The Evolution of Landsat Data Analysis

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Abstract

In this paper a description is presented of how the multispectral data analysis technology, which has come to be synonymous with Landsat, was begun and how it developed and spread through the broader research and user community. The paper is concluded with brief remarks about key factors which moderated the development and what the future may hold for its further development. To describe a 25-year-long activity as varied and complex as the evolution of the Landsat related data analysis is a daunting task. Many significant events must be omitted and others only briefly mentioned. Example activities have been chosen which occurred early and led to perhaps the largest impact in the development of the technology.

Background: Setting the Stage

The people of the U.S. and much of the world were surprised, one might even say shocked, when the Soviet Union successfully launched the first Earth orbiting artificial satellite in October 1957. The impact on the U.S. was immediate and substantial, affecting tangibles such as the U.S. education system, but also intangibles such as how this society thought of itself. One of the significant responses to this event was the National Aeronautics and Space Act in 1958 which created NASA from the National Advisory Committee on Aeronautics. These events resulted in people in various organizations beginning to consider how an ability to operate in space could be used.

In addition to telecommunications, one of the earliest thoughts relative to Earth observation from space turned to the weather, and this quickly resulted in the launch by NASA of TIROS I, the first Earth observational satellite designed for that purpose on 1 April 1960. During the 20 year period of the 1960s and 70s, some 40 satellites providing weather observations were launched, an average of two per year.

Probably no one can pinpoint when or where the idea for Landsat originated, because the idea for it surely evolved over some time and from many different sources. Indeed, there were many anecdotal stories about the idea. For example, one source was said to be the weather satellite sensor supplier who said that there were imaging tubes left over from weather satellites and that it would be easy to re-adjust their dynamic range for the (darker) Earth surface as compared to the (brighter) clouds; this, when young NASA was eagerly looking for useful things to be done with space technology. Another was in that same context of looking for new missions, in beginning to conceive of exploration missions to Mars. There were said to be discussions about how close to Mars an observation satellite would need to come to tell if there were intelligent life on Mars. In seeking an answer, thought was given as to how close one would need to come to the Earth to answer the same question.

But perhaps the most significant motivation for beginning to research space-based remote sensing of the Earth's surface was the growing awareness during this time of the finiteness of the Earth and the need to better manage its resources. In this context, interests tended to be spoken of in categories referred to as non-renewable and renewable resources. Geological surveys for locating mineral deposits were an example of the former group, while agriculture was an important example of the latter. Indeed, agriculture was deemed especially in need of better survey and management techniques because of its dynamics, e.g., with regard to such factors as weather and disease. Then-current survey methods for gathering resource management information were simply not able to respond quickly enough and in an economically suitable fashion to provide credible quantitative data.

Research Leading to Landsat

This need motivated the National Research Council in 1961 to form a study committee entitled the Committee on Remote Sensing for Agricultural Purposes under the chairmanship of J. Ralph Shay of Purdue University. Two other members of this study group were R. N. Colwell of the University of California at Berkeley and M. R. Holter of the University of Michigan. These three individuals, leading research groups at their respective institutions, organized a cooperative interdisciplinary, inter-institution research team among the three institutions funded jointly by NASA and the U.S. Department of Agriculture.

Following several years of preliminary feasibility studies, this effort got formally under way in early 1966. Professor Colwell, of the University of California, Berkeley Forestry Department was already a highly respected and knowledgeable leader in the use of air photointerpretation in forestry and agriculture. Mr. Holter headed a group[1] at the Willow Run Laboratories of the University of Michigan which was engaged in airborne sensing for the U.S. Army Electronics Command under Project MICHIGAN. This group operated an airborne photographic system which, in addition, included some capability to generate line-scanned imagery in the infrared region. They were also involved in devising photointerpretive methods for data analysis. The Purdue University Agricultural Experiment Station supported this effort by making available personal and a number of diverse experimental stations adjacent to the University, and also involving personal from their School of Electrical Engineering to begin devising digital computer means for analyzing such data.

Early thoughts about how to analyze data quite naturally turned to photointerpretation. However, the added possibility of several bands in the infrared increased the complexity of this process. For example, an early data collection tool was the "nine lens camera," which formed three rows of three

[1] In 1973 this group separated from the University of Michigan and became the Environmental Research Institute of Michigan (ERIM).

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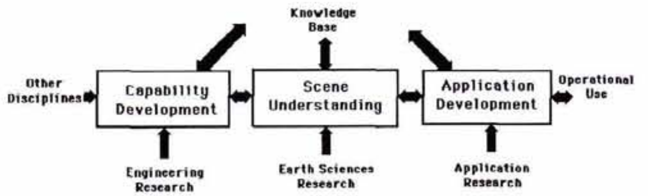


Figure 1. The multifaceted nature of remote sensing technology research and development (adapted from the introduction in IEEE (1995)).

images on a sheet of 9-inch film, each lens containing a different filter passing a different part of the spectrum. Developing a photointerpretive key relative to nine different images was seen to be a daunting task. To develop a quantitative version of the data, thought was given to using a film densitometer to quantify the film density at a given point in each image.

