Zealand's resources - the annual snowpack. The same techniques are effective in supporting Antarctic cartography, glaciology, and surface operations. The development of digital analysis and enhancement techniques for the routine semi-automated evaluation of Landsat data is illustrated. The 1979 field programme will concentrate on an instrumented snow basin for a water yield study. An outline of this satellite/ground programme is presented.

## INTRODUCTION

The annual snowpack is an important natural resource for New Zealand:

1. 50% of New Zealand's electricity consumption in 1976 was derived from hydro power, fed in part from melting snowpack (New Zealand Official Year Book, 1977).

2. Irrigation is increasing in importance as most New Zealand soils have a seasonal moisture deficiency. In the central South Island an irrigation scheme, fed by snow melt, was completed in 1970. It serves 2000 hectares. Construction of an extension to this scheme to serve an additional 14 000 hectares is proceeding (NZ Year Book, 1977).

3. Control of flooding, siltation and erosion is of importance to New Zealand - a country generally of steep unstable hillsides. An assessment of melt potential can allow more efficient control through the dams.

4. Skiing is increasing in popularity.
New Zealand's snow capped mountains receive wide tourist interest; in 1976 over 312 000 international visitors spent NZ$143M in the country (excluding fares) (NZ Year Book, 1977).

In Antarctica, New Zealand has an international mapping commitment in the Ross Dependency. Monitoring of the classes and textures of the different types of snowpack is easily accomplished from Landsat. The resolution (57*79 m), large area coverage in 26 seconds (185*185 km), and near orthographic imagery ($\pm 5.8^{\circ}$ off vertical), make the system corrected data ideally suited to support mapping down to scales of 1:100 000.

The emphasis in New Zealand has been on developing the capability for routine mapping of this snowpack resource from the digital Landsat data. Such mapping must classify and delineate the various types of snowpack. The techniques used are supervised histogram parallelepiped classification for thematic mapping, and subtractive box filtering for textural enhancement. The modules that accomplish this are contained within the Landsat ANalysis SYStem version 1(LANSYS 1) package programmed for an IBM 370/168 in Programming Language 1 (PL/I) (Thomas, 1979). Data is transferred via image tape from the IBM 370/168 to an in-house Varian V76 where histogram equalization is commonly used to further enhance texturally enhanced imagery, in radiance space, before the image data is written out on an Optronics Colorwrite as a positive colour transparency (McDonnell, 1979).

The first New Zealand use of Landsat for snowpack monitoring took place in 1977 during the evaluation of a proposed skifield (Six Mile Creek basin - 41.88°S, 172.85°E) (Thomas et al, 1978). This study was based on a non-automated comparison of the four band MSS radiances along representative transects. It was found possible to map three different types of snowpack using the technique. This study evaluated Landsat data for snowpack studies, indicated manpower time restrictions on analysis techniques and highlighted the problems induced by the terrain.

As a result of this pilot skifield evaluation a snowpack to water yield study was set up in the instrumented Camp Stream basin (43.13°S, 171.70°E) for the 1978 southern winter. This small (50 ha) basin was chosen because:

(i) its "spoon" shaped terrain reduced specular reflection anomalies;
(ii) its geology and geomorphology permitted the water yield to be measured readily at the egress free from seepage effects into, or out of, the catchment;
(iii) its history of snowpack, meteorological, and water yield statistics is known (e.g. Morris and O'Loughlin, 1965; O'Loughlin, 1969);
(iv) its small size allows every Landsat pixel to be considered individually by manual techniques if the need arises (~ 100 pixels over usual snow covered area);
(v) it has both east and west facing slopes to include sunlit and shaded surfaces at Landsat overpass time;
(vi) it has terrain that included tussock and scree surfaces permitting studies on the influence of the basal material on snowpack characteristics;
(vii) there is a 600 m range in elevation from the bushline (at 1070 m) to exposed ridge tops (at 1670 m);
(viii) it is near lesser instrumented skifield basins;
(ix) it is free from casual human influences - well away from ski trails, etc.;
(x) it is near to a serviced field station;
(xi) it appears on the same Landsat scene that covers the site used for a similar agricultural applications investigation. This reduces the New Zealand imagery scheduling load at NASA.

The 1978 programme was inhibited by a lack of Landsat imagery, so the main analytical emphasis has been on the development of the digital processing techniques outlined earlier. These techniques were developed to support time efficient semi-automated reduction of multi-channel Landsat data to single factor products for the management process. Examples of these techniques, applied to the Six Mile Creek, Camp Stream, and McMurdo Sound region of Antarctica (77.40°S, 163.53°E), are presented here.

Field measurements taken during the 1978 season were used to refine the ground support programme and those measurements scheduled for the 1979 season are outlined.

