

# MULTISPECTRAL SCANNING SYSTEMS: THEIR FEATURES AND LIMITATIONS

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Multispectral sensing is a space-age development made possible through a number of technological developments, improved optical-mechanical technology, advances in solid-state detectors and electronics, advances in data handling and recording techniques, and widespread use of computers. Multispectral sensing has the potential for surveying large areas in a short time and for classifying features automatically on the basis of their spectral characteristics. That some classification based on spectral information is feasible is not questioned. Rather the question is, How fine can one carry out the classification process with a given level of complexity? That is, What are its limitations?

•THE INFORMATION in the radiation from a scene is derived from spatial distribution, spectral distribution, temporal variations, state of polarization, and variation of these parameters with the angle of observation.

By their very nature, image-forming sensors produce graphic representations of the spatial distribution of the radiation from the scene. Interpretation of such imagery relies heavily on shape recognition of key elements within the scene and on some analysis of tone. And, to be sure, some sensors take advantage of the spectral distribution of the target and background radiation in order to increase the contrast between objects and backgrounds by selecting optimum film-filter combinations (spectrozoal photography). The relative tone of objects within the scene of spectrozoal photography has proved to have limited usefulness, however, in the differentiation of types of forest plantations, classification of soil, classification of land use, early detection of some crop diseases, and identification of agricultural crops (1, 2, 3, 4, 5, 6, 7). In all instances, a rather limited specific wavelength region is used where gross spectral differences occur among the objects or effects being sought and their backgrounds.

Although quantitative evaluation of tonal variations in single-band imagery has many limitations (1, 2, 3, 4, 5, 6), it does offer a limited means for the automatic interpretation of some types of imagery. An example is in agriculture, where seasonal planting and growth cause fields to undergo dramatic changes as a function of time (7).

In many remote-sensing applications with extensive coverage, identification through shape from high-resolution imagery requires too large a data bulk. Consider satellite photography of the United States with 2-ft ground resolution, for example. It would take roughly 3,000 lb of film to produce this coverage, and it would take a 10-MHz telemetry link 120 days to transmit this information to earth. If some identification can be done on the basis of spectral information, it may be possible to reduce the sensor resolution requirements. In agricultural sensing for survey purposes, one wishes only to know what a farmer has in a field. Resolution of the crop structure itself is not feasible for large-area coverage, but it may be possible to distinguish the crop with a low-resolution system on the basis of its spectral signature. If such a detection is possible, a ground resolution of 200 ft might be adequate—in which case the resulting imagery of the United States could be recorded on  $\frac{1}{3}$  lb of film and the telemetry time reduced to about 17 min.

Although spectrochemical analysis is widely used in the laboratory for identifying materials and spectrophotometric techniques are used for process control and sorting, these techniques have not received widespread use in field applications such as identi-

fication of terrain features or conditions. The reluctance to use them is largely attributable to the lack of controlled conditions associated with field operations; e.g., meteorological conditions affect the radiation received by a remote sensor, and nature produces variance within a given class of material. Notwithstanding these limitations, spectral reflectance and emittance observations made largely by earth resource scientists indicate that moisture stress in plants, vigor of vegetation, land use classification, mineral identification, and crop and soil identification are possible under limited conditions of observation (8, 9, 10, 11, 12, 13). These measurements are not confined to the photographic region, and most are being made by nonimaging sensors.

### MULTISPECTRAL SCANNER

Modern technology makes it possible to build imaging sensors to operate in almost any region of the electromagnetic spectrum. Scene elements or features that are not contrasted in one region of the spectrum can often be contrasted in another region. As a result, many users of remote sensing have resorted to using multiple sensors in order to obtain the information they are seeking. This approach is a mixed blessing because the interpreter of this multichannel imagery must now intercompare corresponding scene points in the various images in order to obtain the desired information. The multichannel imagery approach places an added burden on the interpreter, who is already the limiting link in the information system's throughput. The multispectral scanner offers an approach that can automate the process of analyzing the spectral radiation characteristics of each element in the scene and of making judgments based on this information.

