Digital Image-Processing Activities in Remote Sensing for Earth Resources

GEORGE NAGY, SENIOR MEMBER, IEEE

Abstract—**The United States space program is in the throes of a major shift in emphasis from exploration of the moon and nearby planets to the application of remote sensing technology toward increased scientific understanding and economic exploitation of the earth itself. Over one hundred potential applications have already been identified. Since data from the unmanned Earth Resources Technology Satellites and the manned Earth Resources Observation Satellites are not yet available, the experimentation required to realize the ambitious goals of these projects is carried out through approximation of the expected characteristics of the data by means of images derived from weather satellite vidicon and spin-scan cameras, Gemini and Apollo photographs, and the comprehensive sensor complement of the NASA earth resources observation aircraft.**

The extensive and varied work currently underway is reviewed in terms of the special purpose scan and display equipment and efficient data manipulation routines required for high-resolution images; the essential role of interactive processing; the application of supervised classification methods to crop and timber forecasts, geological exploration, and hydrological surveys; the need for nonsupervised classification techniques for video compaction and for more efficient utilization of ground-control samples; and the outstanding problem of mapping accurately the collected data on a standard coordinate system.

An attempt is made to identify among the welter of "promising" results areas of tangible achievement as well as likely bottlenecks, and to assess the contribution to be expected of digital image-processing methods in both operational and experimental utilization of the forthcoming torrent of data.

I. Introduction

THE OBJECT of this survey is to give an account of experimental developments in digital image processing prompted by the major environmental remote sensing endeavors currently underway, such as the already operational weather satellite program of the National Oceanographic and Atmospheric Agency (NOAA), the projected Earth Resources Technology Satellite (ERTS) and Skylab experiments, the NASA Earth Resources Aircraft Program (ERAP), and the Department of the Interior's Earth Resources Observation System (EROS).

Sources of Information: The most comprehensive and readily accessible source of material in this area is the seven volumes published so far of the *Proceedings of the International Symposium on Remote Sensing of Environment,* held annually under the auspices of the Center for Remote Sensing Information and Analysis of the University of Michigan.

Other useful sources of information are the *NASA-MSC Annual Earth Resources Program Reviews,* the *Proceedings of the Princeton University Conference on Aerospace Methods for Revealing and Evaluating Earth's Resources,* the publications of the American Society of Photogrammetry and of the Society of Photo-Optical Instrumentation Engineers, the *Journal of Applied Meteorology,* the *Proceedings of the IEEE* (pertinent special issues in April 1969 and in July 1972), the *IEEE Transactions on Computers* and the *IEEE Transactions on Man, Machines, and Cybernetics,* the Journals of *Remote Sensing of Environment* and of *Pattern Recognition,* and the proceedings of several symposia and workshops on picture processing and on pattern and target recognition. Previous introductory and survey articles include Shay [185], Colwell and Lent [37], Leese *et al.* [120], Park [167], Dornbach [48], and George [67].

As is the case with most emerging fields of research, the assiduous reader is likely to encounter considerable redundancy, with many experiments republished without change in the electrical engineering and computer literature, in the publications dealing with aerial photography and photogrammetry, in the various "subject matter" journals (agronomy, meteorology, geophysics), in the pattern recognition press, and in the increasing number of collections devoted exclusively to remote sensing.

A depository of relevant published material, government agency reports, and accounts of contractual investigations is maintained by NASA at the Earth Resources Research Data Facility at the Manned Spaceflight Center in Houston, Texas (Zeitler and Bratton [223]). The Facility also maintains a file of most of the photographs obtained by the NASA satellites and earth observation aircraft, and by other cooperating agencies, institutions, and organizations. Provisions are made for convenient browsing through both the printed material and the vast amounts of photography. The Center publishes *Mission Summary Reports* and detailed *Screening and Indexing Reports* of each data-collection operation and acts in principle as a clearinghouse for the exchange of such material. All of its holdings are cataloged by subject, location, and author, but in its periodically published computer compiled *Index* [155]; documents cannot, unfortunately, be located by either author or title. An annotated list of references to the literature is, however, also available [154].

For background information, the book *Remote Sensing,* embodying the report of the Committee on Remote Sensing for Agricultural Purposes appointed by the National Academy of Sciences, is recommended as much for its comprehensive coverage (the chapters on "Imaging with Photographic Sensors," "Imaging with Nonphotographic Sensors," "Applications," and "Research Needs," are particularly interesting) as for the quality of its photographic illustrations [161]. The reports of the other Committees are also available [185].

The International Geographic Union is compiling a survey of current work, including a list of participating scientists, in geographic data sensing and processing. The long-range plans of the United States, as presented to the Committee on Science and Astronautics of the U. S. House of Representatives, are set forth in [197], [38], and [60].

Contents of the Paper: Although much of the current ac-

Manuscript received January 31, 1972; revised June 30, 1972.
The author was with IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. 10598. He is now with the Department of Computer Science, University of Nebraska, Lincoln, Neb. 68508.

tivity is sponsored by NASA, most of the early work in remote sensing was initiated by military intelligence requirements; in particular, the development of imaging sensors was greatly accelerated by the deployment of high-altitude photoreconnaissance aircraft and surveillance satellites. Very little information is, however, available in the open literature about the actual utilization of the collected imagery. The few published experiments for instance, in the *Proceedings of the Symposium on Automatic Photo Interpretation* (Cheng *et al.* [31]), deal almost exclusively with idealized target recognition or terrain classification situations far removed from presumed operational requirements. In view of the scarcity of up-to-date information, this aspect of remote sensing will be discussed here only in passing despite its evident bearing and influence even on strictly scientific and economic applications.

