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Digital Computer Terrain Mapping from Multispectral Data

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Digital computer processing of 17 wavelength bands of visible, reflective infrared and thermal infrared scanner data has resulted in successful automatic computer mapping of terrain in a Yellowstone National Park test site. Target areas were selected for training the computer. Statistical parameters of radiance such as mean, standard deviation, divergence, and covariance were computed for each category of material. These data were used in the computer program to determine which channels are most useful for recognition of all object categories studied, and to classify all the unknown data points into the known categories. Eight terrain types were mapped with 85% accuracy in a 12-square-mile area with 1800 ft of relief. In addition, studies were made of the effectiveness of the proposed Earth Resources Technology Satellite (ERTS) data channels. These simulations resulted in maps with accuracies of 82%, and indicate that many combinations of 3 or 4 channels of data, including the ERTS channels, are likely to be successful for terrain analysis of a wide variety of categories encompassing a broad range of spectral reflectance.

Purpose and Scope

THIS paper summarizes the preliminary results and current status of studies of digital computer processing of airborne multispectral data, the success of automatic recognition and mapping of the distribution of eight different terrain types, and the effectiveness of the proposed ERTS data channels as compared to the computer-selected best four channels in the automatic recognition and mapping of the same terrain types based on simulations, using the same set of data.

This study involves the data from one flight over a test area of about 12 square miles in a region of moderate relief (1800 ft) comprising a wide variety of terrain types (Fig. 1). The data were acquired and processed in analog form by the Institute of Science and Technology of the University of Michigan, and were processed in digital form by the Laboratory for Agricultural Remote Sensing (LARS) at Purdue University. This paper is concerned only with the preliminary study of the digital processing. The U.S. Geological Survey conducted field studies before, during, and after the flight, and actively participated in the computer processing.

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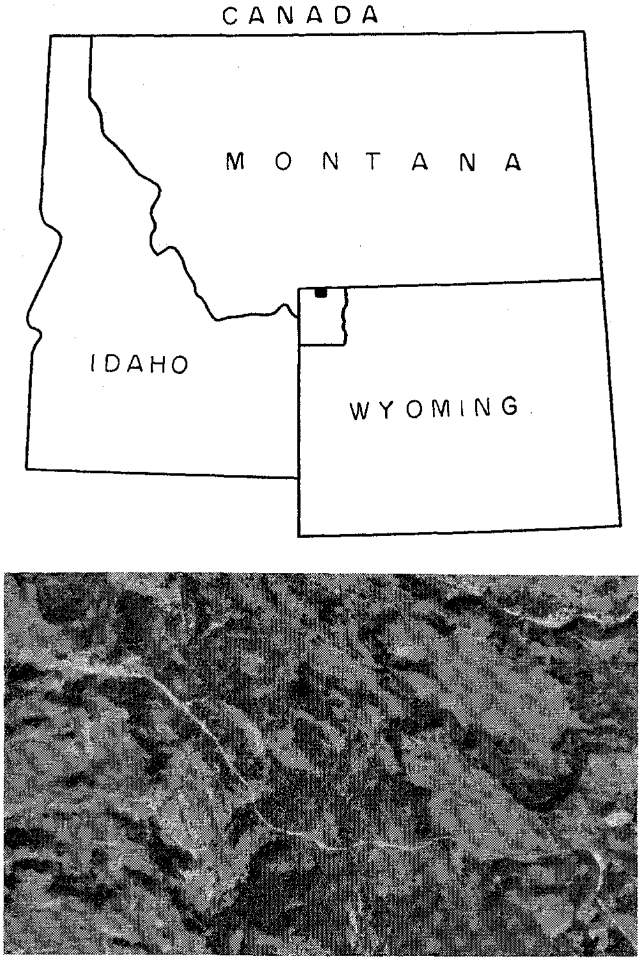

Fig. 1 Index map of test area and aerial photograph of portion of test area in the north-central part of Yellowstone National Park.

Data Acquisition

A multispectral survey was made of selected test areas in Yellowstone National Park during flights by the University of Michigan in September 1967, on a NASA-sponsored contract to the U.S. Geological Survey. The 12-channel scanner in the 0.4 to 1.0 μm range (Table 1) provided the principal data for the computer processing described in this report. In addition, two scanner systems recorded a total of five channels of reflective and thermal infrared data in the region beyond 1.0 μm. A simplified diagram of the scanner spectrometer is shown in Fig. 2.

