H. Schreier
*Department of Soil Science*
*The University of British Columbia*
*Vancouver, British Columbia V6T 2A2, Canada*
L. C. Goodfellow
*Canada Centre for Remote Sensing*
*Ottawa, Ontario K1A 0Y7, Canada*
L. M. Lavkulich
*Department of Soil Science*
*The University of British Columbia*
*Vancouver, British Columbia V6T 2A2, Canada*

# The Use of Digital Multi-Date Landsat Imagery in Terrain Classification

## Multi-date image analysis was employed to determine vegetation communities and, in turn, off-road mobility in northern Canada

Abstract: *Satellite based terrain classifications can often be improved by using multi-date imagery which provides good contrast between vegetation communities and surface materials. Using this concept, a quantitative assessment was made of organic terrain in northern Canada in order to predict off-road mobility conditions. A number of vegetation communities were found to be good indicators of ground conditions, and the potential for off-road mobility of those areas dominated by each vegetation community was assessed in the field. A digital multi-date satellite analysis was then performed to demonstrate the usefulness of such a technique for off-road mobility planning in northern areas where ground information is generally scarce. A principal component analysis was used to identify the two most important* MSS *bands for each image. The selected spectral data from two different images were then combined and subjected to an unsupervised cluster analysis. The resulting color coded images were then related to ground conditions and were found to be directly useful as thematic mobility maps for operational planning in such environments.*

### Introduction

It is the purpose of this paper to discuss a multi-date satellite analysis technique which was developed to assess off-road mobility conditions in organic terrain in northern Manitoba, Canada. In northern Canada, where ground information is scarce and where access is difficult, natural vegetation is often used as an indicator of ground conditions (Sauer and Wilson 1977). In environments where organic materials accumulate at the surface due to poor drainage and prevailing permafrost conditions, some vegetation-ground relationships are distinct enough that ground conditions can be predicted by identifying the presence and distribution of vegetation growing in that location. It was thus of specific interest to (1) determine diagnostic vegetation communities and describe their associated ground condition; (2) evaluate the off-road mobility conditions at each location; and (3) predict off-road mobility by mapping the distribution of diagnostic vegetation communities.

The relationships between vegetation and ground conditions and associated off-road mobility implications were first tested in the field, and a multi-date satellite analysis technique was then

Photogrammetric Engineering and Remote Sensing,
Vol. 48, No. 1, January 1982, pp. 111-119.

0099-1112/82/4801-0111$02.25/0

developed to map the distribution of the vegetation communities and to produce thematic mobility maps which are to be used for the planning of military and rescue operations with off-road vehicles in summer and in winter.

Relatively few computer assisted land classification methods based on multispectral Landsat data have become operational despite the fact that such methods theoretically make better use of the original data and are more quantitative. The slow progress is attributed to two factors: the complexity of the spectral data and the limited ground resolution of the Landsat multispectral scanner. Given the current technological capabilities, no magical solution exists by which terrain classifications can be made consistently and accurately from Landsat data.

Vogel (1977) made an extensive review of the capabilities of Landsat imagery as a source of terrain data for cartographic and military purposes. He concluded that ground resolution is inadequate for classifying most of the basic terrain elements, but noted that a scale of 1:100,000 to 1:1,000,000 the Landsat data are compatible with current map accuracy of the same scale. The advantages are that the information can readily be updated which, of course, is not typically the case with topographic maps. At larger scales the planimetric accuracy is highly variable, as shown by White (1978) in assessing reservoir surface areas and Beaubien (1980) in mapping forest types. The latter author felt that the complexity of the terrain, the mixture of plant cover, and the time of year when the assessment is made are the limiting factors. Kalensky and Wightman (1976) and Vogel (1977) feel that an interactive digital approach is most useful if it includes conventional multi-stage sampling. A more promising aspect of the Landsat system is its multi-date image analysis capability, which has become an active research topic in the last few years. Haefner (1978) suggested the use of Landsat images as updated thematic maps and McGinnis and Schneider (1978), Thomas *et al.* (1978), Wickwake (1979), Fisher *et al.* (1979), Dejace and Megier (1980), and Byrne *et al.* (1980) have experimented with digital multi-date assessment techniques.