We shall also largely avoid peripheral application of digital computers to the collection or preparation of pictorial material intended only for conventional visual utilization, as in the calculation of projective coefficients in photogrammetry or the simulation of accelerated transmission methods independent of the two-dimensional nature of the imagery. Nor shall we be concerned with statistical computations arising from manually derived measurements, as in models of forest growth and riparian formations based on aerial photographs, or in keys and taxonomies using essentially one-dimensional densitometric cross sections or manual planimetry.

Omitted too is a description of the important and interesting Sideways Looking Airborne Radar all-weather sensors. Such equipment will not be included in the forthcoming satellite experiments. Its potential role in remote sensing is discussed by Simonett [187], Hovis [94], and Zelenka [224].

The diffuse and unstructured nature of terrestrial scenes does not lend itself readily to elegant mathematical modeling techniques and tidy approximations; an empirical approach is well-nigh unavoidable. The first ERTS vehicle is not, however, expected to be launched until the second half of 1972, and the Skylab project is scheduled for 1973, hence, preparatory experimentation must be based on other material. Although none of the currently available sources of imagery approximates closely the expected characteristics of ERTS and Skylab, some reflect analogous problems, and several are of interest on their own merits as large scale data-collection systems. These sensor systems, including both spaceborne and airborne platforms, are described in Section II.

A large portion of the overall experimental effort has been devoted to developing means for entering the imagery into a computer, for storing and retrieving it, and for visual monitoring—both of the hardware available for scanning and displaying high-resolution imagery, and of the software packages necessary for efficient manipulation of large amounts of two-dimensional (and often multiband) imagery in widely disparate formats. These matters are discussed in Section III.

Section IV is devoted to image registration, the difficult problem of superimposing two different pictures of the same area in such a way that matching elements are brought into one-to-one correspondence. This problem arises in preparing color composites from images obtained simultaneously through separate detectors mounted on the same platform, in constructing mosaics from consecutive overlapping pictures from a single sensor, in obtaining a chronological record of the variations taking place in the course of a day or a year, and in comparing aspects of the scenery observed through diverse sensor systems. The most general objective here consists of mapping the images onto a set of standard map coordinates.

Section V is concerned with the application of automatic classification techniques to the imagery. The major problem is the boundless variability of the observed appearance of every class of interest, due to variations inherent in the features under observation as well as in atmospheric properties and in illumination. The difficulty of defining representative training classes under these circumstances has led to renewed experimentation with adaptive systems and unsupervised learning algorithms. From another point of view, the classification of observations into previously undefined classes is an efficient form of data compression, an objective of importance in its own right in view of the quantity of data to be collected.

By way of conclusion, we attempt to gauge the progress accomplished thus far in terms of what still remains to be done if automatic digital image processing is to play a significant part in the worthwhile utilization of the remote sensing products about to become widely available.

The remainder of this Introduction lists some of the proposed applications for ERTS and Skylab, outlines the functional specifications for the image collection systems designed for these platforms, and describes the central data processing facility intended to accelerate widespread utilization of the ERTS image products.

A. Objects of the United States Remote Sensing Program

It is too early to tell whether expectations in dozens of specific application areas are unduly optimistic [185], [38], [60]. Certainly, few applications have emerged to date where satellite surveillance has been conclusively demonstrated to have an economic edge over alternative methods; it is only through the combined benefits accruing from many projects that this undertaking may be eventually justified.

Typical examples of proposed applications are crop inventory and forecasting, including blight detection, in agriculture [61], [169]; pasture management in animal husbandry [97], [32]; watershed management and snow coverage measurement in hydrology [135], [22]; ice floe detection and tracking in oceanography [93], [196]; demarcation of lineaments and other geographic and geomorphological features in geology and in cartography [219], [59]; and demographic modeling [209].

Much of the digital image processing development work to date has been directed at removing the multifarious distortions expected in the imagery and in mapping the results on a standard reference frame with respect to the earth. This process is a prerequisite not only to most automatic classification tasks but also to much of the conventional visual photointerpretation studies of the sort already successfully undertaken with the Apollo and Gemini photographs [37].

The pattern recognition aspects of the environmental satellite applications are largely confined to terrain classification based on either spectral characteristics or on textural distinctions. Object or target recognition as such is of minor importance since few unknown objects of interest are discernible even at the originally postulated 300 ft per line-pair resolution of the ERTS-A imaging sensors.

B. Plans for ERTS and Skylab

The ERTS satellites will be launched in a 496-nmi 90-min near-polar (99°) sun-synchronous orbit. The total payload is about 400 lb.

The two separate imaging sensor systems on ERTS-A (the first of the two Earth Resources Technology Satellites) consist 1) of three high-resolution boresighted return-beam vidicons sensitive to blue–green, yellow–red, and deep-red solar infrared regions of the spectrum, and 2) of an oscillating-mirror transverse-sweep electromechanical multispectral scanner with four channels assigned to blue–green, orange, red, and reflective infrared (IR) bands. ERTS-B will carry a fifth MSS channel in the thermal infrared.

The target of the vidicon tubes is exposed for a period of 12 ms/frame; the readout takes 5 s. This design represents a compromise between the requirements of minimal motion smear, sufficient illumination for acceptable signal-to-noise ratio, and low bandwidth for transmission or recording. In the oscillating-mirror scanner high signal-to-noise ratio is preserved through the use of multiple detectors for each band.

The field of view of both types of sensors will sweep out a 100-nmi swath of the surface of the earth, repeating the full coverage every 18 days—with 10-percent overlap between adjacent frames. Every 100-nmi square will thus correspond to seven overlapping frames consisting of approximately 3500 by 3500 picture elements for each vidicon and 3000 by 3000 elements for each channel of the mirror scanner, digitized at 64 levels of intensity.

The resolution on the ground will be at best 160 m/line-pair for low-contrast targets in the vidicon system and 200 m/line-pair in the mirror scanner [126], [159], [160], [12]. A comparison of the various resolution figures quoted for the Gemini/Apollo photography and for the ERTS/Skylab sensors, and more pessimistic estimates of the resolving power of the ERTS sensors, can be found in [34].