## OPERATIONAL ANALYSIS FACILITIES FOR LANDSAT DATA IN NEW ZEALAND

The best analysis package appears to be:

1. Ground Truth (GT) data taken in the test areas with all the variables being monitored that may influence the results. (New Zealand experience with metamorphosing snowpack indicates that the GT data is useless if taken outside "Landsat overpass time ±1 hour".)

2. The discipline oriented user, who will later perform the analysis, should participate in the GT programme. The software technologist should also participate, but less regularly. (This technologist is usually more familiar with the limitations of the data, and applicability of various computing options to the analysis task, than is the discipline oriented user.)

3. First generation texturally enhanced histogram equalized, or stretched, hue enhanced colour composite positive transparencies of the control and test areas should be prepared on the Colorwrite. Such transparencies allow the analyst to assess the subtleties of terrain modification to snowpack characteristics that thematic mapping cannot adequately portray.

4. Colour coded thematic maps in transparency form should be produced on the Colorwrite. The unclassified terrain data can be beneficially incorporated as a black and white background. These thematic maps may be straight classified (e.g. histogram parallelepiped) or include spatial massaging.

From these processed data products a final composite thematic map may be readily prepared, bringing the best of all systems to bear on the analysis.

The New Zealand programme has two major research objectives:

A. To evaluate Landsat snowpack data for incorporation in water yield research and operational management.

B. To provide rapid and low cost topographic mapping of parts of Antarctica to scales of 1:100 000, with low field manpower involvement.

The other objective - the monitoring of snowpack on the Mt. Robert and Six Mile Creek skifields - would be operational if Landsat coverage is obtainable.

Both major research objectives have similar computing needs - texturally enhanced imagery and thematic maps of snow/ice types. They differ in the Ground Truth support that is needed.

The textural enhancement process uses the following equation for each picture element in turn:

$$R' = R - 0.8\overline{R} + 20 \qquad (1)$$

where $R$ is the radiance, in the selected band, for the central pixel

$\overline{R}$ is the average radiance for the N*N nearest neighbour matrix surrounding, but excluding, the central pixel

$R'$ is the synthesized radiance for the pixel considered.

This is programmed in PL/1, uses integer arithmetic, minimal core storage, and is routinely available on a nationwide IBM 370/168 network. Commonly a 3*3 nearest neighbour matrix is used. This textural enhancement is applied to each MSS band in turn.

Once an image tape has been prepared on the IBM 370/168 it is passed to the in-house Varian V76. A sample area for the particular form of enhancement is selected (e.g. for snow or sea or forest, etc.) and the CCT radiance level occurrence statistics for that sample are compiled. From these a histogram equalized or stretch hue enhancement "look-up" table is prepared. The texturally enhanced data is then passed through the look-up table and written to the Colorwrite. Usually MSS 4 is written through a blue filter, MSS 5 through green, and MSS 7 through red, for the standard colour composite. (For further details of the PEL Colorwrite system see McDonnell (1979). Simpson (1978) provides a concise outline of the various usual enhancement options.)

Figure 1 is an example of this textural and hue enhancement applied to a part of Landsat scene 2192-21265 recorded over Central Canterbury, New Zealand, on 2 August 1975 (GMT). The subscene contains the Craigieburn Range with the Camp Stream basin being the southward opening "V" catchment situated on the second from the north, eastward extending ridge. The detail in the snowpack (and all terrain) has been enhanced over the standard product. The composite of MSS bands 4,5,7 has been found to be as effective as the composite of MSS bands 5,6,7 for revealing detail in the New Zealand snowpack.

For some applications, e.g. delineation of boundaries in Antarctic pack ice, etc., it is desirable to scale all regions of uniform radiance to a common level and to highlight departures from this uniformity. The same module in the LANSYS1 package is used but equation 1 is replaced by

$$R' = 0.01(R - \bar{R})^5 + 100 \qquad (2)$$

A 5*5 nearest neighbour matrix is presently being tested. Figure 2 presents results using this boundary enhancement module for a region of sea ice in scene 1174-19433 recorded over McMurdo Sound Antarctica on 13 January 1973 (GMT). The leads and brash ice are clearly delineated.

Thematic maps are also processed initially on the IBM 370/168 to image tapes. Rango and Itten (1976) compared the results of several different classification schemes for the computerized mapping of snowpack. They found little difference between histogram parallelepiped and maximum likelihood results. This finding has been confirmed for other types of target (Honey, 1978). The major influence on the success, failure, or indeterminancy, of any classification process is the accuracy of spectral signature determination for the different target types: in short - good ground truth. The PEL LANSYS1 thematic mapping package is presently based on histogram parallelepiped classification. Multi-date analyses, such as outlined by Luther et al (1975) should dramatically improve