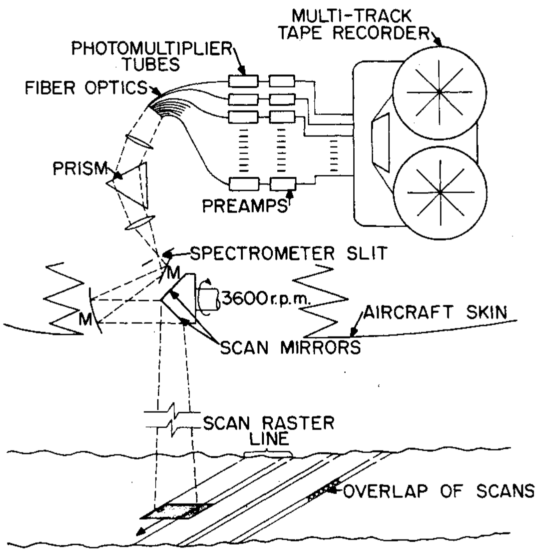

Fig. 2 Diagram of optical-mechanical scanner and spectrometer used by University of Michigan in gathering data for this study. Shaded square indicates ground resolution cell subtended by the 3 mrad scan angle.

Table 1 Wavelength bands of University of Michigan multispectral system

Channel number	Wavelength band μm	Channel number	Wavelength band μm
Scanner No. 1			
1	0.40–0.44	7	0.55–0.58
2	0.44–0.46	8	0.58–0.62
3	0.46–0.48	9	0.62–0.66
4	0.48–0.50	10	0.66–0.72
5	0.50–0.52	11	0.72–0.80
6	0.52–0.55	12	0.80–1.00
Scanner No. 2			
1	1.0–1.4	3	3.0–4.1
2	2.0–2.6	4	4.5–5.5[a]
Scanner No. 3			
...	8.0–14.0[a]		

[a] Denotes thermal infared channels; others are reflective.

As the aircraft flies over the test area (from right to left in Fig. 2) the ground surface is scanned in overlapping strips by successive sweeps as a mirror is rotated at about 3600 rpm. The radiant energy reflected (or, in the case of thermal infrared, emitted) from the Earth's surface is reflected off the rotating mirror and focused, by other mirrors (M), onto the slit of a prism spectrometer, thus refracting the rays into a spectrum.

Fiber optics placed at appropriate places lead to photomultiplier tubes which measure the amount of radiant energy received in each of 12 overlapping bands or channels of this spectrum from 0.4 to 1.0 μm (visible violet to reflective infrared). This energy, which is now a voltage, is fed to a multitrack tape recorder where each of the 12 channels is recorded as a separate synchronized signal on magnetic tape. Similar, separate scanners recorded the infrared part of the spectrum from 1 to 14 μm (see Table 1).

Photographs taken at the same time the scanner data were acquired provide important supplements to the control data—commonly referred to as ground-truth data.‡ These photographs consist of color, color infrared, black and white panchromatic, and black and white infrared film on board the aircraft, and color film from stations on the ground.

Data Processing

Any given channel of magnetic tape data can be reproduced by photographing a cathode ray tube video (C-scope) presentation of the tape data. Alternatively, the data can be processed in digital form by making a digitized copy of the original magnetic tape. This is the procedure used by LARS. The remainder of this report will discuss the LARS method of handling multispectral scanner data, and preliminary results obtained on a section of one flight-line of the Yellowstone Park data.

The amount of overlap of scan lines is a function of aircraft altitude above ground, and ground speed. With this system

‡ Control data or "ground-truth data" refers to all that is known about the site conditions, including types and distribution of materials (determined from conventional field mapping and examination supplemented by study of photographs taken from the air and ground) and measurements of such parameters as temperature, relative humidity, porosity, moisture content, and spectral reflectance of surface materials. Collectively, these constitute the control data with which the test data can be compared.

there is no overlap or underlap at 1000 ft, 50% overlap at 2000 ft and 120 knots. This particular run was digitized in such a manner that, on the average, there was neither overlap nor underlap of adjacent scan lines (Fig. 2). The scanner resolution is 3 mrad, and the aircraft altitude was about 6000 ft above terrain. This required that every 10th scan line be digitized. Also, each scan line contains 220 ground resolution cells. The scanner mirror rotates at constant angular rate whereas the digitizing was done at equal linear rate. This, plus the effects of topographic relief, changes the size and shape of the ground resolution cell from the midpoint to both ends of the scan line. Even so, the average dimensions of the ground resolution cell are approximately 20 $\times$ 20 ft. There is a gap of about 20 ft between cells along each scan line.

The analog data were quantized to 8-bit accuracy. Therefore, each resolution element of each spectral band has one of 256 possible values.