The pictures will be either transmitted directly to receiving stations at Fairbanks, Alaska, Mojave, Calif., and Rosman, N. C., if within range, or temporarily stored on video tape. The vidicon data will then be transmitted in frequency-modulated form in an analog mode while the scanner information is first digitized and then transmitted by pulse-code modultation (PCM) [67]. Canadian plans to capture and utilize the data are described in [198].

The center location of each picture will be determined within one half mile from the ephemeris and attitude information provided in the master tracking tapes which will also be made available to the public.

The sources of geometric and photometric distortion and the calibration systems provided for both sensors are described in some detail in Section IV, where digital implementation of corrective measures is considered. We note here only that estimates for digital processing on an IBM 360/67 computer of a single set of seven ERTS images ranges from 2 min for geometric distortion correction only to 136 min for complete precision processing including photometric correction [217].

The Skylab program will utilize a combined version of the Apollo command-and-service module and a Saturn third stage with a total vehicle weight of 130 000 lb in a low (250-nmi) orbit permitting observation of the earth between latitudes 50° N and 50° S.

The major imaging systems of the Skylab EREP (Earth Resources Experimental Package) consist of a 13-band multispectral scanner covering the ranges 0.4–2.3 μ and 10–12 μ, and of six 70-mm cartographic cameras having suitable film–filter combinations for four bands between 0.4 and 0.9 μ. The instantaneous field of view of the multispectral scanner will be 80 m² with a 78-km swath. The low-contrast resolution of the camera system will be 30 m/line-pair with a 163-km² surface coverage. A number of nonimaging sensors, such as a lower resolution infrared spectrometer, microwave radiometer/scatterometer altimeter, will also be on board, as well as an optical telescope [215], [168].

The multispectral data will be recorded on board in PCM on 20 000 BPI 28-track tape and returned with the undeveloped film at the end of each manned period of Skylab.

C. Throughput Requirements

Only the relatively well-defined processing load of the centralized NASA facility for the ERTS imagery will be considered here, since it is clear that the quantity of data required for each application ranges from the occasional frame for urban planning [165], to the vast quantities needed for global food supply forecasts [71]. The expected requirements of the user community are discussed in some detail in [72] and [146]. The coverage extended for the North American continent is of the order of

$$\frac{3000 \text{ nmi} \times 3000 \text{ nmi (area)}}{100 \text{ nmi} \times 100 \text{ nmi (frame size)} \times 18 \text{ days (period)}} = 50 \text{ sets}$$

of seven pictures per day. Each set of pictures contains approximately 10^8 bits of data, thus each day's output is the equivalent of 125 reels of 1600 bit/in magnetic tape. This estimate neglects the effects of cloud cover, which is discussed in [190] and [68].

At the NASA Data Processing Facility all of the imagery will be geometrically corrected to within at most 0.5 nmi in linearity and at most 1 nmi in location, and distributed in the form of 70-mm annotated black-and-white transparencies prepared by means of a computer-controlled electronic-beam recorder. In addition, about 5 percent of the images will undergo precision processing designed to reduce registration and location errors with both sensors to within 200 ft (to allow the preparation of color composites), and to reduce photometric degradation to under 1 percent of the overall range. All of the precision-processed data, 5 percent of the raw MSS data, and 1 percent of the raw RBV data will be made available on standard digital tape [220], [217], [138]. The current plan is to use the ephemeris and tracking data for the bulk processing and analog cross correlation against film chips of easily observable landmarks for the precision processing [138].

This is, of course, only the beginning; the subcontinent represents but 15 percent of the total area of the globe. While nations other than the U. S. and Canada may eventually obtain the data by direct transmission from the satellite [62], much of the original demand will be funneled through the NASA facility. The initial capacity of the photographic laboratories is to be 300 000 black-and-white and 10 000 color prints or transparencies per week; it is clear that the major emphasis is *not* on the digital products.

II. Characteristics of the Data Currently Available for Experimentation

At the initial stages of an image-processing experiment, the actual content of the pictorial data under investigation is sometimes less important than its format, resolution, distortion, and grey-tone characteristics, and its relation to other pictorial coverage of the same area. Fortunately, a large variety of data, much of it already digitized, is available to the tenacious investigator, and the supply is being replenished perhaps faster than it can be turned to profitable use.

The sources covered in this section include the vast collection of the National Environmental Satellite Center, the photography from the Gemini and Apollo missions, and both

Fig. 1. ESSA-9 mosaic of North America. Traces of the reconstruction from the separate video frames are evident from the fiducial marks. The deviation of the overlay from the true coast lines shows a registration error carried into the mapping program. A programming error, since corrected, may be seen in the checkerboard in NW corner. Note gray wedge and annotation.

photographic and multispectral coverage of over two hundred specially selected test sites obtained by the NASA earth observation fleet.

A. Weather Satellites

Data have been obtained so far from 25 individual satellites beginning in 1959 with Vanguard and Explorer and continuing in the early 1960's with the ten satellites of the TIROS series and later with the Environmental Survey Satellites (ESSA) of the Tiros Operational Satellite System. The current operational series (ITOS) has been delayed because of the premature failure of ITOS-A. Data have also been collected by the Applications Technology Satellites in high geosynchronous orbits and by the experimental Nimbus series.

At present the major meteorological function of these systems is to provide worldwide cloud and wind-vector information for both manual and automated forecasting services, but extensions to other atmospheric characteristics are also underway [222], [41]. The newer satellites provide, for instance, accurate sea-level temperatures in cloud-free regions [123], [174], cloud-height distributions (through the combination of infrared sensor information with ground-based National Meteorological Center pressure and temperature observations [47]), and somewhat less accurate altitude-temperature and humidity profiles (based on the differential spectral absorption characteristics of the atmosphere). Other applications are mapping snow and ice boundaries and observation of sea state [135]. In addition, over 4000 storm advisories have been issued as a result of satellite observed disturbances [120].