There are a number of ways to implement a multispectral scanner. The technique preferred for many band operations is that which combines an airborne line scanner with a multichannel spectrometer (14). In an airborne scanner the ground is scanned in a systematic manner, as shown in Figure 1, and the measured radiation is graphically displayed or recorded. The detector is used as the field stop, and a filter is placed in the radiation path to limit the wavelength of operation to the particular wavelength region of interest (usually 4.5 to 5.5  $\mu\text{m}$  or 8 to 14  $\mu\text{m}$ ). Instead of rejecting this "unwanted" radiation with an optical filter, a multispectral scanner uses the entrance slit of a multichannel spectrometer as the field stop (Fig. 2), and all of the radiation passes through the spectrometer. In such a system, each detector of the spectrometer observes the same resolution element of the scene but in a different wavelength region.

The output signal from each detector element is a video signal corresponding to the scene brightness in the particular wavelength region of operation. This video signal can be used to generate an image of the scene in the wavelength region, which is defined by the position of the detector in the spectrometer. The output signals from multiple detectors can be combined to determine the spectral distribution of the radiation from each scene point. This spectral information then can be used selectively to enhance or suppress the brightness of objects or materials in a scene on the basis of their spectral radiance. Thus, the multichannel video data can be fed to a signal processor that is designed to generate a single video signal where intensity, for example, is a function of how closely the spectrum of a scene point corresponds to a spectrum being sought.

Figure 3 shows a schematic of a multispectral scanning system configured as a research tool. In addition to measuring the radiation from the scene, the scanner observes calibration and reference sources. The data from the various channels are registered in both time and space and are recorded on tape for analysis and processing in the laboratory. One of the more sophisticated multispectral systems has been built by Bendix for NASA to be used in support of NASA's earth observation program (15). The scanner operates in 24 spectral bands between 0.32 and 13.5  $\mu\text{m}$ . Figure 4 shows the airborne scanner subsystem, and Figure 5 shows the ground data subsystem used for screening, editing, analyzing, and processing the tape-recorded data.

Figure 1. Line scanner.

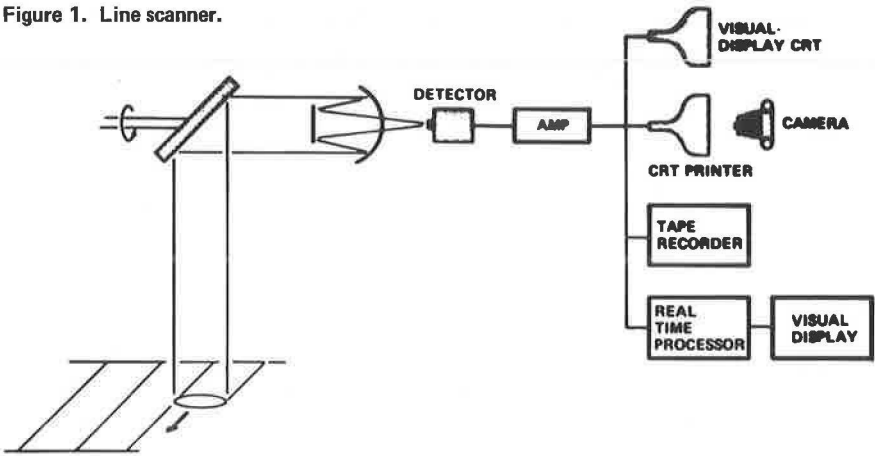


Figure 2. Dispersing multispectral scanner.