The time element is most critical in achieving optimum contrast between different terrain features. Unfortunately, there is no single time period during which all terrain parameters can be separated equally well. A good alternative to this is to superimpose selected satellite images taken at different dates, and then classify the terrain from the new combined data base. This should improve the classification because greater contrast is achieved for those features which have changed from one date to the next. This approach will probably work best in natural environments where spectral changes in terrain features are primarily related to seasonal and cyclic differences. Such a multi-data computer assisted analysis was developed in the present study and was applied to a predominantly organic terrain in the Churchill area in northern Manitoba.

## VEGETATION AS AN INDICATOR OF GROUND CONDITIONS

The area chosen for this research is located in the Hudson Bay Lowland near Churchill, Manitoba, and is dominated by extensive sections of flat organic terrain. Small topographic variations are caused by remnants of beach ridges and eskers, and these have a pronounced influence on drainage and, thus, on plant distribution. In addition, the area is underlain by permafrost, which causes additional impedance to drainage and further helps promote selective vegetation growth. Six distinct vegetation communities were recognized in the field and each group flourished in specific types of terrain conditions. Some of the terrain properties commonly associated with each plant community are provided in Table 1. The composition and density of vegetation, depth to permafrost, and drainage were identified as relevant parameters affecting summer mobility; and snow depth, snow compaction, and vegetation parameters were thought to be important for winter mobility.

## SPECTRAL REFLECTION MEASUREMENTS TO DIFFERENTIATE VEGETATION COVER

The six plant communities listed in Table 1 were readily identified in the test area, not only on the ground but also from aerial photographs. It can thus be assumed that a similar separation is possible from the satellite imagery, provided that each plant community covers large surface areas. To verify the assumption that many of the individual plant species have unique spectral signatures, 86 spectral reflection measurements were made in randomly selected sites within each community in a total of fifteen 300 by 300 m test area. The frequency of clear weather conditions is less than ideal in this part of the world and thus dictated the number of reliable measurements which could be made. A Gamma Scientific Multiband Radiometer (Model 820 A-10) was mounted on an extended tripod and the measurements were made between 20 June and 29 June 1979, using the method described by Robinson and Biehl (1979).

Spectral reflectance curves were created for nine types of plant species using Landsat band filters 4, 5, 6, and 7 and a barium sulfate reference surface. The proximity of the measurements did not allow the generation of integrated spectral signals for each plant community and it is therefore not possible to relate the spectral signals to those obtained by the satellite. Nevertheless, the main

TABLE 1. PLANT COMMUNITIES USED AS INDICATORS OF TERRAIN CONDITIONS

| Group name | Dominant plant species | Topography | Drainage | Organic terrain classification |
|---|---|---|---|---|
| lichen heath | *Cetraria nivalis*<br>*Cladonia* spp.<br>*Alectoria* spp.<br>*Empetrum nigrum*<br>*Ledum groenlandicum* | flat terrain, slightly undulating topography caused by frost polygons | poorly drained | bog |
| heath forest (open) | same as above, plus *Picea mariana* | flat, highest areas of mounds | poorly drained but slightly better than above | bog |
| Sphagnum and sedges | *Sphagnum* spp.<br>*Carex canescens*<br>*Carex stans*<br>*Eriophorum-vaginatum*<br>*Carex canescens* | depressions | very poor drainage, standing water near surface | bog |
| Shrubs-grasses and sedges | *Betula glandulosa*<br>*Salix brachycarpa*<br>*Hyrica gale*<br>*Eriophorum-vaginatum* | depressions | very poor drainage, standing water at or near surface | transitional bog/fen |
| Forest (open) | *Picea mariana*<br>*(Picea glauca)*<br>*Betula glandulosa* | near stream banks and slightly higher terrain | somewhat better drained | transitional |
| Willow and sedges | *Salix brachycarpa*<br>*Carex aquatilis*<br>*Calamagrostis canadensis* | depressional | near seepage channels, very poorly drained, standing water at surface | fen |