The individual frames of Advanced Vidicon Camera System video, obtained from the latest operational polar-orbiting satellites, contain approximately 800 by 800 points at a resolution varying from 1.5 mi at the subsatellite point to 3.0 mi at the edges. The video is quantized to 64 levels of grey, with nine fiducial marks (intended to allow removal of geometric camera distortion), appearing in black on white. The overlap between successive frames is about 50 percent in the direction of the orbit and about 30 percent laterally at the equator; each frame covers about 1700 by 1700 nmi [23]. The two-channel Scanning Radiometer operates at about half the resolution of the AVCS [29].

Digital mosaics are available on a daily basis in either Universal Transverse Mercator or Polar Stereographic projections (Fig. 1). Each "chip" contains 1920 by 2238 points digitized at 16 levels, covering an area of about 3000 by 3000 mi^2. Multiday composites including average, minimum, and maximum brightness charts for snow, ice, and precipitation studies, are also issued periodically. The positional accuracy of any individual point is usually good to within 10 mi. On the high-quality facsimile output provided by the National Environmental Satellite Service geodesic gridlines and coastlines are superimposed on the video to facilitate orientation, but the only extraneous signals in the actual digital data are the fiducial marks from the vidicon camera [26], [24].

The geosynchronous ATS's are equipped with telescopic spin-scan cloud cameras which take advantage of the spin of the satellite itself to provide one direction of motion. The signal from these sensors can be monitored with relatively simple equipment; currently over 600 receiving stations throughout the world take advantage of the wide-angle coverage provided of the Atlantic and Pacific Oceans (Fig. 2). The average altitude is of the order of 20 000 mi, but the high angular resolution of the spin-scan camera allows ground definition comparable to that of the ITOS vidicons. Each frame consists of approximately 2000 by 2000 points. The maximum repetition rate is one frame every 24 min [28].

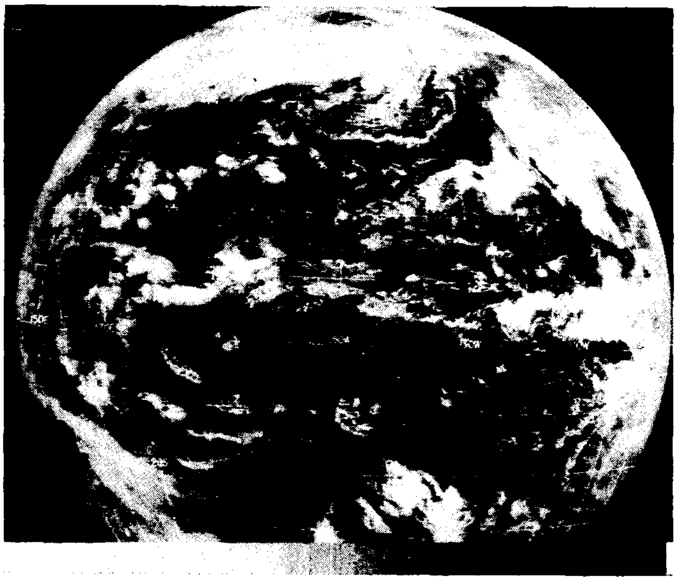
The Nimbus satellites are used mainly for experimentation with instrumentation to be eventually included in operational systems. Nimbus III, for instance, launched in 1969, carries a triad of vidicon cameras, a high-resolution infrared radiometer, an infrared spectrometer, an ultraviolet monitor, an image dissector camera system, and an interrogation, recording, and location system for data collection from terrestrial experimental platforms.

At present, the imagery from the various satellites is archived at the original resolution only in graphic form, but the last few days' coverage is usually available from the National Environmental Satellite Service Center at Suitland, Md., on digital magnetic tape. Medium-scale archival data tapes going back to January 1962 are maintained by the National Weather Record Center in Asheville, N. C. [23].

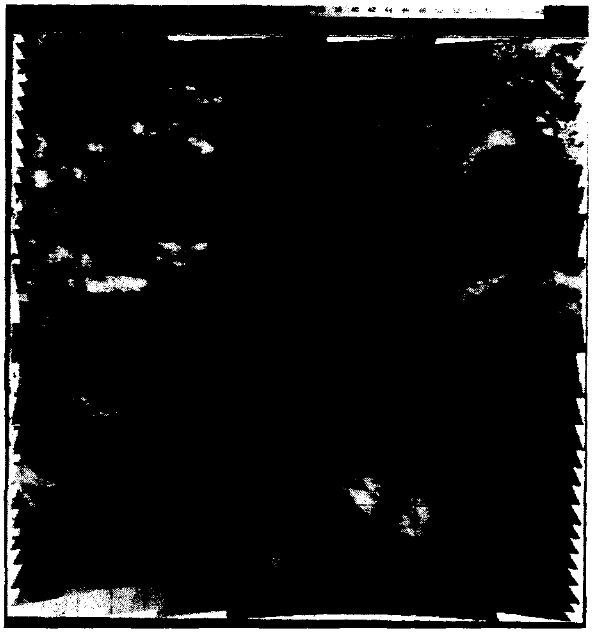
An excellent summary of the history, status, and prospects of meteorological satellites data processing, including an extensive bibliography, is contained in [120] and updated in [41].

B. Gemini and Apollo Photography

Most of the 2000 photographs collected on the six Gemini missions between 1964 and 1968 were obtained with hand-held cameras. The astronauts appear to have favored high-oblique



(a)



(b)

Fig. 2. ATS image. Raw video and Mercator projection of the Pacific Ocean from the first ATS. These illustrations were obtained through the courtesy of the National Environmental Satellite Center.

shots, with considerable variation in the scale and orientation of photographs of the same area [151].

