1. The first step in the process of creating a new product is to identify a market need. This involves conducting market research to understand what customers want and what problems they are facing. Once a need is identified, the next step is to develop a concept that addresses this need. This is often done through brainstorming sessions and the creation of a prototype. The third step is to conduct a feasibility study to determine if the concept is viable. This involves assessing the technical, financial, and market aspects of the idea. If the study is positive, the next step is to develop a business plan. This plan outlines the company's goals, strategies, and financial projections. Finally, the product is launched into the market, and the company monitors its performance and makes adjustments as needed.

PIONEERS IN METHYLENE BLUE TESTING SINCE 1974

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SPECTRAL REFLECTANCE SURVEY
ON THE
POSEN PENINSULA, ELLESMERE ISLAND, N.W.T.

by
DAVID E. ATKINSON, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Arts
Department of Geography

Carleton University
Ottawa, Ontario
June 22, 1992

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SPECTRAL REFLECTANCE SURVEY
ON THE
POSHEIM PENINSULA, ELLESMERE ISLAND, N.W.T.

submitted by David E. Atkinson, B.Sc.
in partial fulfilment of the requirements for
the degree of Master of Arts

Thesis Supervisor

Chair, Department of Geography

Carleton University
June 22, 1992

ABSTRACT

A spectral reflectance survey was conducted on the Fosheim Peninsula, Ellesmere Island, N.W.T., with the following objectives: 1) To determine directional spectral reflectance curves of various natural surfaces in the region; 2) to investigate how these curves vary with site and sky condition; 3) to apply this knowledge in an appraisal of the utility of satellite remote sensing in this region; and 4) to conduct a limited albedo investigation.

Results indicated that many distinct cover types exist, which were spectrally distinguishable. Variation in the direction and intensity of incident solar radiation affected the magnitudes and pattern of the spectral reflectance curves. The potential for satellite imagery is good. The logistic convenience and great utility for larger-scale studies is high. The albedo survey noted that albedo tends to increase with decreasing solar elevation, which is of great significance in the High Arctic.

ACKNOWLEDGEMENTS

A word of gratitude is due those shoulders upon which I stood.

My supervisor, Dr. Mike Smith, provided thoughtful, insightful commentary along the way yet gave me considerable latitude in my work habits: the first built the work into a piece that constitutes a real contribution to the community, and the second built confidence.

Several highly capable scientists at the Geological Survey of Canada must also be mentioned. Dr. Sylvia Edlund, whose logistical support made this entire project possible and whose critical commentary strengthened the final product, was invaluable to this thesis. Dr. Bea Alt lent the benefit of her considerable arctic field experience, and her great patience, to one just learning to walk on that same path. I have also enjoyed our many talks and very much look forward to working with her as my PhD supervisor. Dr. Roger McNeely provided critical insight and support during the attempt to obtain rather expensive satellite imagery.

Dr. John Miller of York University provided another cornerstone of this project, the step-wheel filter radiometer. It required a daunting leap of trust to provide someone he did not know with an expensive instrument to take to the high arctic for six weeks. His critical evaluation was also a welcome contribution. This project is very much in his debt.

My family has been enthusiastic throughout the project, and I am especially grateful to the great patience and unfailing support, both emotional and intellectual, of my wife Catherine, a highly intelligent woman of warm generosity and endless humour. She has been rescued from being a "computer widow" - at least until I am plunged again into the maelstrom of the PhD!

I would also like to thank Steve Prashker for his support (especially his well-designed computer mapping program MIGS), and the faculty and students of the Department of Geography at Carleton. They are friendly people, always willing to provide some thoughtful input.

I think one of the most important lessons of a project such as this is the true awareness of the fact that one never really works alone.

-David Atkinson, August 1992.

Table of Contents

	Page
Title Page	i
Acceptance Sheet	ii
Abstract	iii
Acknowledgements	iv
Table of Contents	v
List of Tables	vi
List of Figures	vii
List of Symbols	xi
List of Appendices	xii
 1 INTRODUCTION	 1
1.1 The High Arctic Integrated Research and Monitoring Area (IRMA)	2
1.2 Thesis objectives	7
 2 BACKGROUND	 9
2.1 Regional overview	9
2.1.1 Topography and geology	9
2.1.2 Climate	11
2.1.3 Vegetation	12
2.2 General radiation budget theory	13
2.2.1 Radiant energy	15
2.2.2 Radiation interactions with the surface	18
2.2.3 Sub-surface and low atmosphere	19
2.3 Satellite remote sensing	20
2.3.1 Atmospheric considerations	22
scattering	23
absorption	24
atmospheric water	24
2.3.2 Surface interactions	25
geometric arrangement	25
bare soil	27
texture and structure	27
soil moisture	27
organic matter	29
iron oxide	30
vegetation	30
2.4 Physical processes/ energy balance applications	33

Table of Contents (continued)

3 METHODS	37
3.1 Sites	37
3.1.1 Selection	37
3.1.2 Site organization	40
Location subsets	41
3.2 Radiometer measurement	41
3.2.1 Instrumentation	41
3.2.2 Field operation	45
3.2.3 Measurement procedure	46
3.3 Other instrumentation	47
3.4 Satellite data corrections	48
3.4.1 Geometric and positional errors	49
3.4.2 Conversion to upwelling radiance	50
Conversion procedure	53
3.4.3 Correcting for atmospheric conditions	53
3.5 Procedure for generation of satellite emulation data	56
4 RESULTS	57
4.1 Radiometric results	57
4.2 Detailed results	65
Modifications to curve pattern	66
Differences in reflectance coefficient	73
4.3 Classification results	75
4.4 Effects of sky condition	77
4.5 Satellite data emulation	81
4.6 Albedo survey results	88
5 DISCUSSION AND RECOMMENDATIONS	95
Utility of satellite imagery to research in the	
High Arctic IRMA	98
Further study	11
APPENDICIES	12
BIBLIOGRAPHY	13

LIST OF TABLES

TABLE	DESCRIPTION	PAGE
1	General uses of the Landsat bands	21
2	Spectral radiometer filters	44
3	Classification routine results	76
4	Satellite data emulation values: different sites	82
5	Satellite data emulation values: different times	82

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE
1	Overview of the Queen Elizabeth Islands, indicating the main weather stations in the region	3
2	Western Fosheim Peninsula, indicating Eureka and Hot Weather Creek	5
3	Electromagnetic spectrum	16
4	Spectral emittance curves for earth and sun	17
5	Wet and dry soil reflectance curves	28
6	Green and red leaf reflectance curves	31
7	Vicinity of Hot Weather Creek Camp	38
8	Closer detail of Hot Weather Creek Camp	39
9	York/CRESS Step-wheel filter radiometer	42
10	Overall average curve	58
11	Group A curves: vegetation	59
12	Group B curves: bare surfaces	59
13	Cluster analysis results: average curves from each of the five clusters	62
14	Vegetation cover progression: location subset A	64
15	Vegetation cover progression: location subset E	64
16	Vegetation cover progression: location subset J	64
17	Diffuse/direct incident radiation contrast: site B1	67
18	Diffuse/direct incident radiation contrast: site F1	67
19	Diffuse/direct incident radiation contrast: site E4	67

LIST OF FIGURES (continued)

FIGURE	DESCRIPTION	PAGE
20	Diffuse/direct incident radiation contrast: site D2	67
21	Hypothesized interaction of diffuse/direct incident radiation with moderately vegetated surface	68
22	Reflectance coefficient reduction under high solar angles: site H1	70
23	Reflectance coefficient reduction under high solar angles: site H1	70
24	Reflectance coefficient reduction under high solar angles: site H1	70
25	Vegetation pattern enhancement under direct illumination, low solar angle	71
26	Vegetation pattern enhancement under diffuse illumination, low solar angle	72
27	Vegetation pattern enhancement under diffuse illumination, low solar angle	72
28	Site B1: contrasting observations taken before and after midnight	74
29	High transmissivity, high solar angle	78
30	High transmissivity, medium solar angle	78
31	High transmissivity, low solar angle	78
32	Reflectance pattern under stratocumulus and thin cirrus/cirrostratus	80
33	Reflectance pattern under altostratus and thick cirrus/cirrostratus	80

LIST OF FIGURES (continued)

FIGURE	DESCRIPTION	PAGE
34	Percent vegetation cover plotted against the ratio of band 4/band 3 from the satellite emulation data	84
35	Satellite emulation results	87
36	Albedo results contrasted for clear and cloudy days	89
37	Hourly albedo results for the entire period	90
38	Radiometer generated albedo values contrasted with standard albedo values	92
AP-A 39	Landsat (near circum-polar) orbital pattern	106
AP-A 40	Landsat scanner sweep	107
AP-A 41	Thematic Mapper sensor schematic	108
AP-B 42	Positional details: location subset A	115
AP-B 43	Positional details: location subset B	115
AP-B 44	Positional details: location subset C	115
AP-B 45	Positional details: location subset D	116
AP-B 46	Positional details: location subset E and F	116
AP-B 47	Positional details: location subset G	116
AP-B 48	Positional details: location subset H	117
AP-B 49	Positional details: location subset I	117
AP-B 50	Positional details: location subset J	118
AP-B 51	Positional details: location subset K	118

LIST OF SYMBOLS

SYMBOL	MEANING
λ	wavelength of electromagnetic radiation
T_s	surface temperature, in Kelvin (K)
E	total energy emitted by an object
σ	Stephan-Boltzman constant ($5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-1}$)
Q^*	net radiation flux (longwave and shortwave)
$K_{\downarrow}$	total incoming, or downwelling, shortwave (250 - 3500 nm) radiation
$K_{\uparrow}$	total reflected, or upwelling, shortwave radiation
$L_{\downarrow}$	total downwelling longwave (3500 - 10 000 nm) radiation
$L_{\uparrow}$	total emitted longwave radiation
α	shortwave albedo
s	effective solar illumination
S	solar illumination at top of atmosphere
β	solar zenith angle
n_{Welec}	unit of electrical power
W_{rad}	unit of radiative power
Z	universal standard time (EST + 5hrs)
D_n	satellite data digital number
D_{max}	largest value of D_n a sensor can return
L_{min}	threshold (minimum) energy intensity required by a sensor to produce a signal distinguishable from background noise
L_{max}	saturation (maximum) energy intensity a sensor can tolerate
τ	atmospheric optical thickness
τ_{O_3}	portion of τ that ozone is responsible for
$\tau_{\text{H}_2\text{O}}$	portion of τ that water vapour is responsible for
τ_A	portion of τ that atmospheric particulate matter is responsible for
τ_G	portion of τ that the other atmospheric gasses are responsible for
T	transmitted energy (through the atmosphere)

LIST OF APPENDICIES

APPENDIX	DESCRIPTION	PAGE
A.1	The LANDSAT Earth Resources Technology Satellites	103
A.2	Detailed site/readings information	109
A.3	Procedure for generation of satellite emulation data	122
A.4	Factor analysis results	129
A.5	Cluster analysis results	130

1 INTRODUCTION

Research in the Canadian High Arctic is conducted by individuals and organizations in many different academic fields. An aspect of this work shared by all participants is the basic logistical complexity of working in an area the size of England, France and Germany combined. An absence of the infrastructure taken for granted in the south means that every detail must be considered and every possibly required item must be transported by aircraft over hundreds and thousands of kilometres. Efficient use of field season time is of paramount concern to Arctic research.

Into this research environment can be introduced satellite remote sensing. From an orbital vantage point, the instruments on board the satellite can gather information about the surface that can be put to many uses. It can be used as a relatively simple tool, for instance serving as nothing more than an interesting map of the region or it can form part of the basic information gathered, such as inputs for energy balance analyses.

Satellite data should, for most applications, be accompanied by a ground survey of the same area. This serves to provide basic information about the surface conditions against which the satellite data can be calibrated. This is the essential focus of this project: the use of a field portable spectral radiometer to collect surface reflectance data that may be used to calibrate satellite data of the same area. This project has been broken into several sections: 1) A discussion of radiation theory and the factors that influence the way radiation is reflected from a surface and transmitted through the

atmosphere; 2) how the reflectivity data were collected, including the instrumentation used; and 3) the results of the study and discussion. The study was conducted at a research site on Ellesmere Island, called Hot Weather Creek.

1.1 The High Arctic Integrated Research and Monitoring Area (IRMA)

To provide a research framework for determining signals of environmental change and possible resultant effects of such change, the Geological Survey of Canada (GSC) established a program called 'The Global Change Initiative' in 1999. The purpose of this initiative is to focus the efforts of current research in three broad areas, called Integrated Research and Monitoring Areas (IRMAs): the High Arctic (the Queen Elizabeth Islands - Figure 1), in the Mackenzie Valley and in the Palliser Triangle (southern Saskatchewan). Research objectives include determination of how the natural sub-systems and physical processes at work in these regions are related, and the provision of general coordination to the many individual efforts at work. The result of the Initiative will be a more comprehensive understanding of how the different sub-systems are linked, and will serve as part of the Canadian input to the International Geosphere-Biosphere Project. From this, sensitive indicators of change in northern environments will be identified and monitored. In this way it is hoped that the Global Change Initiative can serve to provide early indication of "environmental change", or deviations from established baselines of selected environmental parameters (e.g., plant species distribution, active layer depth, or mean July air temperature). In performing this task, past and present research will be examined for any signs of

Figure 1: The Queen Elizabeth Islands, showing the Eureka Intermontane Region (dark line) and the vicinity in which this study was situated (box).

possible long-term trends and appropriate monitoring programs will be established to detect future change.

The main region of focus associated with the High Arctic IRMA is an area known as the Eureka Intermontane Region (Figure 2). Within this area, the principal research location is the Hot Weather Creek site, which is approximately 25 km east of the Eureka weather station on a tributary of the Slidre River known as Hot Weather Creek (Figure 2). The Hot Weather Creek site was selected by the GSC for two reasons:

- 1) It was thought that a more realistic assessment of peninsular 'mean' climatic conditions would be afforded if a monitoring station was established well away from the influence of ice caps or large bodies of water. At the present time, all permanent High Arctic weather stations run by Atmospheric Environment Service Canada, i.e., Eureka, Isachsen (closed in 1980), Mould Bay, Resolute Bay and Alert, occupy coastal locations where meteorological conditions are modified by the presence of adjacent bodies of water (Figure 1). Such effects extend inland only a few kilometres, which means the prevailing meteorological conditions of the land mass are not accurately reflected in the station records. The Hot Weather Creek site, situated in the centre of the largest area in the Queen Elizabeth Islands devoid of rugged mountains and ice caps and well away from large bodies of water, satisfies this requirement.

A regional characteristic of the Fosheim Intermontane Area which renders the area warmer than might be expected for its latitude is its relative topographic isolation. The main brunt of the Polar Ocean winds is deflected by mountains to the west, north, east and southeast. Because of this sheltering effect, the interior of this region tends to

Figure 2: Detail of the western Fosheim Peninsula, indicating the weather station at Eureka and the Geological Survey of Canada's camp at Hot Weather Creek, the base for this study.

be several degrees warmer than other areas in the High Arctic. The reason for selecting a region that seems atypical of the High Arctic is also based on change monitoring in three ways. Firstly, given the scenario of a general climatic warming, it is felt that other areas in the Arctic which are similar in physiography but less protected topographically could begin to develop characteristics (e.g., climatic, botanical, geomorphological) similar to those currently found in the Intermontane Area. Thus study of the present characteristics of the Intermontane Area will allow change occurrence in other areas to be more readily recognized. The second is that, although atypical, under an arctic- or planet-wide climate change, the Fosheim Intermontane Area would presumably change by as great a magnitude as regions around it. In that sense, i.e., monitoring for change, this area is as suitable a location as any other in the High Arctic. Finally, it is of interest to determine what effect climate change would have on the region, i.e., would it become more or less anomalous. For example, research underway there is revealing the large effect the underlying ice-rich ground, under the influence of strong summer melt, has on the landscape and processes at work on the landscape. It is important to identify whether summer melt would be enhanced or reduced under climate change, especially because this region represents a significant area of the Queen Elizabeth Islands.

2) The second reason for selecting this location is a by-product of its mesoscale climate. The interior of the Fosheim Peninsula is one of the most botanically diverse regions in the High Arctic, containing several species of plants that are normally found much further south.

In the Arctic, plants can be very useful proxy indicators of local climatic conditions, thus their careful study at this location could lead to their adoption as an indicator for environmental change monitoring (Edlund, personal communication).

1.2 Thesis Objectives

The essential goal of this thesis study was to obtain information about the reflectance characteristics of various surface conditions in the area and to use this, in part, to explore the potential utility of satellite imagery in High Arctic research. By 'surface condition' is meant the characteristics of a natural surface, such as percent vegetation cover, vegetation type, soil moisture content and soil surface roughness, that determine the way it will reflect radiation. This involved the acquisition of information about the spectral reflectivity of various natural surfaces by generating plots of spectral reflectance versus radiation wavelength, called spectral reflectance curves.

The specific objectives are as follows:

1) To establish basic information about the spectral reflectance of natural surfaces in this area of the High Arctic, and to determine the sources of variation that appear in these spectral reflectances.

2) To formulate and test a data classification scheme which would enable spectral reflectance curves gathered from unknown surfaces to be assigned to known (categorized) surface types.

3) To construct an emulation of satellite data and use the results to examine the effective radiometric and spatial resolution of existing satellite data. 'Emulation' refers to the use of ground data to simulate data the satellite sensor would return, if it had imaged the same area at the same time. This exercise was intended to provide an idea of the extent to which surface cover types could be distinguished and to identify the magnitude of change difference which could be detected by satellite sensor systems (radiometric resolution).

4) To measure albedo in the field area and determine how it is influenced by sky condition, and to use this data set as a check against which albedo values generated by the radiometer readings could be compared.

2 BACKGROUND

2.1 Regional overview

The ground data for this project were gathered in the west-central region of Ellesmere Island, on a large peninsula called Fosheim Peninsula (Study Area, Figure 1), in the vicinity of the Geological Survey of Canada's Hot Weather Creek base camp. Although specific sites were confined within 10 km from the base camp, many of the surface cover types around the camp are characteristic of large areas of the Fosheim Peninsula. The camp and its environs thus provided a selection of surface types typical of most of the peninsula.