| Group name | Depth to permafrost June 24-29, 1979 (cm) | Snow depth March 5-9, 1979 (cm) | Snow compaction March 5-9, 1979 vane cone penetrometer (in kg/cm² at 18kg torque) |
|---|---|---|---|
| lichen heath | $\bar{x}$ = 20 cm<br>(Range = 15 – 25 cm n = 36 sites) | $\bar{x}$ = 36 cm*<br>(Range = 5 – 150<br>n = 19 sites) | $\bar{x}$ = 1.05 kg/cm²*<br>(Range = 0.63 – 1.5<br>n = 19 sites) |
| heath forest (open) | $\bar{x}$ = 16 cm<br>Range = 10 – 25 cm n = 10 sites) | | |
| Sphagnum and sedges | $\bar{x}$ = 23 cm<br>(Range = 15 – 28 cm n = 9 sites) | | |
| Shrubs-grasses and sedges | $\bar{x}$ = 24 cm<br>(Range = 7 – 28 cm n = 18 sites) | $\bar{x}$ = 65 cm*<br>Range = 15 – 150<br>n = 22 sites) | $\bar{x}$ = 0.70 kg/cm²*<br>(Range = 0.42 – 1.05<br>n = 22 sites) |
| Forest (open) | $\bar{x}$ = 15 cm<br>(Range = 7 – 25 cm n = 19 sites) | | |
| Willow and sedges | $\bar{x}$ = 27 cm<br>(Range = 20 – 30 cm n = 9 sites) | | |

* A significant statistical difference was found between the two snow depth and snow compaction categories (x = 0.01, Hann-Whitney U-test).

component of five of the six communities listed in Table 1 have unique spectral properties (Figures 1 and 2). A Mann-Whitney Significance test showed that, if we use Cetraria-Cladonia, Betula-Picea, Sphagnum, Carex-Eriophorum, and Salix-Carex species as main components for each of the six communities listed in Table 1, a significant separation between the spectral population was ob-

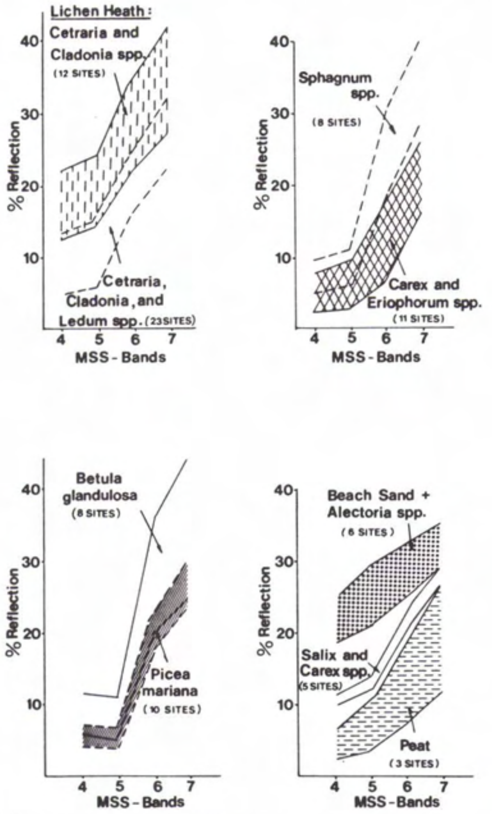

Fig. 1 Spectral reflection curves of different plant species and surface conditions as determined by in situ field measurements.