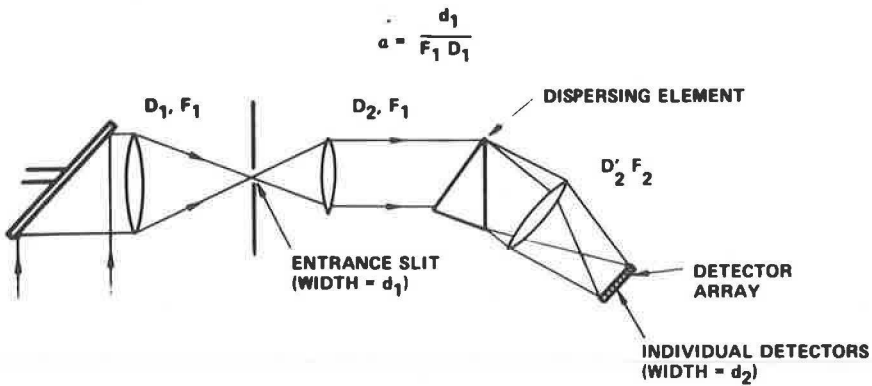
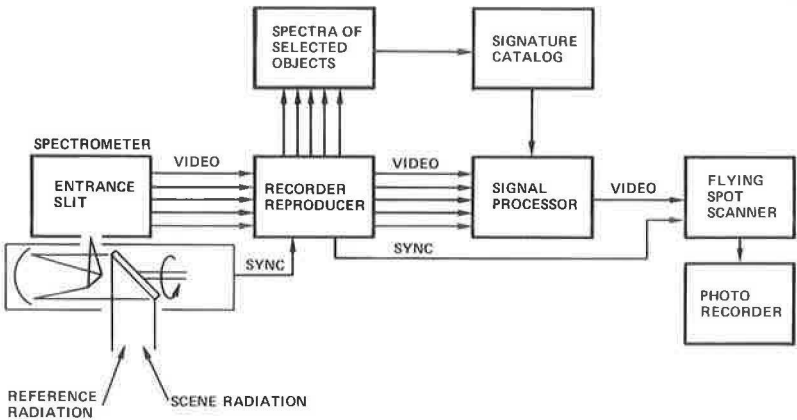


Figure 3. Multispectral scanner and data processor.



## EXAMPLES OF MULTISPECTRAL APPLICATIONS

The potential of multispectral scanners for probing the environment around us and for assessing the allocation of natural resources available to us is constrained at present by the relatively limited research into applications of the techniques. Although such research is being conducted by a number of investigators, the applications-oriented research has been limited in scope by the few multispectral scanners and ground data processing stations available. Multispectral scanners are currently being flown by the University of Michigan, the Bendix Corporation, and the NASA Manned Spaceflight Center (MSC). Ground processing stations are currently in use at the Purdue University Laboratory for Applications of Remote Sensing (LARS), the University of Michigan Institute of Science and Technology, the Aerospace Systems Division of the Bendix Corporation, and MSC. A ground station for processing multispectral data from the ERTS satellite was delivered to NASA/Goddard last fall (16). Thus, although the availability of such equipment is still limited, a number of new equipments will be available in the near future.

The major advantages over manual photo interpretation expected from multispectral scanners include relatively rapid assessment of large areas and/or detection and enhancement of relatively subtle spectral variations, among features using statistical analysis techniques. The processed data output can be presented to the user in a number of ways, of which some representative examples will be shown.

The first example is a computer-generated classification map on which printer symbols are used as the target identifier (17). The data were gathered with the University of Michigan 18-channel multispectral system in May 1967. Aerial photography was also collected for comparison with the processed scanner data. The purpose of the program was the automatic mapping of soil surface conditions. The test area was in Morgan County, Indiana, near Bloomington. The left half of Figure 6 shows an aerial photograph of a portion of the test area. The multispectral scanner data were processed by the LARS data processing facility to yield the computer printout shown on the right half of the figure. The computer was programmed to distinguish bare soil from all other targets and to print only target cells in the data recognized as soil. In addition, the computer was programmed to recognize dark and light patterns in the soils. These categories of soil patterns were printed as dark, medium, and light soils. The process could be continued until the number of levels desired by the user was obtained or until the noise limitations inherent in the data were reached, whichever occurred first.