The principal goal of remote sensing is the gathering of information about the surface of the earth. To make more effective use of satellite data it is useful to understand what processes act on the surface of the earth to influence its appearance. In association with weathering, erosion and deposition, the underlying geology determines the nature of the soil and rock found at the surface and its essential topographical form. This, combined with the effects of prevailing climatic conditions, such as local thermal regime, precipitation and winds, limits the biological communities that are established.

Topography and Geology

A major influence on the appearance of the surface is what underlies the region of interest, i.e., the regional topography and geology. In the High Arctic, bare soil or rock surfaces form part of the visible surface area. Awareness of the origin of the material (soil) comprising the surface (e.g., parent rock) may be of assistance in interpreting remotely sensed data.

Figure 2 shows the general physiography of the peninsula, which includes three main highland regions that dominate the surrounding undulating lowland region. The three highland regions comprise the Sawtooth Mountains to the south and southeast of the camp, Blacktop Ridge to the west of the camp, and the highland range along the west coast of the peninsula.

Blacktop Ridge and the west coast range consist of a series of exposed strata of lower Mesozoic age. The region from the west coast to the eastern edge of Blacktop Ridge forms a broad anticline that has been subjected to displacements due to minor faulting and differential weathering of the exposed layers. The Sawtooth Range consists of a series of major upthrust faults exposing material dating back to lower Permian (upper Palaeozoic) (Thorsteinsson, 1971, 1971 and 1972).

The region between the older formations in the west and the Sawtooth Mountains forms a broad syncline which consists of a thick layer of Tertiary age material. This layer, called the Eureka Sound formation, underlies the central Fosheim Peninsula and is comprised mainly of light-coloured sandstone, with some siltstone, conglomerate, shale and small, isolated quantities of coal (Hodgson et al., 1991; Thorsteinsson, 1971, 1971 and 1972). At elevations below approximately 140 m a.s.l. the surface is overlain with sandy silt and silty clay deposited during Holocene marine incursions (Pollard, 1991 after Hodgson, 1985 and Egginton and Hodgson, 1990).

The rolling topography of the central Fosheim Peninsula is in keeping with a well established nival and riverine weathering environment, and is subjected to modification by the presence, aggradation and degradation of

ground ice (Hodgson et al. 1991 after Lewkowicz, 1990; Pollard, 1991; Edlund et al., 1989a).

Climate

Climate is a fundamental force acting on the surface. It determines the nature and intensity of weathering and deposition, and influences the variety and amount of the vegetation present (Kellman, 1980; Haber, 1986). For example, the location of the northern limit of boreal forest coincides with the mean July position of the Arctic frontal zone (Barry and Chorley, 1982, p. 214). Edlund (1987) and Edlund and Alt (1989b) discuss similar climate-dependent vegetation patterns in the High Arctic.

The mean summer temperature of the Fosheim Peninsula is about five degrees celsius warmer than the majority of the region around it. This climatological difference makes possible a biological uniqueness (Edlund et al., 1990) and influences the area in other ways, such as early snow melt (Woo et al., 1991) and late-summer recharge of surface moisture due to ground ice melt (Edlund et al., 1989a). For these reasons, brief reviews of the local and regional climates are presented.

The climatic record generated by the Eureka Weather Station is not indicative or typical of its 80°N latitude in the Queen Elizabeth Islands, nor is it indicative of the interior climate of the Fosheim Peninsula. For its latitude, the average temperatures recorded at Eureka (30-year July mean is 5.4°C) tend to be higher than for other areas in the islands (Maxwell, 1980); the interior of the peninsula records temperatures that are higher still (mean July temperature for 1988 and 1989 was 12.7°C - Edlund et al., 1990) than those at Eureka.

The climate of the Fosheim Peninsula is in part a byproduct of the

topography of the Queen Elizabeth Islands, which shields the Fosheim Peninsula from the larger scale climatic activity of the Queen Elizabeth Islands. The 90 kPa (ca. 1000m) flow (i.e., the average wind direction) tends to be from the northwest for the central Ellesmere region (Alt and Maxwell, 1990). However, meso-scale climate characteristics on Fosheim Peninsula are also governed by the regional topography. This topographical modification involves the forced orographic lifting of the northwesterly flow when it encounters the highlands of Axel Heiberg and northwest Ellesmere Islands. As it descends the lee side into central Ellesmere Island the air mass warms and relative humidity decreases. The air thus tends to be clearer, allowing more solar radiation to penetrate and warm the ground, and possessed of greater ambient temperature (Alt and Maxwell, 1990; Alt, 1987). This sets the peninsula apart, climatically, from its latitude (Alt and Maxwell, 1990; Edlund and Alt, 1988; Edlund et al., 1990; Edlund et al., 1989a).

The Fosheim Peninsula has low annual precipitation (<70 mm/a) (Maxwell, 1980). Despite this, the vegetation communities present indicate moisture levels greater than what summer precipitation alone would generate. This is a byproduct of ongoing melt of ice-rich ground (e.g., areas with ice content greater than what would be predicted based on soil pore size alone - Pollard, 1991) throughout the summer. This source of moisture maintains vegetation communities, even in the virtual absence of summer precipitation (Edlund, 1990).

Vegetation

The Fosheim Peninsula contains an unusually large range of vascular plant species for its latitude (Edlund, 1990). This is a result of the

climatic conditions discussed previously. The additional summer warmth allows species normally found farther south to survive at this location.

The most prevalent habitat areas are upland surfaces, and include sandy/gravelly terraces and areas that contain well developed polygon/hummock surfaces. These well drained areas contain vegetative covers that range from 0 - 50%, accounting for approximately 30 vascular plant species. Poorly-drained areas are less common in the region, but occur around lakes, at polygonal junctions and in some valleys. Vegetative cover in these wet areas is usually high, and some 50 vascular plant species may be found (Edlund et al., 1990; Edlund et al., 1989a).

Salix is the most common woody species on the Peninsula, being found on most surface types. Overall, Fosheim Peninsula supports vegetative growth that is extensive in terms of both the diversity and community types that may be found, e.g., bare, sandy upland terraces or saturated valley floors (Edlund, 1987).

2.2 General radiation theory

The surface environment of any land region harbours a complex and highly interrelated array of physical and biological conditions.

The importance of understanding what happens when solar radiation is absorbed by the surface can be appreciated when this surface interrelatedness is considered. As Geiger (1965) indicates, the ground surface "...absorbs and emits radiation, evaporates and condenses water, and retards all air movement...[and] profoundly affects the overlying layer of air" (p.55). This project is concerned with the first element mentioned in the quote, but as Geiger alludes, all of these processes are interrelated; that is, they affect, and are affected by, each other.

Almost all weather phenomena take place between the surface and the tropopause, and, generally, most biological activity within the soil will take place to the depth at which diurnal variations in soil temperature are no longer discernible. A large proportion of life on earth exists within this thin soil/atmosphere layer; therefore, the way in which solar radiation, the primary energy source, interacts with the surface is of fundamental importance (Irons et al., 1991; Geiger, 1965).

The nature of the surface, e.g., vegetation cover, soil colour and texture, moisture content, as well as the underlying soil/rock material, determine the extent of ground heating. Not only is this important for heating of the atmosphere above, but it also establishes the thermal regime of the ground. The ground thermal regime influences the intensity of and depth to which biological activity (including plant growth) proceeds. (Floral activity generally requires a certain threshold ground temperature.) Soil moisture content is also influenced by soil temperatures. For example, a patch of lighter coloured soil might reflect more shortwave radiation, heat up less than adjacent areas, experience less moisture loss to evaporation, and thus allow more plants to germinate. In Arctic regions, surface heating will also melt ground ice, increasing soil moisture content. As well, the depth of the active layer is influenced by the surface temperature regime, as is the thickness, temperature and areal extent of any permafrost present.

2.2.1 Radiant energy

All radiation, e.g., solar radiation, is a form of electromagnetic energy, also termed radiant energy, that is measured along a continuum called the electromagnetic spectrum (Figure 3), which is subdivided by wavelength. The dominant wavelength at which any object, such as the sun, emits energy is governed by the surface temperature (Figure 4). Radiation of wavelengths from 400 - 800 nm comprises what is termed visible light; shorter wavelengths include ultraviolet and x-rays, and longer wavelengths include regions such as infrared and radio waves (including radar).

The wavelength of maximum emission $\lambda_{\max}$ for any radiating body is expressed by Wien's law:

$$\lambda_{\max} = \frac{2897 (\mu\text{m K})}{T_s (\text{K})} \quad (1)$$

where T_s is the surface temperature of the emitting body. The total quantity of energy emitted by an black body (a theoretical perfect emitter of absorbed energy) is described by the Stefan - Boltzman law:

$$E = \sigma T_s^4 \text{ (W m}^{-2}\text{)} \quad (2)$$

where σ is the Stefan-Boltzman constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-1}$).

Solar radiation, generated by an effective radiative temperature on the sun of some 6000 K, has a spectral distribution that ranges from 200 nm to 4000 nm, with a peak around 500 nm. Almost half of the sun's radiation output lies within the visible waveband. Conversely, the Earth, which has a mean surface temperature of about 290 K, radiates at longer wavelengths, from 4000 to 50,000 nm, centred around 10,000 nm. This Earth radiation lies wholly in the infrared region of the spectrum. The ranges of radiation emittance for the Earth and Sun are almost completely

Figure 3: The electromagnetic spectrum

Figure 4: Spectral emittance curves for the sun and earth. Solar surface temperature is approximately 5800 K; that of the earth is approximately 290 K.

exclusive of one another. The spectral range encompassed by solar radiation is termed shortwave radiation and the range of terrestrial radiation, longwave. Although the net longwave radiation balance is of importance, incident shortwave radiation is the principal source of energy for the earth.

2.2.2 Radiation interactions with the surface

At a microscale, the nature of the surface, including its colour, texture and moisture content, will determine the quantity and the wavelength of incident shortwave radiation which is absorbed. An expression describing the radiation balance at a surface is as follows:

$$Q^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow) \quad (3)$$

where Q^* = net radiation

$K\downarrow$ = total incoming or downwelling shortwave
(direct and diffuse) radiation,

$K\uparrow$ = reflected or upwelling shortwave radiation,

$L\downarrow$ = longwave (thermal) radiation incident on
the surface (emitted by the atmosphere),

$L\uparrow$ = longwave radiation emitted by the surface,

Downwelling (incident) shortwave radiation falling on a surface is the sum total of a direct and a diffuse component. The direct component refers to the beam emanating from the point of the sun and the diffuse component is scattered radiation incident on the surface from directions other than that of the sun (see Section 2.3.1 on scattering). Incident shortwave radiation that is not absorbed by or transmitted through the surface is reflected. For a given wavelength of radiation, the ratio of shortwave energy reflected by a surface to that which was incident is termed reflectivity. The term reflectance coefficient describes the reflectivity of a surface when integrated over a range of wavelengths, i.e., a waveband

(modified from Monteith and Unsworth, 1990). The term is used in this paper to describe the overall or average reflectance of a spectral reflectance curve. Albedo is the term given to the reflectance coefficient for the specific case of solar radiation. Although, technically, albedo applies to radiation streams of any wavelength (e.g., Geiger, 1966), in practice the term has come to refer specifically to shortwave radiation, or the realm of solar irradiation in the visible and near infrared bands. Albedo, α , is generally expressed as the decimal fraction:

$$\alpha = K\uparrow/K\downarrow \quad (4)$$

The radiation balance equation (3) as modified to incorporate the expression for albedo becomes:

$$Q^* = K\downarrow(1 - \alpha) + (L\downarrow - L\uparrow) \quad (5)$$

The albedo of a surface expresses the proportion of incident shortwave radiation it will absorb.

2.2.3 Effects on the sub-surface and low atmosphere regimes

As mentioned, solar radiation ($K\downarrow$) is the primary source of energy for the surface environment. At the surface, some of the shortwave radiation absorbed by the ground warms the soil and some goes to the evaporation of water or, if the ground is frozen, to the melting of ice within the ground. The extent to which the soil is warmed will allow biological processes to proceed, as influenced by topography, soil type and other climatic factors.

It is from the surface of the earth, warmed by incident shortwave radiation, that the lowest levels of the atmosphere are heated. This occurs when thermal energy resulting from the absorption of incident

shortwave radiation is radiated (L_f) into the atmosphere and absorbed. From the lower levels atmospheric heat is transferred and mixed up through successive layers by convective and turbulent motion processes. Diurnal variations in the vertical temperature profile of the atmosphere are discernible to heights in excess of 1000m.

At a regional scale, air temperatures are generally a product of the prevailing air mass. However, at smaller scales in the low layers of the atmosphere (i.e., areas on the order of up to a few square kilometres), the nature of the surface may modify considerably the local atmospheric temperature and moisture content. Because of this, the scale at which much research into physical process at the earth's surface is conducted is within the realm of such small scale, or microclimatological, considerations. Thus an understanding of how the surface reflects and absorbs radiation is an important part of research at this scale.

2.3 Satellite remote sensing

The vehicles which conduct satellite remote sensing are essentially space borne platforms equipped with instruments designed to gather information about the earth. 'Information' consists of numerical data collected for discrete area units, called picture elements or pixels. Pixel size is a function of the instrument, its intended uses, and its distance from the target (feature of interest). Sensors record the intensity of electromagnetic radiation in various discrete wavelength 'bands' (Table 1) in the visible and near-infrared (see Figure 3) that is reflected from the target (usually the surface of the earth). The greater the intensity, the larger the corresponding numerical value (termed "digital number") the sensor will assign to that pixel.

Table 1: General uses of the Landsat thematic mapper bands; (units for filters and bands are nanometres, unless specified).

York Univ. Radiometer Filter	LANDSAT TM Band	Uses
4: 432-452	1: 450-520	Water mapping, sediment content, forest type ID, cultural features ID
5: 517-533	2: 520-600	Plant discrimination, vigour assessment, cultural features ID
6: 540-560		
7: 591-608		
8: 679-685	3: 630-690	Aids in plant discrimination
9: 730-810		
10: 790-810	4: 760-900	Primary band for vegetation type ID, biomass content estimation, vigour assessment
1: 1240-1260		Although filters 1 and 2 have no counterpart on the thematic mapper, radiometer filters 1, 2 and 3 are very useful for determining the presence and, to some extent, quantity of water within the soil
2: 1440-1460		
3: 1550-1750	5: 1550-1750	Soil, vegetation moisture content, differentiate clouds from snow
	7: 2080-2350	Mineral and rock type discrimination
	6: 10.4-12.5 (μm)	Thermal mapping, vegetation stress

The way by which such systems can provide information about a target depends on the fact that all things reflect radiation in a characteristic way (e.g., that is why things have different colours), given uniformity of all influencing variables. The readings from each band are sequentially plotted by wavelength, producing the spectral reflectance curve (or reflectance signature). Once known, the reflectance signature can be remotely monitored for changes. If change is detected, follow-up investigation could be conducted to determine the cause.

For systems sensitive in the visible and near-infrared bands, a ground survey is usually conducted with a portable spectral radiometer to establish the reflectance characteristics of the area of interest. The radiometer is also able to sense radiation in various wavebands (Table 1). Specific surface types are then associated with the radiometer results, which are in turn associated with the satellite data. This serves to effectively calibrate the satellite data. Once this has been performed the data may be fully utilized.

2.3.1 Atmospheric considerations

Shortwave radiation incident upon the surface of the Earth must travel through the atmosphere. It is readily apparent that reflected radiation incident upon the sensors of a space-borne detection system must travel through the atmosphere twice. The way in which radiation is modified by its passage through the atmosphere will directly affect the quality and utility of the resultant image. For example, increased scattering due to hazy conditions will cause reflected radiation from pixels beside the area of interest to be scattered into the beam travelling from the pixel of interest to the sensor, resulting in

decreased contrast between pixels. This represents extraneous information which can possibly mask features of interest, and is termed adjacency effect (Kaufman, 1989; Kaufman 1985). A difference in atmospheric composition between two images of the same region could alter the resulting spectral signatures enough to prevent comparisons for subtle change from being realistically conducted (Curran, 1986). Thus, consideration of the effects of the atmosphere upon the beam of shortwave radiant energy is of concern to those wishing to maximize the information returned by such sensors.

Atmospheric effects may be classed into two basic types: scattering and absorption. Generally, scattering effects account for a 25% depletion of the beam of incident radiation and absorption (including that caused by clouds) accounts for another 25% (Barry and Chorley, 1982).

Scattering occurs when photons of the incident beam have their velocity vector altered by an encounter with a particle or molecule of any sort, i.e., a collision that changes the direction of the photon. In most cases, the resultant change in direction of the photon removes it from the path of the original beam, but the photon is still incident upon the surface of the earth. Photons that are scattered in this manner are responsible for what is termed diffuse radiation, which forms a significant component of total downwelling shortwave radiation - from 14% to 50% when the sky appears clear, and up to 100% as the sun becomes completely obscured by cloud. Diffuse downwelling radiation is responsible for 'backlighting', the illumination of areas in shadow.

Any downwelling photon that, upon collision with an atmospheric particle or molecule, has its direction vector altered such that it is no

longer incident upon the surface will, excluding further collisions, exit the atmosphere. The ratio of radiative flux incident upon the atmosphere to that scattered back into space without contacting the surface defines the atmospheric albedo. Such reflected photons are detectable in space by a satellite sensor. However, they carry no information about the surface of the earth and are thus undesirable because they reduce the strength of the surface signal (Cracknell, 1981).

Absorption of an incident photon occurs when a collision with an atmospheric particle results in the conversion of the photon into some form of molecular energy: translational, rotational, vibrational or electronic (Henderson-Sellers, 1984). The photon is considered to have been removed from the incident radiation stream, and plays no further role.

One of the most important climatological constituents of the atmosphere is water. Atmospheric water can be found in all three physical states: as invisible vapour, or in a condensed liquid or frozen state as visible clouds. Water vapour absorbs incident shortwave radiation in certain specific wavebands. The higher the atmospheric water content, the greater will be the absorption from the incident stream. The total impact generated by water vapour alone is, overall, minor (Barry and Chorley, 1982). The presence of clouds, however, can affect large proportions of incident shortwave radiation because they are able to reflect almost all shortwave radiation that strikes them, a result of their high albedo.

