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Dorothy K. Hall

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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Dorothy K. Hall
Hydrological Sciences Branch, Code 924
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

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Dorothy K. Hall
Hydrological Sciences Branch
NASA/Goddard Space Flight Center

ABSTRACT

Using remote techniques, advances have been made in studying many permafrost-related features such as: aufeis, tundra, thaw lakes and subsurface ice features. Landsat imagery was used to measure the extent and distribution of aufeis in Arctic Slope rivers over a period of 7 years. Inter-annual extent of large aufeis fields was found to vary significantly. Digital Landsat data were used to study the short-term effects of a tundra fire which burned a 48 km² area in northwestern Alaska. Vegetation regrowth was inferred from Landsat spectral reflectance increases and compared to in-situ measurements. Aircraft SAR (Synthetic Aperture Radar) imagery has been used in conjunction with Landsat imagery to qualitatively determine depth categories for thaw lakes in northern Alaska. Finally, short-pulse radar has recently been used to locate and measure subsurface permafrost features such as ice wedges, ice lenses and ice cores in pingos. For these and other studies, the use of Landsat data, SAR imagery and short-pulse radar data has substantially increased our knowledge of surface and subsurface processes operating within continuous permafrost.

UTILIZATION OF REMOTE SENSING IN ALASKAN PERMAFROST STUDIES

INTRODUCTION

Continuous permafrost underlies all of the Arctic Slope of Alaska, and discontinuous and sporadic permafrost underlie most of the rest of Alaska. The presence of permafrost presents unique problems relating to construction, waste disposal, water supply and transportation in Alaska. Many of the permafrost-related features and processes which are relevant to these problems can be studied with remote sensing techniques. Sensors which operate in the microwave portion of the spectrum are necessary to augment the more readily available information derivable from Landsat, mainly because the microwave data have two distinct advantages over the visible: penetration into the ground, and ability to "see" through cloud cover. However, some advantages of Landsat are its repetitive coverage, its relatively good resolution (~80 m) and the substantial amount of data collected (since 1972). In addition, the combined use of the visible and near-infrared Landsat MSS (Multispectral Scanner Subsystem) data offers the opportunity to discriminate between wet and dry areas of snow and ice.

Only a few applications of remote sensing to permafrost studies will be discussed in this paper, although many other studies have been performed. Studies are cited which involve the use of Landsat imagery and digital data, aircraft SAR (synthetic aperture radar) data and short-pulse radar data. Distribution and variability of aufeis (overflow river ice), qualitative lake depth determination, tundra recovery from wildfire and analysis of subsurface permafrost features are discussed.

LANDSAT STUDIES OF AUFEIS DISTRIBUTION AND EXTENT

In areas of human activity in the Arctic, aufeis can pose a serious problem. Aufeis is a mass of surface ice formed by successive freezing of water that seeps from the ground, a river or a spring (Carey, 1973). It can be detrimental to structures and must be avoided during construction. Furthermore, poorly located road cuts can create aufeis where there was none previously. Large

stream aufeis occurs in most of the rivers in northeastern Alaska. Distribution of aufeis and changes in the interannual extent of large aufeis fields have been monitored using Landsat MSS data (Childers et al., 1977; Harden et al., 1977 and Hall, 1980). Stream aufeis occurs in approximately the same part of a river channel each year when the aufeis is fed by a spring upstream from a potential constriction to streamflow. This is the case in many streams on the Arctic Slope of Alaska.

Distribution of aufeis was determined from Landsat Band 5 (visible) imagery. The visible Landsat bands are best for determination of aufeis extent because in spring and summer good contrast exists between the aufeis and the surrounding snow-free tundra (Figure 1). The aufeis fields were transferred from Landsat images onto 1:250,000 scale U.S.G.S. topographic maps using a Zoom Transfer Scope and then measured using a dot grid for the years 1972-1979. When interannual variations in aufeis extent were compared with the meteorological variables which are



Figure 1. Landsat MSS Band 5 (Visible) Image Showing Large River Aufeis in Northeastern Alaska. Area "A" is Aufeis on the Echooka River; Area "B" is Aufeis on the Saviukviayak River

believed to control aufeis extent, no statistically significant relationships were found (Hall, 1980), thus calling into question the accepted theories on aufeis formation.

Table 1 shows the extent of aufeis on six Arctic Slope rivers for the years 1973-1979. Due to extensive cloud cover in June of 1976 and 1978, very little aufeis was visible in these years.

Table 1
Landsat-Derived Measurements of June Aufeis Extent (km²)
from Selected Arctic Slope Rivers (1973-1979) (From Hall, 1980)

	Canning	Echooka	Hulahula	Kongakut	Sadlerochit	Shaviovik
1973	16.69	18.31	2.94	26.69	5.06	3.13
1974	4.44	23.63	3.69	27.31	8.31	3.81
1975	10.44	26.69	2.25	19.69	7.69	2.44
1976	No Data Available for 1976					
1977	21.81	19.63	3.50	16.56	5.50	1.19
1978	No Data			29.00		
1979	26.00	22.88	No Data		6.88	4.25

ORIENTED LAKE DEPTH DETERMINATION

Thousands of lakes on the Arctic Slope of Alaska are oriented in a north-northwest--south-southeast direction. Whereas aufeis is located preferentially in the eastern part of the Arctic Slope, the oriented lakes are predominately found in the western part. The dividing 'line' is the Colville River. Small, less well-oriented lakes are found in the eastern Arctic Slope. This type of thaw lake is unique to permafrost because it forms from the thawing of ground ice in continuous permafrost.