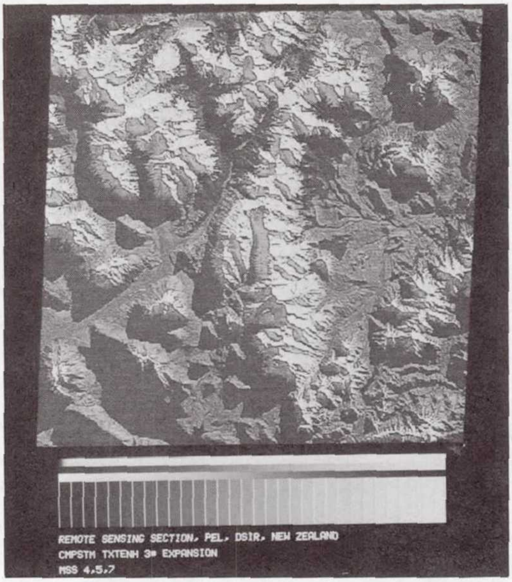

Fig. 1: A texturally and hue enhanced treatment of the Craigieburn Range, including the Camp Stream basin, from Landsat scene 2192-21265 recorded on 2 August 1975.

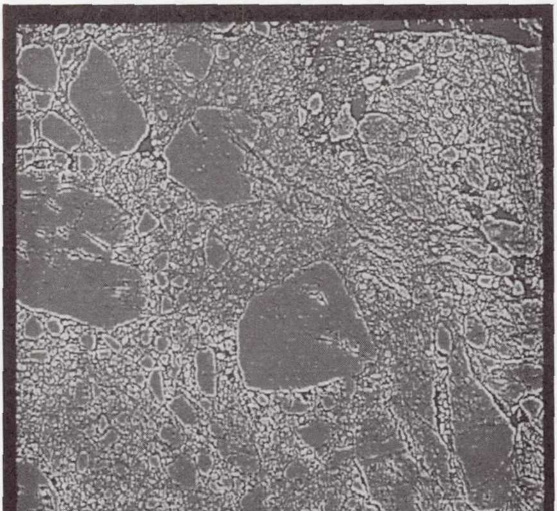

Fig. 2: A region of sea ice in McMurdo Sound, Antarctica (Landsat scene 1174-19433) has been boundary enhanced to highlight edge effects associated with leads and brash ice.

classification accuracy, but currently place quite a time and storage load on computing systems.

The first step in preparing a thematic map is the determination of the spectral signature ranges for each target type. Modules within the LANSYS1 package permit both unscaled and scaled coded lineprinter outputs to be prepared. The unscaled outputs have no compensation for scale differences brought about by the differing 'along-line' and 'across-line' spacing between characters extant on most computer lineprinters. The scaled output module resamples the data along a Landsat scan line. For the New Zealand system, the final product is scaled to approximately 1:18 810. Non-overprinted characters are used so that the radiance level range associated with each character may be clearly determined. A 57 character set is employed with the range of the set adjustable both by varying the lower limit, so the full range may be covered with a CCT level resolution of 1 level, or by varying the step increment. The work of Gordon (1978a,b) indicates that atmospheric variations, together with quantization and decompression uncertainties, may account for ±1 to 2 CCT levels. Hence a step increment of 2 is usually suggested.

Scaled lineprinter maps are a cost and time effective way of routinely monitoring snowpack state in regions like the Mt. Robert and Six Mile Creek basins. Figure 3 presents the scaled results for the Six Mile Creek basin recorded by Landsat in scene 2984-21002 on 2 October 1977. The base snowpack had just been overlaid by fresh powder snow - hence the apparent uniformity and high radiance levels in the illustrated channel.

Trial spectral signatures are determined from such lineprinter outputs for the different types of snowpack to be thematically mapped. These signatures are then inserted into the supervised histogram parallelepiped module and test areas classified. Output to the lineprinter are: areas in each class, a coded thematic map, occurrence statistics for the spectral signature range for each band for each target class, the mean and standard deviation for each range, a new suggested spectral signature range (based on the mean ±1 standard deviation), and the occurrence statistics expressed in radiance (mw/ster/cm$^2$/bandwidth) terms - to facilitate snowpack reflectance intercomparisons between channels and target types. This process is repeated until satisfactory signature ranges have been determined for each snowpack type.

This supervised histogram parallelepiped classification proceeds in a preselected target order and can be exploited for snowpack studies by classifying in decreasing radiance 'gate' order. This facet 'comb-filters' snowpack classes and can improve classification discernment in regions of many different snowpack types or terrain variations.

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                THIS IS A SCALED ("X" DIRECTION) PRINT OUT
                     PIXELS  625 TO  720 OUTPUT ABOVE
                   (LEVELS ABOVE  166 REPRESENTED BY "+")

*****************************************************************************************
*THE ABOVE OUTPUT HAS BEEN APPROXIMATELY SCALED TO BE APPROX EQUAL IN BOTH "X" & "Y" DIRECTIONS AT 1:18810*
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Fig. 3: An example of a coded lineprinter output used to monitor the area of snowpack for potential skifield evaluation. Portrayed here is the Six Mile Creek basin on scene 2984-21002 shown in MSS 5 where the "@" symbol indicates a CCT level range of 126-127. The alphanumeric characters indicate lower (~120) radiance levels. The lineprinter output has been resampled to a scale of 1:18 810.