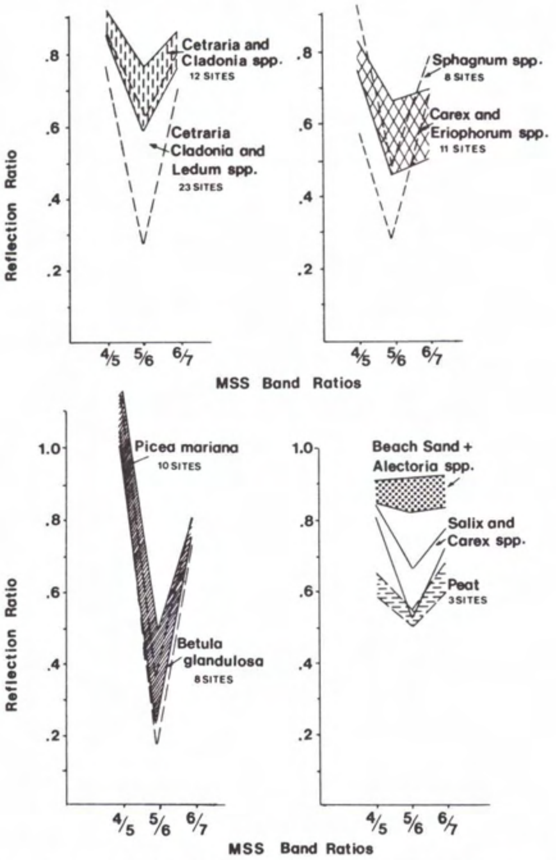

Fig. 2 Spectral reflection band ratios from in situ field measurements of different plant species and surface conditions.

served in at least one band ratio at $\alpha = 0.05$. Only the heath and open heath forest communities could not be separated due to the fact that the individual species in the heath forest had very contrasting spectral curves and an integrated signal could not be observed from the ground-based platform.

## Multi-Date Satellite Image Analysis

To classify the vegetation cover in the Churchill Test area, three Landsat tapes consisting of April, May, and June, 1975, coverage were selected. This image sequence included a snow covered scene (April), coverage under partial snow melt (May), and an early summer scene. In each image different terrain properties were highlighted. In the April image an optimum delineation of the coniferous forest cover was possible because the other vegetation was without leaf cover and thus camouflaged by snow. Despite the fact that the study area is very flat, an impression of relief is gained from the May image. During early snow melt the drainage channels are accentuated, and this facilitates the analysis of the drainage pattern and micro-relief. Finally, the early summer image provides the best contrast for water bodies, drainage, and vegetation cover other than coniferous forest. Since each scene provides optimum contrast for different properties, it is of advantage to superimpose all three images and use the combined data for terrain analysis. This should provide an improved classification of terrain features.

### IMAGE REGISTRATION AND DATA TRANSFORMATION

The three images were registered on the Image Analysis System (CIAS) at the Canada Centre for Remote Sensing in Ottawa (Goodenough, 1979). The June 1975 Landsat image was used as a control to which the April and May images were registered. Four control points were used for coarse registration and 30 points were located for the fine registration at 1:125,000 scale. The program identified poorly matching pairs of control points, which were relocated or replaced to keep the mean registration error below 0.6 pixel. The April and May images were then resampled, using the nearest neighbor technique, to overlay the June image.

When using multi-date imagery, one is quickly confronted with massive computational problems because the inclusion of any one new date adds four spectral channels of data. The color display system is designed to handle four spectral channels at any one time, and this constraint can only be overcome by either using a more versatile analysis system or by data transformation. The latter method was used in this study because the available data are used in an efficient manner. As demonstrated by Donker and Mulder (1976), data from Landsat spectral bands 4, 5, 6, and 7 are often correlated. The full data set therefore contains some redundant information, which makes the computational process more complex and ultimately introduces bias to the classification. A principal component transformation technique can be used to identify those spectral properties which show the greatest contribution to the total variance. The original data from the four MSS bands were subjected to a linear transformation where the new variables (principal components) are a linear combination of the old. The process is performed in such a way that each new variable accounts for a successively smaller amount of the total variance (Hotelling, 1933; Jenson and Waltz, 1979). For Landsat MSS data, Donker and Mulder (1976) found that up to 98 percent of the total variance is contained in the first two principal components. The additional components can thus be deleted from the data analysis since they add very little additional information.

To display the enhanced principal components on the CIAS after transformation, the data are scaled and mapped into the color space described by Taylor (1974). This mapping yields an enhanced image with good color contrast, thus aiding human visual perception.