Landsat is an excellent platform for studying the size and distribution of the oriented lakes. Landsat imagery is useful for qualitative determination of thaw lake depth (Sellman et al., 1975). It has been observed even prior to Landsat that deeper lakes retain their ice covers longer into the

summer than do shallow lakes. Three depth categories have been recognized: shallow (< 1 m deep), intermediate (1-2 m deep) and deep (> 2 m deep) based on relative date of summer ice cover dissipation. Deeper lakes (with thicker ice) retain ice covers longer into the summer than do shallower lakes. The use of Landsat imagery has facilitated observation of the summer ice cover dissipation and thus the categorization of lakes by depth.

During maximum ice thickness in April, aircraft SAR data have been used to classify the oriented lakes into two depth categories: less than 2 m deep and greater than 2 m deep. This is possible using SAR data because lakes which are not frozen to their beds (i.e. where water is present between the ice cover and the lake bed) are more reflective to the radar signal than are lakes which are frozen to their beds. It is known that ice in these lakes obtains a maximum thickness of approximately 2 m on the Arctic Coastal Plain of Alaska.

The real part of the dielectric constant (ϵ) of fresh water ≈ 80 and for ice $\epsilon \approx 3.5$; for soil $\epsilon \approx 4.0$. There is a high dielectric contrast in ice-covered lakes with water underneath the ice cover (3.5 to 80) as compared to lakes which are frozen to their beds (3.5 to 4.0). This high dielectric contrast between water and ice contributes to the high radar returns in deep lakes but does not fully explain these bright returns. According to Weeks et al. (1978), elongated air bubbles at the ice/water interface act as scatterers to the radar signal and contribute to the high radar reflections in the deep thaw lakes. Used together, April SAR imagery and summer Landsat imagery are useful for qualitative determination of lake depth. Lake depth information is useful for several reasons. First of all, there is a shortage of freshwater in the Arctic during the winter. Settlements and construction teams must rely on freshwater lakes (not frozen to their beds) for their water supply in the winter. Furthermore, lakes known not to freeze to the bottom could be stocked with fish for food supply (Weeks et al., 1978).

Moving equipment and supplies in the Arctic is logistically easier during the winter when the ground is frozen solid. In the summer, severe damage to the tundra may result from improperly

transporting materials and people. Thus, in spite of the cold, in many ways it is advantageous to work during the winter.

TUNDRA RECOVERY FROM WILDFIRE

The tundra is a delicately balanced system which is vulnerable to the vagaries of climate and man. Tundra is a treeless expanse of vegetation found above the treeline in Arctic and Alpine areas. Fire is a part of the natural ecological balance of the tundra (Vioreck, 1973). However, the effects of natural fires on the tundra are not well understood (Brown and Grave, 1978). By increasing our understanding of the recovery of tundra following a wildfire, we can gain insight into the dynamics of permafrost and its capacity for recovery following disruptions caused by man.

Landsat data have been used to locate and monitor wildfires in Alaska (Haugen et al., 1972 and Hall et al., 1978). Recently, Landsat digital data have been used to monitor the short-term recovery of tundra following a fire in northwestern Alaska by Hall et al. (1980a).

During the summer of 1977 a drought rendered the tundra in northern Alaska vulnerable to lightning-induced wildfires (Ernst and Matson, 1977). One such fire burned a 48 km² patch of tundra near the Kokolik River in northwestern Alaska. U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) scientists landed at the site of the fire after the burning had ceased to make observations (Hall et al., 1978).

Landsat MSS data were acquired before, during and directly after the fire, and approximately one year after the fire (August 1979). Using the GSFC Atmospheric and Oceanographic Image Processing System (AOIPS), the Kokolik River burned area was extracted from a full Landsat scene and enlarged. Three burn severity categories (Figure 2) were inferred from Landsat spectral response values (digital counts ranging from 1 to 256) and from comparison of the Landsat data with in-situ field measurements.