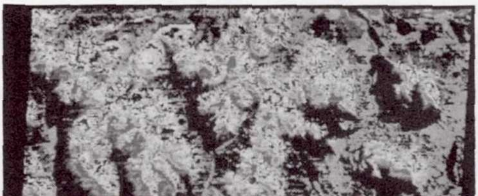

Fig. 4: The Craigieburn Range has here been classified for different snowpack types using straight supervised histogram parallelepiped classification. The colour codes are presented in Table 1. (Landsat scene 2192-21265.)

The final step in creating the image tape for the Varian V76 is the allocation of a number, and hence colour on the Colorwrite, to each target class. The user selects appropriate colours and allocates the numbers in one of the LANSYS1 modules.

In Figure 4 the Craigieburn Range region, shown texturally enhanced in Figure 1, is presented classified for ten different terrain modified snowpack types. It has been classified with the straight supervised histogram parallelepiped module. The unclassified sections of the MSS 5 band are usually laid down as a background black and white image. This background usually has the dual advantages of (i) assisting in relating the classified areas to topographic detail, and (ii) enabling the user to assess how appropriate to actuality were his choice of spectral signatures. In the classification examples presented here the MSS5 background is omitted as: most of the scene is classified, thus reinforcing the need to refer to the texturally enhanced colour composite to check the validity of the classification; and little of the remaining scene would be occupied with MSS5 data.

The histogram parallelepiped classifier, like many other classifiers, considers each pixel as a separate entity without recourse to the classification results for the surrounding elements. The LANSYS1 package includes a spatial massaging module which permits a central pixel to be reclassified (or declassified) depending on the classification status of its immediately nearest orthogonal neighbours (see Thomas, 1979, for a fuller discussion). The spatial massaging process aggregates classified pixels of like type or rejects those that have been thrown up perhaps as 'noise' in the classification process.

For some applications maximum detail may be required to study the high frequency contribution of the terrain to the classification of the lower frequency overlying target class. Snowpack studies may be such an application. Consequently both forms of computer produced thematic map are used: one with spatial massaging, to emphasize the overlying snowpack type; and one without, to highlight the contribution of specular variability to the resultant spectral signature.

Figure 5 presents the results of a spatial massaging process applied to the Craigieburn Range results given in Figure 4. The same scene, spectral signatures and colour allocation were used in both figures. The aggregation of snowpack types and reduction in solitary classified pixels is evident.

The classification leading to Figures 4 and 5 has proceeded without Ground Truth. The figures demonstrate the technique rather than ground actuality. It is hoped that concurrent Landsat overpasses and Ground Truth programmes will occur in Canterbury in 1979.

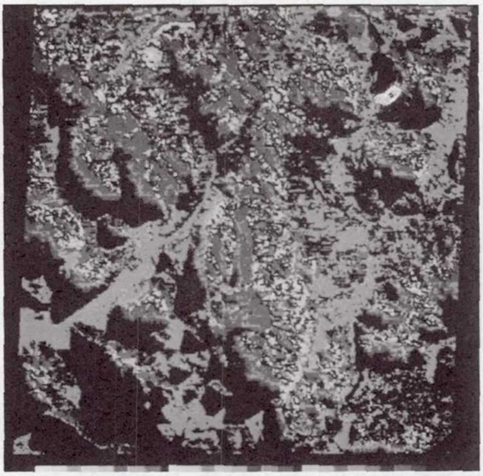

Fig. 5: The same classification has been applied as in Fig. 4 but spatial massaging has been implemented to reduce "noise" and aggregate snowpack conglomerates.