A computer printout of the data from any given channel is made to simulate the analog video display by breaking the continuous tones of the gray scale into a finite number of discrete gray levels by assigning a letter or symbol to each level in accordance with the relative amount of ink each symbol imprints onto the paper. Each of the 15 reflective and 2 thermal channels could be printed as video and/or digital printout images, constituting 17-channel multiband imagery (see Lowe,[1] Fig. 12a and 12b, p. 94 and 95).

It is virtually hopeless to attempt to integrate and evaluate data for each spot on the ground on all 17 images by visual inspection. However, now that the data are recorded as electrical signals on magnetic tape, they can easily be processed electronically in several ways to enhance selected features and to determine the statistical parameters of the spectral radiance (reflectance or emittance) of each category of material in the scene.

In the pattern-recognition method being used by LARS-Purdue, specific, known, target areas in the scene are selected as training areas. The gray-scale printout serves as a base for locating these areas. The area coordinates are fed to a computer system,§ which then computes the statistical parameters of each category of material. These statistics are calculated from the relative response in each channel (Fig. 3). Relative response can be considered as an uncalibrated reflectance measurement, where the lack of calibration between channels allows only relative comparisons of the various categories of materials within each channel. The statistical parameters calculated are based on an assumed gaussian distribution of the data, and include the mean, standard deviation, covariance, and divergence (i.e., the statistical measure of the separability of classes). The results are stored by the computer and are used to represent the multispectral characteristics of each designated category of material. They constitute the multispectral pattern or "fingerprint" of each terrain category, and are used in the computer program to 1) determine which channels are most useful for recognition of all object categories studied and 2) actually classify the unknown data points into the known categories using a gaussian maximum-likelihood decision scheme.

Four channels were used in this study. This decision was based on experience at LARS which has shown that the use of only 4 of the 12 channels in the 0.4 to 1.0 μm range results in approximately as good a classification as does the use of more channels. Computer time, which increases in a geometric fashion with the number of channels used in the classification, is costly; therefore, some optimum for the

§ An IBM 360 model 44 computer with 64K bytes (8 bits per byte) of core storage was used. The principal computer language used was FORTRAN, with ASSEMBLY used for some of the support programs.

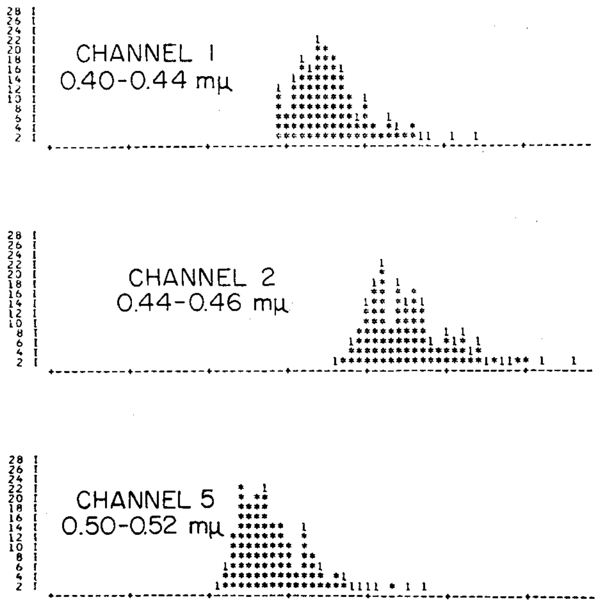

Fig. 3 Histograms of reflectance of talus in channels 1, 2, and 5. The abscicca is relative radiance (brightness), increasing to the right. The ordinate gives the number of resolution elements with a given relative radiance; each * represents 2 points.

number of channels used, the quality of results, and funds expended must be achieved.

The channel-selection part of the computer program provides the capability of measuring the degree of separability of categories and determining the optimum set of channels for doing so. This is done by calculating the statistical distance in N-dimensional space between the classes, N being 12 in this case.

The classification part of the computer program involves the actual classification (mapping) of an arbitrary number of classes using an arbitrary number of channels and a gaussian maximum-likelihood scheme. The display part of the program displays the results in line-printer form, and analyzes the recognition performance in each training area.

A rejection capability is provided in the display process. If the resolution element does not exceed a preset threshold, that is, if the element does not look sufficiently like a member of the class to which it has tentatively been assigned even though that is the most likely class, then final classification of that element is declined and that element is assigned to a null category (rejected) and displayed as a blank. Different thresholds may be assigned to each of the classes individually.