Processing of multispectral scanner data is not limited to the digital computer approach. Analog processing techniques may also be used to yield similar results, and analog-digital hybrid techniques may be used. An example of processed multispectral scanner data using analog techniques is shown in Figure 7; the left half of the figure shows an aerial photograph of part of the test area, and the right half shows processed multispectral scanner data (18). The data were collected on March 24, 1969, near Lake Charles, Louisiana; a Bendix 9-channel multispectral scanner was used. The program was sponsored by the Geographic Science Division, U.S. Army Topographic Laboratory, Ft. Belvoir, Virginia. The purpose of the program was to develop techniques for automatic detection and classification of construction materials. The output of the Bendix data processing facility was in the form of a color-coded image consisting of 3 target classes: water, colored blue; sand, colored brown; and vegetation, colored green. The reproduction here is a black-and-white copy of the original color image. The classification was performed by the use of a hybrid technique: The determination of the method of processing to be used was performed in a digital computer by using samples of the target categories from the scanner data for "training," while the actual data processing was performed in an analog data processing facility and was based on the results of the computer analysis.

The 2 types of processed data presented above are called "decision imagery" because the processing system made a decision as to the most likely target material present in each scanner resolution cell and produced only the results of that decision in the form of a target identification. In this type of presentation, the target is presented as a



Figure 4. NASA 24-channel airborne multispectral scanning system.

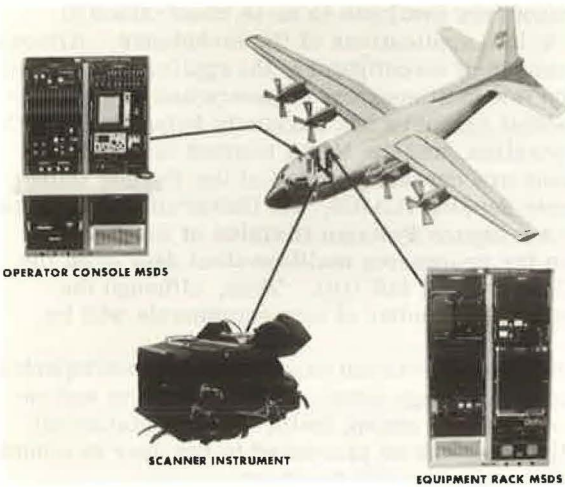


Figure 5. 24-channel scanner subsystem for data analysis.

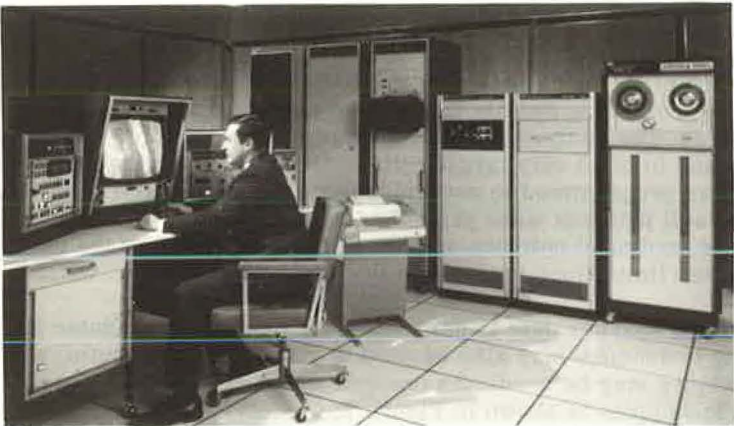


Figure 6. Aerial photograph and computer printout of dark, medium, and light soils.