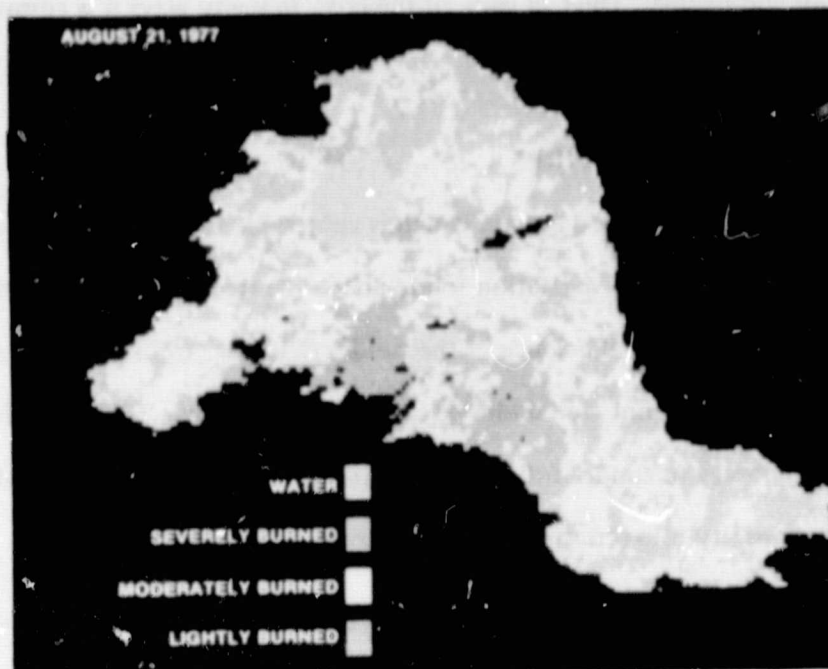


Figure 2. Subscene of an August 21, 1977 Landsat Scene of the Kokolik River Burned Area Classified Digitally Into Three Burn Severity Categories

An August 1978 subscene was also analyzed. Results showed that there were significant increases in spectral reflectance within the three areas of burn severity which were determined from the August 1977 subscene (Table 2). This corroborated in-situ measurements by CRREL scientists which indicated substantial vegetation regrowth in the one year period following the fire (Hall et al., 1980a). Higher spectral reflectances are indicative of more vegetation. In fact, some lightly burned areas appeared fully recovered by August 1978 based on Landsat spectral response and in-situ measurements of vegetation.

Tundra fires can have significant impact on the hydrology of the tundra. If a fire occurs following a prolonged drought, intense burning can result and the permafrost can be stripped of its insulative cover of vegetation. Thawing of near-surface ice can occur and cause considerable amounts of water to be released and result in thermal erosion which will increase each summer until a new thermal equilibrium is established and the vegetation regenerates (Brown, 1970).

Table 2

Percent Increase in Spectral Reflectance Between August 1977 and August 1978 Used to Infer Increases in Live Ground Cover (after Hall et al., 1980a)

Mean Digital Counts, \bar{x}			
Burn Severity Categories	1977	1978	Percent Increase
Severe	8	13	62.5
Moderate	21	30	43.0
Light	30	46	53.0

SUBSURFACE PERMAFROST FEATURES

Tundra surface disturbances that affect construction and transportation are a result of slumping of the ground surface in response to 'thermal erosion' or melting of ice-rich permafrost. Ice-rich permafrost contains such features as ice wedges and ice lenses. Ice wedges are vertically-oriented masses of ground ice caused by surface water (from snowmelt) seeping into thermal contraction cracks in the spring in permafrost and freezing in the winter over thousands of years. Ice lenses are masses of ground ice which form parallel to the surface as a result of moisture filling in interstices in fine-grained soils. Until recently, airborne remote sensing could only be used to infer subsurface conditions from surficial expressions. It now appears promising that the use of a short-pulse radar operating at a frequency of 480 MHz may be useful for detecting and measuring subsurface permafrost features. This radar system has been flown experimentally over the proposed Alaskan gas pipeline right-of-way on a helicopter in order to investigate the ground in which the pipeline will be placed (Hall et al., 1980b).

Subsurface penetration of approximately 3 m was achieved and signatures of ice wedges, ice lenses and pingo ice cores were observed. (Pingos are conical-shaped features which form in permafrost and are generally ice-cored in the continuous permafrost region.) Linear features having bright

returns were found to extend approximately 3 m below the ice cores of pingos. Similar bright linear features were seen beneath frozen lakes. In addition, the location and distribution of ice wedges were determined and ice wedges were measured.

The short-pulse radar data were found to be very useful for determination of subsurface homogeneity. A very homogeneous area may only require one borehole for investigation, while an inhomogeneous area (as determined from the short-pulse radar data) may require several boreholes to determine the condition of the subsurface so that construction may begin. Boreholes are very expensive to drill, and they disrupt the tundra and permafrost. It is therefore advantageous to limit boreholes to a minimum if the needed geophysical information can be acquired in other ways.

CONCLUSION

Since the advent of remote sensing, much progress has been made in studying the periglacial environment. Landsat imagery has been used to classify thaw lakes based on size, location, degree of orientation and depth, and to determine spatial and temporal variability of many features and processes such as aufeis, and to monitor the extent and recovery of tundra fires. The use of aircraft SAR data and short-pulse radar data has enabled us to "see" beneath the surface in order to study thaw lakes and subsurface permafrost features. Oftentimes, the use of sensors operating in different parts of the spectrum is necessary to augment in-situ data. In addition, it is far less disruptive to the permafrost and overlying tundra if geophysical information can be obtained remotely.

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