2.3.2 Surface interactions

The ultimate objective of earth resources (as opposed to meteorological) satellite remote sensing is the gathering of information about the surface of the earth. For this reason, it is useful to describe how shortwave radiation interacts with the surface and what typical spectral reflectance curves look like.

The geometric arrangement of the incident beam with respect to the surface is an important factor influencing the reflectance curve and albedo generated by a surface. Essentially, there are two extreme cases, specular and diffuse reflectance; all possibilities lie between them. In the case of specular reflectance, radiation incident upon a surface is reflected in only the direction which is equal and opposite to the angle of incidence. This is how the surface of smooth water reflects at low solar angles. Other surface types, e.g., bare soil, can act as partial specular reflectors under low solar angles. For example, Kriebel (1979) reported that solar angles of less than 30° resulted in an increase in the amount of specular reflectance from a surface. The second case is diffuse, or Lambertian, reflectance. This occurs when radiation incident upon a surface is reflected equally in all possible directions (i.e., in a hemispherical pattern). Generally the rougher a surface is the more it tends to act as a diffuse reflector.

The solar angle affects the intensity of incident radiation. Note that for this paper 'solar angle' refers to solar elevation angle, or the angular distance between the sun and the horizon as measured from the horizon. With increasing solar angle the intensity of target illumination also increases (i.e., the radiation flux density is greater), as described

by the following relationship:

$$S_e = S \cos(90 - a) \quad (6)$$

where S_e is the effective solar illumination, S is the solar constant at the top of the atmosphere, and a is the solar angle. Albedo can also vary considerably with solar angle (Ranson et al., 1991; Teillet et al., 1988). For example, lower solar angles will introduce shadows within a vegetated surface, reducing its albedo (Kriebel, 1979). Another factor that will influence the geometry of the incident beam is solar azimuth, which along with solar angle is a function of time of day, latitude and time of year.

The geometry of a surface, i.e., its slope angle and aspect, is another important consideration. If the surface is not uniform when viewed from different directions, variations in solar azimuthal position will result in different reflectivities. Even identical solar angles at different azimuthal positions (e.g., two hours before and after solar noon) will not necessarily produce identical surface reflectivity signatures (Chapelle et al., 1979). It is for this reason that consideration of the geometry of the sensor with respect to the target surface is important (Rao et al., 1979).

Also of importance is consideration of sensor position relative to the sun. When the sensor is positioned looking in a direction somewhat parallel to the incident radiation stream, the reflectances measured tend to be lower and the chance of encountering specular, or direct, reflection is less than when the sensor is positioned in an azimuthal position 180 degrees from the direction of the incident radiation (Curran, 1985; Ranson, et.al., 1991).

The most important influence on the appearance of a surface is the

composition of the surface itself; i.e., what it is made of and what rests upon it. Although most natural surfaces are a mixture of bare soil and vegetative cover, it is useful to examine their reflectance properties separately. In general, the reflectivity for an area of **bare soil** is smallest at the shortest wavelengths and tends to increase gradually as wavelength increases until, about the mid infrared region of the spectrum, it levels off (Figure 5). The main soil properties that govern reflectance characteristics are structure, texture, organic matter content, soil moisture and iron oxide content (Curran, 1985; Stoner and Baumgardner, 1981; Condit, 1970). Overall, bare surfaces possess higher reflectance coefficients than vegetated surfaces.

Texture and structure are important properties of the soil: *texture* refers to the size of the soil particles and *structure* refers to the way in which the particles are bonded together. Together, these properties determine how smooth or coarse the surface is. The smoother a surface is, the more incident radiation it will reflect. Surface roughness, resulting from protrusions and small holes, will tend to scatter or trap a greater percentage of incident radiation, thus reducing surface albedo (Musik and Pelletier, 1986; Geiger, 1965). Soil composition is related to parent mineralogy. It will affect the existence of crystal faces on the constituent particles. Crystal faces will increase the reflectance of soil particles; as well, parent mineralogy, in part, determines the size of soil particles.

Soil moisture is another important factor. Water exists in soil as

after Condit, 1970

Figure 5: Typical spectral reflectance curve for dry soil and the same soil wetted.

films which cover soil particles and stretch over the pores between particles. These films of water allow incident radiation to enter, but via internal reflectance then inhibit its departure. The presence of water in soil affects the spectral reflectance curve in two ways: the first is a decrease in the reflectance coefficient (Figure 5), due to the tendency of water to strongly absorb visible and near-infrared wavelengths (Petzold and Rencz, 1975). The second is manifested as two major absorption bands located at $1.45\mu\text{m}$ and $1.95\mu\text{m}$. At these points the reflectance curve is abruptly interrupted with a brief, sharp drop in reflectance of up to 70%. These dips, a result of strong internal reflectance, only occur at certain coefficients of refraction, which is why only certain wavelengths are affected (Monteith and Unsworth, 1990; Stoner and Baumgardner, 1981; Geiger, 1965). The magnitude of the dips is proportional to the percent soil moisture content.

The **organic matter** content of the soil has an important influence, since organic matter is very dark. Inclusion of only a few percent by volume is sufficient to modify the appearance of soil; more than five percent organic matter renders the soil black in colour in almost all cases (Curran, 1985). Organic matter also tends to hold moisture well, thus, such soils will also exhibit the same moisture absorption lines and overall decrease in reflectance coefficient that wet soils do.

Thus a very dry soil would bear little trace of the moisture absorption dips and, although regions devoid of soil moisture and significant organic matter content are the exception on the surface of the earth, there do exist regions where such conditions dominate, i.e., hot deserts (Stoner and Baumgardner, 1981).

Although of little bearing at the research location of this particular study, another important spectral reflectance modification factor is the presence of iron oxide in the soil. Particles of iron oxide either coat or stain other soil particles with their colour (Curran, 1985). The soils of Prince Edward Island and of parts of Brazil are good examples of this.

The typical reflectance curve for healthy green vegetation is very distinct and consists of two major absorption and reflection features. Almost all incident radiation in the blue (400-500nm) and red (600-750nm) regions (wavebands) is absorbed by the plant leaves. These are the wavebands of photosynthetically active radiation (Tucker, 1978). Reflectance coefficients for these wavebands are typically on the order of a few percent. Reflectance peaks occur in the green (500-600nm) and the infrared (800-2000nm) bands of the spectrum. Typically, reflectance coefficients for green range are around .25, while those for the infrared wavelengths can be as high as .6 and .7 (Figure 6). Within the visible wavelengths, the peak and the two dips are the reason human eyes see most plants as green - that is the colour they reflect most strongly, apart from the invisible infrared.

This reflectance pattern is a byproduct of the pigments and internal structure of leaves. The pigments (e.g., chlorophyll) are responsible for the absorption of red and blue light; the infrared reflectance properties of a leaf are a result of the internal cellular structure. As well, because leaves contain water and radiation can penetrate into a leaf, vegetation also exhibits the water absorption dips at 1450 and 1950nm (Curran, 1985). The spectral reflectance of vegetation will be modified

After Curran, et.al., 1991.

Figure 6: Typical spectral reflectance curves for two types of leaves. Black surface reflectance is for contrast.

by pollutants, stage of growth and water availability (Schutt, 1979; Tucker, 1978).

Tucker (1978) conducted an experiment to determine the relationship between reflectance of senescent vegetation and biomass. The main point of interest arising from the study is that, with senescence and subsequent death, vegetation reflectance tends to increase. This is attributable to the loss of water, which is a strong absorber in the mid infrared, and the breakdown of the chlorophyll and carotenoid pigments within the plant which absorb blue and red wavelengths. Thus the cessation of photosynthesis with the onset of senescence means that blue and red wavelengths are reflected to a greater extent (Schutt, 1979; Tucker, 1978). This will cause the vegetation curves to appear more like unvegetated surfaces (Siegal and Goetz, 1977).

Another consideration, relevant to the Arctic, is the plants that contain a red pigment, red amaranth, as the dominant photosynthetically active agent in their leaves. Curran et al. (1991) examined the effects of this pigment on the reflectance curves of leaves as contrasted with the green pigments. Results showed that it tended to reduce the overall reflectance coefficient and moved the "red edge" into longer wavelengths, or to the right on the curve. The red edge is the point at which the reflectance value rises steeply out of the region of low red waveband reflectance and into the region of high infrared reflectance. The green reflectance peak is almost non-existent (Figure 6) (Curran et al., 1991).

There are several other factors that influence the overall reflectance of a vegetated area: leaf area index (LAI), the nature of the vegetation canopy, the location of the sun and the location of the sensor.

Leaf area index is the unit leaf area per unit soil area as viewed from above. It provides an idea of how much of the surface is covered with leaves (Pollock and Kanemasu, 1979). For example, if the LAI is low the measured reflectance curve will be mostly influenced by the reflectance of the soil (Rao et al., 1979). The types of plants and the way they grow will also affect the reflectance of a vegetation canopy. Tall, large trees, for example, will cast large shadows, which will reduce (darken) the background soil reflectance coefficient, whereas plants that spread out over the surface of the ground will not cast the same area of shadow.

Although there is no vegetation on the Fosheim Peninsula capable of casting large areas of shadow, a vegetation canopy still exists. A small canopy will cast shadows within itself, lowering its reflectance coefficient (Section 2.2.2). The orientation of the leaves within a canopy will determine periods of exaggerated and masked vegetation pattern in the reflectance curve signature, depending upon the position of the sun. For example, if the leaf surfaces are perpendicular to the incident beam, the vegetation pattern in the overall reflectance will be more apparent than if they are arranged parallel to the incident beam.

2.4 Physical processes/ energy balance applications

Many projects have utilized data gathered by satellite-borne sensors in a multitude of ways in the 20 years or so since the launch of the first such satellites. A review of all the projects undertaken is beyond the scope of this report; however, there does exist a body of work consisting of applications that are of relevance to this project. They serve as an indicator of the sorts of applications for which satellite imagery is

being used, will see use (Ardanuy et al., 1991), and as ideas for projects that could be conducted at the Hot Weather Creek site or on the Fosheim Peninsula in the future.

The measurement of accurate quantitative values to serve as input for surface energy balance equations is fundamental to the study of physical processes at the surface over large areas. Soil moisture studies, foliage density determinations, low level climatology, and vegetation, evapotranspiration, and aerodynamic resistance studies, as performed using remote sensing data, all require information about surface energy balance. To rapidly assess regions that are large in areal extent or logistically difficult to access, or to conduct studies which require high repeat frequency of data gathering, researchers have turned to satellite information as an economic and expedient solution (Lucchitta et al., 1986).

Reginato (1987) provides a brief overview of the use of remotely-sensed data to monitor surface energy balance and evapotranspiration and to calculate aerodynamic resistance over a vegetated surface; Moran et al. (1989) and Pollock and Kanemasu (1979) have conducted similar studies. Gurney and Hall (1983) and Hall (1991) conducted investigations into the use of satellite data for detailed surface energy balance studies. Hope (1988) also conducted a study designed to determine the aerodynamic resistance of a vegetated surface from satellite data. Bartlett et al. (1990) describe a study that utilized spectral vegetation indices, single numbers that represent combinations of several spectral bands, to determine net carbon dioxide exchange. It is hoped such information can contribute to the important problem of monitoring the global carbon cycle.

Other studies involve consideration of physical processes at the surface that could be monitored by satellite data on a global scale. This involves monitoring the state of vegetation (e.g., Brown et al., 1990; Franklin, 1989), or other parameters, such as those linked with the cryosphere or other aspects of Arctic biota (Ryerson and Cihlar, 1990). In this respect, investigations of remote sensing applications in the High Arctic are of great relevance: it is the region where effects (warming) associated with increasing carbon dioxide scenarios are hypothesized to be of the greatest magnitude, and where they will thus be discernible first. Similarly, small alpine glaciers or icecaps could provide another monitoring opportunity (Franklin and Peddle, 1975).

Investigation of surficial materials and permafrost is another major avenue of research. Studies in this area that incorporate satellite data seek to generate maps over large areas, to reduce the time and expense associated with traditional approaches. Again, the usefulness of satellite data is readily apparent, given the extreme remoteness of most High Arctic regions. Other studies have applied satellite data to the identification of selected geological deposits (e.g., Abrams et al., 1977; Hunt and Ashley, 1979), a more general delineation of surficial materials (e.g., George and Dusseault, 1987; Hornsby, 1987), the mapping and study of permafrost (e.g., Morrissey, 1983; Gurney et al., 1983) and Arctic cover types in general (Franklin and Peddle, 1989; Gaydos and Witmer, 1983; Petzold and Rencz, 1975).

Note that, in some cases, the research did not attempt to rely solely on satellite data. Two main approaches exist: 1) Establishing an empirical (or theoretical) relationship between the parameters of interest

and satellite data, subsequently inputting satellite data into the expression and 2) using satellite data in conjunction with strategically placed ground control points and interpolation to fill in the gaps.

3 METHODS

In order to fulfil the objectives outlined in section 1.3, the author spent three weeks, July 20 to August 10, 1990, on Ellesmere Island collecting reflectivity data at the ground surface. The main instrument utilized was a portable step-wheel filter radiometer. Other instrumentation included a pair of solarimeters set up to measure albedo.

Surfaces investigated included terrain types that are widespread in the region, as determined from aircraft overflights, in addition to terrain types that are relatively distinctive. A satellite sensor will most readily record features that are widespread in areal extent or, if very small, spectrally distinct from neighbouring areas.

3.1 Sites

3.1.1 Selection

Site selection was based on two criteria. First was ease of positive identification on satellite imagery. As mentioned, this involved the selection of sites (see Figures 7 and 8) that were either typical of large areas or that were small but very distinct.

The second criterion was proximity and relevance to other studies already in place. For example, six sites at the Hot Weather Creek location have been instrumented for complete hydrological monitoring. These include four slopes of different aspect (north, south, east and west), as well as a plateau and a valley site. There are several additional sites where rain gauges or wind and radiation monitoring devices are set up, including three in the valley of Heather Creek and one in the valley of Hot Weather Creek. Where convenient, radiometer sites were established alongside these experiments.

Figure 7: Map of the immediate vicinity around the base camp, indicating the positions of the major locational subsets. Not appearing on the map is site I1, located approximately 3 km to the northwest beside Heather Creek, and sites K1, K2 and K3, which are located approximately 20 km to the north beside Hot Weather Creek.

Hot Weather Creek: site locations

Figure 8: Larger scale map of the same vicinity, showing greater detail of the creek and other drainage features near the most frequently visited sites.

A third criterion involved selecting sites that would be used to provide the reflectance characteristics for a larger area by combining the individual reflectances. The reason for this is that some important (i.e., widespread) landscape features, most notably hillsides, are composed of several surface types that are each smaller than a 30m x 30m pixel. This means that there is no single characteristic reflectance for a 'hillside', but rather it is a composite of several surface types.

3.1.2 Site organization

The measurement sites were organized into three groups: 1) A main set consisting of sites on which visual and statistical (i.e., factor and cluster) analyses were conducted; 2) a set of seven 'typical' surfaces which were used as test sites for the classification scheme developed from the main set; and 3) a single site beside the automatic weather station (AWS) to investigate the effects of sky condition and time of day on spectral reflectance.

The main set of sites was broken into 11 subsets, the defining criterion being location. For example, one locational attribute was slope aspect. This was called a location subset and was, in turn, broken down into individual sites; the number of individual sites within any location subset varying between one and five. Many sites were visited several times, resulting in an overall total of 65 spectral reflectance curves for the main set. This set was used for the statistical analyses; a factor analysis was performed in an effort to determine sources of variation in the reflectance data and a cluster analysis was used to generate a classification scheme.

A further seven sites comprised the second group of 'typical' sites.

These sites were chosen only on the basis of their expected visibility from orbit and thus satisfied the appearance requirements outlined in Section 3.1.1. Reflectance curves for these sites were not incorporated into the statistical analyses but served instead as test sites for the classification scheme derived from the cluster analysis results.

The third set of readings was a group of 27 reflectance curves gathered at a single site for different times and sky conditions to ascertain their influence on reflectance.

Location subsets

The sites comprising each location subset were chosen to satisfy two further requirements of the study: 1) The collection of data from diverse cover types to meet the needs of a basic reflectance study and 2) the collection of data from appropriate sites that are of sub-pixel resolution but that are part of a larger, distinctive feature, as mentioned in the "main sites" paragraph above. Site characteristics and positional details are presented in Appendix B.

3.2 Radiometer measurement

3.2.1 Instrumentation

A York University tripod mounted step-wheel filter radiometer (Figure 9), acquired on loan through Professor J.R. Miller, was used to measure the incoming and outgoing radiative fluxes at each site. The radiometer has two sensors, silicon and germanium photodiodes, either one of which may be fitted into a socket on the front of the device. The ranges of sensitivity of the sensors are:

Silicon (Si) : 400 to 1050 nm
Germanium (Ge): 1100 to 1800 nm

**York/CRESS
Step-wheel Filter
Spectral Radiometer**

Figure 9: The spectral radiometer used for this study.

The radiometer provides readings in units of power and there are several sensitivity settings to cover a variety of ranges.

The filter wheel houses ten filters, any one of which can be selected by rotating a handle. For any given reading, the sensor gathers radiation over a 5 degree solid angle (i.e., a cone) extending around the optical path axis of the instrument. The radiation travels through an aperture approximately 1 cm in diameter and through the selected filter. The remaining radiation continues up a black tube 10cm in length until it contacts the surface of the photodiode sensor on the front end of the radiometer. The filter wheel housing is constructed of aluminum and anodized matt-black to absorb stray radiation.

The filters available on the filter wheel are indicated in Table 2. The filter wavebands correspond approximately to five of the seven spectral bands employed in the Thematic Mapper multispectral scanner (Figure AP49 in Appendix A). This scanner system is currently carried by the Landsat-4 and -5 satellites, and is planned for use on the Landsat-6 satellite to be launched in the spring of 1992. The wavebands of the filters therefore allow ready comparison of radiometer generated data to satellite imagery. In addition, it is possible to generate reflectivity coefficients for each of the wavebands represented by the filters (Section 2.2.2).