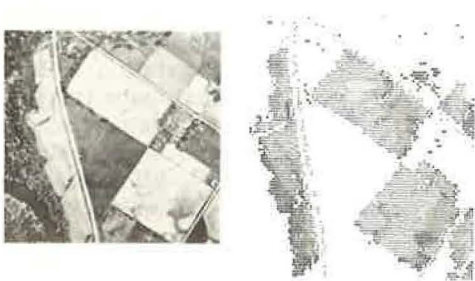
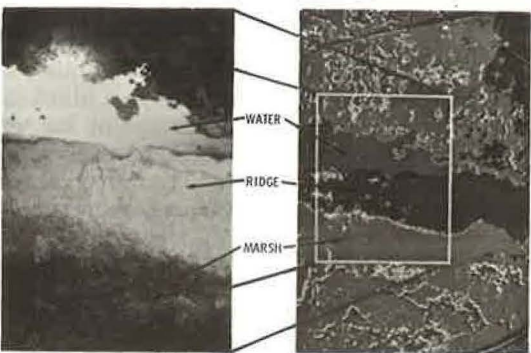


Figure 7. False color classification of multispectral data from computer analysis.



symbol or a color with no tonal variations or gray scale. The processed results can also be presented as "enhanced" imagery, where tonal variations represent the probability that the imagery contains the desired target material. The imagery can be presented as black and white for a single target type, or it can be presented as different colors for multiple targets and the color saturation can indicate specific target category probabilities. Color enhancement can also be used to accentuate subtle variations in the imagery for easier interpretation by the investigator. Examples of enhanced imagery are not shown in the text because of the limitation of black-and-white offset reproduction.

Digital processing techniques are not limited to computer printout presentations. Digital processing systems can be built, and do exist, that drive a color film recorder with presentations similar to that of analog systems. The principal advantages of digital systems that use general-purpose computers are programming flexibility and, if the data are available in the form of computer-compatible magnetic tapes, wide availability of existing large-scale computer facilities. The principal advantages of analog processing systems are real-time, high-speed processing and lower facility cost. The mathematical basis for performing the processing and the statistical analysis theory on which the processing is based are similar in both cases.

Although the advantages of automatically processing data from large areas of terrain have been cited and the system does exist as a potential, most research conducted to date has consisted of feasibility demonstrations using data from small areas. Use of the techniques has been confined to small-scale feasibility demonstrations both because of the paucity of suitable equipment and because of the limitations in reducing the techniques to operational procedures. These limitations can be discussed in terms of the parameters that affect classification accuracy.

#### PARAMETERS AFFECTING CLASSIFICATION ACCURACY

In the examples of processed multispectral imagery previously presented, a number of common factors exist. In both the color imagery and the computer line-printer imagery, the observables of interest could be easily sorted into 3 distinct classes: vegetation, water, and soil (sand in the color imagery). In the Purdue line-printer imagery, the additional classification of soil tone was performed within the target class soil. In both examples, the variations between target classes were large compared to variations within the individual classes themselves; consequently, the classification could be performed with a high degree of accuracy and a low false alarm rate. Regardless of the application or use to which the data are being put, 2 conditions must exist for automatic classification of target categories:

1. The target classes must be separable in the data as seen by the collection instrument, and
2. The variations within the target classes must be small relative to the variations among target classes.

Before describing environmental, instrumentation, and background effects that affect these 2 conditions, let us illustrate the 2 conditions with an example. The color imagery shown previously was generated from data collected with the Bendix 9-channel multispectral scanner. For computer analysis, "training samples" were selected from the desired target categories in the imagery to determine the methodology to be used in the analog data processing. For the example, only the first 8 channels were used in the processing. Figure 8 shows the means and the standard deviations for the 3 target categories arranged as 8-channel spectra of the targets. To increase the ease of separation of the 3 target categories, a coordinate rotation of the 8-channel data was performed that concentrated the characteristics for separating the target categories into a limited number of synthesized channels (18). It is beyond the intent of this paper to go into the details of automatic data processing; therefore, the details of the coordinate rotation will not be discussed. Figure 9 shows the 3 target categories in the rotated coordinate system, again with the means and standard deviations of the target categories. For the first 2 channels, the variations within target classes are

small compared to the variations between target classes, and the target classes are separable. This meets the 2 conditions specified for classification. (The 2 conditions were not met in the raw data; an important function of the data processing is to manipulate the data so that the 2 conditions are satisfied.)