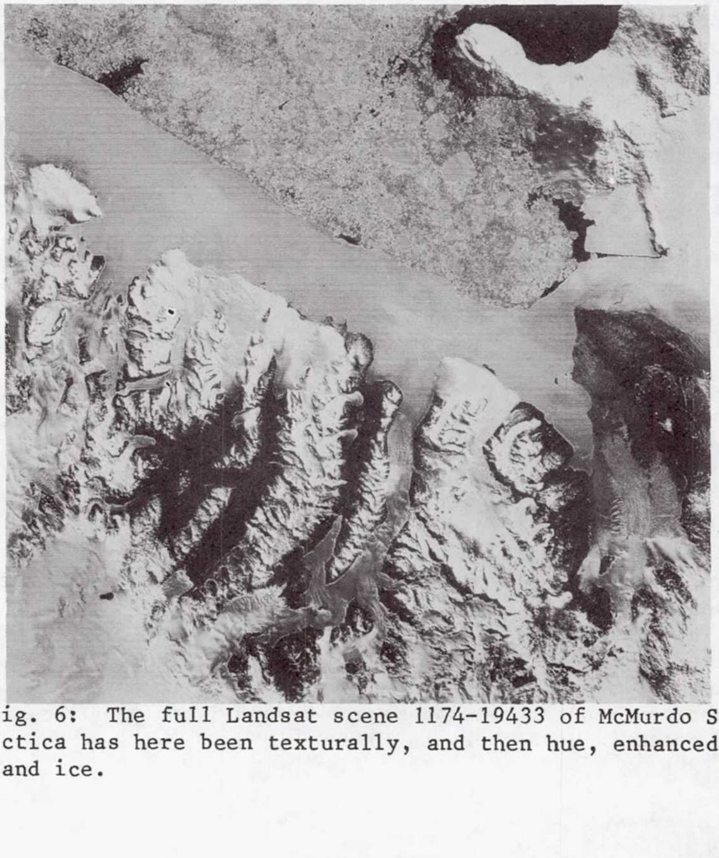

Fig. 6: The full Landsat scene 1174-19433 of McMurdo Sound Antarctica has here been texturally, and then hue, enhanced for snow and ice.

Most of the needs for Antarctic mapping that can be satisfied by Landsat data can be met by the LANSYS1 package. Figure 6 is a textural and hue enhancement, for ice, of scene 1174-19433, recorded over McMurdo Sound on 13 January 1973 (GMT).

A subscene of Figure 6 was overlaid with the best available cartographic linework for Ross Island and is presented as Figure 7. This is accomplished easily photographically and provides quick and cost effective mapping to the limit of the system corrected Landsat imagery - 1:100 000.

The surface traveller can obviously benefit from such texturally enhanced imagery. He can be further aided by thematic mapping of different snow and ice types. In Figure 8 such a thematic map for the piedmont at the mouth of New Harbour is presented. It differentiates snow/ice types into like radiance regimes. Again it is a demonstration of technique rather than actuality - ground truth was not available for this image.

## THE GROUND TRUTH PROGRAMME

Ground Truth (GT) programmes have evolved to support both the skifield evaluation in the Six Mile Creek basin and the snowpack to water yield study in the Camp Stream basin. During the 1977 and 1978 southern winters the research GT programme has developed to that presented below - scheduled for the 1979 season, principally for Camp Stream.

Three common-altitude survey lines have been permanently located around the basin. All three courses will be used when elevational differences in snow properties are found to exist. In periods of relative homogeneity only the central course will be monitored.

GT data will be collected on an areal scale compatible with the Landsat pixel resolution. Supplementary measurements will be made to refine the various data as the snowpack changes.

Snow depth and density measurements will be taken along the courses using a Mount Rose snow sampler and depth probes. Snow depth will normally be sampled every 20 m and density every 100 m - as the density has been found to be more spatially consistent than depth. The Mount Rose sampler, apart from permitting a coarse integrated density to be derived for the snow column, will also provide data to extrapolate the detailed layering and density data obtained from the snowpits.

The snowpits will be dug along or between the snowcourses, depending on conditions. The basic control sampling will be: two snowpits on the sunlit and shaded faces along the central snow course. Of these, two pits will be dug on a scree base and two on a tussock base. Special

Fig. 7: Part of scene 1174-19433, covering Ross Island, Antarctica, - from Fig. 6 - has been overlaid by cartographic line work to support New Zealand's Antarctic mapping programme.

Fig. 8: A region of the sea ice, ice shelf, piedmont, and shore snowpack at the mouth of New Harbour in McMurdo Sound (scene 1174-19433) has here been thematically mapped (histogram parallelepiped + spatial massaging) using the colour codes listed in Table 1 for the different ice types.

emphasis will be placed on the upper 20 cm of the snowpack - the zone which most influences the Landsat data.

The following measurements will be taken at each snowpit:

(i) A depth probe.

(ii) A Mount Rose density profile.

(iii) A normal 1 kg rammsonde profile.

(iv) A lightweight rammsonde (0.25 kg mass for both the ram mass and ram block, $60^{\circ}$ ram apex angle) profile of the upper 20 cm. (Both rammsonde profiles will quantify the 'vertical' hardness of the snowpack.)

(v) A Brinell hardness assessment of the ice bonding of the surface snowpack layer - see Appendix A.

(vi) An analysis of snow grain type, size and interrelated structure at the surface and for each subsequent layer. This analysis will be initially based on the International Snow Classification for falling snow (Figure 4, La Chappelle, 1969) and on the scheme of Magono and Lee (Figure 5, La Chappelle, 1969) for both precipitated and falling snow. Further data on grain size, etc., will be classified according to the scheme reported in Appendix B of Perla and Martinelli (1976). These measurements will be supported by a micro-photographic system.