When coordinates of other known areas (test areas) are fed to the computer, the computer determines the classification of those areas and computes the accuracy of classification. Appraisal of numerous test areas gives a more complete and meaningful evaluation of the over all recognition performance of the computer program.

Results of Digital Computer Processing

Computer-Selected Best Set of Four Data Channels

A terrain map (top section, Fig. 4) was generated by the digital computer on the basis of 4 channels selected from 12-channel scanner data and the statistical definition of classes provided by the training areas. The part shown is composed of 6724 data points—about 2.5% of the full map. The full map covers an area of about 2 $\times$ 6 miles and is composed of 269,060 data points. Eight terrain categories were selected arbitrarily, not on the basis of composition or genesis, as we traditionally do in the course of geologic mapping, but on the basis of their over-all surface color and brightness inasmuch as that is what the sensor was recording.

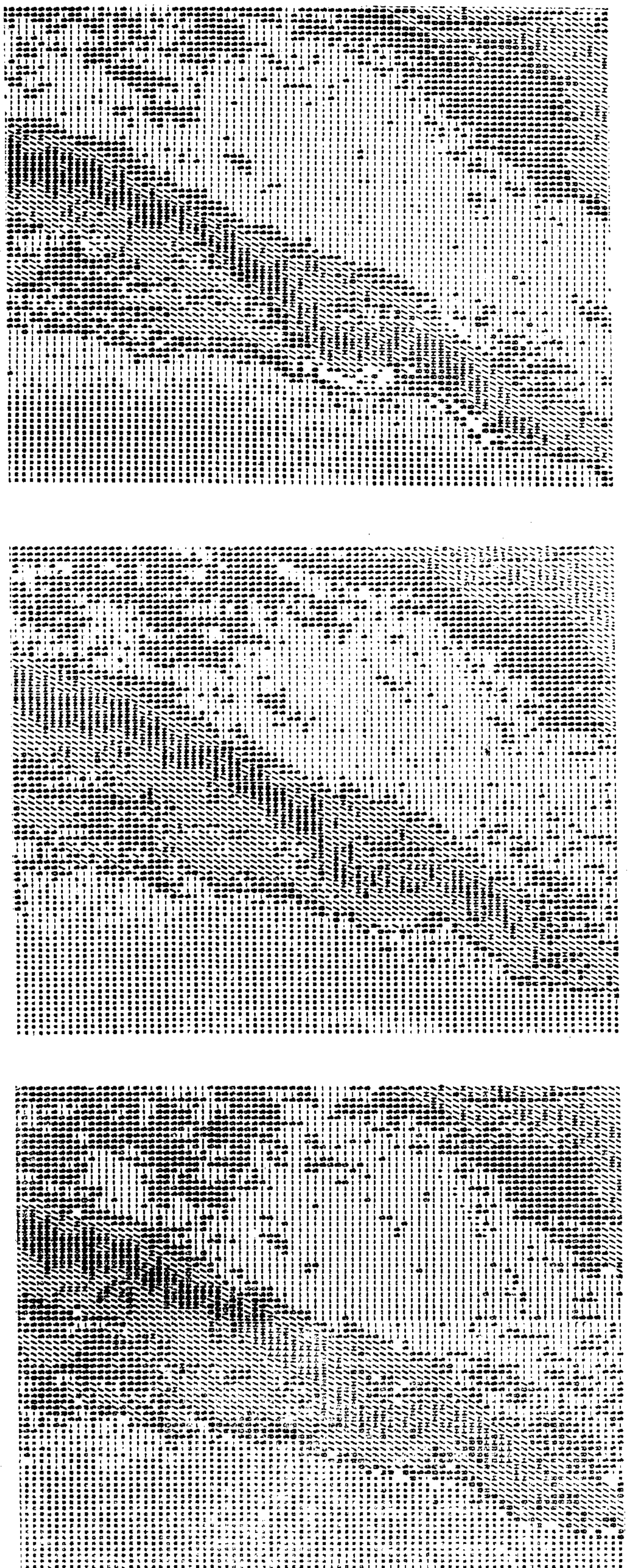

Fig. 4 Small segments of the terrain maps. Upper map was obtained by using the computer-selected best four channels of reflective data; the middle map by using a simulation of the ERTS 4-channel scanner; the lower map by combining thermal and reflective channels of data. Length of each segment is about $\frac{3}{4}$ mile on the ground. South is to the top. Symbols used to designate the terrain units are: . bedrock exposures, \$ vegetated rock rubble, = glacial kame, − glacial till, ′ bog, 8 talus, / forest, W surface water, H shadows, and (blank) thresholded.