The multiplication of each reading by the appropriate conversion factor allows the instrument readings to be converted into units of radiative flux ($\text{Wm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ - see Appendix C, page AP-C 106 for an explanation). The conversion values are not necessarily the same for each

Table 2: Spectral radiometer filters

Filter	Centre (nm)	Width (nm)	Conversion factor (units $nW_{elec}/W_{rad} m^{-2} sr^{-1} \mu m^{-1}$)
4	442.0	9.75	3.55
5	525.0	8.19	5.64
6	550.0	10.0	6.56
7	598.8	8.19	3.50
8	682.0	3.0	2.22
9	733.0	3.0	2.22
10	799.8	9.75	4.76
1	1250.0	10.0	4.92
2	1450.0	10.0	6.00
3	1650.0	100.0	91.13

where: W_{elec} is a unit of electrical power

W_{rad} is a unit of radiative power

filter (see Table 2) because: A) The response of the photodiodes is not uniform over their range of sensitivity; and B) the filters differ in their spectral bandwidth and wavelength of peak transmittance.

3.2.2 Field Operation

For all sites the instrument set-up was as follows. The instrument was positioned to avoid excessive interference from the tripod legs. This meant pointing the instrument at a slight angle to normal (i.e., the vertical position at right angles to the surface) and directing its line of sight to a point located between the tripod legs. Care was taken to ensure the target area was not affected by shadow that was not of natural origin, i.e., tripod or operator legs. The instrument look angle of approximately four degrees from normal to a horizontal surface was adopted for practical considerations of instrument operation, although it was as close to normal as possible, to fall within the typical range of satellite look angles. The look angle was consistent over all surfaces, including slopes (e.g., Rao et al., 1979).

The instrument aperture was located approximately 1.5m above the ground which, given a viewing cone of 5 degrees, provided approximately 140cm^2 of surface area coverage. This area was large enough to provide a representation of the surface features present for any terrain type: the majority of micro-scale features, such as clusters of plants or small topographical or frost features, were small enough to be represented within an area of this size. At 1.5m the instrument was judged high enough to prevent interference by blockage of incident shortwave radiation (direct and diffuse): at this height, the instrument bulk physically blocks approximately 0.6% of the area available to incoming diffuse

radiation. As well, a height of 1.5m above the ground allowed convenient operation of the device.

3.2.3 Measurement procedure

The procedure for obtaining measurements was as follows. The device was set up at the location of interest, and parameters including time, sky conditions and relative luminosity of the sun (termed "solar visibility"), slope angle and aspect were recorded. As well, a general description was made of the larger feature(s) within which the site was encompassed, e.g., a valley or hillside, and how the sites within each location subset were positioned. For most sites, the vegetation was described and for every site a close-up photograph was taken of the exact area (140 cm²) of measurement, to verify the results of the analyses.

The filter wheel was positioned at filter 4, the first in the range of the silicon photodiode sensitivity bandwidth (Table 2). A measurement of shortwave radiation incident at the site was obtained using a white cotton sheet fastened to a board, 0.4 m on a side. Such a surface acts as a near-perfect Lambertian reflector - one that reflects equally in all directions - and is not subject to increased reflectance when angles of direct solar reflectance are approached (Miller, personal communication; Manual of Remote Sensing, p. 48). The sensor thus recorded a value for both direct and general atmospheric diffuse incoming shortwave radiation, the two constituents of total downwelling shortwave radiation. The reflectance standard was held just far enough away from the instrument aperture to allow its cone of sensitivity to fall completely on the standard without allowing radiation reflected from the ground surface to enter.

Following that, a reading of surface reflectance was immediately obtained for the selected filter. This process of measurement for up- and downwelling radiation was repeated for each filter up to and including filter 10. At that point, the silicon photodiode was exchanged for the germanium photodiode and a further three measurements were taken using filters 1 to 3.

A set of measurements at any given site therefore consisted of ten pairs of data, each pair consisting of a reading of radiation reflected from the surface and the total shortwave radiation incident on the surface. The two readings were taken less than one minute apart and an entire set of ten pairs for a site could be completed in under ten minutes. In this way, any effects of changing sky conditions were kept to a minimum.

The microwatt setting that resolved to one decimal place was the sensitivity range selected on the radiometer. The nearest lower setting range was found to be too low: it would saturate at higher readings and it generated noise at very low readings. The level of instrument background noise was determined by securely screwing the black aperture cover in place and noting the display. Almost all readings recorded were easily distinguished from the noise signal; however some readings taken with filter 2 were too low to be confidently distinguished from noise and were, therefore, discarded. Miller and Burger (1986) encountered a similar problem, that of very low radiation intensities at low solar angles.

3.3 Other Instrumentation

Two solarimeters were set up to measure albedo (Section 2.2.2). Values were recorded once every hour, based on an average of readings

taken every minute, and incident shortwave radiation was recorded every minute. The albedo solarimeters recorded continuously during the last two weeks of spectral radiometer measurements. As well, throughout the entire period, general meteorological observations were recorded, at the very least at 12 UCT and 00 UCT and, for the first four weeks, at three-hour intervals.

3.4 Satellite data corrections

Retrieval of information from satellite sensors about the surface of the earth is not a straightforward process. Details concerning the operation of the satellite platform and sensors and the atmospheric medium through which the radiation streams must pass should be thoroughly considered to determine how the resultant data might be detrimentally modified (Henderson-Sellers and Hughes, 1984; and Robinove, 1982). Although not performed for this project due to an unavailability of satellite imagery, the methodology is included here for information and reference. Use of satellite imagery requires that the ideas presented in the following section be borne in mind; there are considerations that should be taken into account during the planning stages of a project.

Proper processing of satellite data involves two main steps: 1) Conversion of satellite digital data values to absolute radiative flux readings, and 2) systematic removal of atmospheric attenuation effects on the radiative flux.

In many cases, when the target feature is very different from neighbouring features or when the temporal changes of interest are manifested in a very apparent way (e.g., the urbanization of farmland), comparison of pixel digital numbers may be sufficient. This represents,

in essence, a visual comparison and evaluation, much like an aerial photo interpretation approach. For subtle change detection, however, such as crop maturity monitoring during a single season or year-to-year changes in soil moisture, the following procedures and considerations should be followed.

3.4.1 Geometric and positional errors

Satellite systems, despite their great height above the surface, do not render a geometrically correct reproduction of a large region. This is a byproduct of several factors.

The satellite cannot be simultaneously directly over every point on the image; the angle of viewing, therefore, changes from one side of an image to the other. To use the Landsat system as an example, the satellite scanner has a sweep of approximately 7.5 degrees on either side of its nadir, or overhead point (Landsat-4 users handbook). Atmospheric refraction, which increases as the angle off of the nadir viewing point increases (i.e., out towards either side of the image), will cause distortion, as will the curvature of the earth under the 185km wide scanner sweep.

Other distortions result from various motions and orbital changes associated with the satellite platform and sensors. The satellite is moving very rapidly relative to the ground. The sweep of the scanner has its own motion, as well as overlap and underlap of the scan lines and jitter caused by the rapid motion of the scan mirror (Seto et al., 1991). The earth is rotating underneath the satellite as it is imaging. The altitude of the satellite can vary from pass to pass. Each of these should be accounted for in some way and corrected.

Geometric correction of an image must, therefore, be performed; the final geometric accuracy required depends on the anticipated use of the data. For most purposes, correction of the largest errors is sufficient; although if the imagery is to be put to cartographic use, it must be corrected to a greater degree of accuracy.

There are two main methodologies which can be followed to perform geometric correction: theoretical correction and empirical correction. Theoretical correction attempts to measure and quantify, before an image is produced, as many of the potential sources of error as possible (e.g., Seto et al., 1991). Formulae describing the anticipated distortions are then produced which may be applied to correct the image geometry. Empirical correction utilizes the image returned from the unaltered computer tapes (the basic information generated by the satellite) and overlays it with a cartographic standard, such as a digital topographic map base. Known reference points, spaced evenly over the image, are compared with the standard and modifications to the image are made as necessary. The two methods are usually employed together to produce cartographic quality images. Note that some correction for distortion does take place on board the satellite before the image data are sent back to earth, for example, the distortion caused by the motion of the scan mirror (Landsat-4 Data Users Handbook, 1984; Cracknell, 1991).

3.4.2 Conversion to upwelling irradiance

Upon contacting the sensor on board a satellite, the photon(s) are converted to an electrical signal, amplified, compared against a standard and recorded as a discrete digital value lying within the range of the satellite sensor, somewhere between saturation and sensor instrumental

background noise. The gradation of shade on the sensor is not infinitely subtle, thus some intensity accuracy is sacrificed when the recorded value is assigned the appropriate shade level or gray tone (Landsat-4 Data Users Handbook, 1984).

An image may be produced using the digital values provided by the satellite without correction or conversion. This is accomplished by assigning one of three colours available on a colour display monitor (i.e., red, green or blue) to any three of the possible spectral bands represented by a sensor (e.g., seven bands available on Landsat 5). The digital numbers in each selected band are converted to colour shade intensities. Thus each pixel on the image or, in this case, each dot on the colour monitor will contain a mixture of red, green and blue light of various intensities which produces a single colour for each pixel (or dot). This results in a combination of the information from several spectral bands which is termed a "colour composite image". It is thus apparent that a qualitative assessment of the surface represented on an image can be made after learning what the different colours on the image mean in terms of surface features. Many projects have proceeded from this point, generating images utilizing various band combinations and performing statistical manipulations on the raw digital values to isolate features or characteristics of interest (e.g., Franklin, 1989). Further, some projects conduct direct comparisons between images gathered at different times and even by different spacecraft.

Proceeding in this manner may yield misleading results if certain problems inherent in satellite data are not addressed. The assumption that sky conditions are uniform across an image may or may not be valid

(e.g., Irons and Irish, 1988; Pollock and Kanemasu, 1979). Early NASA work in fact demonstrated that this is not always valid (personal communication, Eric Moore; Hall, et al., 1991). This assumption, applied to images of the same area at different times, different areas at roughly the same time, or different areas at different times, is even more questionable (Gaydos and Witmer, 1983; Chavez, 1989). Comparison of images between satellites, without conversion to absolute radiance units, is of no value because sensor systems on different satellites are calibrated differently, meaning identical radiant flux intensities will not result in identical digital values. Therefore, it is important to consider sources of error when generating quantitative values from satellite data. Cess et al. (1981) have even suggested that results generated by physical process models that utilize satellite data as input may be dependent upon the satellite system from which the data set came. While the result stated by them was within the context of a specific application, the general relevance is evident.

It is apparent that in order to properly utilize these data they must at least be converted into units of absolute radiance via the conversion factors provided in the operating manuals. Note that while calibration is performed before launch, it is also automatically performed internally after launch (Landsat-4 Data Users Handbook, 1984) and that the pre-launch values may become unreliable as the operational life of the satellite wears on (Chavez, 1989; Teillet et al., 1988).

Conversion to absolute units of irradiance or, by using a related technique, to reflectance permits the comparison of data gathered at different times and places by various satellites (Robinove, 1982; Chavez,

1989).

Conversion procedure

The conversion of satellite digital number data to units of radiance ($\text{mW cm}^{-2} \text{ sr}^{-1}$) is a straightforward process involving use of the calibration constants for the particular sensor on board the satellite. The sensors are calibrated for saturation intensity and minimum activation intensity (essentially the level of instrument background noise). The continuum between these extreme values is quantized into discrete grey levels (256 in the case of the thematic mapper sensor). The conversion equation is as follows:

$$\text{Radiance} = D_n/D_{\max} (L_{\max} - L_{\min}) + L_{\min},$$

where D_n is the digital number, $D_{\max}$ is the maximum number of digital levels for that particular sensor, $L_{\max}$ is the maximum saturation intensity constant and $L_{\min}$ is the minimum saturation intensity constant, with the units for intensity being radiance (Robinove, 1982).

A similar procedure is followed to obtain a value for percent surface reflectance. It utilizes the radiance incident at the top of the atmosphere, plus appropriate modifiers to account for differences in solar elevation and for the fact that the propagation of radiation from the surface occurs over a hemisphere:

$$\text{Reflectance} = \pi/S_0 \sin(\beta) (\text{Radiance})$$

where E is the radiance incident at the top of the atmosphere and β is the solar zenith angle (Duguay and LeDrew, 1991; Robinove, 1982).

3.4.3 Correcting for atmospheric conditions

Conversion to radiance is only a first step. Analysis of satellite imagery is not complete until atmospheric effects are removed so that the

signal is representative only of the surface (Section 2.2.1). Therefore, the atmospheric modification must be modelled in some way to separate it from the surface reflectance signal (e.g., Rao, et al., 1979; Hall et al., 1991). Electromagnetic radiation passing through the atmosphere may be scattered or absorbed by the particulate and molecular constituents of the atmosphere. The main source of radiant beam attenuation is scattering, which accounts for the reduction of the direct incident beam intensity of approximately 20% (the scattered radiation is still incident on the surface as diffuse radiation) (Moustafa et al, 1983; Barry and Chorley, 1982).

The difficulties posed by atmospheric effects can be somewhat mitigated by statistical manipulations of the digital values provided by the satellite (Curran, 1985). However, it is more desirable to remove the atmospheric effects. A problem associated with the removal of atmospheric effects is the requirement for additional, somewhat specialized, information about atmospheric conditions, i.e., moisture content, particulate content and ozone concentration (Irons et al., 1991) (although there can be exceptions, e.g., Philpot, 1991). Lack of such information is the reason this step tends to be omitted. Necessary equipment includes such devices as a solar photometer (or pyrheliometer), to determine the aerosol content of the atmosphere, wet and dry bulb temperatures, to determine roughly the water vapour content (Deering, 1989) or radiosonde ascents, to provide profiles of temperature and water vapour content with height (Reginato, 1987). There are satellite systems now in the design phase which will be capable of gathering information necessary to reconstruct the state of the atmosphere at the time of

imaging (Ardanuy et al., 1991). Substitution of an arbitrary 'standard' atmosphere into a model can be made, but in fact statistical analyses of the satellite digital values (e.g., Lucchitta et al., 1986; Musik and Pelletier, 1986; Pollock and Kanemasu, 1979) are perhaps suitable for most applications, given the general lack of the necessary atmospheric data.

Removal of the atmospheric component of the signal entails, as mentioned, the gathering of information about certain conditions of the atmosphere (i.e., related to opacity) at the time of imaging by the satellite. The optical thickness of the atmosphere (τ) is the most important parameter. When this is known, a function, such as the Lambert-Bouguer law of transmission (Chahine, 1983, p.175), or the methodology detailed by Turner and Spencer (1972; after Rao et al., 1979) may be employed to determine the effect of atmospheric scattering and absorption on the incident beam (Moustafa et al., 1983).

The overall value for atmospheric optical thickness is determined by adding together the values for the constituents. These include separate values for ozone (τ_{O_3}), water vapour (τ_{H_2O}), particulate matter (τ_A), and the other gaseous components (τ_G) of the atmosphere. Each of these components affects certain wavelengths and all increase with the distance radiation must travel through the atmospheric layers (i.e., this increases at low solar angles - Irons et al., 1991), thus, the optical thickness is the sum of these components expressed as a function of radiation wavelength and distance through the atmosphere:

$$\tau(\lambda, z) = \tau_G + \tau_{O_3} + \tau_{H_2O} + \tau_A$$

The value for optical thickness is input as an "extinction coefficient" into the following expression that defines the amount of energy

transmitted (T) through the atmosphere:

$$T = \exp [-\tau]$$

Thus, working backwards, a value for the actual energy reflected from the surface may be generated.

3.5 Procedure for generation of satellite emulation data

This procedure is included to determine roughly how selected surfaces in the vicinity of Hot Weather Creek would look had they been imaged by the Thematic Mapper sensor on board the Landsat satellite (see Appendix C for mathematical details). Specifically, this emulation was performed to satisfy three objectives: 1) To determine the digital value that would be recorded by Landsat for a given cover type; and 2) to examine how readily changes in the surface condition would be manifested in the satellite data. Note that while Landsat was selected for this example, there are several potential systems from which to choose; a choice would be made after a thorough assessment of project requirements (Milazzo, 1984).

This process involves calculating the quantity of radiation reflected from the ground over the area measured by the radiometer and multiplying that by a suitable factor to arrive at the equivalent reflectance for an area the size of an entire pixel (i.e., 30m x 30m). After that, atmospheric attenuation is accounted for and the radiation stream modified accordingly (see Appendix C), to arrive at the signal strength upon contact with the sensor on board the satellite. (Landsat-4 will be the assumed platform.)

The final step converts the energy incident upon the sensor into the digital value that would be recorded.

4 RESULTS

4.1 General patterns

The data generated by the radiometer were plotted in the form of spectral reflectance curves: directional reflectance value against filter wavelength.

Almost all of the spectral reflectance curves displayed increasing reflectance with increasing wavelength, i.e., reflectances were low in the blue and increased towards the red/near-infrared end of the spectrum. This general reflectance pattern is typical of most natural surfaces. The first vector score in the factor analysis (see Appendix D), which accounted for 45% of the variance, indicated high correlations of filter reflectances with each other, confirming the presence of a strong basic pattern. A reflectance curve generated by averaging the filter reflectances of the entire data set exemplifies the trend (Figure 10).

Around this general trend, the observations can be separated into two dominant curve patterns (Figures 11 and 12), which will be called group A and group B. Group A curves have reflectance values which are very low in blue, increase in green, are steady or decrease slightly in red and show a strong increase into near infrared. Group B curves generally start with higher reflectance values in the blue and increase at a more-or-less steady rate to reach high values in the near-infrared, though frequently not as high as group A. Group A curves are those typically recorded from vegetated surfaces, group B curves from bare soil or rock surfaces.

Essentially, any natural land surface on the earth that is not snow or ice covered either consists of bare soil or rock, or has some

Figure 10: A curve generated by plotting the averages of all the data.

Figure 11: Group A curves. These curves are typical of the pattern produced by vegetation.

Figure 12: Group B curves. These curves are indicative of bare or almost bare soil or rock surfaces.

quantity of vegetation present. This defines the continuum: group A curves at one end represent fully vegetated surfaces and group B curves at the other end represent bare surfaces.