However, in 1966, the University of Michigan group succeeded in extending the range of the infrared scanner on their aircraft into additional regions of the spectrum. The result was a scanner that could collect electronic data simultaneously in up to 18 spectral bands extending from 0.32 µm in the UV to 14 µm in the thermal infrared. The data were recorded on a multiband analog tape recorder. This system continued to be modified and improved over the next several years and eventually became known as the M-7 scanner.[2] This system became the mainstay of this and many later research efforts.

The Purdue group succeeded in developing a capability to simultaneously electronically sample and digitize all bands of the Michigan scanner analog tapes, thereby producing individual vectors for each pixel. This made possible, and indeed convenient, data analysis based upon digital multivariant statistical methods. Because the early form of the Michigan scanner was actually made up of two double-ended scanners, thus producing four different data sets per flightline, the Purdue group also created an early capability for the precision registration of such data sets, concatenating the four sets of measurements into one vector for each pixel.

The Multispectral Concept

When beginning such an endeavor as this, it is logical to think first of the use of images and of image processing methods. The decision to base analysis methods not on image characteristics but on spectral characteristics was motivated by several considerations. At the time, computational capabilities were much more limited than now, as was the state of image processing technology. The use of spatially based approaches with their inherently greater complexity, did not seem like it could lead to practical, usable technology in the near term. Rather, a spectral approach, given the Michigan system's ability to deliver a fairly complete spectral sampling for each pixel, allowed for a basic simplicity which was an important practical characteristic.

But perhaps more significantly was the matter of economics and spatial resolution. There was a strong intention in the research program to produce a technology that was not any more expensive to devise and use than necessary. To base the proposed technology on image characteristics would have required high spatial resolution for such materials as agricultural crops. Spatial resolution is one of the more expensive parameters of such a system. Data volume increases as the square of resolution. Pointing precision also increases rapidly with spatial resolution, as does the required downlink capacity. Thus, focusing on spectral characteristics while using the lowest spatial resolution necessary seemed like the optimum approach, if it could be made to work.

In considering approaches to the analysis of such data, one concern at the time was the great volume of data to be processed. Neural network analysis was popular then, but it had (and has) the disadvantage of requiring substantial computing time involved with training the algorithm each time. Because, in the case of remotely sensed data, it was envisioned that the analysis algorithm would need to be retrained for each new data set, this was seen as a significant disadvantage. There was also the problem of a paucity of analytical tools related to it.

To handle the large volume of data, analog computer processing was also considered briefly; however, the rapid development of digital computation at that time, together with its inherent flexibility, quickly favored the digital approach. Thus, the research effort became focused upon basing the derivation of information for managing Earth resources on a so-called single aperture scanner coupled with digital statistical pattern recognition data analysis methods.

Promising preliminary results came within the first few months of the effort,[3] and a broader, more fundamentally based research effort was formulated. This included not only research on understanding the spectral response of materials in laboratory and field environments, but also on broadening to include additional user disciplines beyond agriculture.

In 1967, the National Research Council conducted a major summer study entitled "Useful Applications of Earth-Oriented Satellites." This study was intended to cover the full range of possible space applications through 13 separate panels, including such applications as several forms of telecommunication, navigation and traffic control, and geodesy and cartography. One panel was also included on economic analysis. Ones related to remote sensing included the discipline panels on Forestry-Agriculture-Geography, Geology, Hydrology, Meteorology, Oceanography, and Sensor and Data Systems. The study illustrates the breadth with respect to the various disciplines to which interest had spread by that time. Discussion also took place with regard to both photographic film and electronic data collection and a wide variety of optical and microwave sensor configurations. A sense emerged that first-generation systems would need to be image oriented with the scale tipping toward electronic imaging devices with electronic data transmission to Earth, but a second-generation approach using multispectral line scan sensors was already seen as appropriate. This study provided a major impetus for devising a satellite series to be known as Earth Resources Technology Satellites (and later as Landsat), the design of which began in earnest within the next year. However, though there were promising preliminary results existing by this time, clearly much more research was needed to be ready for the launch of a land-looking satellite series.

The Structure of the Remote Sensing Research Effort

It was early recognized that to create the new remote sensing technology and begin its utilization would require a multidisciplinary or, more ideally, an interdisciplinary effort. Figure 1 illustrates the ideal but difficult relationships that had to be achieved for the optimal development environment, as well as the relationship between engineering, science, and applications objectives.

Such an effort must be led by engineering research to produce a capability to collect and analyze data, for the

[2]The Michigan M-7 Airborne Scanner is described in more detail in Swain and Davis (1978). See also Hasell (1972; 1974).

[3]See, for example, Landgrebe and Staff (1967), soon followed by Fu *et al.* (1969).

other parts cannot proceed without this capability. This is coupled with an effort to deepen the understanding of the scene materials and how they exist in their environment, which, in turn, leads to research to focus the capabilities and knowledge developed to the various application situations which would become of interest. Operational uses could then result. All of these research efforts contribute to the knowledge base for the field. The significance of the double-ended arrows of the diagram is that they imply a great deal of two-way communication; thus, the desirability for the overall effort to be interdisciplinary rather than simply multidisciplinary.

It is this scheme that was followed during the 1960s and 70s for research leading to the various Landsat systems. Engineering research led to significant innovative advancements in airborne and spaceborne sensor systems as already mentioned. This, in turn, allowed for significant work in areas such as pattern analysis algorithms, spectral feature selection algorithms, image registration methods, and the use of spatial relationships as an augmentation to spectral features.