(vii) Volume/weight measurements of each snow layer will be taken to produce a detailed vertical density profile.

(viii) Temperatures will be measured in the air - 10 cm and 1 cm above the snowpack - in the surface and succeeding layers, and at least every 10 cm through the snowpack to produce a temperature gradient profile (2.5 cm near surface).

(ix) Horizontal 'hardness' of the snowpack will be quantified using hardness gauges modelled on those of the National Research Council of Canada - these are similar to soil hardness gauges.

(x) Free water content will be assessed using the method outlined in Appendix B of Perla and Martinelli (1976) and quantified by using a melting calorimeter.

(xi) Thermal quality - the percentage by weight of the snowpack's water equivalent which is in the form of ice - will also be measured using the melting calorimeter. The amount of energy required to move the composite snowpack at $0^{\circ}C$ to water at $0^{\circ}C$, per gram, may then be quickly assessed from the latent heat of fusion of ice (O'Loughlin, 1969).

In addition the Camp Stream basin will carry the following instrumentation to support the programme:

1. A recording weir at the egress for monitoring water yield.
2. A snow lysimeter to estimate snowcover run off from a single plot (25 $m^2$).
3. A recording three point distance thermograph to monitor snowpack temperatures.

4. A thermograph and barograph for recording air temperature and barometric pressure.
5. A totalizing anemometer.
6. Snow deposition will be continuously recorded in the basin.
7. A snow ablation/evaporation study.

As part of the wider New Zealand monitoring programme the Forest Research Institute continuously records air, snow and soil temperatures over a 600 m elevation range on the nearby Mt. Cheeseman (8 km southwest).

It is envisaged that during the 1979 season (May-October) the Camp Stream basin will be monitored collaboratively by personnel from the Geography Dept., University of Canterbury, Forest Research Institute, NZ Forest Service, and DSIR. Intensive monitoring is scheduled for each Landsat 3 overpass date, with back-up monitoring for the Landsat 2 overpass dates (brought on by unfavourable weather conditions).

## COMPARISON OF SNOW/ICE RADIANCE RANGES BETWEEN NEW ZEALAND AND ANTARCTICA

New Zealand and Antarctica have obvious climatic differences that lead to different types of ice and snow being sensed by Landsat over the two regions.

The New Zealand snowpack is more likely to have liquid water coating the crystals or moisture freezing to form ice layers and coatings within the crystalline snowpack. O'Brien and Munis (1975) noted that the reflectance of wet or refrozen wet snowpack was less than snowpack that had no melt or free water associated with it. The densities of the wet and/or refrozen snowpack were higher than those samples free from melt. Antarctica, even on the coast, is usually free of such wet conditions. Consequently we would expect Antarctic snowpack to generally have higher reflectances than New Zealand snowpack.

O'Brien and Munis (1975) also found that snowpack reflectance decreased with increasing density, induced by increasing snowpack age. Mellor (1961), working with surface snowpack in the Antarctic, found lower densities to be related to lower mean annual temperatures, below -10°C. He cited a mean annual temperature for the McMurdo Sound region of -4°F (-20°C).

Consequently, on comparing surface snowpack between New Zealand and Antarctica as a function of both free water accretion and density, one would expect less dense surface snowpack to prevail in Antarctica with consequently higher radiances being recorded by Landsat.

These contentions are borne out by the results cited in Table 1. Presented there are the spectral signature upper and lower limit values for the supervised histogram parallelepiped classifiers that led to the thematic maps of Figures 4, 5 and 8. The values, presented in CCT level terms as they were used in the classification, may be readily converted to radiances in