The second vector score in the factor analysis indicated the presence of two major groupings based on pattern, the result of the influence of site conditions on the reflectance curve. The vector score showed a high correlation between the presence of vegetation and reflectance magnitude in the near-infrared wavelengths, indicating that the presence of vegetation was regularly associated with strong reflectances in these wavelengths. As well, the fact that this is the second vector score meant the correlation of vegetation with wavelength did not account for all of the variance. This was due to the fact that few of the surfaces surveyed possessed significant vegetative cover. This has a further implication. The fact that the general trend discussed earlier (increasing reflectance with wavelength) is similar in pattern to group B curves is not coincidence, but instead indicates the dominant incidence of sites low in vegetative cover.

There existed large variations within these two main groups which were caused by the influence of several other variables acting alone or in combination. Individual spectral reflectance curves may assume almost any shape on a continuum that lies between extremes defined by Group A and Group B curves (Figures 1 and 2). As mentioned, the most influential variable - the one which in fact determined the fundamental shape of the reflectance curve - was site condition. 'Site condition' describes both the basic appearance of the surface (e.g., amount and type of vegetation) and temporary influences which may act to change the

surface (e.g., moisture content).

Further grouping of the curve patterns was carried out using cluster analysis. This indicated five major groups into which the majority of the curves could be placed (Figure 13). Of the five clusters identified, two were characteristic of a bare soil reflectance signal, while the other three contained a vegetation signal to varying degrees.

1) The first group contained seven curves with high reflectance coefficients dominated by strong bare soil signal patterns. These sites were of low percent vegetation cover and the reflectance data were gathered under diffuse illumination conditions.

2) The second group, which included 22 curves gathered under diffuse illumination conditions, was typical of bare soil, with a few irregular curve types mixed in. The irregular curves were either byproducts of changes in illumination conditions while the radiometer readings were being taken or they were curves which possessed anomalous reflectance value spikes in certain filters. Either way, this problem usually resulted in curves that did not exhibit a pattern characteristic of either bare soil or vegetation.

3) The third group, 15 curves, contained sites that exhibited a relatively weak vegetation signal; the curves generally exhibited lower reflectance coefficients than those in group 2). These curves included a mixture of sites with low to medium percent vegetation cover, recorded under various conditions of illumination.

4) The fourth group, consisting of seven curves, contained sites that exhibited a very strong vegetation signal with a relatively high reflectance coefficient. They are representative of moderately

Figure 13: Cluster analysis results.

vegetated sites (i.e., 30-60% vegetation cover) in strong direct illumination or well vegetated sites (i.e., >70% cover) in diffuse illumination. The reflectance curve from one particular site, F1, had a vegetative cover of only 10%; however, the data were gathered at 2130hrs and most likely exhibits low solar angle enhancement of vegetative cover (Section 4.2).

5) The fifth group of 14 curves, contained sites that exhibited a vegetation signal of relatively weak strength and low reflectance coefficient. Most of the sites in this group were well vegetated; several sites were covered largely with dark red vegetation. These sites were imaged under diffuse illumination conditions.

The cluster analysis identified cover type and illumination conditions as the main defining characteristics of the spectral curve groups. The pattern of strong lighting accentuating the vegetation signature on a site with low percent vegetation cover, noted in the visual analysis, was again revealed. Siegal and Goetz (1977) also noted this effect, and reported that as little as ten percent vegetation cover was enough to alter the reflectance curve of the underlying soil beyond recognition. This effect was most pronounced for conditions of low solar angle (i.e., solar altitude $< 15^\circ$).

The five groups essentially describe a progression of surface conditions from bare soil or rock to a fully vegetated surface, given uniformity of all other influencing factors. There were several location subsets that possessed curve sets which approximated this progression, and which were recorded under essentially uniform sky conditions (Figures 14-16). These curve sets were adopted as rough

Figure 14: Location series A: Coal Lake

Figure 15: Location series E: north-facing slope

Figure 16: Location series J: slope across the valley from camp

Figures 14-16: Three sets of curves recorded at locational subsets which each had a series of sites with progressively decreasing vegetative cover.

standards for cover types in the region against which other curves from similarly covered surfaces were compared. This assumed that surfaces with similar percent vegetative cover would generate similar reflectance curves. Causes for any major deviations of a curve from a standard were attributed to influencing factors other than percent vegetation cover, which were then searched for. This was useful to help identify the sources of variation that modified the pattern and/or magnitude of the spectral reflectance curves.

A secondary aspect of site condition is the action of temporary influences, such as an increase in soil moisture content due to rain. Effects of temporary modifications to surface condition were not investigated due to the lack of adequate opportunity, and will not be discussed further. Despite this, it is important to mention the influence of soil moisture content differences, because of its impact on the Fosheim Peninsula. As work by Pollard (1991) and Edlund (1989) shows, this region can be subject to significant recharge of surface soil moisture in the late summer as a result of the melting of massive ice bodies within the ground. Reference to Figure 4 shows how increased moisture content results in a decrease in reflectance coefficient.

4.2 Detailed results

The two basic curve patterns indicated above, i.e., vegetated and bare surface, exhibited considerable variation. Analysis revealed that the main source of variability was changes to the nature of the radiation incident on the surface, itself a function of sky condition (which concerns the proportion of its energy that falls directly, as opposed to diffusely, on the surface), solar azimuth and solar angle.

The influence of these variables was superimposed onto the basic form of a curve, as generated by the site condition, and caused changes in one, or both, of two ways: alteration to the magnitude of the reflectance coefficient, or the pattern (shape) of the curve. Often it was difficult to identify confidently the contribution of any one factor. Because of this, they will be treated together in the discussion concerning reflectance curve variability.

Modifications to curve pattern occurred when the reflectance of some feature of the surface was either masked or highlighted. Solar visibility, the intensity of the direct component of the incident radiation, was found to modify the reflectance pattern at sites possessing low to moderate vegetation covers (10 - 65%). In many cases, unobscured incident radiation (i.e., sun in clear sky or behind thin cloud) would mask the reflectance signal of the bare soil background, artificially enhancing the vegetation signal. This did not occur on well vegetated sites (>70% vegetation cover) (Figures 17-20). It is suggested that bare soil or rock surfaces tend to act as specular reflectors under low angles of direct incident radiation, resulting in the radiation reflected off those surfaces being directed away from the instrument (Section 2.3.2) (Kriebel, 1979). This means that the instrument only records the radiation reflected off the diffuse reflector, the vegetation, thus enhancing its signal. This would also explain the absence of the phenomenon both on well vegetated sites, where there is little bare ground to act as a specular reflector, as well as under conditions of diffuse light, as illustrated in Figure 21. Generally, diffuse radiation possesses little directional bias although

Figure 17: Site B1, 40% vegetation covered

Figure 18: Site F1, 10% vegetation covered

Figure 19: Site E4, 90% vegetation covered

Figure 20: Site D2, 80% vegetation covered

Figures 17-20: Contrasts of reflectance pattern between partially and fully vegetated sites under different illumination.

Figure 21: Contrast of high and low angles of incident solar radiation under clear and cloudy skies upon a moderately vegetated surface.

it is suggested that there was some directionality bias under very low solar angles (Figure 21).

Vegetation pattern enhancement did not occur when the solar angle was greater than about 26° . In this case, direct solar radiation tended not to alter the curve pattern but instead acted to decrease reflectance coefficients. This was most likely due to partial specular reflectance. Taking the example of a surface with low percent vegetative cover, at higher solar angles the proportion of incident radiation reflected away from the sensor was smaller than at low solar angles. The reflectance curve pattern remained indicative of bare soil, however, some specular reflectance would occur, reducing the reflectance coefficients (Figures 22-23). This resulted in surfaces generating greater reflectance coefficients under weak (i.e., diffuse) illumination conditions than under direct radiation, as Figure 24 indicates.

While enhanced vegetation patterns were noted on moderately vegetated surfaces under conditions of a brightly visible sun at almost all solar angles and azimuth, it was found to occur most frequently under low solar angles, most particularly, in the early morning or evening (Figure 25). This effect was also frequently noted under cloudy conditions during early morning or evening (Figures 26 and 27). In these cases, despite the high proportion of diffuse radiation, it appeared that there was still a directional bias due to the low solar angle.

Slope angle and aspect act to modify the effective solar angle and azimuth, thus the effects may be related back to those indicated for solar angle and azimuth.

70

Figure 22: Site H1 (20% vegetated). Both data sets were gathered under direct solar radiation.

Figure 23: Site I1 (20% vegetated). Both data sets were gathered under direct solar radiation.

Figures 22-23: Effects of solar angle greater than approximately 25 degrees.

Figure 24: Sites G1 (west) and G2 (east) (30% and 10% vegetated, respectively). 'OBS' means the sun was obscured; 'BV' means the sun was brightly visible. This plot shows the differences that were noted under clear and obscured solar conditions.

Figure 25: Low solar angle enhancement of vegetation pattern on moderately vegetated surface.

Figure 26: Site E1 under cloudy skies

Figure 27: Site E2 under cloudy skies

These figures show the effect of low solar angle on vegetation pattern at different sites under cloudy skies.

Differences in reflectance coefficient were the other way the spectral reflectance curves varied. This was frequently the result of changes to solar azimuth, which acts in combination with one or more characteristics of a site to produce modification to reflectance coefficients. The geometry of the vegetation canopy is one of these characteristics. As the sun moves around the horizon, the reflectance from individual leaves is alternately enhanced and suppressed, modifying the reflectance curve if enough leaves are affected together. Another site characteristic is microtopography, which can modify the reflectance coefficient because of the shadows cast by small relief features. The pattern of shading will change with solar azimuth, its magnitude increasing with decreasing solar angle.

The effects of solar azimuth variation acting on site vegetation canopy orientation and microtopography would be expected to consist of small changes to the reflectance coefficient of the basic pattern of a site, that is, via alterations in the pattern of shading on the site surface (Paltridge and Mitchell, 1990; Kriebel, 1979; Rao et al., 1979). However, it can be seen how the pattern of the curve could be altered if, for example, a site that is 50% vegetated had shadow fall across the vegetation - leaving only the signal from the bare soil area to be recorded on the radiometer (Irons et al., 1988). Work by Musick and Pelletier (1986) suggested that variation in solar angle did cause changes to reflectance curve pattern, via interaction with surface roughness. Such is suggested for the evening observations at site B1 (Figure 28).

Figure 28: Reflectances recorded at site B1 under clear skies. Note the different periods of suppressed and enhanced vegetation pattern, possibly caused by site-specific microtopographical differences.

4.3 Classification results

Classification of reflectance curves consisted of matching the curve in question to one of the existing standard curves identified by the cluster analysis (Section 4.1), these being considered the defining curves for the vicinity. The unknown curves were not incorporated into the cluster analysis, thus the classification procedure was unbiased.

The matching process compared curve shape and magnitude with the standards. A routine was devised to conduct this comparison mathematically: for each filter, the difference between the unknown curve and the standard was found. These differences were then squared and the results summed and repeated for each of the five clusters. The lowest total should indicate the best fit. This is known as a least-squares (LS) fit.

It was decided that the best course was to use the LS fit only as a guide. If another value was close to the best score, a visual examination was performed to verify the classification. Of the 16 test curves subjected to the procedure, 11 were properly classified by use of the LS scores alone; visual assistance resulted in the reclassification of three of the curves. The other two curves were not representative of their surface type, e.g., vegetation curve for a rocky surface, and they were not properly classified even with visual assistance.

It is of interest to note that an initial visual comparison, conducted without mathematical assistance, resulted in the same classification results as did the least squares approach. This seems to indicate that the curves generated by the cluster analysis were sufficiently distinct to allow for the ready visual classification of

Table III: Classification Results: The results of the least squares comparison

Site	Clus 1	Clus 2	Clus 3	Clus 4	Clus 5	Class	Uncert.	Corct?
Test 1	342	39	269	310	2350	2	none	yes
Test 2	339	783	332	35	2675	4	none	no a
Test 3	2029	3410	5241	3821	180	5	none	yes
Test 4	569	221	57	213	3188	3	none	yes
Test 5	1316	1361	238	351	4995	3	some-4	yes b
Test 6	32	620	821	286	1282	1	none	no c
Test 7	677	648	43	92	3671	3	some-4	yes d
Test 8	636	163	126	342	3192	3	some-2	yes e
Test 9	1095	1117	2822	2340	643	5	none	no f
Test 10	56	746	1030	414	1104	1	none	yes
Test 11	275	1094	1897	1076	426	1	none	yes
Test 12	332	11	388	406	2136	2	none	yes
Test 13	851	232	1347	1406	1840	2	none	yes
Test 14	1060	545	52	389	4327	3	none	yes
Test 15	4041	3858	7006	6324	1651	5	none	no f
Test 16	914	1159	2844	2208	306	5	none	no f

Notes:

- a: rocky surface with a vegetation pattern
- b: the confusion arises from low reflectance magnitudes in filters 4-8 increasing rapidly to produce a strong vegetation pattern of high reflectance magnitude in filters 9 and 10
- c: there is vegetation at this site, even though it was classified as a bare surface
- d: confusion arises because of a weak vegetation signal - it could be either class four or three
- e: confusion between a red vegetation site possessing low reflectance magnitudes and a strong vegetation pattern of high reflectance magnitudes
- f: these sites, although classified as bright bare surface, actually possessed strong vegetation signals, and were thus misclassified

unknown curves.

The results of the least squares classification are presented in Table III. Based upon a visual assessment of the mathematical classification of the test sites (using the least squares scores) sites Test 9, 15 and 16 were reclassified, each from cluster 5 to cluster 2. These sites were misclassified because of the magnitude of their reflectances: although they possessed strong vegetation patterns their high reflectance coefficients caused them to be misclassified into cluster 5.

4.4 Effects of sky condition

Sky condition effects were studied using observations drawn from the baseline site set (B1), totalling 31 spectral reflectance curves taken under various conditions of cloud cover and solar intensity.

Reflectance curves recorded under optically thin atmospheres (i.e., bright sun) at medium and high solar angles (15 to 27 degrees above the horizon - during the 'day') were very similar in pattern, varying somewhat in reflectance coefficient according to time of day (Figures 29 and 30). An average of these readings could be used as the characteristic reflectance curve for this area for use with satellite imagery, because this is typically the time during which satellite passes occur. Curves recorded under optically thin atmospheres at low solar angles (< 15 degrees - during the 'evening') (Figure 31) exhibited patterns that departed from those recorded at higher solar angles. Curves recorded between 2000 hrs and midnight possessed low reflectance values and bore little trace of a vegetation pattern, while those recorded between 0100 and 0700 were greater in magnitude, with a very

Figure 29: Reflectances recorded at site B1 under clear skies and high solar angle (around solar noon).

Figure 30: Reflectances recorded at site B1 under clear skies and moderate solar angles (morning or afternoon).

Figure 31: Reflectances recorded at site B1 under clear skies and low solar angle (throughout the evening).

strongly enhanced vegetation pattern. Interestingly, this period corresponded to the time period in which the albedo peak was recorded by the solarimeters set up nearby.

Curves recorded under conditions of low atmospheric transmissivity (i.e., obscured sun) tended to fall into two categories which were apparently related to cloud thickness. Thin cirrus and stratocumulus resulted in curves of high reflectance coefficient and strong vegetation patterns (Figure 32). Thicker and lower clouds, such as altostratus and stratus, seemed to result in a suppression of the vegetation pattern (Figure 33). It is speculated that differences in the ratio of direct to diffuse incident radiation are responsible for this variation. This ratio would be affected by both cloud type and total cloud cover (percent fraction of cloud covering the sky) (Arking, 1986). Herman (1977) has indicated the fact that different cloud types have differing optical properties.

The variation observed in the reflectance curves taken at site B1 has several sources. As mentioned, time of day affects solar azimuth and solar angle, each of which affects surface reflectance. Solar azimuth influenced the reflectance curve through changes to the geometrical interaction of the solar beam with the arrangement of the leaf canopy and microtopographical features. This change is continuous throughout the day, and is a possible contributor to differences between curves taken as little as fifteen minutes apart (e.g., Figure 29, the readings taken at 1200 and 1215 hrs). Solar angle effects consisted of changes to the geometry of the incident beam, similar to solar azimuth, and changes to the intensity of the beam as per the cosine of the solar

Figure 32: Reflectances recorded at site B1 under stratocumulus (Sc) and thin cirrus/cirrostratus (Ci/Cs) type clouds.

Figure 33: Reflectances recorded at site B1 under altostratus (As) and thick cirrus/cirrostratus (Ci/Cs) type clouds.

Differences in cloud thickness and/or type constitutes the most plausible explanation for the differences in reflectance patterns and intensities.

angle (Section 2.3.2).

There are other possible sources of variation that, although mentioned here, were not monitored. The region was dry and experienced a number of windy periods during the period of observation which were strong enough to raise dust (Edlund and Woo, 1992). A fine coating of dust on the vegetation would alter its reflectance properties, most likely acting to mask its influence. The appearance of damp patches on the surface in the vicinity of the camp was noted from the beginning of August. These were the result of the active layer reaching the upper layers of ground ice bodies. Although no such damp spot appeared at site B1 it is possible that a sufficient increase in soil moisture content occurred to modify the spectral reflectance curve of the site. Instrumental error is another possible source of variability.

4.5 Satellite data emulation

The purpose of this exercise was to determine: 1) whether or not differences between sites recorded by the radiometer would be similarly discerned in satellite data and 2) how well satellite data would be able to detect change in surface condition.

Tables IV and V present the results of an emulation of satellite data generated using the method outlined briefly in Section 3.5 and in more detail in Appendix C. The only readings utilized were those recorded when atmospheric conditions were either clear sky or very thin, high cloud. This was to emulate the conditions under which actual satellite data would be returned, i.e., not when the surface is obscured by cloud. Readings from various times of the day are included, since although the Landsat satellites pass overhead at a fixed time (about

Table IV: Satellite data emulation values: different sites This table consists of the digital numbers, as would be registered by the Thematic Mapper sensor on board the Landsat-4 satellite, based on radiometer results gathered at various sites. The column labelled "ratio" contains the ratio of Band 4 to Band 3.