Substantial work was also needed to develop suitable laboratory and field instruments and measurement techniques. Spectroscopy, long used in the chemistry laboratory, had to be adapted to the rigors of the field with its heat, dust, changing lighting conditions, and the like, and had to be made capable of observing the target from varying angles. Laboratory and field studies were deemed important to achieving a more sound understanding of the way in which Earth surface materials reflect, transmit, and absorb optical energy as a function of wavelength. Thus, new instruments had to be specified, designed, and constructed, and once available, suitable techniques for collecting samples in the field and in the laboratory had to be developed. Means for calibrating such data also needed to be created.

As a result of these activities, several extensive databases of laboratory and *in situ* spectra were assembled.[4] The intention of these data were not that they would be used in direct conjunction with aircraft and spacecraft data, because the problem of reconciliation of the circumstances of its collection with those of the aerospace data were felt to be either insoluble or unnecessarily complex. Instead, the focus was on scene understanding and building the knowledge base (Figure 1) so that the most knowledgeable choices could be made when new experiments, sensors, or processing schemes are to be designed.

Early Research Literature

Being cross-disciplinary, this newly emerging field was significantly different from those then existing. Also, there were no research journals directly suited to report new findings. Thus, much of the early work was only discussed and documented in various symposia specially focused for that purpose. The earliest of these, the then-so-called Michigan Symposia, were the forerunner of the current ERIM International Symposia on Remote Sensing of Environment. This series had begun somewhat earlier focused upon infrared imaging technology, a subject under study for the U.S. military. They were quickly adapted to the broader thrust including multispectral sensing. Another set of meetings which served the purpose of documenting and providing for technical interchanges between the now growing community of researchers were the NASA annual program review meetings. In 1968, a series of meetings were begun at Purdue University called the Machine Processing Symposia focused specifically on methods for digital processing of multispectral data. The proceedings of all of these series of meetings provide not only a picture of how this technology emerged, but contain many results and ideas still relevant today.

It was not long before serial journals on this topic began to be published. The journal *Remote Sensing of Environment* was first published in 1969 with Professor David Simonett, then at the University of Kansas, as the organizing Editor-in-Chief. It was specifically intended as an interdisciplinary journal and, as such, was not associated with any of the existing technical societies. The American Society of Photogrammetry renamed its journal *Photogrammetric Engineering & Remote Sensing*, adding the "and Remote Sensing" in 1975. It officially added "and Remote Sensing" to its Society name in 1985. The IEEE Geoscience Electronics Society changed its name to the IEEE Geoscience and Remote Sensing Society and changed the name of its journal to the *Transactions on Geoscience and Remote Sensing* in 1979. In 1981 the first of the annual International Geoscience and Remote Sensing Symposia was held in Washington, D.C. A number of additional journals and symposia were begun in this period in the U.S. and elsewhere.

Various types of books soon began to appear. An early handbook, the *Manual of Remote Sensing, First Edition*, was published by the American Society of Photogrammetry in 1974. The research monograph, *Remote Sensing of Environment*, was published by Academic Press in 1976. One of the first books intended specifically as a textbook, *Remote Sensing: The Quantitative Approach*, was published by McGraw-Hill International Book Company in 1978.

Early Tests and Demonstrations of the Technology

Many of the uses of Landsat technology were envisioned to require detailed thematic maps of small (e.g., 25- by 25-mile) areas. However, the new and really unique capability that Landsat technology could provide is a way to rapidly and economically acquire information of a broad scale regional nature. During the 1970s, a series of the latter type of use were performed. These served a very important research function in that they were a way to test the overall technology as it was being developed to see where there were weaknesses. They also served the additional function of demonstrating to the potential user community the viability of the new technology.

The first of such broad scale tests of the technology came about in a crisis environment and became known as the 1971 Corn Blight Watch Experiment (CBWE) (MacDonald *et al.*, 1972). During the latter stages of the 1970 growing season, a pathogen to which essentially all of the U.S. corn crop was susceptible emerged in the southern U.S. and began to move northward. This pathogen, called Southern Corn Leaf Blight, developed from airborne spores and first showed up as brown lesions on the lower leaves of the corn canopy. The lesions would grow in size and spread upward in the canopy until, ultimately, the entire plant was destroyed. The broad susceptibility of the corn crop stemmed from the fact that most varieties of corn in the U.S. were hybrids utilizing a single type of cytoplasm and it was this cytoplasm that was the basis for the susceptibility. By the time the danger was realized, seed corn for the 1971 year had already been produced, and so it was feared that, if Southern Corn Leaf Blight spores could over-winter through the 1970-71 winter, it could spread rapidly during the 1971 growing season and devastate corn production.

Because of the potentially devastating nature of the threat, even though much of the technology was quite new and untested, it was decided to see if remote sensing technology could be used to monitor the spread of the blight over the entire U.S. Corn Belt throughout the 1971 growing season. Unfortunately, Landsat was still more than a year away, and so the experimental test had to be done with air-

[4] See, for example, http://dynamo.ecn.purdue.edu/~frdata/FRData/ on the World Wide Web.