### NUMERICAL CLASSIFICATION

For quantitative analysis it is necessary to classify the data numerically, and this was accomplished by using an unsupervised classification known as migrating means cluster analysis (Ward, 1963; Ball, 1965). With this technique it is possible to quantify the most common spectral categories in the image. The cluster analysis can be applied to transformed data by using the data from the first two components, or it can be applied to those MSS bands which have been identified as the largest contributors (highest loadings) to the first two components. Both techniques were examined, but more interpretable results were obtained from the second technique (Schreier and Lavkulich, 1980).

In order to apply this methodology to multi-date imagery, the following section process was made: first, the April MSS data were subjected to a principal component transformation and this was followed by a similar but separate analysis of the June MSS data. The partially snow covered May image is not directly related to ground cover and was therefore excluded from the analysis. For the April and June data it was found that the first two components contributed to over 97 percent of the total variance. MSS bands 5 and 7 were identified as having the highest loadings, on principal components one and two, and the original data from these two bands were used in the subsequent cluster analysis. The principal component transformation technique was thus used to partition the variance and to determine those MSS bands which contribute most to the total variance. Theoretically, these data should then provide a better contrast and should thus result in a more efficient and effective classification of the data. The calculations for the principal component transformation are provided in Tables 2 and 3 and the statistical description from the subsequent cluster analysis is given in Table 4. The spatial distribution of the clusters was portrayed on the CIAS-TV screen and color processed images were produced.

### DATA INTERPRETATIONS AND APPLICATIONS FOR OFF-ROAD MOBILITY

The four numerically derived clusters were found to be representative of distinct types of terrain features, and several of the plant communities listed in Table 1 could be verified in the cluster categories. The first cluster was representative of the areal distribution of the exposed surface water (lakes and rivers). The second cluster coincided with the distribution of the forest cover. The third cluster reflects the lichen heath cover but included the heath forest; these two categories could not be differentiated on the basis of the Landsat data, probably due to the fact that the trees in the lichen heath are stunted and extremely scattered. It appears that the tree density is too low to have a significant effect on the spectral signal. The fourth cluster category was representative of the willow-sedge and the shrub-grass-sedge categories where again no separation was possible.

Finally, the sphagnum-sedge vegetation class could not be identified because it occurred in sites

TABLE 2. VARIANCE-COVARIANCE MATRIX FOR FOUR SPECTRAL BANDS OF APRIL AND JUNE IMAGERY

| | April Image | | | | June Image | | | |
|---|---|---|---|---|---|---|---|---|
| MSS Bands | 4 | 5 | 6 | 7 | 4 | 5 | 6 | 7 |
| 4 | 57.7 | | | | 2.3 | | | |
| 5 | 40.2 | 35.1 | | | 3.3 | 5.5 | | |
| 6 | 39.6 | 33.1 | 34.0 | | 5.3 | 8.1 | 18.1 | |
| 7 | 41.6 | 30.8 | 32.1 | 35.3 | 5.5 | 8.5 | 19.9 | 23.1 |

The sum of the diagonal elements, the trace of the matrix is the total variance.

TABLE 3. EIGENVALUES AND MATRIX OF EIGENVECTORS

| | Principal Components April | | | | Principal Components June | | | |
|---|---|---|---|---|---|---|---|---|
| Eigenvectors | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| MSS 4 | 0.60 | 0.46 | 0.46 | 0.47 | 0.19 | 0.29 | 0.62 | 0.70 |
| 5 | −0.68* | 0.58* | 0.46 | −0.21 | 0.44 | 0.78* | −0.03 | −0.41 |
| 6 | −0.45 | −0.40 | 0.21 | 0.77 | 0.16 | −0.33 | 0.75 | −0.56 |
| 7 | 0.16 | 0.54* | 0.73 | −0.39 | 0.86* | −0.44 | −0.21 | 0.14 |
| Eigenvalues | 151.3 | 6.1 | 3.8 | 0.9 | 45.7 | 2.6 | 0.4 | 0.3 |
| % of total variance | 93.3 | 3.7 | 2.5 | 0.5 | 93.3 | 5.3 | 0.8 | 0.6 |
| Cumulative % of total variance | 93.3 | 97.0 | 99.5 | 100 | 93.3 | 98.6 | 99.4 | 100 |