Figure 10 shows the data points of the training set corresponding to the first 2 channels plotted against each other. The data points fall into "clusters." The color imagery shown was generated by electronically generating classification windows and assigning a color to each of the windows. The white areas in the imagery are data points that fell into none of the windows. Some of the nonwindowed data points are targets that did not fall into the 3 categories of sand, marsh, and water (such as roads and artifacts), while other data points were targets of the desired categories whose radiation characteristics did not, in fact, fall within the expected window. For discussion purposes, let us assume that the imagery contains only the 3 target categories and that all points that fall out of the windows are misclassifications. What are the factors that cause misclassification of the data?

Ideally, it would be desirable for target categories to fall in small, closely knit groups with different target categories widely separated from each other. In actuality, this does not occur for a number of reasons. There are 4 general sources of variance in the data:

1. Poor correlation between the observables and the desired target categories,
2. Variations within the target categories,
3. Environmental effects, and
4. Instrumentation effects.

The first source, poor correlation between the observables and the desired target categories, is the only source that determines the inherent ability to distinguish between target categories and that can be regarded as related to the separation among the means of the target clusters. An inherently distinguishable set of targets can be degraded by other factors, in effect, by increasing the size of the target clusters through other sources of variance until the clusters are overlapped beyond distinguishing. An important first step in a feasibility investigation should be to determine with laboratory measurements, field measurements, or other means that the targets in question have sufficient signature or spectral differences for classification. It must also be borne in mind that multispectral scanners detect only surface phenomena. If detection of phenomena beneath the surface visible to the scanner is desired, there must be a correlation between the subsurface phenomena and the surface effects, and the correlation must be established. The methodology of data processing also contributes to the ability to distinguish among targets. In the example cited, a transformation or coordinate rotation of the data was performed to increase the separability of the target classes. After rotation, the targets were sufficiently separable to permit classification with simple rectangular windows. The major emphases in signature-processing research and development are currently placed on development of transformation techniques to ensure the maximum separability of target categories and on methods of storing target distributions (the window approach is a simplistic target-distribution storage method) to map adequately the boundaries between target categories.

If it is assumed that the observable targets of interest are inherently capable of classification and that the observables are related in some way to the desired phenomenology, the remaining sources of error cited as causes of misclassification contribute to increasing the size of the target clusters relative to the spacing between the clusters; hence, the contribution to misclassification is no less than the area of statistical overlap between the 2 or more target clusters. Each of these sources of error will be discussed in turn.

Variations within target categories can be caused by intrinsic variations in the targets themselves, such as the soil tonal variations in the computer printout examples, or by environmental or instrumental factors, which will be discussed separately. Intrinsic target variations can be handled in several ways. Each variation in the target category can be treated as a separate target. This was done, in effect, in the computer printout example. An alternative method of treatment is to derive a target

Figure 8. Reflectance spectrum of 3 terrain types.