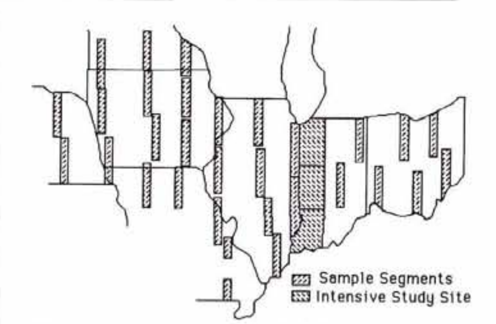


Figure 2. 1971 Corn Blight Watch Experiment sample flightlines.

craft. A stratified sampling scheme was laid out in which some 200 segments were to be overflown every two weeks. NASA made available an RB-57F high altitude reconnaissance aircraft for photographic data collection over these sites, there being no multispectral sensor system at that time capable of covering the Corn Belt with that frequency. A map showing the flightlines containing these segments is given in Figure 2.

In order to test the new multispectral technology, a series of 30 segments was located in the western third of Indiana, and the now (formerly University of Michigan) ERIM aircraft system, a C-47 platform carrying its multispectral scanner, was assigned to the task. Figure 3 shows the location of these segments in the Intensive Study Site region.

Even though the CBWE arose due to an anticipated emergency rather than being motivated by a perceived research need, it proved to be a propitious research event. The core idea was, in addition to using photographic methods, to test the ability for a multispectral sensor in conjunction with supervised pattern and related algorithms. It provided an effective test of a number of aspects of the technology, just as Landsat 1 (then known as ERTS-1) was in preparation for launch. Some of these aspects are as follows:

- A *Challenging Discrimination Problem.* The problem at hand, identification of the level of the degree of stress in a specific plant species, was a challenging one. It not only required reliably discriminating between a specific plant species, corn, and all others in the scene but subdividing that species and determining the level to which the disease had affected the plants in view. The primary discrimination algorithm used was the Gaussian maximum-likelihood classification scheme. Calibration and preprocessing matters were held to a minimum, thus demonstrating that such preprocessing, which is expensive and time consuming, can be avoided in large measure.
- *Use of a Quantitative Feature Selection Algorithm.* The multispectral data were collected in 17 spectral bands over the range from 0.40 to 11.1 μm. Most classifications were done at much lower dimensionality by using a feature selection algorithm to select the best four or so features with which to do the classification at hand. This procedure worked very well. It also provided insight into what bands were the most useful for a problem of this nature. For example, it is common today to see people dismiss the thermal band of Thematic Mapper data "because of its poor resolution," and yet the thermal band of the CBWE data was at lower spatial resolution than the others but, over the growing season, it was the band most frequently selected by the feature selection algorithm.
- *Stratified Sampling Methods.* Such sampling methods were then and are now commonly used. However, this was perhaps one of the most comprehensive uses, certainly in remote sensing applications. The area involved extended over seven states, and an entire growing season. The intensive study area involved a third of a state. This approach proved the significance of such a technique to remote sensing. So called "wall-to-wall" sensing was not necessary and indeed would have been wasteful. Further, this problem could not have been done with a sensor of the spatial resolution of, for example, the AVHRR (Advanced Very High Resolution Radiometer) if it had been available, because the pixels would have been too large, and the effect to be measured too subtle.
- *Variability Aspects.* The CBWE problem provided a unique opportunity to become familiar with the degree of variability that exists in the scene over a growing season and over a large geographical area. The collection of such high spatial resolution data over that many sites and times probably has rarely if ever been duplicated.
- *Comparison with Then-Conventional Remote Sensing Methods.* The fact that the new multispectral remote sensing was being used alongside a more conventional air photointerpretation on such an extensive scale was a unique opportunity to judge the viability and potential of the new technology. The two technologies are clearly different, with different strengths and weaknesses. In terms of final conclusions for the detectability of corn blight, the general post-experiment evaluation was that the photointerpretation of photography was not as sensitive, making possible discrimination to a yes-or-no level of detail, while the multispectral data allowed for reliable discrimination into three classes, little or none, moderate, or substantial to severe blight.
- *Technology Robustness.* Was the technology sufficiently developed that a large group could rapidly learn to use the technology? The short term and emergency nature of the manner in which the problem arose, where there was not time to draw up budgets, reallocate funds, hire people with specific skills and the like, meant that the work had to be done by people already in place, if for other purposes. Some 1000 people from 17 federal and state agencies were ultimately directly involved.
- *Many Operational Aspects.* In carrying out such a far flung activity with the time schedule of data collection and analysis cycles which must be completed for 230 segments every two weeks using ground observations gathered each cycle from over a seven state area using personnel already in place at the various sites resulted in many operational matters that had to be dealt with. For example, the scheduling of missions over the various sample segments relative to the expected cloud conditions resulted in a substantial increase in understanding about cloud relationships to remote sensing.