NOTE: The sum of Eigenvalues is equal to the total variance *MSS Bands with the highest loadings or principal components.

which were too small to be discerned from the digital satellite data. Approximately 7.6 percent of the test area remained unclassified, and it appears that these data are predominantly indicative of surface areas having little vegetation cover where soils and sands are directly exposed. These areas are remnants of old beach ridges and alluvial terraces along river channels.

Knowing the water bodies and the ground conditions generally associated with the identified plant communities, it was possible to predict summer and winter field conditions for clusters 1-4 and, consequently, general interpretations with regard to off-road mobility could be made. Areas which had been traversed with armored personnel carriers (APC) were identified to us by Canadian Forces personnel in Churchill, Manitoba, and from this it was possible to predict off-road mobility potential for the other areas in the test section by using the analog approach provided by cluster analysis. Since different factors affect mobility at different times of the year, two mobility predictions were made: one for summer conditions and one for winter conditions. The interpretations were restricted to simple "go," "slow go," and "no go" maps. In order to traverse a "go" area, the driver has a probability of greater than 70 percent of crossing the unit, a "slow go" area has a 50-70 percent probability, and a "no go" area has a less than 50 percent crossing probability.

As can be seen in Table 5, different interpretations and colors were assigned to each cluster group. The classified and color coded images were then displayed and copies are provided in Plates 1 and 2. These color coded images can be used directly as thematic mobility maps. Plate 1 for example is a summer mobility map which indicates that only the area in black can be traversed while areas in purple, red, and blue are to be avoided. Similarly, in Plate 2 areas in blue and red can be traversed while purple areas are to be avoided during winter.

These mobility maps and interpretations are intended for the planning of military and rescue operations, and they are not to be confused with operational field maps. They simply identify areas which are to be avoided and areas which have promising mobility conditions. They thus help in the identification of corridor locations in northern areas where ground information is usually lacking. Once such corridors are identified, a detailed survey in close proximity to the ground is necessary

TABLE 4. RESULTS OF UNSUPERVISED CLUSTER ANALYSIS

| | Euclidean Centres (standard deviations) | | | | | | |
|---|---|---|---|---|---|---|---|
| | June 1975 | | April 1975 | | | | |
| Cluster | MSS-5 | MSS-7 | MSS-5 | MSS-7 | Number of pixels | Area on ground (km²) | % of total surface |
| 1 | 7.8<br>(1.7) | 11.6<br>(4.6) | 43.8<br>(5.8) | 33.3<br>(4.6) | 9220 | 42.9 | 3.5 |
| 2 | 8.9<br>(1.5) | 14.0<br>(3.2) | 55.7<br>(3.7) | 42.5<br>(2.9) | 22707 | 105.8 | 8.7 |
| 3 | 5.7<br>(1.5) | 3.4<br>(3.4) | 62.8<br>(0.8) | 51.0<br>(4.3) | 27410 | 127.8 | 10.5 |
| 4 | 10.2 | 15.5 | 62.9 | 52.6 | 182739 | 851.7 | 69.7 |
| Unclassified | (1.5) | (2.4) | (0.4) | (2.4) | 20060 | 92.8 | 7.6 |

TABLE 5. CHARACTERISTIC CLUSTER THEMES AND ASSOCIATED MOBILITY CLASSES

| Cluster | Type of surface | Summer mobility | Color (Plate 1) | Winter mobility | Color (Plate 2) |
|---|---|---|---|---|---|
| 1 | forest cover | *No-go* (soft ground and tree obstruction) | purple | *No-go* large snow accumulation and tree obstruction | purple |
| 2 | willow & sedges shrub-sedges-grasses | *No-go* (soft very wet ground) | red | *Slow go* (considerable snow accumulation but frozen surface) | yellow |
| 3 | water bodies | *No-go* (soft shoulders and problems with water depth) | blue | *Go* (frozen surface, little snow) | blue |
| 4 | lichen heath and heath forest | *Slow go* (soft ground, hummocky but permafrost at 20 cm) | yellow | *Go* frozen surface | blue |
| | Unclassified | *Go* open, poorly vegetated, well drained surfaces, beach sand and river banks | black | *Go* frozen, little snow accumulation | red |

in order to identify local conditions and obstacles which inhibit mobility and which cannot be revealed from such sources as Landsat data.