For registration experiments, three Gemini photographs of Cape Kennedy obtained within a three-year interval are quite suitable. Two of these photographs are almost at the same scale and show little foreshortening, while the third is an oblique view extending clear across Florida [10].

In addition to hand-held cameras, some of the Apollo missions were equipped with a bank of four boresighted 70-mm Hasselblad cameras. The SO-65 project on the Apollo-9, in particular, was designed to assess the capabilities and limitations of multiband photography in a variety of applications. The satellite photography was carefully coordinated with aerial photography from almost a dozen aircraft flying at altitudes ranging from 3000 to 60 0000 ft, with airborne multispectral scanner coverage, and with the simultaneous collec-

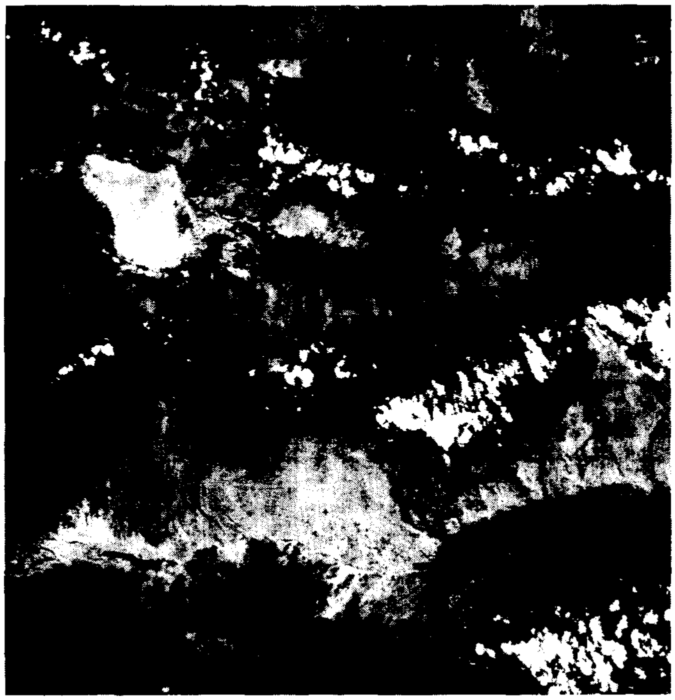


Fig. 3. Digitized Apollo photograph. This photograph of central Arizona was digitized at a resolution corresponding to 4200 lines on a drum scanner and was then recorded on film using the same device. The fiducial marks were introduced in the digital data for testing certain reseau detection algorithms [10], [11].

tion of terrain information ("ground truth") from several test sites [152].

For agricultural purposes, the most popular test site appears to be the Imperial Valley of California. Extensive coverage is available for this area, with overlapping frames both in the same orbit of the Apollo-9 and in successive orbits several days apart. Each photo-quadruplet consists of three black-and-white negatives in the green, red, and infrared, and of a false-color composite including all three of these bands. The scale of the vertical photography is about 1:1 500 000 [153].

The photographs are obtainable in the form of third-generation prints, negatives, or 35-mm slides from the Technology Application Center of the University of New Mexico. Several dozen photographs, including some of the Imperial Valley and Cape Kennedy pictures mentioned above, have been digitized by Fairchild Camera and Instrument Corporation, Optronics International, Inc., and IBM (among others), at a resolution corresponding to 4000 lines/frame (Fig. 3). The quality of the pictures gives little justification for higher resolution [5].

C. High-Altitude Photography

The MSC Earth Resources Aircraft Program operates half-a-dozen specially equipped airplanes gathering data over some 250 NASA designated test sites [48]. The particular missions flown are decided largely on the advice of 200 or so principal investigators of diverse affiliations appointed for specific research tasks involving remote sensing. About 500 000 frames are collected annually, and are available from NASA "by special request."

Detailed descriptive material is available for each mission, including flight log summaries, charts showing flight lines, lists of camera characteristics (some missions fly as many as a dozen different cameras (see Fig. 4), film and filter combinations, roll and frame numbers, and plots of the earth loca-

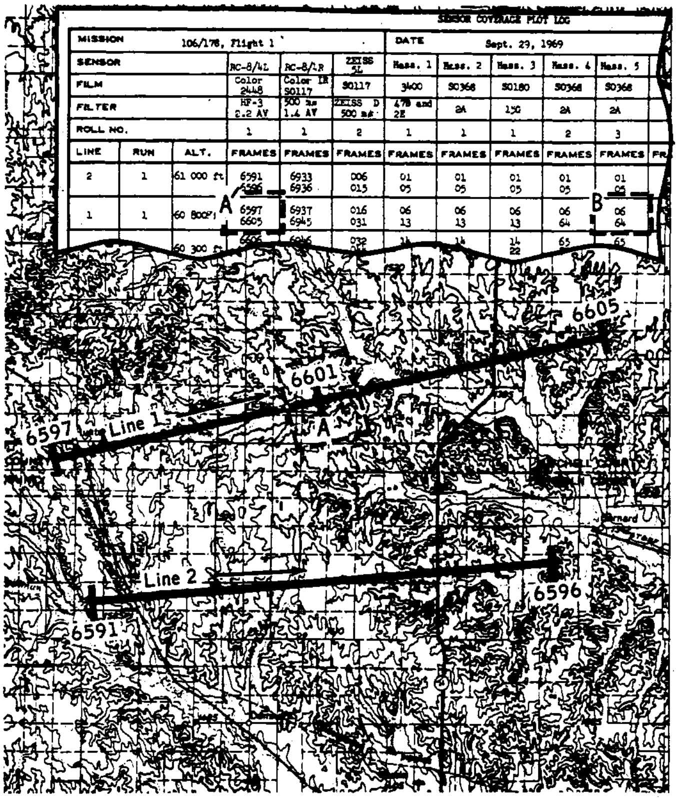


Fig. 4. NASA–ERAP documentation. Example of photographic coverage plot and corresponding plot for a high-altitude flight of the Earth Resources Observation Program (excerpted from NASA–MSC Screening and Indexing Report, Mission 123, Houston, Tex., July 1970).

tion of selected frames. For simulation of future satellite data, the most suitable imagery is probably that obtained by the 60 000-ft ceiling RB-57 twin jet reconnaissance aircraft and by the recently acquired "ERTS-simulator" U-2's equipped with four multiband cameras (red, green, pan-IR, color-IR) with 40-mm lenses imaging the earth at only twice the resolution of the expected ERTS coverage.