| Snow/Ice Type | Scene/Date | Sun Az/El | %** Total Area | CCT Level Radiance Ranges | | | |
|---|---|---|---|---|---|---|---|
| | | | | MSS 4 | MSS 5 | MSS 6 | MSS 7 |
| Maximum Value | | | | 127 | 127 | 127 | 63 |
| New Zealand | | | | | | | |
| Fresh powder snow | 2984-21002 771002 | $62^{\circ}/32^{\circ}$ | - | 126-127 | 126-127 | 126-127 | 62-63 |
| Snow 1 (Mauve*) | 2192-21265 750802 | $46^{\circ}/15^{\circ}$ | $1.3^{+}$ | 126-127 | 126-127 | 126-127 | 62-63 |
| Snow 2 (Yellow) | | | 0.3 | 114-126 | 126-127 | 126-127 | 62-63 |
| Snow 3 (Purple) | | | 0.4 | 106-114 | 120-127 | 120-127 | 55-62 |
| Snow 4 (Lt Yellow) | | | 2.0 | 90-106 | 120-127 | 120-127 | 44-55 |
| Snow 5 (Orange) | | | 3.3 | 69-90 | 90-118 | 90-118 | 30-48 |
| Snow 6 (Red) | | | 6.6 | 40-71 | 55-93 | 53-94 | 20-37 |
| Snow 7 (Lt Green) | | | 7.8 | 21-47 | 24-56 | 24-58 | 8-24 |
| Snow 8 (Dk Green) | | | 19.1 | 10-25 | 10-25 | 7-25 | 2-14 |
| Snow 9 (Lt Blue) | | | 40.9 | 6-12 | 4-15 | 5-15 | 0-10 |
| Snow 10 (Dk Blue | | | 18.1 | 6-19 | 3-16 | 2-13 | 0-2 |
| Total Area Classified as Snow 477.1 km$^2$ | | | | | | | |
| Antarctica | | | | | | | |
| Ice 1 (Dk Blue*) | 1174-19433 730113 | $87^{\circ}/22^{\circ}$ | $5.7^{++}$ | 126-127 | 117-127 | 99-111 | 36-42 |
| Ice 2 (Dk Blue/Green) | | | 10.0 | 123-127 | 108-127 | 93-108 | 33-39 |
| Ice 3 (Lt Blue/Green) | | | 12.9 | 120-127 | 111-120 | 93-102 | 33-36 |
| Ice 4 (Dk Purple) | | | 52.6 | 114-126 | 108-117 | 87-96 | 30-36 |
| Ice 5 (Yellow/Green) | | | 6.0 | 111-120 | 102-111 | 84-93 | 30-36 |
| Ice 6 (Orange) | | | 0.1 | 111-120 | 99-114 | 81-93 | 30-36 |
| Ice 7 (Lt Purple) | | | 12.7 | 99-114 | 87-108 | 69-87 | 24-30 |
| Total Area Classified as Ice 870.7 km$^2$ | | | | | | | |

* The colours are those portrayed in the thematic map products - Figures 4,5,8

** Area percentages calculated from spatially massaged classification

$^{+}$ For region covered in Fig. 5. $^{++}$ For region covered in Fig. 8.

TABLE 1 A comparison between the radiance ranges in CCT level terms, for snow/ice types between New Zealand and coastal Antarctica.

mw/ster/cm$^2$/bandwidth on recourse to the "Landsat Data Users Handbook" (1976). The colour codes employed in the thematic mapping are indicated. In the absence of detailed ground truth no more than a demonstration of the technique is possible and no attempt has been made to compensate the classification types for terrain modification. Also in Table 1 are given the areal percentage occurrence figures for each type of the classified snowpack. The figures are based on the spatially massaged classification results portrayed in Figures 5 and 8. The preponderance of lower radiance snowpack in the New Zealand test area is evident. One could conclude that the Camp Stream snowpack possessed a higher density and had, possibly, a closer association with free water than the Antarctic snowpack.

Glacial ice in its movement is subjected to pressure differentials. Mellor (1961) cites bore hole results in glacial ice of increasing density with depth (or pressure). (The crystal size was also noted to increase with depth.) The results O'Brien and Munis (1975) presented indicated (i) that denser snowpack was associated with lower reflectances, and (ii) the reflectance in the 0.8-1.1 $\mu$m region was less than that between 0.5 and 0.7 $\mu$m. Consequently we would expect glacial flow ice to have lower reflectance than stable surface snowpack. Such glacial ice is expected to be cyan to blue in colour in the standard false colour composite of MSS 4, 5, 7 printed, additively, through blue, green, and red filters respectively. The colour may be quickly deduced from the expected radiance levels in each MSS band, the printing filters for the respective channels, and an additive colour wheel (e.g.

Rib, 1968). Again, by extrapolating the results of O'Brien and Munis (1975), we would expect that as the ice density increased, the colour in the composite would progress from white through cyan to dark blue. Thus the colour may be used to indicate pressure fields in glacial icepack. An inspection of Figure 6 illustrates these contentions.

## TERRAIN MODIFICATION OF SPECTRAL SIGNATURES

It has been tacitly assumed in all New Zealand classification work that the semi-automated classifiers interpret gross terrain modification of the signature from the same target type, as being assigned to different classes. For example, snowpack of type 1 in direct sunlight is regarded as class 1, the same snowpack in partial shadow as class 2, and in deep shadow as class 3. An inspection of the texturally and hue enhanced colour composite together with the colour coded thematic map quickly allows the final thematic map to be compiled aggregating all three classes as the one snowpack type.

Band ratioing will be implemented after acquisition of an intelligent graphics terminal (a Hewlett Packard 2647A) in mid-1979. This will permit various empirical band ratio formulae to be quickly developed and evaluated for different types of study. Without such distributed processing it has not been time-effective to pursue this work with the present systems. Band ratioing is expected to further reduce the influences of terrain modification upon the classifiers.