The test vegetation was used to establish the map, and no independent vegetation data other than that derived from aerial photo interpretation were available; thus, the accuracy of the map could not be assessed directly. Also, summer mobility in this area is restricted due to cost and the fragile environmental conditions. However, the approximate locations of three winter traverses by military personnel were placed on the thematic winter mobility map and they were found to be accurate 70 percent of the time.

## CONCLUSIONS

Multi-date satellite data analysis can be made efficiently using principal component transformation techniques and subsequent cluster analysis. The method was applied to data of a test area in northern Canada, and the resulting classification was applied to off-road mobility assessments.

This technique was found to have the following advantages:

- *Enhanced contrast using multi-date imagery.* Contrasts between vegetation communities and between surface materials were enhanced by combining imagery from different dates. When the dates are well chosen the contrasts are greater, thus improving the results of cluster analysis.
- *Improvements in the efficiency of data analysis.* Using principal component analysis, it was possible to identify and use the data from only those MSS bands which showed the greatest contribution to the total variance. This reduced the computing process and eliminated correlated or redundant data.
- *More flexibility and rapid updating.* Terrain classifications can be made more efficiently, not only because of increased contrast but also because the digital method is interactive and the digitally processed images can be used directly as thematic maps. They can be updated more readily and digital data from other sources can be superimposed. The flexibility and rapid updating capabilities make the technique most useful for northern areas where survey data are generally sparse or non-existant.
- *Recognition of potential mobility corridors.* For mobility operational planning, it is most useful to know what areas are to be avoided and what areas can potentially be traversed. The digital technique provides a framework for corridor selection and thus facilitates the operation planning.

The main disadvantages are as follows:

- *Ground resolution.* The Landsat ground resolution is insufficient for detailed terrain analysis and mobility assessments at the operational level. It is for this reason that mobility interpretations were made only for general operation planning. However, the next generation of satellites will provide improved resolution, and it is suggested that the above described technique can then successfully be applied to more detailed assessments.
- *Weather conditions.* The variability in cloud cover and the frequency of satellite coverage are such that multi-date images with optimum contrast are still difficult to obtain. In the present case it was possible to get the proper spring-summer sequence only once over a six-year period. Thus, the variability of northern weather

PLATE 1. Summer mobility map derived from unsupervised cluster analysis of selected Landsat MSS bands. (Mobility interpretation: purple, red, and blue = "no go," yellow = "slow go," and black = "go.")

PLATE 2. Winter mobility map derived from unsupervised cluster analysis of selected Landsat MSS bands. (Mobility interpretations: purple = "no go," yellow = "slow go," blue and red = "go.")

patterns still does not allow the use of multi-date imagery on a frequent basis.

- *Multi-date image registration.* Using rectified satellite data, it was found that registration by point overlay was tedious and time consuming. This is partially attributed to the fact that in northern areas easily recognizable control points such as road intersections, towns, etc., are often absent and controls along river channels are less reliable because they are subject to seasonal changes.

## ACKNOWLEDGMENTS

This research was supported by the Defence Research Establishment, Contract #8SU78-00232. The plant identifications were made by Corine Selby, and assistance in data processing was provided by the Canada Centre for Remote Sensing.

## REFERENCES

Ball, J., 1965. ISODATA: Data analysis in the social sciences: What about the details? *Proc. of the Fall Joint Comp. Conf.*, pp. 533-559.

Beaubien, J., 1980. Forest type mapping from Landsat digital data, *Photogr. Eng. and Remote Sensing,* Vol. 46, pp. 135-144.