For example, geologists are more interested in the areal distribution of a sand and gravel unit, such as glacial till, than in the distribution of forest. Conventional maps would show the extent of till regardless of whether it was the site of a meadow or was covered with dense forest. The terrain units of this study necessarily show the unforested till as one unit (till) and the forested till as a different unit. In fact, all forested terrain, regardless of underlying rock or soil unit, is shown as a single unit.

Initial processing disclosed that at least 13 categories could be separated. Several of these were subunits which were later combined to make the maps shown in Fig. 4. The following is a brief description of the 9 categories (including shadows) mapped, and the accuracy of the computer classification as compared with the control data.

1) *Rock*—bedrock exposed by erosion and mantled by minor amounts of loose rubble. These are unvegetated except for lichens and sparse tufts of dry grass, and have high reflectance in nearly all channels. This category was moderately well classified. Where misidentified, it generally was classified as vegetated rock rubble—a closely similar unit into which it grades.

2) *Talus*—talus and blockfields of basalt lava flows, volcanic tuff, and gneiss, formed by frost-riving and solifluction from outcrops. These are blocky and well-drained deposits; trees are widely spaced or absent. Blocks generally are covered with dark-gray lichens. The blocks range from a few inches to a few feet in diameter; most are larger than 3 in. The slopes range widely, from 35°–45° at the head, to 5° or less at the toe. All of the known and a few previously undetected areas of this unit are clearly delineated.

3) *Vegetated rock rubble*—locally derived angular rubble, frost-riven from bedrock. Grasses, lichens, evergreen seedlings and mosses now cover more than three-fourths of the surfaces underlain by this debris. Blocks range in diameter from less than 1 in. to several feet and occur on slopes of from 0° to about 25°. The general areas classified are realistic, but in detail this unit is the least well classified. Because of the small size of the individual areas occupied by this unit, it is not possible to locate precisely a homogeneous training area.

4) *Glacial kame*—meadow areas underlain by sand and gravel, and mantled by sandy silt. These deposits are well drained and are vegetated by grass and sagebrush. About one-fourth of the area of this unit is exposed mineral soil. Deer and elk manure locally covers as much as one-fourth the surface area. Areas of kame meadows are accurately depicted. Areas of forested kame sand and gravel between open meadows of kame were erratically classified by the computer, mostly as other units. Control data show that in some places this unit occurs as small scattered patches surrounded by till; in those places it was misidentified by the computer.

5) *Glacial till*—meadow areas underlain by glacial till. These are grassland and sagebrush areas (largely dormant at time of flight) with mineral soil exposed over about one-fifth of the area. Mineral soil consists of mixtures of silty to bouldery debris. Deer and elk manure locally is abundant in these meadows. This unit was first classified as four separate subunits on the basis of change in illumination across the flight path, but the four were later combined into one unit for the map printout. Classification is ~95% accurate over the entire flight strip. The other classification symbols scattered throughout areas of this unit generally are correct, for there are small areas of vegetated rubble and of bogs in meadow areas underlain by till. Although both the till and kame deposits are the sites of meadows, the differences in amount of soil exposed and the subtle differences in soil composition and texture apparently permit these two categories to be accurately distinguished by the computer.

6) *Forest*—Douglas Fir and lodgepole forest. Local clusters of deciduous trees were recognized separately, but combined with evergreens in this display. This forest unit

generally is well recognized in large almost uniformly patterned blocks. All forest areas seem to be consistently recognized.

7) *Bog*—moist areas supporting tall lush growth of sedges and grasses. Bogs are rather abundant because of glacial scour and derangement of drainages. This is one of the best recognized units. All known bogs and many previously unknown small bogs were correctly mapped.

8) *Surface water*—Though not shown on this segment of the map, the Yellowstone River and Floating Island Lake were clearly recognized. Phantom Lake was dry at the time of flight, and so was correctly classified as bog rather than water. Parts of the Yellowstone River were omitted or generalized, principally because the width of the river is near the threshold of resolution, and because some data points were integrated values of river plus some other category or categories. Stretches of white-water rapids were rejected. In places, the shaded north edges of patches of forest were printed as scattered points of water or talus.

9) *Shadows*—Cloud shadows are near west and south-central margins of the test area, and deep shade occurs at base of north-facing cliffs and along north edge of forest areas. All were recognized well.