## PROJECTED DEVELOPMENTS FOR THE 1979 SEASON

Detailed mapping of the Camp Stream basin is presently underway to prepare a base map to support hydrologic modelling of the basin. The map is to be at 1:5000 scale with 10 m contours.

A multi-channel, including thermal, scanner may be flown over the Camp Stream basin in early spring to evaluate the applicability of such an airborne multi-channel digital scanner to snowpack studies in New Zealand.

During the season it is expected that spectrophotometric scans will be taken of a variety of snowpack types 'in situ' in Camp Stream basin. The prime objective is to acquire more data on moisture/age/density influences within different snowpack classes upon the spectral reflectance characteristics. Specular and goniometric studies on the undisturbed field snowpack will also be conducted.

Band ratioing studies will be pursued on the intelligent terminal.

Ground truth programmes will be mounted to support Landsat data acquisition over both Camp Stream and McMurdo Sound (NASA Path 078 Row 090, and NASA Path 056 Row 116, respectively).

## CONCLUSION

An analysis package has been developed that supports the semi-automated assessment of snowpack. It works directly from the linear digital Landsat CCT data to both delineate and classify different classes of snowpack.

The routine comparison of two skifields is proceeding from the Landsat data, based on coded lineprinter outputs.

A combination of cartographic linework with texturally and hue enhanced imagery, or with a colour coded thematic map, is now routinely available to support Antarctic mapping to 1:100 000 scale. The research into snowpack/water yield is now supported by semi-automated analysis techniques together with a detailed ground truth programme. All is ready for the 1979 season.

Fundamental to any operational implementation of Landsat in this application are two factors: (i) frequent coverage, and (ii) rapid throughput of data to the user.

Frequent coverage is the only way valid area/type measurements may be implemented in a hydrologic forecasting model. New Zealand suffers from the very factor that nurtures the natural resource considered here - the native name for the country, Aotearoa means "land of the long white cloud"!

Rapid transmission of the data to the user is necessary for its incorporation in time-effective analysis and management procedures. Currently, April 1979, New Zealand is awaiting the arrival of MSS CCT products acquired over the test areas in July 1978.

To partially alleviate both these problems in the implementation of Landsat into the management scene, New Zealand is presently seriously considering the establishment, in stages, of a national Landsat receiving station and processing installation. This would permit imagery to be acquired of regions that are cloud free.

## APPENDIX A

## Monitoring Surface Snowpack Bonding Via the Brinell Hardness Parameter

Landsat senses mainly the surface layer of snow/ice crystals. Of vital importance to the problem of relating Landsat recorded radiances to snowpack data is the study of the composition and structure of this top layer. The crystal shape, structure, size and state are to be monitored in the Camp Stream programme.

As the snowpack metamorphoses, either through temperature or age, the surface structure can change. Ice bonding between individual crystals can lead to the thin surface layer, generally known as the 'crust'. The formation of this crust can change the recorded spectral signature dramatically - as we have discussed comparing the New Zealand and Antarctic snowpacks. In order to quantify this ice bonding several 'hardness' rigs were tested and one based on the Brinell parameter will be used during the 1979 programme.

Batson and Hyde (1931) indicate that the hardness of a body should be measured by the normal pressure per unit area which must act at the centre of a circular surface of pressure in order that at some point in the surface the stress may just reach the perfect elastic limit. This elastic limit is the maximum stress per unit area to which the surface layer may be subjected and still be able to return to its original form, on removal of the stress. The apparatus used in the New Zealand programme presently consists of an inverted hemi-spherical cap which is placed, rounded side down, on the snowpack and loaded by set masses. The diameter of the indentation left by the spherical segment (marked with washing blue) is then measured. The loading is chosen to allow the surface to perform elastically. In this way a measure of the surface bonding property is obtained, rather than the resistive forces of the underlying layers.

As $$H_B = \frac{P}{A}$$

and $$A = \pi Dh$$

$$h = \tfrac{1}{2}(D - \sqrt{D^2 - d^2})$$

then $$H_B = \frac{P}{\pi \frac{D}{2} (D - \sqrt{D^2 - d^2})}$$

where:

| | |
|---|---|
| $D$ | is the diameter of the sphere (mm) |
| $d$ | is the diameter of the indentation (mm) |
| $h$ | is the depth of the indentation (mm) |
| $P$ | is the total mass (kg) |
| $A$ | is the spherical area of the indentation ($mm^2$) |
| $H_B$ | is the Brinell Hardness number |

This technique has the advantage of quantifying the crust, for intercomparisons, irrespective of whether the crust is supported by other layers, or bridges an air pocket. Standard rammsonde techniques are affected by this crustal ice bonding, supporting layer resistive forces, and oblique cone forces, etc., as they break through the surface layer - the layer that influences the Landsat data the most.

Currently the equipment is being tested for use on sloping surfaces. It will be developed further during the 1979 season.

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