Byrne, C. F., P. F. Crapper, and K. K. Mayo, 1980. Monitoring land cover changes by principal component analysis of multi-temporal Landsat data, *Rem. Sen. of Environm.* 10: 175-184.

Dejace, J., and J. Megier, 1980. Agreste Project: Experience gained in data processing, main results on rice, poplar, and beech inventories, in G. Fraysse, ed.: *Remote Sensing Applications in Agriculture and Hydrology,* A. A. Balkema, Rotterdam, pp. 309-325.

Donker, N. H., and N. J. Mulder, 1976. Analysis of MSS digital imagery with the aid of principal component transformation. *13th Congress of the Intern. Soc. of Photogrammetry,* Helsinki, 1976, 33 pp.

Fisher, L. T., F. L. Scarpace, and R. G. Thomsen, 1979. Multi-date Landsat lake quality monitoring program, *Photog. Eng. and Remote Sensing,* Vol. 45, pp. 519-527.

Goodenough, D. G., 1979. The image analysis system (CIAS) at the Canada Centre for Remote Sensing, *Canadian J. of Remote Sensing,* Vol. 5, No. 1, pp. 3-17.

Haefner, H., 1979. Thematische kartierungen mit hilfe von multidimensionalen satellitendaten, *Geographica Helvetica,* Vol. 33, pp. 21-24.

Hotelling, H., 1933. Analysis of a complex of statistical variables into principal components, *J. Educ. Psych.,* Vol. 24, pp. 417-442 and 498-520.

Jenson, S. K., and F. A. Waltz, 1979. Principal component analysis and canonical analysis in remote sensing. Paper presented at the ASP-ACSM Ann. Meeting, March 18-23, 1979, Washington, D.C. 12 pp.

Kalensky, Z., and J. M. Wightman, 1976. Automatic forest mapping using remotely sensed data. Forest Management Institute, Env. Canada. Invited Paper XVI IUFRO-World Congress, Oslo, Norway, June 20-July 2, 1976. 21 pp.

McGinnis, D. F., and S. R. Schneider, 1978. Monitoring river ice break-up from space, *Photogr. Eng. and Remote Sensing,* Vol. 44, pp. 57-68.

Robinson, B., and L. Biehl, 1979. Calibration procedures for measurement of reflectance factor in remote sensing field research, *Measurements of Optical Radiations* SPIE, Vol. 196, pp. 16-26.

Sauer, K., and W. Wilson, 1977. Vegetation indicators for terrain evaluation in prairie environments, *Canadian Geotechn. Journ.,* Vol. 14(4), pp. 445-465.

Schreier, H., and L. M. Lavkulich, 1980. *The use of numerical and remote sensing techniques for terrain mobility assessments,* Contract Report for Defence Research Establishment Suffield, March 31, 1980. 105 p.

Taylor, M. M., 1974. Principal components color display of ERTS imagery, *Proceedings 2nd Canadian Symp. on Remote Sensing,* Guelph, Ont., pp. 295-313.

Thomas, I. L., L. J. Lewis, and N. P. Ching, 1978. Snow field assessment from Landsat, *Photogr. Eng. and Remote Sensing,* Vol. 44, pp. 493-502.

Vogel, T., 1977. *An analysis of Landsat system for cartographic and terrain information,* U.S. Army Topographic Laboratories, Fort Belvoir, Report #9, ETL Series on Remote Sensing, 58 p.

Ward, J., 1963. Hierarchical grouping to optimize an objective function, *Am. Stat. Assoc.,* Vol. 56, pp. 236-244.

White, M., 1978. Reservoir surface area from Landsat imagery, *Photogr. Eng. and Remote Sensing,* Vol. 44, pp. 1421-1426.

Wickwake, G. M., 1979. *Wetland classification and environmental monitoring using Landsat digital data.* Unpublished M.Sc. thesis, McMaster Univ., Hamilton, Ont. 113 pp.

(Received 16 January 1981; revised and accepted 7 July 1981)