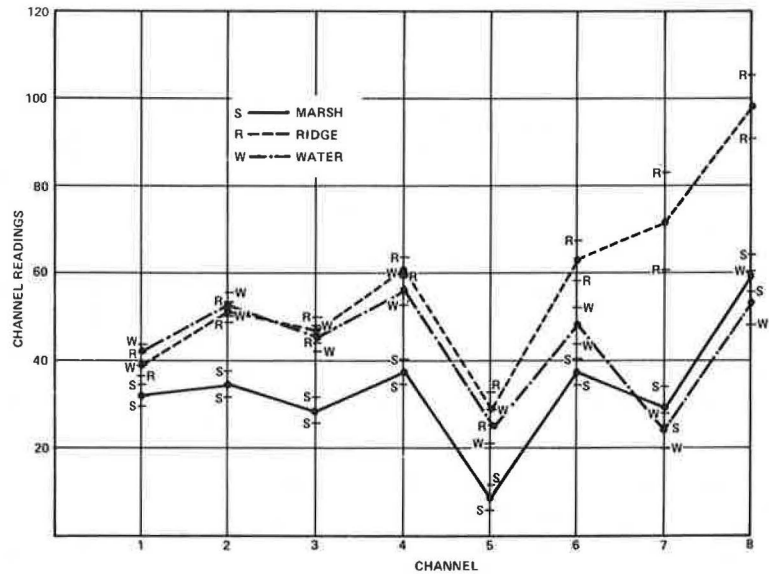


Figure 9. Factor score distribution of 3 terrain types.

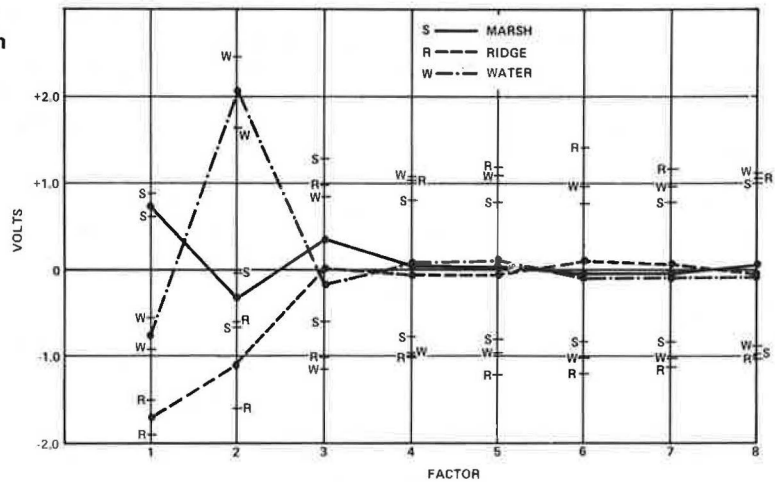
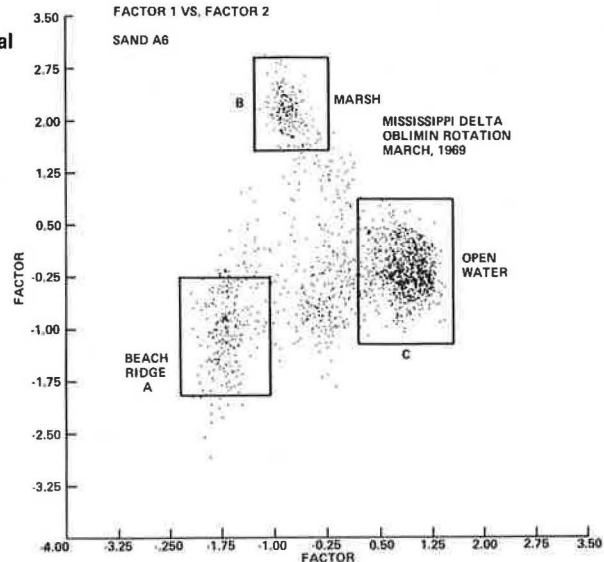


Figure 10. Scatter diagram of multispectral data.



distribution description that follows the apparent boundary of the target cluster. Both approaches are being used in data processing technique development. In either case, it is very important to include a sufficiently large number of target data samples in the training set to ensure that all likely variations of the target signature are included. If this is not done, misclassifications can occur because an allowable variation of the target is not recognized.