Several of the aircraft are equipped with line scanners of various types. Such instruments will be described in the next section.

D. Airborne Multispectral Scanners

In instruments of this type, one scan direction is provided by the forward motion of the aircraft and the other by the rotation or oscillation of a prism or mirror (Fig. 5). Emitted or reflected radiation from the ground is imaged onto an array of detectors sensitive to various bands in the spectrum; the recorded output is an array of multidimensional vectors where each vector represents a specific position on the ground and each component corresponds to a spectral channel [92].

Scanners in operation today have anywhere from one to twenty-four spectral channels of varying bandwidths; cover all or part of the spectrum from the ultraviolet to the thermal infrared; offer a spatial resolution of 2 mrad down to about 0.1 rad; and differ widely with respect to calibration sources, attitude control and tracking accuracy, and method of recording the information. In general, most of the instruments can be flown in various configurtions in conjunction with other sensors including photographic cameras, nonimaging probes, and radar [126].

Most of the published work is based on data obtained by

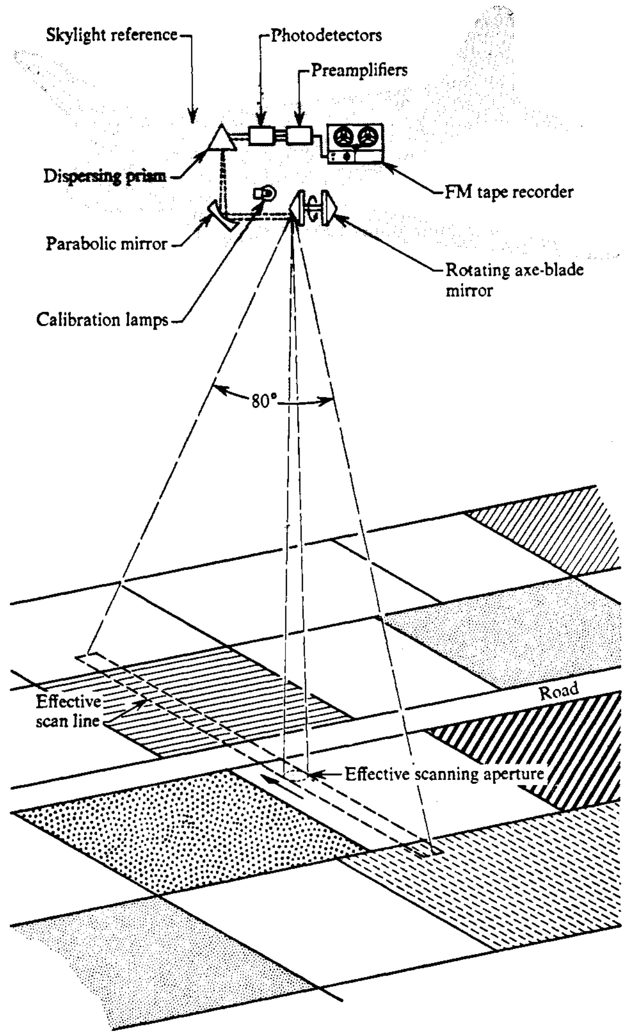


Fig. 5. Multispectral data collection. Schematic diagram showing how the light reflected or radiated from the ground is decomposed into its spectral components, converted into an electric signal, and recorded on board in analog form for subsequent digitization.

means of the scanners mounted on an unpressurized (10 000-ft ceiling) C-47 aircraft operated for NASA by the University of Michigan. Since 1966, over 150 missions have been completed, with such varied purposes as the study of soil distribution, arctic ice, bark attack on ponderosa pine, water depth, sinkhole-prone conditions, water-fowl habitats, urban features, and most recently and extensively, corn blight. Only a small fraction of the collected information has been automatically analyzed; the remainder is printed out in analog form for visual examination [148].

Digitized data from one of the Michigan flights are typically in the form of an array of 12-dimensional vectors (there are additional channels available but due to separate mounts they are not all in spatial register), with 220 samples perpendicular to the flight direction and up to several thousand samples along the flight line. Ground resolution at 5000-ft flight altitude is of the order of 60 ft.

Several calibration sources are viewed and recorded during the period that neither surface of the rotating axe-blade mirror is looking at the ground. These sources include lamps filtered to match the solar spectrum as closely as possible, black-body thermal references, and background illumination collected through a diffuser [112], [124].

After the flight, the analog signal recorded on FM tape is digitized, corrected for roll angle, unskewed, and normalized with respect to the calibration signals. Noise bursts, out-of-sync conditions, and other anomalies are detected by elaborate preprocessing programs which also provide appropriate coordinate labels for subsequent identification with respect to photographs or other sources of independent terrain information.

Michigan is currently testing the new M7 scanner which is designed for recording wavelengths from 0.34 to 12 μ [39]. In addition, NASA is testing a 24-channel scanner on a C-130 Hercules (30 000-ft) aircraft equipped with an elaborate automatic data annotation system for facilitating earth location of the imagery [111], [221], [218], [69]. Other scanners with a smaller number of channels and less flexible arrangements are flown on smaller aircraft (such as Bendix's Beechcraft, and Colorado State's Aerocommander) for special missions.