10) *Other*—All data points whose reflectance did not closely fit the statistical data for any of the above nine categories were rejected, and shown as blank regions on the map. A few of these are very light and bright areas of shallow water where bottom deposits show through or are white-water rapids and gravel bars. A blacktop road can be detected in places as a line of anomalous mixed colors, but is not consistently recognized as any particular category. The road is about as wide as a single data point and hence is at the threshold of resolution. Although all bedrock types were classified as a single unit, the spectral reflectance histograms, spectrograms, and the divergence data indicate good possibility of distinguishing among several of the rock types present. Further testing over areas of larger rock exposure seems justified.

Thermal Overlay

Another aspect of the work underway is a terrain classification made by substituting one or more data channels from the infrared scanners (1.0–14 μm) for those of the 12-channel scanner (0.4–1.0 μm). For this test, channels 1, 3, 5, 7, and 9–12 of the 12-channel scanner were combined with the 1.0-14-μm, 2.0-2.6-μm, 4.5–5.5-μm, and 8–14-μm channels. A computer program recently developed at LARS made it possible to overlay the data from these two separate scanner systems. The computer selected the best set of four of these channels for classification of the terrain in the same manner as before. The maximum mismatch of registry is no more than three ground resolution cells, and probably is mostly no more than one cell.

The map on the bottom of Fig. 4 is the result of overlaying one thermal and three reflective channels (0.66–0.72, 0.80–1.0, 2.0–2.6, and 8–14 μm). Only one of these channels is in the visible range. The close correspondence of this display with the others indicates the accuracy of classification.

These studies should enable us to further extend the range of potential diagnostic spectra for existing categories and may point out some additional terrain categories. In addition, they will be useful tests of how well computer programs can take data from different scanner systems and automatically overlay them to produce a single set of multispectral data.

Simulation of ERTS Data Channels

Along with the studies of evaluating the accuracy of performance, we are studying how well data in wavelength bands tentatively designated for the proposed ERTS might serve for automatic mapping of the same 8 terrain categories in the same area. The midpoints of the channels of the proposed ERTS 4-channel scanner, and the peak transmissions of the three Return Beam Vidicom (RBV) cameras were matched with the closest channels of the University of Michigan 12-channel scanner. These data are summarized in Fig. 5. The classification using the *simulated* ERTS 4-channel scanner is shown in the middle display in Fig. 4. Note the close agreement with the top display; that based on the computer-selected best set of four channels.

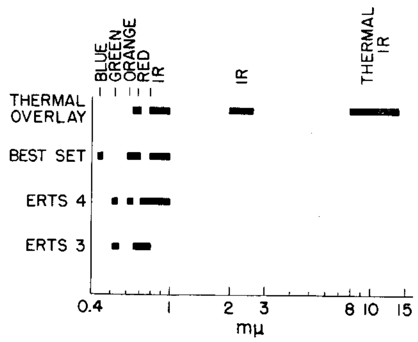

Fig. 5 Comparison of wavelength bands used in the computer study.

Accuracy

In general, the products are highly satisfactory terrain maps which portray *physiographic units* or *rock-soil-vegetation association units.* Accuracy is determined by comparing the computer-generated maps with the ground control data. Where terrain categories were areally extensive, they were correctly identified by the computer. Most inaccuracies occurred where the units were small and where some were below the threshold of resolution; accordingly, the radiance for a given resolution cell was a complex combination of several categories. Presumably, the computer usually selected the dominant terrain unit or, by rejecting, indicated that the spectral properties did not clearly fit any of the classes.

For comparison of the performance of classification using the ERTS simulations with the best sets of 4 channels, the computer rated itself in the training areas only. For example, of the total of 5418 data points used in training the computer, less than 20 of those were subsequently classified (using the best set of 4 channels) as something other than what they were called during the training. Ratings for the training areas and those for test areas give the over all performance recorded in Table 2.

The drop in accuracy from 99% to 86%, etc., from the training to the test areas, is understandable, because we would expect the computer to perform well in the areas where it was trained (by circular reasoning), unless the reflectance of two or more categories were closely similar in all channels used.

The ratings for test areas are the most meaningful, but these figures should be taken as approximations only. They agree with a preliminary visual estimate that the over-all accuracy of all displays is more than 80%, and indicate that the best set of 4 channels gives slightly better results than the other 3 displays, all of which are about equally good.

Table 2 Ratings for training areas and test areas

	Training areas	Test areas
Best set of 4 channels	99.6%	86%
Thermal overlay	98.8	81
ERTS 4-channel scanner	97.7	83
ERTS 3-RBV cameras	93.8	82

For the training areas, the classification made using the overlay of thermal and reflective channels was virtually as accurate as the best classification—that using the computer-selected best set of 4 reflective channels (98.8% vs 99.6%, respectively). However, for the test areas, the thermal overlay was least accurate (about 81% vs 86%). The slight mismatch of registry in parts of the thermal overlay test undoubtedly results in a less accurate classification than if all channels were in complete registry, as would occur if a single scanner system could cover the range of 0.4 to 14 μm or more.