Environmental effects as a source of misclassification are 1 of the 2 major limitations of multispectral scanners today. The major factors considered under environmental effects are atmospheric attenuation and scattering, spectral and intensity variations in illumination, signal variations with view angle and sun angle, and surface conditions such as snow, moisture, and wind. Many of these factors can be accommodated provided that an adequate theoretical model of the environmental effect exists and that practical methods of implementing corrections of the raw data can be carried out. Many investigators are already incorporating corrections for view angle, sun angle, and illumination variations as preprocessing steps in manipulating the data (19). The NASA 24-channel scanner includes 2 channels specifically designated to measure atmospheric attenuation between the aircraft and the ground; and, if there is an adequate atmospheric model, the measurements can be used to correct the signals from the remaining channels. In addition, if the target clusters are well separated, the environmental effects can be considered as another source of target variance in the processing.

Nothing can be done about environmental effects such as snow cover because the multispectral scanner observes only surface phenomena.

The second major current limitation of multispectral scanners is the classification errors caused by instrumentation effects. Signal-to-noise deficiencies in a scanner will increase the apparent size of the target cluster by superimposing a Gaussian distribution on an otherwise normal target distribution if the noise is random. If not random, a non-Gaussian distribution will be imposed. Random system calibration errors will have the same effect, and nonrandom errors will distort the distribution in some manner. Calibration errors can occur in the instrument itself, in the data recording and reproduction process, or in the data processing system. It has been mentioned that field measurements should be made to determine the inherent separability of target categories. An important reason for performing these measurements is to determine the amount of random variations tolerable in the multispectral scanner and to separate the target classification and instrumentation problems.

A source of instrumentation error that can also be classed as target variation is interaction of the instantaneous field of view, or resolution cell, of the scanner with the target. In the cluster diagram shown in Figure 10, a number of data points are randomly scattered in the spaces among the windows. If it is assumed that only the 3 target types exist in the imagery, these points can occupy this space for either of 2 reasons. First, more than one target could have been in the resolution cell when the sample was taken. Obviously, if the sample contained half sand and half vegetation, the data point will fall between the 2 target clusters and will be classified as neither. The second possible reason is channel-to-channel misregistration in either the scanner or the tape recorder. If one channel is looking at a different ground patch containing a material different from that in other channels, the target signature will be distorted and misclassified. Misregistration in the instrument can be solved by the use of a spectrometer for spectral channel selection and by the use of a field stop in the collecting optics image plane as the entrance aperture of the spectrometer. Tape recorder misregistration can be solved by the data being recorded digitally. Both approaches are being used in the new second-generation multispectral scanners.

## SUMMARY

Multispectral sensing is a space-age development made possible through a number of technological advances, including improved optical-mechanical technology, advances in solid-state detectors and electronics, advances in data handling and recording techniques, and widespread use of computers. Multispectral sensing has the potential for surveying large areas in a short time and classifying features automatically on the basis



of their spectral characteristics. The feasibility of some classification based on spectral information is not questioned. But its limitations need to be known. To what specific extent can one carry out the classification process with a given level of complexity?

Most of the limitations in multispectral sensing arise from a lack of experience in the use of this new sensing technique. Like a child, the technique will have to undergo the time it takes for training, failures, and successes that lead to maturity and fulfillment. Successful applications will come only through experimentation. Many of the limitations are brought about by an underlying philosophy of "let's keep the instrumentation simple or at least minimize its complexity" in order to make the technique attractive. For example, one is certain that the spectral radiance of a scene element is affected by the view angle and solar insolation angle. Even though both of these parameters are known, they are not generally accounted for in the ensuing data processing. In contrast, human perception adapts to these factors by accounting for them automatically. In many instances, a trade-off analysis must be conducted, for minimizing the limitations may involve a price to pay in complexity, dollars, or throughput or all of these. But the potential and the payoff of multispectral sensing warrant the patience to evaluate the technique experimentally in order to determine its limitations for a given application.

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