The design of a 625-line color television system intended for airborne service is described in [142].

III. Image-Processing Systems

Although the availability of a large general-purpose digital computer is a valuable asset for experimentation with processing techniques, special hardware is required for converting the raw data into computer-readable form, for monitoring the results of the processing operation and for entering ground truth or other ancillary data pertaining to observed features of the image.

Many experimenters feel that parallel processors must also be available for performing the calculations at the speed necessary to evaluate the results on a significant enough variety of imagery. With conventional processors a large amount of programming work of a rather stultifying nature is required to decompose two-dimensional arrays containing up to 10^7 bytes into fragments of a size suitable for manipulation within the constraints imposed by core size, sequential tape access, blocked disk formats, and, possibly, multiprogrammed operating systems, and to reconstitute these arrays after transformations which may involve changes in the relations between, as well as within, the segments. Some alternatives to sequential digital processing are discussed by Preston elsewhere in this issue.

The large initial investment necessary to begin coming to grips with the more interesting problems offered by *real* data (as opposed to mathematical abstractions or shreds of hand-picked and selected imagery) accounts for the domination of this area of research by a few relatively large institutions, as reflected in the bibliography accompanying this paper.

It is not, as mentioned before, indispensable for each institution to provide means for digitizing the raw data. In principle, this is a one-time operation. In practice, however, it is a very ticklish procedure, and shortcomings may be discovered only after considerable experience with the digitized imagery. For this reason, many experimenters believe it necessary to develop their own scanners and other analog-to-digital conversion equipment, a challenge usually outlasting their purse and patience.

The equipment required for precision conversion of multispectral FM recordings and directly captured weather satellite pictures is so specialized that it will not be described here. Some of the calibration and synchronization problems encountered are described in [148] and [28]. Optical scanners suitable for diverse applications are, however, commercially available and will be briefly discussed.

There is no question that adequate grey-tone output must be conveniently available for experimentation, but opinion seems divided as to whether a television-type screen display with some interactive capability or a high-quality hardcopy output is preferable. A common compromise is a low-resolution CRT display with higher resolution (because flicker-free operation is not required) Polaroid recording capability.

Other less easily defined aspects of processing *large* pictures discussed in this section are the operating systems and utility programs necessary for any sort of coherent experimentation, special processors for anticipated quantity production, and the role of man–machine interaction in both experimental and operational systems.

Some examples of digital-computer-oriented remote sensing facilities, and of the equipment they contain are as follows:[1]

NOAA's National Environmental Satellite Center at Suitland, Md.: three CDC 6600's, CDC 160A, two ERM 6130's and 6050's, CDC 924, three 5000 by 5000 element Muirhead recorders, Link 35-mm archival microfilm unit [28], [29];

NASA–MSC's complex for the analysis of multispectral recordings and photography: 160 by 111 digital color display, closed-circuit television display, Xerox hardcopy output, Grafacon tablet, keypack, analog tape drives, IBM 360/44 processor [56], [58];

Caltech's JPL operation: film-scanner, CRT display, FM tape conversion, facsimile hardcopy, IBM 360/75 [18], [162];

University of Michigan multispectral facility: SPARC analog computer, drum scanner, analog film recorder, CRT display, FM tape conversion, CDC 3600 [131];

Purdue University's Laboratory for Applications of Remote Sensing: 577 by 768 element flicker-free 16-level digital TV display, light pen, continuous image motion, selective Polaroid or negative hardcopy without obstruction of display, FM tape conversion, IBM 360/67 [116], [117], [203];

University of Kansas KANDIDATS (Kansas Digital Image Data System) and IDECS (Image Discrimination, Enhancement, and Combination System): three flying-spot scanners for transparencies (25 mm to 3 by 4 in) and a vidicon camera controlled by a PDP 15/20, electronic congruencing unit (rotation, translation, and change of scale), 20 by 20 element linear processor and level selector, 24-channel digital disk storage, monochrome and color displays with built-in crosshatch generator, film output, GE-635 computer [77];

Computing Science Center of the University of Maryland: flying-spot film scanner, drum scanner/recorder, CRT display, vidicon, Univac 1108 [171];

University of Southern California Image Processing Laboratory: IER 1000 by 1000 element flying-spot color scanner and display, Muirhead rotating-drum color scanner and recorder, digital color television and display, Adage vector display with joystick and light pen, IBM 360/44, IBM 370/155, and HP 2100 computers connected to ARPA net [173];

Perkin-Elmer's Sampled Image Laboratories: drum scanner/recorder, flying-spot scanner, high-resolution traveling-stage microscope image-plane scanner, CRT and storage tube displays, precision plotting table, linked IBM 360/67, XDS 930, H-516, and Varian 620-i computers [212];

[1] Some of this information, obtained through personal communication, is more recent than the references would indicate.

IBM Research Division's facility at Yorktown Heights: film scanner, CRT output, image dissector, digital color TV display, graphic tablets, 360/91, 360/67, and 1800 computer net [85].

Another group of facilities is dedicated primarily to automatic photointerpretation, with only fragmentary information available about the work. Examples of this group are as follows:

McDonnell Douglas Astronautics: a compact vidicon scanner with 70-mm film scanner and a minicomputer, and a larger interactive system with a 1024-line (nominal) image dissector, scan converter, rear-projection viewer, 16-level digital TV display, alphanumeric display, joystick, XDS 930 computer [104], [105];

SOCRATES (Scope's Own Conditioned-Reflex Automatic Trainable Electronic System), a 20 by 20 photodiode and threshold logic array, the successor to Conflex I [164], [211];

SARF, General Motors' phoenix-like interactive Signature Analysis Research Facility [192];

MULTIVAC, Hughes Research Laboratories' 10 by 10 element binary array processor [8];

Litton Industries' Automatic Target Recognition Device, a hybrid system with a programmable CRT scanner, Recomp II process control computer, and interactive operation [205];

Cornell Aeronautical Laboratories' adaptive image processing operation using 35/70-mm CRT scanner, storage scope output, PDP-9, IBM 360/65 and 370/165 [134], [143];

ASTRID, Ohio State's Automatic Recognition and Terrain Identification Device, a hybrid computer system oriented toward processing line segments [163].