Site	Band 1	Band 2	Band 3	Band 4	Time	Veg. cover	Ratio
B27241645	11	14	12	39	1645	100	3.3
E47262135	3	4	4	11	2135	90	2.8
J57281205	8	9	7	11	1205	75	1.6
B17211410	13	16	15	43	1410	40	2.9
J47281140	9	9	7	11	1140	40	1.6
G17251000	11	13	12	21	1000	30	1.8
F27241445	11	13	12	19	1445	20	1.6
H17251130	17	21	23	25	1130	20	1.1
H17301500	13	16	17	19	1500	20	1.1
I17301345	38	46	49	53	1345	20	1.1
F17241440	21	26	28	32	1440	10	1.1
G27251030	18	21	20	25	1030	10	1.3
J37281115	11	15	17	31	1115	<10	1.8
F37241515	16	19	20	21	1515	<5	1.1
E57241550	13	17	23	27	1550	0	1.2

Table V: Satellite data emulation values: different times This table consists of the digital numbers, as would be registered by the Thematic Mapper sensor on board the Landsat-4 satellite, based on radiometer results gathered for different times at site B1 (veg. cover = 40%).

Site	Band 1	Band 2	Band 3	Band 4	Time
BAS18	4	5	7	14	0400
BAS19	14	8	11	19	0630
BAS20	7	8	9	15	0825
BAS3	16	20	23	44	0850
BAS4	15	20	20	38	1045
BAS5	13	17	17	34	1110
BAS6	13	16	17	32	1135
BAS7	15	19	20	37	1200
BAS8	16	20	21	38	1215
BAS27	11	14	15	23	1245
BAS12	11	14	15	26	1250
BAS13	11	14	15	27	1345
BAS14	12	15	16	27	1530
BAS9	14	18	20	37	1540
BAS1	4	5	5	10	2000
BAS2	5	6	7	12	2020
BAS15	3	3	3	4	2145

1300 local time in the Arctic), other satellites will not necessarily be so restricted.

The generated values listed in Table IV show that differences between individual sites can be readily discerned. The column labelled "ratio" contains the ratio of Band 4 digital numbers to those of Band 3, an indicator commonly used in the remote sensing community to indicate the presence of vegetation. The larger the ratio, the greater is the relative difference between Bands 4 and 3, and thus, too, should be the percent vegetation cover. Table IV shows a strong correlation between the ratio magnitude and the amount of vegetative cover; these are plotted in Figure 34. To extend this to real satellite imagery, this correlation means that not only can the presence of vegetation be indicated, but an idea as to cover density may also be had.

Given access to satellite imagery, the procedure involved in an initial analysis would be as follows: a ground survey, similar to what has been performed for this project, would be conducted around the time of satellite overpass. The sites imaged by the radiometer would then be located on the satellite image and a curve similar to Figure 34 generated. Then, using the satellite reflectance data, which would be identical in appearance to Tables IV and V, ratios for unknown areas could then be determined. These would be located on the curve and percent vegetative covers read off. While simplistic, this provides an idea of how a rapid initial analysis would proceed. Further analysis would then be conducted to trap anomalous results. For example, using the vegetation ratios described above, site J37281115 would be misclassified as an area with approximately 40-50% vegetation cover

21 of/de 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

PIONEERS IN METHYLENE BLUE TESTING SINCE 1974

MICRO

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Figure 34: Percent vegetation cover plotted against the ratio of band 4/band 3 from the satellite emulation data.

when it actually possesses less than 10%. To get around this, a ratio of Band 2 to Band 3 could also be taken, because vegetation has a small peak in green wavelengths (Figure 6). As can be seen from Table IV, all the sites that possess 30% vegetation cover or more had values for band 2 that were at least equal to those in band 3. Any site with 30% or more vegetation cover would thus have a band 2/band 3 ratio of 1 or more. Any site that thus had both a relatively high value for its band 4/band 3 ratio and a band 2/band 3 ratio of 1 or more would be considered to possess the vegetation cover indicated by the original band 4/band 3 curve. Sites possessing a band 2/band 3 ratio of less than 1 would be considered anomalous and classed as bare, or almost bare.

For an actual project, the details of the above analysis would most likely differ. A regression analysis performed on Figure 34 results in an r^2 value of .61, .78 with the two anomalous ratio values removed. A project dedicated to this would have many more sites imaged, improving the confidence interval of the plot. However, it is apparent that the data returned by a satellite are of sufficient detail as to allow discrimination of subtle variations in surface condition and, with careful use of patterns in the data returned by both the satellite and the radiometer, potential problems may be reduced.

The subtlety of cover type discrimination means that satellite data also possesses the detail necessary to perform monitoring work. Another example is provided to illustrate. If satellite data record several regions that, based on satellite band ratio curves supported by field radiometer work, possess a vegetation cover of approximately 70-

80%. Before the time of the following year's satellite pass several wind events occur which cover most of the vegetation in these areas, effectively reducing vegetation cover to about 20%. According to Table IV, this change in surface condition would be discernible on the satellite data in several ways. The band 4/band 3 ratio would drop, the average reflectance magnitudes of bands 1, 2 and 3 would rise, and the band 2/band 3 ratio would drop below 1. These indicators together would confirm the conclusion of a significant change in surface condition, i.e., a drop in vegetation cover in this case, which could be investigated in the following field season.

Table V indicates the effect of different solar angles on the reflectance pattern of the selected surface (site B1). Figure 35, a comparison of each band at the different times of observation, reveals in detail the nature of this variable. It is apparent that the intensity changes, but that the pattern retains its essential form. This manner of modification points to those influences which affect all wavelengths of the incident beam, for example, increased shadow across the site, as opposed to something which affects a narrow wavelength band, such as exposed leaf area.

Although there is a large difference for various times, it must be remembered that the satellite is overhead at essentially the same time during any pass, thus most of the variability indicated on Figure 35 would not occur.

Thus, based on the results presented here, satellite data possess the spectral and radiometric resolution sufficient to provide a detailed discrimination of surface conditions.

Figure 35: Satellite data emulation results for site B1. It is apparent that, under clear conditions, the variable time does not modify curve pattern.

4.6 Albedo survey results

Albedo readings were gathered 1) to provide for this research location a measurement of albedo and an indication of how it varies, and 2) to serve as a check against which albedo values generated by the radiometer measurements could be compared.

Results for the standard albedo measurements are presented in figures 36 and 37. Generally, albedo was linked to the position (both altitude and azimuth) and intensity of the sun. Under clear skies, a strong diurnal pattern was evident which was absent under overcast skies (figure 36).

During the period of observation the diurnal albedo pattern could only be followed through solar elevation angles ranging from 10 to 30 degrees, the limits of solar travel at 80° north latitude. Under cloudy conditions, albedo values tended to remain somewhat constant at the lowest end of the observed range, about 0.15. The pattern of increasing albedo with decreasing solar angle was not apparent when the sun was obscured by cloud, indicating that the peaks observed in Figure 36 are associated only with direct solar radiation.

The albedo peak recorded under clear skies coincided in time with those readings at site B1 that were of the greatest magnitude. Figure 31 indicates this particular curve, occurring at 0400 local time, and the next largest two that bracket the 0400 reading (taken at 0220 and 0630 local time).

To aid in isolating the source of the peak, i.e., to determine if it was a byproduct of the instrument or an actual phenomenon of the surface, radiometer readings for the same times and sky conditions were

Figure 36: Albedo hourly values contrasting clear and cloudy conditions. These values were generated by the two solavimeters.

Figure 37: Albedo record for the entire time of operation (July 24 - August 22, 1990).

examined. The radiometer readings showed a strong increase in all filters at the time of the albedo peak. In addition, because the solarimeters are sensitive beyond 800nm (the limit of radiometer filter #10 - Table 2) to 3000nm, when available, values for filters 1,2 and 3 (1250, 1450 and 1650 nm, respectively) were examined. They were also found to be elevated. The range of sensitivity of the radiometer is 450-1650nm, which accounts for approximately 90% of the solar radiative output, as reference to Figure 4 confirms. Reference to the reflectance coefficients generated by the radiometer should therefore provide a reasonable check of the solarimeter albedo values.

Figure 38 displays the results obtained for meteorological standard albedo values derived from the radiometer directional reflectance measurements. A trend line drawn through the calculated (radiometer) albedos tend to underestimate the meteorological albedo values. Since the radiometer covered 90% of the solar output, the underestimation probably lies with the fact that the three radiometer filter bands representing the mid-infrared were not included in the albedo calculation, because of problems mentioned earlier. Their omission likely resulted in erroneously low albedo values because the reflectances recorded for these filters tended to be high.

The magnitude of underestimation was not consistent. During the day and early morning, the trend of the radiometer albedo tended to follow the standard albedo but, without representation in the longer wavelengths, the radiometer albedo consistently underestimated standard albedo. This pattern was deviated from during the early evening when the radiometer albedo was significantly lower than standard albedo. The

Figure 38: Radiometer generated albedos contrasted with standard albedo values.

fact that ^{at}_^ this time of evening low values for radiometer albedo were generated, whereas in the early morning higher values were generated is associated with the same phenomenon described in more detail later in this section.

Other researchers (e.g., Irons et al., 1988; Brest, 1987; Pinty and Tanre, 1987; Kimes and Sellers, 1985; Kriebel, 1979) have met with varying degrees of success when trying to generate meteorological albedo from radiometer measurements (both satellite and ground based). The main difficulty associated with the use of satellite data for this purpose is its restriction to a single sensor viewing angle. Although existing satellites of the Landsat series are limited to a single viewing angle, future Landsats will feature pointable sensors. Acquisition of surface data from multiple viewing angles should improve the accuracy of albedo estimates.

Explanations of the reflectance/albedo peak as an instrument artifact come readily when considering the solarimeter, but they do not hold up when applied to the radiometer for two reasons. One involves the area of sensitivity of the two instruments. The solarimeter has a hemispherical sensing area, which could allow stray specular reflection to strike the down-facing solarimeter. The narrow cone of sensitivity of the radiometer would make it less susceptible. The second involves the entrance apertures of the two instruments. The sensing surface of the solarimeter is enclosed by two hemispherical glass domes, which could possibly refract excess radiation onto the sensor. The sensing surface of the radiometer is reached through a long tube, without optical components to potentially modify the incident radiation beam.

It would thus appear that a rise in surface reflectance at low solar angle is a real phenomenon and not instrument artifact.

Given this, the matter of why the peak should occur four hours after local solar midnight, and not at the time of lowest solar angle, is not clear. Why is there not a corresponding peak four hours before solar midnight also? There is a small increase at that time, but it is not of similar magnitude. This is most likely similar to the phenomenon reported by Chapelle et al. (1979) (Section 2.3.2), which is a result of surface non-uniformity.

Early morning albedo peaks have also been recorded by Labine (1992, personal communication) at Alexandra Fiord; others have noted a similar result in the course of other studies (e.g., Irons et al., 1988, after Kimes et al., 1987 and Idso et al., 1978).

5 DISCUSSION AND RECOMMENDATIONS

This study has provided field information about the spectral reflectance of a variety of natural surfaces in the vicinity of the Fosheim Peninsula, Ellesmere Island, N.W.T. It has also revealed links between spectral reflectance, sky conditions, and time of day, including an intriguing relationship between low solar angle and surface reflectance. While some of the observed patterns had apparent explanations, there remain unanswered questions. The nature of the study, in encompassing many different sites, limited the amount of field time that could be devoted to any particular site or variable.

The reflectance curves generated for the sites surveyed were generally commensurate with what was expected for such surfaces, based on established spectral reflectance curves from the literature. For many sites, however, deviations from the expected occurred under low solar angles, a condition which is normally of little interest for studies conducted at more southerly latitudes because the times of low solar angle are of short duration. At high latitudes, however, the sun can spend large portions of the day at low angles of elevation. For example, in mid July, the solar angle varies between 27° at solar noon and 7° at solar midnight at 80° north latitude.

Investigation into the effects of low solar angle (i.e., enhancement of vegetation pattern on moderately vegetated surfaces) is an important consideration that should be pursued if remote sensing is to see widespread application in arctic research. Results of this study, as well as those of other researchers, indicate that low solar angle affects both broad spectrum reflectance, or albedo, and multiple

narrow band reflectances, or spectral reflectance. These findings are of interest to workers in the areas of remote sensing, energy balance modelling, and meso- and micro-scale climatology, all of whom work intimately with albedo and surface reflectance. As discussed in Chapter 2, the albedo of a surface determines the quantity of incident shortwave radiation absorbed, which is of fundamental importance to the energy balance of the surface. Therefore the phenomenon of increasing albedo with decreasing solar elevation is of particular interest to high arctic research. The differences noted between clear and cloudy sky albedos is also of interest. Such information input into energy balance models, surface resistance studies (Hope, 1988; Gurney et al., 1983) and global circulation model (GCM) parameterizations will refine the accuracy of their output.

Another important phenomenon, apparently similar to low angle vegetation enhancement, is that of albedo peaking during the early morning. The fact that both sensor types, each of very different design, indicated the rise suggests it to be an inherent characteristic of the surface. So too does the fact that the peak was not symmetrical about solar midnight; i.e., the reflectance rise was generally associated with low solar angles, but was not directly dependent upon a specific angle or range of angles. Measurement of such 'grazing angle' reflectance has previously been of little interest and thus has not been adequately addressed; studies dealing with reflectance measurements under low solar angle are unavailable.

Those employing remote sensing to determine surface condition details using computer analysis of the curves must be aware of the

potential for variability in surface spectral reflectances, when variation could occur, and what form it might take. The fact that reflectances from low and moderately vegetated surfaces are not equal in all directions (anisotropic) could result in error when trying to thematically classify a satellite image in terms of surface cover type. The strong tendency for surface reflectance to respond variably to solar azimuthal position (especially inclined surfaces), apparent even under uniform cloud, should be noted by workers in this field.

Plant senescence is of particular relevance in the Arctic because plants may begin to senesce before the beginning of autumn. As plants age they begin to assume the spectral characteristics of the soil background. Thus, results from satellite data classifications might be misleading, e.g., exaggeration of percent bare soil cover.

The results of the emulation (Section 4.4) showed that satellite data, recorded at a ground resolution of 30 metres square, is able to readily distinguish between surface cover types. It was also found to be sensitive to the occurrence of change, being able to discern differences in the upwelling radiance on the order of 5%. The fact that it has poorer radiometric resolution than a ground- or aircraft-based radiometer can be advantageous because slight variations recorded from reading to reading will be smoothed. This provides a clearer and more consistent reflectance pattern for sets of readings of a certain surface type, reducing the data noise that would accompany a set of readings obtained from several similar sites across a region. There is also a considerable advantage in expense per area covered.

The classification results (Section 4.5) met with guarded success,

but did show that a relatively quick classification may be conducted using the radiance values as calculated from the digital numbers returned by the satellite.

This classification methodology applies directly to spectral reflectance curves generated by satellite imagery. Designated calibration areas (i.e., regions of physiographically distinct, known surface type) are selected on the image; these form groups of distinct pattern and intensity against which unknown areas from the rest of the image may be compared and classified.

It must be noted that this can only provide a rough breakdown of surface type, and that detailed research into surface process proceeds from this point into the field. Greater spatial and radiometric accuracy of future satellite systems will provide maps of correspondingly enhanced detail.

Utility of satellite imagery to research in the High Arctic IRMA

Two important advantages offered by satellite imagery are spatial and temporal perspectives (Lucchitta et al., 1986). The capacity to rapidly gather data over a large area and to acquire similar imagery periodically make such data very useful for conducting monitoring programs and surveys of large areal extent, especially important in remote areas (Pickup and Foran, 1987). The use of such data could enable a researcher to increase the area under investigation, which might otherwise be impossible.

Of foremost potential benefit to the work at the Hot Weather Creek Integrated Research and Monitoring Area (HWC IRMA) is the monitoring aspect satellite imagery can offer - most remote sensing satellites

provide good temporal perspectives because they are able to frequently gather images of a site. The fact that the Hot Weather Creek research location was established in part to monitor physical systems in the area means that satellite imagery could be used as one source of information input for a given project. Upon the establishment of basic characteristics of the system under study, satellite data could then be used as a monitoring tool, once links between the surface condition and the appearance of the image were established (e.g., Frank, 1984). To serve the High Arctic IRMA, several images could be obtained for each season to examine the surface during times of particular interest, such as snowmelt or vegetation flowering. Changes that are apparent could then be the focus of ground investigations to determine details. The large distances and general inaccessibility of the region make utilization of such imagery appealing.

A sensor located in space possesses the spatial perspective to return information over large areas - a Landsat 5 image covers almost 40 000 square kilometres. The utility of such perspective is apparent. For example, if a hydrological monitoring program reveals some interesting phenomenon occurring on a south facing slope under investigation, satellite imagery could be examined to ascertain the extent of this occurrence, i.e., whether south facing slopes all over the region exhibit the phenomenon or whether it is relatively confined.

The small size of the plants common to the region and the limited areas formed by their communities render impossible detailed plant species identification and mapping using currently available satellite imagery (Gaydos and Witmer, 1983). However, based upon results in this

report, there is some potential for determining whether vegetation cover exists and, if so, the approximate extent (percentage) of that cover. Maps drawing on detailed knowledge of the types of locations and microclimates that various species prefer have been prepared for several regions in the Arctic (Edlund, 1986). These maps are essentially vegetation community classification schemes and, although at a scale that is too detailed for satellite resolution, a similar classification scheme could be prepared with satellite resolution in mind. This process could be applied to other topics of interest, such as surficial materials, landslides, glacial positions, or areas of early snow melt, all of which are current research interests associated with the High Arctic IRMA research effort.

The higher resolution imagery that will be available from Landsat-6, coupled with its capacity to acquire off-nadir imagery (see Appendix A), will enable large-scale detailed digital topographic databases to be created. Future satellite systems will provide even greater spatial and spectral resolution, such as the proposed 5 metre ground resolution of Landsat-7 (Furniss, 1991). Such advances, which are not confined to the Landsat series (Irons and Irish, 1988), will further refine capacities described above, generating detailed maps which will provide a solid reference from which field researchers may operate.

The small glaciers present near the camp in the Sawtooth Mountains might prove to be useful indicators of climatic changes. Satellite imagery could be used to determine the areal extent of these glaciers from year to year, again with relative logistic simplicity (Hall et al., 1991).

The albedo component of energy budgets could be determined over large areas of the Fosheim peninsula. This would be of use to arctic climatologists and hydrologists, as well as botanists, all of whom require knowledge of the energy state of the ground. Likewise, permafrost and surface stability investigations could benefit from large-scale monitoring of the energy balance of a region (Hall et al., 1991; Moran et al., 1989; Gurney et al., 1983; Morrissey, 1983).