Though the CBWE and its impact on the preparation for the launch of the Landsat series can only be briefly outlined here, it is perhaps clear from the above that this experiment

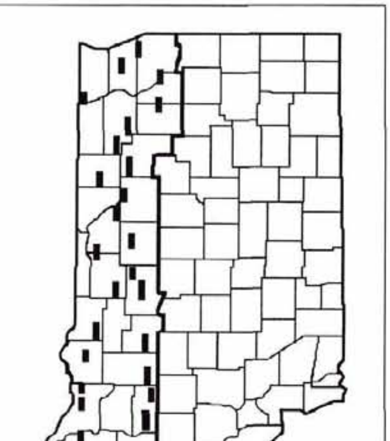
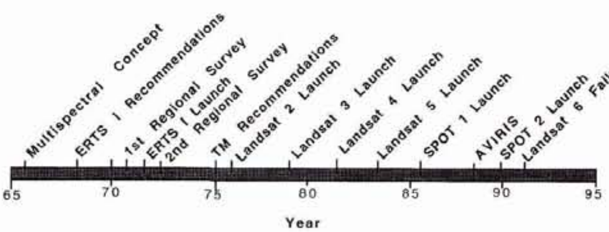


Figure 3. The sample segments of the CBWE Intensive Study Site.



CIVIL LAND REMOTE SENSING MILESTONES

Figure 4. A timeline for the Landsat era.

made a very significant contribution to the technology needed for such a satellite program and gave confidence that this technology was indeed ready. The data set collected, with its large number of spectral bands collected over a large area throughout an entire growing season, has probably not been equaled to this day.

One of the remaining problems at the time, then, was that the community of people who possessed this technology at that point was very much too small relative to the potential for use which such a system had. This pointed to the need for substantial efforts in so called technology transfer. This point will be addressed further shortly.

There were many other activities that contributed to the preparation for the launch of ERTS-1 (Landsat 1). One of the important ones, especially with regard to providing a wide opportunity for involvement with it, was the call for proposals to analyze data from ERTS-1. Such a call was issued as the time for first launch approached. There were more than 700 proposals submitted to this call, with more than 400 ultimately being funded.

The Landsat Era

The Landsat era really can be said to have begun with the launch of ERTS-1 in July 1972. As is well known, the first series contained a set of return beam videcons (RBV) which were for the purpose of producing framed images, whose geometry was more familiar to photogrammetrists. ERTS also contained the multispectral scanner (MSS), the first generation spaceborne multispectral sensor system. The MSS must certainly be seen as a primitive multispectral device, both in terms of today's capabilities and in terms of the ERIM aircraft system which led to it. It had only four bands that were quite broad and closely spaced, and the signal-to-noise ratio could only support a 6-bit dynamic range, i.e., 64 shades of gray per band. It could not have supported a problem as subtle as the corn blight monitoring. Nevertheless, it broke new ground. It demonstrated to skeptics that line scanning devices were viable. Indeed, not only did the MSS become essential as a result of the early failure of the RBV system on ERTS-1, but the RBV failure resulted in an acceleration in the rate at which techniques for dealing with the new geometry of line scan devices presented to cartographers. Further, the demand for data in digital tape form, as compared to hard copy film, grew well beyond planned levels.

Figure 4 shows a time line for some major events of the Landsat era. It shows the preparation period described above, including the first regional survey, the 1971 Corn Blight Watch Experiment, as well as the times of later launches.

A second regional-sized survey, one of the first done using Landsat or, more specifically, the MSS, was begun in 1973. In the early 1970s there was growing concern about the Great Lakes, and the anthropogenic effects on their water quality. The U.S.-Canada International Joint Commission, in an effort to begin to solve the problem, indicated a need for land-use maps of the Great Lakes drainage basin. As a result, a project was funded during the first year of Landsat to generate land-use maps for each of the 192 counties of the U.S. portion of the drainage basin. The region involved is shown in Figure 5.

The project resulted in thematic maps being made using MSS data and supervised maximum-likelihood classification for each county in classes of the Anderson Level 1 land-use classification system, and tables for Anderson Level 1 and 2 classes, showing the approximate proportion of each class in each county. The total cost of the project was approximately $2500 per county, a cost much below that possible by any other means. This demonstrated the viability of the Landsat sensor and analysis technology, although it was clearly limited by the limited spectral capabilities of the MSS. A more complete description of the project and the methodology used is given in Swain and Davis (1978).

In addition to the diverse and numerous smaller demonstrations of what the Landsat technology could do, there was a series of larger scale programs that were conducted during the 1970s and 80s. Notable among there were LACIE (the Large Area Crop Inventory Experiment) and AgRISTARS (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing).

LACIE was begun in November 1974 and was intended to test and demonstrate a real-time capability for inventorying crop production. It culminated in such an inventory of the USSR wheat production in the 1977 growing season, which gave an estimate of the number of bushels of wheat produced by the USSR within 6 percent of the final Soviet figures 6 months before their release. MSS data were used to identify and determine the area of acres in wheat. This was followed by the use of available meteorology data from the area applied to crop yield models to predict the number of bushels of wheat which would result. Results were well within the USDA accuracy goals. The program was separately budgeted with a budget of $10M/yr at its peak. More than 200 support contractor personnel were involved, with the majority of the effort conducted at the NASA Johnson Space Center. A more complete description of LACIE and the results achieved is given in MacDonald and Hall (1980).

There were a number of notable contributions of the program to the technology of data analysis. One was a means to label training samples for the supervised classifier in an unbiased fashion without observations from the ground, because these were not possible in this program. Another was

Figure 5. The Great Lakes drainage basin and the boundaries of the U.S. counties involved.