Nevertheless, these studies indicate that the infrared region is promising in the classification of some terrain units. For example, in the test areas the thermal overlay classification was better than the computer-selected best four channel classification for glacial till (95% vs 93%), glacial kame (82% vs 74%), and bog (81% vs 80%). The accuracy of classification of talus in the test areas was only about 49%; however, most of the error was due to talus being misclassified as vegetated rock rubble—a unit which actually is quite similar to talus. If talus and rock rubble are combined as a single unit, the accuracy jumps to about 83%, whereas the same combination was classified only about 76% when using the best set of 4 channels in the test areas.

In geologic applications it is more desirable to know what kind of material the forest is growing on than simply to know where the forest is. The thermal overlay classification has some potential in this regard; it has been shown[2] that thermal infrared in forest areas can in places indicate the sites of thick, unconsolidated, well-drained gravels vs bare or thinly mantled bedrock.

An obvious advantage of infrared data channels for space applications is the haze penetration ability. Further investigations are needed to adequately assess the potential of these channels, particularly over areas of extensive rock outcrops.

Studies presently underway also include careful evaluation of the over-all accuracy by point-to-point comparison with control maps. It is important to recall the recognition of previously undetected areas of occurrence of some terrain units. This means that errors in the control maps are being detected at the same time errors in the computer printout are being sought.

In general, the ERTS simulations differed from the computer-selected best 4 channels as follows:

1) For areas correctly shown as forest on the classification using the best 4 channels, the ERTS 4-channel classification showed small to moderate amounts of talus and water, whereas the RBV 3-channel classification showed greater amounts.

2) In places both ERTS classifications showed considerably more bogs than are present in areas that were correctly classified by the best 4 channels.

3) Slightly poorer classification of water was performed in the ERTS classification. However, few of the bodies or areas of water in the test area are of sufficient size to serve as good training areas, so we do not view this part of the classification as a good test of the ability of the ERTS data channels to permit automatic identification of water.

We wish to point out that these are not complete simulations of the ERTS data channels, but are only first approximations, because we have not attempted to simulate 1) the poorer resolution of the satellite sensors due to vast difference in scale, 2) the effects of atomspheric attentuation, or 3) the broader wavelength bands of most of the ERTS sensors. Studies presently underway at the University of Michigan are aimed at more closely simulating the actual wavelength bands of the ERTS sensors.

We further emphasize that all of the experiments, including the simulations, are based on only one set of data along 6 miles of traverse. However, the fact that these data were not gathered under optimum conditions¶ means that the accuracy of detection and the number of detectable terrain categories are apt to increase for data gathered under conditions closer to optimum.

The results of these limited experiments on a single set of data, taken together with the vast store of accumulated data from studies of agricultural crops, demonstrate clearly that multispectral terrain analysis can separate a wide variety of categories encompassing a broad range of spectral radiance, and that the data channels selected for ERTS are likely to be about as successful for terrain analysis as any other combination of channels that might have been selected.

Application

In spite of how well the computer was able to classify and map this test area, an experienced interpreter could have done as well or better with stereopairs of color and color infrared aerial photographs, for (among other things) he has the ability to distinguish objects on the basis of spatial in addition to spectral patterns.

For several years now there have been discussions and expressions of concern about the neeed to examine vast areas of the earth's surface, the desirability of satellite-borne remote sensors to gather the needed data, and at the same time concern for the appallingly vast quantity of data that are needed and that would become available from satellites. Handling these data will require automatic processing by computer—not to make the final and only decisions of classification, but to perform the first rough culling and reconnaissance interpreting, calling attention to special places that warrant examination by a human interpreter. For, although in general a human can do a better job of interpreting, the computer can do it much faster. It's simply a matter of data compression.

It is with this need in mind that we have engaged in this study of automatic data processing by computer that includes 1) testing the suitability of existing sensors and computer software, 2) determining how many and what kinds of natural and manmade terrain elements can be satisfactorily classified in this particular climatic region, and 3) simulating the spectral response of the proposed ERTS sensors.

The existing scanners of the University of Michigan are basically well suited for these studies. Satellite application will, of course, require miniaturization, including combining the present three separate scanner systems into one that covers the range 0.4-14 μm or more.