Further study

The results of this study have identified several directions continuing research could take:

- 1) A site-specific study to further investigate and quantify the effect of solar position and sky condition on spectral reflectance.
- 2) An effort should be made to gather spectral reflectances during the specific time(s) of satellite pass. This would be required to better relate satellite imagery to the surface condition, given the observed capacity of solar azimuthal position to modify spectral reflectance.
- 3) Satellite imagery should be obtained, to determine relationships between it and ground radiometer data and to ascertain more thoroughly its applicability in the high arctic context.
- 4) A more extensive albedo survey should be performed to seek occurrences and determine cause(s) of the low solar angle albedo peak. This study would be performed preferably with another type of sensor (e.g., a spectral radiometer)

gathering readings of the same areas at the same times. Such effort is warranted, given the effect of albedo on energy balance and modelling (especially global circulation modelling). Such work would ascertain whether the phenomenon of heightened albedo/reflectance is a real feature of the reflectance pattern of surface under low solar angles or an artificial byproduct of the instruments themselves.

- 5) More work should be done to attempt to generate accurate albedo values from spectral radiometer measurements; specifically, different bands of sensitivity could be employed along with the use of multiple viewing positions at a given site.

Appendix A: The LANDSAT Earth Resources Technology Satellites

In 1972 the U.S. National Aeronautics and Space Administration (NASA) launched the first of what was to become a very successful, long lived line of Earth Resources Technology Satellites. Initially called ERTS-1, the series was later renamed LANDSAT, and to date (1991) five have been launched and a sixth is due to be launched in May of 1992. Launched as a response to the promising results the earlier manned space missions had generated, Landsat was an experiment to explore and demonstrate the utility of space-borne remote sensing as a new source of information about the surface of the earth.

Landsat-1 was equipped with two distinct types of instrument which gathered and returned information in seven channels. Each channel represented a specific waveband along the electromagnetic spectrum; more accurately, along the visible and near-infrared portions of the spectrum. The first three channels were occupied by a sensor known as a Return-Beam Vidicon television camera. These sensors suffered from technical problems on Landsats 1 and 2 and, although an improved version saw more extensive use on Landsat 3, the instrument type was discontinued and it has not been carried on board subsequent satellites in the series. The data that were acquired from these systems was of high geometric accuracy, and images gathered by Landsat-3 have been put to use in mapping. They do suffer from low radiometric resolution, however, which placed further constraint on the effective number of available images.

The sensor that has established itself as the most prolific is the multispectral scanner systems (MSS) carried on all of the satellites in the series. The Landsats 1, 2 and 3 carried an MSS system that has become

known by that name. Landsats 4 and 5 were outfitted with an improved version of the MSS known as the thematic mapper (TM); in addition to the TM sensor they carried the older version MSS identical to Landsats 1, 2 and 3 in order to maintain a continuity of gathered information throughout the series. Landsat 6 will carry a sensor system that diverges completely in operation from the MSS type sensors of its earlier siblings: termed a push-broom sensor, it is a completely solid state device that will offer images of greater spatial resolution and greater flexibility in the way in which images are gathered.

All the Landsat satellites orbit the earth in what is termed a near-circumpolar sun-synchronous orbit. Near-circumpolar means that the plane of the orbit is tilted several degrees off the axis about which the earth rotates. The actual amount of tilt is nine degrees, which means that the regions of the earth north of 81 degrees north and south of 81 degrees south latitude never fall within range of the satellite sensors (figure). The placement of the spacecraft in an orbit that seems to compromise their capacity to image the entire surface of the earth was necessitated by the sun-synchronous aspect the planners also wished to incorporate. Sun-synchronous means that the satellite is overhead any given point along its orbital track at essentially the same local time, plus or minus about half an hour, moving westward with the sun. This nominal time is about 9:30 am local time, and this feature of the satellites' orbit ensures uniformity of lighting conditions from image to image and from place to place. The time of day was chosen to provide ample target lighting, while yet maintaining a solar angle low enough to adequately highlight relief and terrain features.

Landsats 1, 2 and 3 were placed in an orbit of about 900km altitude, which provided for a repeat interval of 18 days. That is, the satellite will be overhead any given point once every 18 days. Landsats 4 and 5 were both placed in a lower altitude orbit of 705km. This allowed for an increase in frequency of repeat coverage, now once every 16 days, because of the greater orbital velocity associated with the lower altitude orbit.

Orbital groundtrack of Landsat 4 & 5

Repeat coverage every 16 days

Coverage continuous between 81N and 81S

AP39: Landsat orbital ground trace. The path the Landsat series of satellites describes over the surface of the earth: a near-circumpolar sun synchronous orbit.

Landsat Scan Path Details

AP40: Landsat scan detail. The directions of scanner sweep at the surface.

Thematic mapper sensor schematic

AP41: Schematic detail of the Thematic Mapper optical mechanical multispectral scanner, including major optical components and pathways and the scan line corrector.

Appendix B: Site Descriptions: slope angle and aspect, vegetation; number of readings, times, sky conditions. The notes in the last column describe site position, moisture, vegetation present, soil colour and type (and any microtopographical features), and elaboration of a "variable visibility" indication (vV).

Site	Angle	Aspct	R#	Time	Sky	Vg %	Vegetation/Sfc. notes
A1	flat	-	1	1300	c25 v5 c44	100	adjacent to lake on small peninsula; saturated; moss and peat layer, representing about 60% of cover, on which are growing sedges, Carices some <u>Salix</u> and various herbs
A2	flat	-	1	1315	c25 v5 c44	95	10m from lake; very wet; moss and peat layer about 50% of cover, on which are growing sedges and some <u>Salix</u>
A3	flat	-	1	1330	c26 v6 c43	85	20m from lake; wet; sedges and <u>Salix</u>
A4	irreg	WSW	1	1400	c27 v8 c43	20	30m from lake; dry; <u>Salix</u> , sparse sedges; light brown silt with some peat deposits on surface; mud boils
A5	irreg	WSW	1	1430	c28 v8 c42	10	40m from lake; dry; <u>Salix</u> ; light brown silt with some dessication cracks. The vicinity of sites A4 and A5 had some white salt deposits on surface
B1	irreg	-	1	1020	c22 vV c42	40	plateau top; dry; <u>Salix</u> , <u>Kobresia</u> , some herbs; hummocks (~0.5m diameter) in brown clayey-silt; v8 for 4-10, v1 for 1-3
			2	1410	c23 v1 c43		
B2	flat	-	1	1645	c22 v1 c42	100	saturated tundra pond depression; cotton grass (in seed), some herbs
			2	1145	c24 v5 c43		

Appendix B (continued)

Site	Angle	Aspct	R#	Time	Sky	Vg %	Vegetation/Sfc. notes
C1	20	WNW	1	1015	c24 vV c35	10	slope top; dry; <u>Dryas</u> , <u>Salix</u> , some <u>Kobresia</u> and herbs; soil light brown silt with sand component; v4 for 4-9, v6 for 10-3
C2	20	WNW	1	1040	c24 v4 c35	15	mid slope; dry; <u>Dryas</u> , some <u>Kobresia</u> , <u>Salix</u> and herbs; soil same as C1
C3	7	WNW	1	1100	c24 v4 c35	25	slope bottom; wet; <u>Kobresia</u> , some <u>Dryas</u> and <u>Salix</u> ; brown silt in HWC floodplain
D1	17	E	1	1450	c26 v7 c52	50	slope top; dry; <u>Salix</u> , <u>Dryas</u> , <u>Carex</u> , <u>Saxifrage</u> , <u>Kobresia</u> , some moss; hummocks in light brown silt
			2	1955	c13 v8 c24 c33		
			3	0925	c21 v5 c49		
D2	-5	E	1	1510	c26 v5 c52	80	near slope top; damp; <u>Salix</u> , <u>Dryas</u> , moss, <u>Kobresia</u> and some <u>Cassiope</u> and other herbs; sfc. very irregular; large, deep hummocks in brown silt
			2	2005	c23 v5 c33 c42		no direct radiation on site
			3	0945	c21 v5 c49		
D3	8	E	1	1530	c26 v6 c52	30	mid slope; dry; <u>Salix</u> , <u>Kobresia</u> , <u>Dryas</u> , some grass and <u>Papaver</u> ; hummocks in light grey-brown silt
			2	2020	c26 v5 c33 c42		

Appendix B (continued)

Site	Angle	Aspct	R#	Time	Sky	Vg %	Vegetation/Sfc. notes
			3	1000	c21 v5 c49		
D4	flat	-	1	1540	c26 v6 c52	70	slope bottom; wet; Carices, <u>Salix</u> , <u>Dupontia</u> and some herbs; dark brown silt
			2	2030	c26 v5 c33 c52		
			3	1015	c21 v5 c49		
E1	17	N	1	1030	c25 v6 c 3 3 c52	<10	slope top; very dry; <u>Salix</u> and some <u>saxifrage</u> ; light yellow-brown silt with pebbles; area under influence of eolian activity that is burying plants
			2	2210	c12 v7 c22 c45		
			3	1750	v7		
E2	15	N	1	1045	c25 v6 c33 c52	40	mid slope; dry; <u>Drvas</u> , <u>Puccinellia</u> , some <u>Salix</u> ; very light yellow silt
			2	2200	c12 v7 c22 c45		
			3	1740	v5		
E3	17	N	1	1115	c24 v5 c32 c52	70	lower mid slope; dry; <u>Cassiope</u> , some <u>Salix</u> , <u>Drvas</u> , moss, lichen; light yellow silt
			2	2150	c12 vV c22 c45		sun v5 for 7-10, otherwise v4
			3	1735	v5		

Appendix B (continued)

Site	Angle	Aspct	R#	Time	Sky	Vg %	Vegetation/Sfc. notes
E4	flat	-	1	1130	c24 v5 c32 c52	90	slope bottom; wet; <u>Carex</u> , some grasses and cotton grass growing in moss; near Heather Creek floodplain
			2	2135	c12 v4 c22 c45		
			3	1715	v5		
E5	flat	-	1	1550	c22 v3 c42 c52	0	plateau above the E sites; very dry; very light brown sandy-silt, partially deflated with many smooth, large pebbles on surface
			2	2215	c12 v7 c22 c45		
F1	8	S	1	1440	c22 v2 c32 c53	10	mid slope; dry; <u>Salix</u> with some grasses; brown silt, sfc. somewhat irregular with some cracking and white salt deposits
			2	2125	c13 v5 c22 c35		
F2	8	S	1	1445	c22 v2 c32 c53	20	near slope bottom; dry; <u>Dryas</u> , <u>Kobresia</u> , some <u>Salix</u> ; grey-brown silt with some cracking
			2	2115	c13 v5 c22 c35		
F3	5	SSE	1	1515	c22 v2 c42 c53	<5	near slope top; very dry; some <u>Oxyria</u> and grasses; yellow-brown sandy-silt highly deflated, surface covered almost completely with pebbles and cobbles
			2	2100	c13 v5 c22 c35		

Appendix B (continued)

Site	Angle	Aspct	R#	Time	Sky	Vg %	Vegetation/Sfc. notes
G1	3	WNW	1	1000	c21 v2 c53	30	top of ravine near plateau; dry; dead <u>Dryas</u> , some <u>Kobresia</u> and <u>Carex</u> ; light yellow-grey silt with some white sulphate deposits on surface
			2	1550	v7		
G2	0	-	1	1030	c21 v2 c53	10	other side of G1 ravine; very dry; <u>Dryas</u> and <u>Salix</u> ; yellow-brown silt laced with hexagonal dessication cracks
			2	1545	v7		
H1	-2	SSW	1	1130	c22 v1 c52	20	large island in Heather Creek; dry; <u>Dryas</u> with some <u>Oxyria</u> ; dark brown silt with some large pebbles on surface
			2	1520	c22 vV c54		sun v4 for 4-10, v6 for 1-3;
			3	1500	vV		sun v1 for 4-10, v5 for 1-3
I1	0	-	1	1615	c22 v5 c54	20	top of plateau; dry; <u>Salix</u> ; light yellow silt, surface uneven with hexagonal dessication cracking
			2	1345	v1		
J1	0	-	1	1040	vV	<5	plateau; very dry; grasses; light yellow-brown sandy silt with angular cobbles on deflated surface; v5 for 5-8, v7 for 4, 9, 10, and 1-3
J2	40	WNW	1	1100	v7	<5	slope crest; very dry; some grass; light yellow-brown sandy silt with many large cobbles and pebbles on deflated surface
J3	20	NW	1	1115	v1	<10	upper slope; dry; <u>Salix</u> ; very light brown sandy silt has many large pebbles on deflated surface

Appendix B (continued)

Site	Angle	Aspct	R#	Time	Sky	Vg %	Vegetation/Sfc. notes
J4	15	NW	1	1140	v1	40	mid slope; damp; <u>Dryas</u> , <u>Kobresia</u> , <u>Salix</u> , <u>Saxifrage</u> , mosses; light brown-grey silt with very hummocky surface
J5	3	NW	1	1205	v1	75	slope bottom; damp; <u>Dryas</u> , <u>Kobresia</u> , some <u>Salix</u> , mosses, <u>Oxyria</u>
K1	flat	-	1	1015	v8	<1	hilltop; dry; grasses; light yellow-brown sandy silt with many pebbles on deflated surface
K2	30	NE	1	1025	v8	60	mid slope; dry; <u>Dryas</u> , <u>Kobresia</u> , some grass, moss and lichen; light grey sandy silt with hummocky surface
K3	20	KW	1	1040	v8	30	mid slope; dry; <u>Kobresia</u> , some <u>Salix</u> and <u>saxifrage</u> ; light grey sandy silt almost entirely covered with pebbles

AP-B 42: Site positional details for location subset A, near Coal Lake. Surface vegetation cover decreases away from the lake.

AP-B 43: Site positions for location subset B, on the plateau about 100m from the base camp. The albedo site is nearby.

AP-B 44: Site positions for location subset C, the instrumented west slope.

AP-B 45: Site positions for location subset D, the instrumented east slope.

AP-B 46: Site positions for location subset E, the instrumented north slope, and F, the instrumented south slope.

AP-B 48: Site positions for location subset G, a dry plateau site about 1.5 km up from where Heather Creek meets Hot Weather Creek.

AP-B 49: Site position of H1, the single site at this location. It is situated on a large island around which flows Heather Creek, about 3 km WNW of base camp.

AP-B 50: Site position of I1, the single site at this location. It is situated on a dry hilltop above Heather Creek, about 6 km up WNW from base camp.

AP-B 51: Site positions for location subset J, a hillslope of northern exposure across the creek from the base camp.

AP-B 52: Site positions for location subset K. It is situated about 25 km north of base camp, farther up Hot Weather Creek.

Guide to the classification schemes associated with Appendix B

SITE: The letter refers to the location series and the number refers to the specific site within that location series. A location series represents a grouping of sites that are geographically or topographically related. (Refer to Appendix C for detailed descriptions of the sites and the reasoning for their choices).

ANGLE: The angle of the surface under investigation as measured from horizontal. In some cases, the surfaces were not uniformly level, but contained frost features (e.g. hummocks) which rendered the surface quite irregular, in some instances.

ASPECT: The azimuthal facing of the slope as measured from true north, given to the nearest 20 degrees

R#: The particular reading number for which the relevant observations are applicable.

TIME: Local time of day that the readings were gathered. Local time is central standard time (CST), which is Universal Standard Time minus five hours.

SKY: The prevailing sky conditions under which the readings were taken. The code is arranged as such:

cXX vX

cXX

where 'c' refers to the clouds present and 'v' is an estimate of solar visibility. The first digit for the cloud readings refers to the dominant cloud type in that layer and the second digit refers to the portion of the sky covered by that layer. There could in fact be more than one cloud type present in a particular layer, however, only the dominant type is indicated.

The number codes for cloud type are:

1	low stratus
2	low cumulus
3	mid level stratus
4	mid level cumulus
5	high level stratus (including cirrus)
6	high level cumulus

The number codes for cloud cover fraction are straight forward: they are a decimal fraction of the visible sky obscured by the indicated type of cloud.

The presence of more than one cloud condition indicator represents a corresponding observable layer of cloud, judged distinct from the layer receding it, for example c23 v4 would indicate one observable layer of cloud, whereas c34 v5 would indicate two observable layers of cloud.

^ c52

There were never more than three layers of cloud reported.

The number codes for solar visibility are:

- 1 perfectly clear
- 2 sun possibly shining through very thin cirrus
- 3 sun very brightly visible
- 4 sun brightly visible
- 5 sun dimly visible
- 6 sun very dimly visible; at this intensity shadows were just discernible
- 7 solar disk not visible, but general location of sun apparent
- 8 incident radiation perfectly diffuse: no trace of sun
- V incident radiation variable during readings: details in vegetation/sfc. type comments area

Note that the section dealing with cloud conditions and solar visibility reporting represent a best attempt to quantify what is qualitative data.

VG%: This is an estimate of the amount of visible surface covered by vegetation of any type in the immediate vicinity of the measured site (i.e. an approximate 10m radius).

VEGETATION/SFC. TYPE: This provides a brief description of the major plant species or general surface conditions found at the site. There are several species indicated; general characteristics of each are detailed below. Note that this list represents only a selection, not all, of the species in the region.

Salix arctica, (arctic willow): A species of willow that has adapted to high arctic conditions. It is a small, prostrate shrub with branches that radiate out up to 0.5m from a central core which never attain more than a few centimeters in height above the ground. The species favours areas where snow accumulates (the snow cover serves a protection from winter winds). It requires moderate moisture supply and tends not to favour dryer conditions. It has large, thick leaves of medium green colour.

Dryas integrifolia, (arctic avens): A matted shrub that has many very small leaves of medium green colour and dead leaves that are red-brown in colour. It is found in moderately drained areas.

Sedges: Sedges are plants that possess long, slim leaves which grow from a central clump. Although grass-like in appearance, these plants have wider, generally straighter leaves. Kobresia myosuroides produces very thin leaves of a very light green-yellow colour. This species tends to favour dry locations. Other species include Carex aquatilis var. stans and Carex maritima; these tend to favour wetland areas. Carex nardina and Carex rupestris are found in moderately drained and well sheltered areas.