Figure 6. Location of sites of terminals on the Purdue/LARS remote terminal system.

the Tasseled Cap transformation (Kauth and Thomas, 1976), a transformation providing a feature space in which human perception of the interpretation of the contents of a given pixel is enhanced. This program also stimulated the work to use temporal information, e.g., in the form of a "crop calendar" for purposes of determining or predicting the state of maturity of crops in the analysis process.

AgRISTARS was initiated in 1980 as a cooperative program between NASA, USDA, USDC, USDI, and USAID. Its goals were to extend the crop commodity forecasting capability which was begun with a wheat emphasis by LACIE to all major grains. The program accounted for about 75 percent of the federally funded research in the remote sensing of renewable resources area in the 1980-83 period. The program was divided into eight project areas covering crop condition assessment, inventory technology, yield modeling, soil moisture assessment, domestic crops and land cover, renewable resources inventory (forestry), conservation and pollution, and supporting research. It, too, generated a whole series of developments which moved the technology forward. A special issue of the *IEEE Transactions on Geoscience and Remote Sensing* (IEEE, 1986) was devoted to the results of this program. Bauer (1985) contains a review of the developments in crop identification and condition assessment up to that time, including an extensive bibliography.

The parameters for the Thematic Mapper, the second generation Landsat multispectral sensor system, were set beginning with a NASA working group meeting held 30 April and 1-2 May 1975 at Purdue University. At that meeting, a group of 35 invited participants selected the location of the spectral bands and other parameters for this instrument. Members of the working group felt strongly that a seventh band should be included; however, the NASA managers had limited considerations to six bands on projected cost grounds. Thus, band numbers 1 to 6 were selected, and detailed planning for the Thematic Mapper began. Later, the NASA managers relented, allowing the second middle infrared band to be added as the band now labeled band 7. This is what led to the non-sequential numbering of the Thematic Mapper bands in use to this day.

Technology Transfer

Prior to the launch of the first Landsat, because the technology of multispectral sensing and analysis was new, but the community of potential users of this technology would be large, there was a significant technology transfer problem to be overcome. The technology had to be moved from the small number of people who knew it to the large number who could use it. What was needed went well beyond the normal vehicles used within the research community, because most of the user community would not see such documentation occurring in archival research journals and symposia proceedings. Thus, significant efforts began to be exerted to make available user-oriented documentation, short courses, and other forms of communication appropriate to this problem.

One particularly unique scheme resulting from the unusual characteristics of remote sensing was the Remote Terminal System, created and operated by Purdue's Laboratory for Applications of Remote Sensing (LARS), based on NASA funding. The LARS group, having been involved in the creation of the technology, codified the digital computer algorithms emerging from their research into a computer software system called LARSYS. Beginning in 1970, this software system, implemented on a mainframe time-share computer, was made available for use by others via remote terminals connected either by leased lines or dial-up modem. Various training materials, including audio tutorial tapes, videos, and pamphlets were created to show how to use the system for analyzing multispectral data from a user's own laboratory. The cost to the user was only the cost of supplying a teletype style terminal and the cost of the communication line. Because the processing and the data were resident at LARS, only processing instructions and results needed to be sent over the communication lines; thus, the bandwidth required between the host computer and the remote terminals was modest.

This system was operated in this fashion from 1970 prior to the launch of Landsat until 1982. Figure 6 shows some of the sites which had such installations. The intention was for sites to have an opportunity to try out multispectral analysis methods with very little expense. If it appeared to be useful, then they could create their own capability either by building their own hardware/software system or by receiving a copy of the LARSYS[5] system, which was available at no cost either from Purdue or from NASA Office of Technology Transfer sources. A number of NASA, University, other government, and private commercial organizations did so.

On Analysis Methods and their Development

The fundamental premise of remote sensing is that information is transmitted through space via force fields and, in particular, via spatial, spectral, and temporal variations of those force fields.

Then, to capture remotely sensed information, one must *measure those variations and relate them to classes of material of interest.*

The sensor system must measure the variations, and then the analysis system must provide for relating the measurements to the classes of materials of interest in any particular case and with acceptable accuracy. As has already been pointed out, the decision was made early on relative to preparing for Landsat to focus on spectral variations for pragmatic reasons, although spatial and temporal variations have not been ignored over the years.

The matter of how the variations are represented mathematically and conceptually is an important first step in defining how the analysis process should proceed. There have been three principal ways in which multispectral data are represented quantitatively and visualized:

- In image form, i.e., pixels displayed in geometric relationship to one another;
- As spectra, i.e., variations within pixels as a function of wavelength; and

[5]An application software system which is a descendent of LARSYS, but implemented for personal computers, is available for downloading from the world wide web at no cost at the following URL: http://dynamo.ecn.purdue.edu/~biehl/MultiSpec/.