The existing capabilities of classification programs developed at LARS-Purdue are equally well suited for these studies of automatic data processing. Their programs were established for agricultural purposes to work with the University of Michigan multispectral scanner data. Our present studies principally involve an extension of their work into

¶ The data were gathered at about 2 p.m., September 19, 1967 along a nearly east-west traverse at about 6000 ft above mean terrain elevation. No appreciable rain had fallen for several weeks; therefore the ground was very dry. To minimize shadows and illumination-angle variations, it would have been better to fly at midday along traverses directly toward or away from the sun's nadir (roughly north-south). Flights at higher elevations above terrain would also reduce variations in illumination angle and scale; however, there probably is some altitude (not yet determined) above which the advantages gained in more-uniform illumination angle and scale might tend to be canceled by the adverse effects of the thicker column of atmosphere between the ground and the sensors. Flights made shortly after a rain would have been better to emphasize or detect differences in soils on the basis of their porosity and permeability as manifested by relative content of moisture. Flights earlier in the summer would have been better to emphasize differences in vegetation and, probably, in soil moisture.

another kind of terrain—one that presents something other than row crops in flat fields.

All four of the experiments (three of which are displayed in Fig. 4) produced good results. They are good classifications. We don't wish to set any specific limits on how good "good" is. Obviously, some are better than others, and none is perfect, but neither is the manmade control map. We are convinced, however, that all can be considered as more than adequate for the reconnaissance first-approximation kind of interpreting and mapping which we expect to accomplish with the satellite data.

If we examine the spectral range spanned for each of the displays (Fig. 5), we see that they vary by a factor of nearly 50, from 0.28 μm for the 3-camera ERTS system to 13.34 μm for the thermal overlay classification. This implies that, for a broad range of terrain categories, many combinations of 3 or 4 channels of data in the 0.4-14 μm range would be satisfactory. More complete simulations, in which the effects of the atmosphere are considered, undoubtedly will require identification as to what channels would be more suitable. For example, the haze penetration ability of some reflective infrared channels, mentioned earlier, is an obvious advantage for satellite applications, whereas the blue part of the spectrum is apt to have low signal-to-noise ratio and therefore be of limited use except for oceanography. We need worry about careful selection of specific wavelength bands only if a specific category is being sought. Inasmuch as the ERTS program is aimed at covering many scientific disciplines and user groups, hence involving many terrain categories, the highly specific requirements are not now pertinent to tests of the suitability of the proposed satellite sensors.

We believe that the concept, rather than the specific immediate results, is the most important product here. It is not really important to find that talus occurs on the shore of a lake here or that a narrow bog lies there; the important point is that eight or more widely different terrain units could be accurately mapped automatically. In fact, we believe that these particular maps (Fig. 4) are overclassified in comparison with what we will want to attempt from space, at least for our first attempts. It may well suffice to map out such features as water, vegetation, bare soil, and rocks, and to interpret other things, such as geologic structure, from the resulting patterns and their relation to topography.

Especially significant applications in geology and other fields will be for those features that change with the seasons or with a few years' time; the areas of change can be periodically mapped automatically in terms of material, location, and the amount of area changed. We suggest that economically feasible geologic applications will include those that contribute to regional mapping, engineering geology, hydrology, and volcanology. Other applications may be in the fields of agriculture, cartography, land-use and land-management studies, and in still other fields in which seasonal and other changes are more rapid than in most geologic applications. In many fields, these data will become more useful by combining them with other (nonspectral) data, such as the engineering or military application to trafficability studies, combining these terrain data with slope (from radar images or topographic maps).

The fact that we are sensing surface material emphasizes the need for multidisciplinary approach to terrain mapping because the surface involves the complex interplay of at least bedrock and surficial geology, hydrology, soils, vegetation, and meteorology. Traditionally, in mapping many regions of the earth, we interpret the geology secondarily from the patterns of other materials and features.

Cost Statement

The cost of computer time and for digitizing of analog data was about $7400. The cost of the entire multispectral survey, of which the present test site is a small part, was about $26,000. Salaries of research personnel are not included in these cost estimates. In view of the fact that these studies are research- and development-oriented, it is impractical to attempt to establish costs for man-hours involved. Years of work and research are represented in the developing and continual refining of the scanner systems used in gathering the data and the computer programs used in processing the data.

Now that the geologists and the computer specialists have experience in working together as a team, with this kind of data, it is likely that the costs would be somewhat less for such a study of similar terrain elsewhere.

References

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More detailed information on optical/mechanical scanners and the various techniques and computer programs described in this report can be found in the following:

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