Grasses: Grasses also possess slim leaves which grow from a clumpy base plant. Species include Poa glauca, Puccinellia angustata, and Agropyron violaceum which can grow in well-drained disturbed areas and are saline tolerant. Other grasses, such as Alopecurus alpinus and DuPontia fisheri are found in poorly drained areas.

Saxifragia oppositifolia, (Purple saxifrage): A plant which possesses a dense grouping of very small, green leaves that grow in small clumps. The plant grows on disturbed areas which tend to be well drained. Another species which possesses red leaves is Saxifragia tricuspidata. Another less common species is Saxifragia hieracifolia.

Eriophorum scheuchzeri, (cotton grass): A grass-like plant that produces a seed pod which is very similar in appearance and texture to a cottonball. This species favours wet, preferably saturated, areas. It is widespread in wetlands and is of interest because it can serve as a ready visual identifier of tundra pond activity, such as the case at site B2.

Other species: There is a wide variety of vascular plant species in the area. One of the more prevalent is the woody species Cassiope tetragona (arctic heather), a plant with small, green leaves that forms mats on the ground. Another woody species with red leaves is Vaccinium uliginosum. Other herbaceous species include Pedicularis sudetica, Alopecurus alpinus, Juncus biglumis, and Equisetum arvense in wet areas and Oxyria digyna (a sorrel), Papaver radicum (arctic poppy), Polygonum viviparum, Stellaria longipes, Arctagrostis latifolia, Minuartia rubella, Lesquerella arctica, and Breva purpurescens in areas with better drainage.

Mosses and lichens: Saturated and poorly drained areas tended to possess a mat of moss, typically Drepanocladus, on which the sedges plants grew; in these areas mosses can account for up to 50% of the observed surface cover. This was limited to wet areas which were stable. Mosses were not present on wet areas that undergo seasonal inundation because of proximity to a creek or stream (floodplains). A species of lichen, Thamnochloa vermicularis, was present on some surfaces in very limited quantities.

Appendix C: Procedure for generation of satellite emulation data

This process consisted of several steps. The first involved determining, using the radiometer, the quantity of radiation reflected from the ground and multiplying that by a suitable factor to arrive at the equivalent reflectance for an entire pixel (Thematic Mapper assumed sensor; thus 30m x 30m). The next step was to incorporate the effects of atmospheric attenuation. The bandwidths of the sensors are then compared to similar bands on the TM sensor. For all of the radiometer bands, the widths of sensitivity were less than the equivalent bands on the Thematic Mapper. For this reason, a factor of greater than one is applied to the radiometer bands, to accurately reflect the greater quantity of radiant flux available over the wider band TM band. Next, a beam dispersion factor was incorporated, to account for the loss of energy due to distance from the point of radiation, and finally the internal energy step-up ratio of the TM sensor was applied. The end product is the signal strength at the point of contact with the photoelectric sensor on board the satellite.

In lieu of actual satellite data, which was requested but which was unavailable due to prevailing climatic conditions, this process provided a rough idea of signal strength differences between sites, to determine how readily such differences would appear on actual satellite data. Differences in atmospheric condition, which also vary the way in which the radiation stream is modified, can also be examined. This will provide an indication as to what differences in surface cover can be discerned from a satellite image, i.e. the determination of surface state/type, and to what extent identification of subsequent change may be possible, in order to better evaluate its usefulness as a monitoring tool.

The exact steps are thus detailed.

1) Readings taken directly from the radiometer, expressed in units of electrical power (nW) are converted to units of radiative intensity (power) per solid angle of emittance per wavelength ($\text{W m}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$) using the appropriate conversion factors (Table 2). The unit ($\text{W m}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$) is radiance (W) incident upon and perpendicular to a given area (m^2) per unit of solid angle in the instrument gathering cone (steradian, sr) per wavelength in the range of gathered radiation (μm of wavelength).

2) The average equivalent radiance over the appropriate Landsat band must be determined. First, area of the Landsat band occupied by the filter band(s) is determined. Second, if more than one filter band lies within a Landsat band, a weighted average of the values is taken. Third, the filter values are multiplied by an appropriate factor to represent a band equal in width to that of the Landsat band.

3) The solid angle of acceptance (Ω) for the radiometer must be determined to provide the radiance per unit wavelength; it is as follows:

$$\Omega = 2\pi(1 - \cos\theta_h)$$

This factors in the actual size of the radiometer solid angle of acceptance (i.e. its cone of sensitivity); multiplying through leaves ($\text{W m}^{-2}\mu\text{m}^{-1}$).

4) To properly represent the actual ground area sensed by the instantaneous field of view of the satellite sensor, 900 m^2 in this case (i.e. a pixel), the radiance value is multiplied by a factor of 900. The fact that the area of sensitivity of the ground radiometer was not 1 m^2 , but 0.014 m^2 , means that the radiance value must be multiplied by a value

to generate an actual result for lm^2 . This is 71.43, and coupled with the factor of 900 results in a total factor of 6.429×10^4 .

5) Loss from atmospheric attenuation is now accounted for. In lieu of proper information about the state of the atmosphere (e.g. section 3.4.3) a loss of 25% may be applied; this assumes a clear, pollution free atmosphere.

6) In addition to losses due to atmospheric attenuation, there are losses which result from the fact that propagating radiation does not follow parallel paths; this may be termed geometric dispersion, the rate of loss of energy due to which is related to the inverse square of the distance. Because the radiometer can intercept only a limited area of the entire hemisphere of exitance possible, it is appropriate to subject the radiation reflected from the pixel to the satellite to dispersal over a similar area. Thus, the cone formed by a point on the surface and the 1 cm diameter (d) radiometer aperture located at a height (h) of 1.5 m above the surface will be reproduced at the scale of the satellite. At the altitude of the satellite (705 km), the pixel may be treated as a point source. This angle of dispersal (δ) is determined from the ground radiometer measurements as follows:

$$\delta = 2 \arctan\left(\frac{\frac{1}{2}d}{h}\right) \quad \text{E1}$$

Solved for the values associated with the ground radiometer, $\delta = 0.382^\circ$. Elaboration of the point source idea is as follows. The satellite orbits at an altitude of 705 km. The sensor may thus be treated as though it is positioned on the surface of a sphere with a radius of 705 km. The area

of the surface of the sphere is:

$$A_s = 4\pi r^2 ,$$

which for a radius of 705 km gives an area of $6.26 \times 10^{12} \text{ m}^2$. A 30m x 30m pixel occupies 900 m^2 on the ground, which is 1.44×10^{-10} of the area of the sphere, or 1.4×10^{-8} percent of the area of the sphere. This percentage is small enough such that the radiance from any given pixel may thus be treated as a point source by the satellite sensor.

7) The quantity of radiation incident upon the scan mirror of the satellite sensor is now determined. This involves multiplying the energy incident upon the altitude of the sensor by a ratio that compares the area occupied by the scan mirror with the total area the point source has dispersed to, for that altitude.

8) The units are now converted from those used by the ground radiometer to those used by the satellite radiometer.

9) The energy is now multiplied by an internal step-up ratio. This is a large number that accounts for the intensification of the energy stream as it is focused from an area the size of the scan mirror (2200 cm^2) to that of the actual photoelectric sensors ($8.2 \times 10^{-5} \text{ cm}^2$). In the case the ratio is 2.683×10^7 .

10) The actual calibration values for the satellite sensor, termed sensor gain and offset, are now applied to arrive at the equivalent digital number(s) the satellite would have output, had it sensed the area at the same time.

An example is presented. Band 4 of the Thematic Mapper sensor, the near infrared band, will be used to demonstrate the process. Its range of

sensitivity must be compared to that of the corresponding filter on the spectral radiometer:

Band 4: 760 - 900 nm, for a bandwidth of 140 nm

Filter 10: 790 - 810 nm, for a bandwidth of 20 nm

Use of a radiometer site taken on a surface type typical of the region, i.e. site B1, was deemed appropriate because the largest areas which are relatively homogeneous of surface will be the areas most readily detected and positively identified by the satellite sensor. The readings should be taken from a set recorded as close to 1300 local time as possible (the time, +/- 1/2 hour, of satellite overpass), on a day with essentially perfectly clear conditions, to properly emulate the solar conditions that would be attendant (i.e. satellite data gathered when the surface of interest is clouded over is not suitable for studies of the surface).

A set of readings gathered at 1240, August 7 from site B1 satisfied the above requirements; Filter 10 indicated 0.10 nW (electric). Multiplication by the appropriate calibration factor (Table 2) yielded $0.476 \text{ W m}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$. This value will be assumed to be an average across the entire range of band 4.

Based on the values noted above, the bandwidth of the TM sensor is seven times that of the radiometer; thus the amount of radiant energy potentially available to the TM sensor as the radiation begins its journey up to the satellite is $7 \times 0.476 \text{ W m}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$, or $3.332 \text{ W m}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$.

Multiplication by a factor of 6.429×10^6 , to reflect the total area contributing to the upwelling signal, yields $2.1421 \times 10^5 \text{ W m}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$ emitted from the pixel. Losses due to atmospheric attenuation, assumed to

be 25 percent, reduce the available energy to $1.6066 \times 10^5 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$.

The total area of geometric dispersal is found by solving equation E1 for radius (r), using an angle of $\frac{1}{2} 0.382^\circ$ and an altitude of 705 000 m. The radius at the altitude of the satellite is 2350.21 m, giving a total area of

$1.7353 \times 10^7 \text{ m}^2$. From this can be determined the energy intercepted by the scan mirror. It has an area of $.22 \text{ m}^2$; the area over which the energy that left the surface is now dispersed is $1.7353 \times 10^7 \text{ m}^2$. The quantity intercepted by the scan mirror is therefore

$$\frac{0.22 \text{ m}^2}{1.7353 \times 10^7 \text{ m}^2} \times 1.6066 \times 10^5 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$$

which equals $2.037 \times 10^{-3} \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$.

A unit conversion must now be performed because the satellite records radiant energy in units of $\text{mW cm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$. The value of the radiant energy stream under consideration thus becomes $2.037 \times 10^{-4} \text{ mW cm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$.

Application of the internal step-up ratio (5.81×10^3) results in a value of $1.183 \text{ mW cm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ incident upon the actual sensors. Finally, application of the gain and offset results in a digital number of 24.

The amount of energy actually intercepted by the satellite will be reduced, because of dispersion, as follows:

$$\phi_{\text{intercepted}} = L \text{ A cos } \theta \left(A_s / R^2 \right)$$

where ϕ is radiant flux, L is radiance from the ground, A is the area of radiance, θ is the angle of sensor view as measured from zenith, A_s is the

area of the intercepting sensor and R is the distance from the surface to the sensor. Assuming the sensor is located directly above the surface, i.e. in the nadir position, the term $\cos \theta$ will be one. Given a sensor area of $.22 \text{ m}^2$, a satellite altitude of 705 km and an area of pixel radiance of 900 m^2 , $\phi_{\text{intercepted}}$ will equal $2.7 \times 10^{-9} \text{ W/m}^2\text{-sr-}\mu\text{m}$. Conversion to TM units of radiance give $2.7 \times 10^{-10} \text{ mW/cm}^2\text{-sr-}\mu\text{m}$. The internal step-up ratio for the TM sensor is 4.81×10^9 , which results in $1.3 \text{ mW/cm}^2\text{-sr-}\mu\text{m}$ incident upon the photo sensitive surface of the detectors for band 4.

The number that the satellite would then record is a dimensionless digital number that is related to the incident radiance as follows:

$$\text{DN} = O_s + (G_s \times L_\lambda)$$

where O_s is the sensor calibration offset, G_s is the sensor amplifier gain and L_λ is the radiance. Thus for the example the calculated incident radiance would result in a DN of 16.

APPENDIX D: Factor Analysis Results

This is a factor analysis of all variable that was set to retrieve FIVE factor components, despite the occurrence of only four classically suitable ones (eigenvalues >1).

Extraction 1 for Analysis 1, Principal-Components Analysis (PC)
Initial Statistics:

Variable	Communality	*	Factor	Eigenvalue	Pct of Var	Cum Pct
		*				
ZRTIME	1.00000	*	1	5.84637	45.0	45.0
ZF4	1.00000	*	2	1.92392	14.8	59.8
ZF5	1.00000	*	3	1.51030	11.6	71.4
ZF6	1.00000	*	4	1.26091	9.7	81.1
ZF7	1.00000	*	5	.88193	6.8	87.9
ZF8	1.00000	*	6	.50294	3.9	91.7
ZF9	1.00000	*	7	.41610	3.2	94.9
ZF10	1.00000	*	8	.28098	2.2	97.1
ZSUN_VIS	1.00000	*	9	.17016	1.3	98.4
ZCLOUD	1.00000	*	10	.07665	.6	99.0
ZGVEG	1.00000	*	11	.05682	.4	99.4
ZRVEG	1.00000	*	12	.05016	.4	99.8
ZSUN_ANG	1.00000	*	13	.02276	.2	100.0

Rotated Factor Matrix:

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5
ZF5	.94752	.19643	-.01258	-.01493	.09054
ZF8	.94134	.15890	.01179	-.01231	.13690
ZF6	.93786	.25423	-.00532	.01553	.15428
ZF7	.93000	.24026	-.05623	-.04712	.10400
ZF4	.88991	.07255	.01742	-.07910	.08978
ZGVEG	-.60163	.56970	.01108	-.14227	.29379
ZF10	.42636	.86239	.04936	.09300	.01608
ZF9	.51999	.79778	-.01923	.07585	-.01025
ZSUN_VIS	.16195	.01526	.91416	.03112	-.04207
ZCLOUD	-.19556	.01094	.88553	.15580	.05217
ZRTIME	-.07634	.14577	.07103	.86212	.20339
ZSUN_ANG	-.01842	.07454	-.12318	-.79338	.31681
ZRVEG	-.30943	-.04300	-.01399	.04204	-.89693

Appendix E: Cluster Analysis Results

This is a cluster analysis performed on the basic reflectance data from the first data set. There were no other variables included other than the reflectance data generated at each filter wavelength (4 -> 10).

Agglomeration Schedule using Ward Method

Stage	Clusters Combined		Coefficient	Stage Cluster 1st Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	40	51	.045136	0	0	8
2	19	33	.106665	0	0	14
3	53	55	.170949	0	0	13
4	42	49	.264193	0	0	9
5	43	61	.368058	0	0	47
6	15	18	.472807	0	0	29
7	11	45	.588616	0	0	17
8	38	40	.714567	0	1	11
9	12	42	.841928	0	4	41
10	3	23	.998596	0	0	27
11	22	38	1.176894	0	8	42
12	8	9	1.369324	0	0	25
13	5	53	1.566934	0	3	20
14	17	19	1.770660	0	2	19
15	32	36	1.974433	0	0	46
16	6	64	2.183305	0	0	28
17	11	14	2.401330	7	0	28
18	2	25	2.622787	0	0	36
19	17	35	2.888811	14	0	37
20	5	46	3.155319	13	0	52
21	44	48	3.440337	0	0	30
22	21	59	3.771142	0	0	34
23	4	16	4.103406	0	0	39
24	34	37	4.445115	0	0	37
25	8	41	4.796823	12	0	35
26	31	50	5.179390	0	0	33
27	1	3	5.572306	0	10	32
28	6	11	6.011102	16	17	52
29	13	15	6.480680	0	6	32
30	29	44	6.969306	0	21	39
31	52	63	7.554911	0	0	38
32	1	13	8.248745	27	29	46
33	28	31	8.975896	0	26	44
34	7	21	9.733117	0	22	45
35	8	62	10.511377	25	0	55
36	2	24	11.302223	18	0	55
37	17	34	12.121085	19	24	53
38	52	57	13.011724	31	0	50
39	4	29	13.912670	23	30	48
40	30	60	14.824661	0	0	51
41	12	47	15.781754	9	0	47

AP-E 131

42	22	65	16.754145	11	0	49
43	26	58	17.999741	0	0	50
44	28	39	19.668362	33	0	58
45	7	20	21.485149	34	0	49
46	1	32	23.425272	32	15	53
47	12	43	25.422146	41	5	57
48	4	54	27.546259	39	0	51
49	7	22	29.958378	45	42	59
50	26	52	32.436440	43	38	56
51	4	30	35.679836	48	40	59
52	5	6	38.959862	20	28	57
53	1	17	42.410999	46	37	61
54	10	56	46.250221	0	0	56
55	2	8	50.250141	36	35	62
56	10	26	57.319370	54	50	64
57	5	12	64.865875	52	47	61
58	27	28	72.802475	0	44	60
59	4	7	81.481560	51	49	60
60	4	27	97.911346	59	58	63
61	1	5	120.211281	53	57	62
62	1	2	153.986847	61	55	63
63	1	4	241.905106	62	60	64
64	1	10	448.000000	63	56	0

F37262100	47	7	7	4	4	4	4	1	1	1
F37271045	48	3	3	3	3	3	3	3	2	1
G17251000	49	7	7	4	4	4	4	1	1	1
G17301550	50	10	9	8	7	6	3	3	2	1
G27251030	51	5	5	5	5	3	3	3	2	1
G27301545	52	8	6	6	6	5	5	4	3	2
H17251130	53	4	4	4	4	4	4	1	1	1
H17251520	54	3	3	3	3	3	3	3	2	1
H17301500	55	4	4	4	4	4	4	1	1	1
I17251715	56	6	6	6	6	5	5	4	3	2
I17301345	57	8	6	6	6	5	5	4	3	2
J17281040	58	8	6	6	6	5	5	4	3	2
J27281100	59	5	5	5	5	3	3	3	2	1
J37281115	60	3	3	3	3	3	3	3	2	1
J47281140	61	7	7	4	4	4	4	1	1	1
J57281205	62	2	2	2	2	2	2	2	1	1
K17291015	63	8	6	6	6	5	5	4	3	2
K27291025	64	4	4	4	4	4	4	1	1	1
K37291040	65	5	5	5	5	3	3	3	2	1

Dendrogram using Ward Method

Note: The site identification scheme is as follows:

first letter: the location subset
 second number: the site identifier
 third number: the month
 fourth and fifth numbers: the day (the data were gathered)
 last four numbers: the time of day

For example: J37281115 would refer to site number three of location subset J. This particular data set was gathered on July 28, at 1115 hrs local time.

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