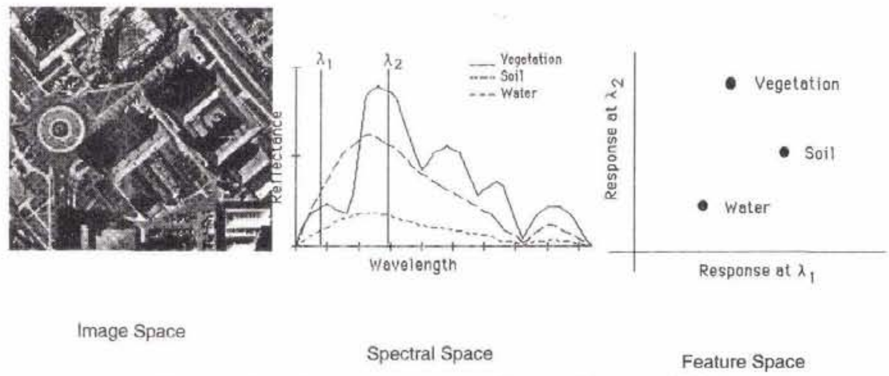


Figure 7. The forms for representing multispectral data.

- In feature space, i.e., pixels displayed as points in an *N*-dimensional space.

See Figure 7. We will refer to these three as image space, spectral space, and feature space, and next summarize some of the ramifications of these three perspectives.

Image Space

Though the image form is perhaps the first form a new researcher or user thinks of when first considering remote sensing as a source of information, its principal value has been somewhat ancillary to the central question of deriving thematic information from the data. Data in image form serve as the human/data interface in that image space helps the user to make the connection between individual pixel areas and the surface cover class they represent. It also provides for supporting area mensuration activities usually associated with use of remote sensing techniques. Thus, it becomes very important as to how accurately the true geometry of the scene is portrayed in the data. However, it is the latter two of the three means for representing data that have been the point of departure for most multispectral data analysis techniques.

Spectral Space

We have already described why spectral variations early on became the focus of the field. In the 1960s, the term "spectral signature" began to be used, first to succinctly indicate to non-technical persons the then-new idea that materials could be identified by their spectral variations alone. However, some extended this idea to hypothesizing that each material has a unique spectral response which is identifiably different in an absolute sense from all others. This assumption set a course for analysis studies based upon this assumption, even though, after 30 years of study, there is no general agreement on the efficacy of this hypothesis. Still, many analysis algorithms which appear in the literature begin with a representation of a response function as a function of wavelength. Early in the work, the term "spectral matching" was often used, implying that the approach was to compare an unknown spectrum with a series of pre-labeled spectra to determine a match, and thereby to identify the unknown. This line of thinking has, at various times, led to attempts to construct a "signature bank," a dictionary of candidate spectra whose identity had been pre-established.

A second example of the use of spectral space is the "imaging spectrometer" concept, whereby identifiable features within a spectral response function, such as absorption bands due to resonances at the molecular level, can be used to identify a material associated with a given spectrum. This approach, arising from the concepts of chemical spectroscopy which has long been used in the laboratory for molecular identification, is perhaps one of the most fundamentally, cause/effect based approaches to multispectral analysis.

Feature Space

The third basis for data representation also begins with a spectral focus, i.e., that energy or reflectance versus wavelength contains the desired information, but it is less related to pictures or graphs. It began by noting that the function of the sensor system inherently samples the continuous function of emitted and reflected energy versus wavelength and converts it to a set of measurements associated with a pixel which constitute a vector, i.e., a point in an *N*-dimensional vector space. This conversion of the information from a *continuous* function of wavelength to a *discrete point* in a vector space is not only inherent in the operation of a multispectral sensor, it is very convenient if the data are to be analyzed by a machine-implemented algorithm. It, too, is quite fundamentally based, being one of the most basic concepts of signal theory. Further, it is a convenient form if a more general form of feature extraction is to precede the analysis step itself.

Another key characteristic which is fundamental to the engineering task of optimally designing a data analysis system is the basis for the mathematical representation of the data. A number of approaches have been considered for multispectral data over the years. The following are some examples:

- Deterministic Approaches
- Stochastic Models
- Fuzzy Set Theory
- Dempster-Shafer Theory of Evidence
- Robust Methods, Theory of Capacities, Interval Valued Probabilities
- Chaos Theory and Fractal Geometry
- AI Techniques, Neural Networks

Deterministic approaches have been by far the most common. This is no doubt because they are the most intuitive. Spectral matching and imaging spectroscopy are specific examples of these. Stochastic methods are also quite common. They have the advantage of being powerful, rigorous, and well-developed in the engineering literature, and have many background tools available.

As the Landsat data analysis technology has formed over the years, another fundamental characteristic of analysis methods is that of identification versus discrimination. Is the intent of the algorithm to *identify* the contents of a pixel or area? Or is the intent of the algorithm to *discriminate* between a defined set of candidate classes? The former is spoken of as absolute classification while the latter is said to be

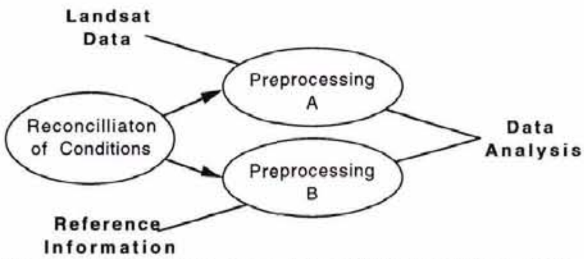


Figure 8. Data analysis as a merging of Landsat data with reference information.

a relative classification scheme. That of identification is clearly the more conceptually appealing, especially to the non-technical user, while schemes based on the latter are likely to produce the more accurate results in a given situation at the expense of usually being the more difficult to implement.

A final fundamental characteristic of Landsat data analysis methods that distinguish between various approaches is the human data interface. How does the human become involved in specifying what classes are of interest in a given analysis task? And how is this interest related to the spectral response of the various materials in the scene? As displayed in Figure 8, the data analysis process in the remote sensing context is basically a merging of spectral characteristics present in the current Landsat data set to be analyzed with that of reference information about the scene.

This reference information can take a wide variety of forms. It can be in the form of quantitatively expressed reference spectra gathered for the classes present in the Landsat data, but at a previous time, and perhaps from laboratory or field measurements. At the other extreme, the required reference information can simply be input by the analyst, designating in the Landsat data set to be analyzed, example areas of each class of interest.

As indicated in Figure 8, there must be a reconciliation of the scene, weather, and illumination conditions at the time the Landsat data are collected with those present in the reference data. This can be done by adjusting the Landsat data to those of the reference data (Preprocessing A) or by adjusting the reference data to those of the Landsat data (Preprocessing B). As a third alternative, both could be adjusted to a third set of conditions, for example, converting both sets of data to geophysical units. Each approach has its advantages; however, any such data adjustment is never perfect and to some extent could have an unknown or unsuspected deleterious effect.

For example, "correcting" for the atmosphere, a part of Preprocessing A, might seem to be an obviously good thing to do. However, it must usually be done based on measurements of the atmospheric state which are inexact. Thus there are circumstances in which it is not helpful and, indeed, could reduce overall performance. On the other hand, if the reconciliation is achieved by the analyst manually or otherwise designating example areas for each class of interest in the data set to be analyzed, this has the advantage of automatically reconciling the reference information with the current data set, thus preprocessing can be held to a minimum or omitted altogether.

The Future

It is appropriate to speculate upon the future for this technology, but as a part of doing so, it is appropriate to first take a look at the past. At the beginning of the space age in the early 1960s, multispectral remote sensing was seen to have great potential both for gathering land-cover information over broad areas and very detailed information over more limited areas. The Michigan/ERIM airborne system, together with multispectral discriminant analysis methods, was able to quickly demonstrate that promise as seen by the 1971 Corn Blight Watch Experiment. However, there have been several factors present which have limited the achievement of the potential the technology seemed to have at the outset.

- *Spectral Limitations.* The early ability to collect multispectral data from space was a significant limiting factor. The four relatively broad, relatively low signal-to-noise ratio bands of the MSS were a long way from delivering the information content of the 12 to 18 bands of the Michigan/ERIM scanner. Even the seven bands of the Thematic Mapper still present a substantial such limitation. It is questionable whether a discrimination problem as subtle as measuring degrees of blight infestation over the variability conditions of a broad area and an entire growing season could be done successfully with Thematic Mapper.
- *Data Delivery Delay.* The delay in delivering data to the user has been a chronic problem over the Landsat period. This delay has had two deleterious effects. (a) For many applications of this technology, the information contained in the data is quite perishable. Month-long or even week-long delays in delivering satellite data to the user/analyst eliminates the interest of a significant user community. (b) Such delays affect the analyst more directly in the analysis process. They have served to disconnect the analyst from the scene. Many types of land cover change substantially between data collection and data analysis during such a delay period, and this reduces the ability of the analyst to make subtle perceptions about what shows in the data relative to what was present in the scene. As a result, many analysts don't even think of the scene, only the data as data. Add to these two the uncertainty in being able to obtain data over a given site in a given time interval due to the relationship between cloud conditions and the infrequent passage of the satellite over a site of interest.
- *Data Costing Practices.* Given the other limitations, the decision to begin commercializing the Landsat system during the Carter administration was probably premature. The technology and its user community were simply not that far along by that time. Aside from the effect on the user community, the effect on the research community was substantial. Most researchers could not afford to design and carry out experiments in the normal fashion, not being able to afford the data. Thus, they fell into a mode of "making do" with whatever data they could have access to.
- *Policy Problems.* U.S. Government policy over the period relative to remote sensing has been uneven and inconsistent. This has inhibited the development of both commercial providers of services and users of the products that could be produced.

From the perspective of these past limitations, however, there is reason to see a bright future. Advances in the field of solid state technology in the intervening years have made possible space sensors with substantially larger numbers of spectral bands while at the same time providing substantially greater signal-to-noise ratios without sacrificing spatial resolution. Government policy relative to the commercial community and even with regard to data pricing has been clarified in recent years, and while the cost of data for research purposes has not improved as far as would be desirable, it has improved. It remains to be seen what will be the case with regard to data delivery delays, but there is no technological reason why it cannot be substantially better, even to the point of delivering data in near real time.

There are many aspects that remain important research questions. Perhaps chief among these is the matter of rigorous, broadly applicable, and user-acceptable analysis procedures for the more complex data that future Landsats will surely provide. It seems clear that sensor systems with large numbers of spectral bands and greater signal-to-noise ratios will make theoretically possible substantially more accurate and detailed information from such sensors. The challenge, then, is to reduce this theory to practices and to do so in a way that will be found acceptable to the Earth science and application communities.

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