A good review of image enhancement facilities for remote sensing throughout the country is available in [37]. Among the systems discussed are the following: the NASA–USDA Forestry Remote Sensing Laboratory Optical Color Combiner at Berkeley, Calif.; the University of Kansas IDECS system; the two-band 1000-line Philco-Ford Image-Tone Enhancement System; and the Long Island University Multispectral Camera-Viewer. Abroad, we know of sustained activity only at the Institute for Information Processing and Transmission of Karlsruhe University [106], [89], [107], though some earlier European work is described in [21].

A. Optical Scanners

Since the data most closely resembling the expected ERTS and Skylab imagery in terms of resolution are available in the form of photography, optical scanners are necessary to translate the grey-tone (or color) information into computer-readable code.

CRT flying-spot scanners and television cameras (image dissectors or vidicons) are the most inexpensive and fastest devices available, but beyond a degree of resolution corresponding to about 500 by 500 picture elements quantized at 16 levels of intensity, the nonlinearities introduced by such scanners tend to exceed the degradation and distortion present in the photography itself. Owing to the nonuniform sensitivity, scanning the pictures section by section introduces even graver problems in juxtaposing adjacent sections.

Mechanical-drum and flatbed microdensitometers (50 000 dollars and up) are easily capable of the accuracy required for almost any type of photography, with even the less expensive digitizers (15 000 dollars) producing 2000 by 2000 arrays with up to eight bits of grey-scale quantization. Owing to the narrow spectral range of the source of illumination and matching detector configuration, most of these machines cannot be readily converted to color work. For this purpose, one must turn to scanners specially designed for the simultaneous production of color-separation plates in the printing industry, suitably modified by the addition of an analog-to-digital interface. The low speed of operation of such scanners (of the order of $\frac{1}{4}$ s/scan-line) generally requires off-line operation or an elaborate interrupt structure [141], [210], [171], [212].

Due to the lower contrast of opaque prints, positive or negative transparencies constitute the preferred medium for scanning. Because of multiple surface reflections, transparencies cannot be scanned with a reflection scanner by simply providing a uniform reflective background. Drum scanners designed for film have either a glass drum or some self-supporting arrangement with edge guides.

B. Grey-Tone Output Devices

Many flying-spot scanners and drum microdensitometers can be modified to operate in a write mode. This is a particularly convenient arrangement since the format conversion problems are altogether eliminated, and compatible resolution and sensitivity characteristics are guaranteed. The only drawback is that closely controlled wet processing with attendant time delay is usually required for consistent grey-tone reproduction. Film recorders may also be used with Ozalid foil overlays to produce high-quality color transparencies [130].

Facsimile recorders are less expensive and can provide 16 levels of grey on a 4000 by 4000 array (Fig. 2). Programmable flying-spot recorders with special character masks, such as the widely used Datagraphics 4020, provide about 500 by 500 distinct elements, but elaborate programming is necessary, with frequent recalibration, to secure even eight reasonably uniformly distributed intensity levels on either paper or film. Spatial resolution may, however, be traded off for grey-scale resolution by resorting to halftone techniques [79], [183].

Although all of these devices are generally used in a fixed-raster mode of operation, control of the beam deflection in an electron-beam recorder being developed by CBS Laboratories is the intended mechanism for the correction of "bulk-processed" video tapes at the NASA–ERTS Data Processing Facility [138]. This is an essentially analog system under control of an XDS Sigma 3 digital computer. A laser-beam recorder with a 10-μ spot over a 20 by 20-cm area has been developed at ITEK Corporation [125].

Line-printer overstrike programs are still useful for quick turn around, particularly with elongated formats such as that of the Michigan MSS. The visual qualities of this form of output are greatly improved by judicious use of watercolors and transparent overlays; modifications intended for on-line terminal use are, however, agonizingly slow. Isometric, perspective, and isodensity Calcomp plots offer another alternative for the impecunious investigator.

Television-type grey-scale displays are generally refreshed either from a high-speed core buffer or from a digital video disk. A single-line buffer is sufficient to fill the video disk, but a full-frame buffer (typically 520 by 600 bytes or picture elements) renders it much easier to change only parts of a picture without regenerating the entire frame.

Color displays need three times as much buffer storage as black-and-white pictures, but offer no particular difficulty if registered color separations are available in digital form. The calibration procedures necessary to produce color composites from *multiband* photography (filtered black-and-white exposures) are discussed in [19].

It is possible to circumvent the need for an image buffer by resorting to the now available grey-scale storage scope. Such a device requires a much simpler interface than a refreshed system, but the saving is to some extent illusory since most of the cost resides in the programming system necessary to select, retrieve, edit, and otherwise manipulate the displayed pictures.

Without a sophisticated programming system, the display can be used only to show the coarsest changes in the picture or as a conversation piece with lay visitors. For meaningful experimentation, it is desirable to be able to show two or more versions of the same picture simultaneously, to form overlays, to label specified features, to display intensity histograms and other computed functions, to vary the density modulation to bring into prominence regions of different intensity or to compensate for the amplitude nonlinearities of both the data collection system and the display itself, and to to perform many other more specific functions quickly and effortlessly.

Just how good a display must be to prove useful is a moot point and depends largely on the ingenuity of the user in casting the relevant information in a form compatible with the available display capabilities. So far, there is insufficient evidence to evaluate, in realistic terms, the contribution of display systems to the development of specific image-processing algorithms.

C. Operating Subsystems and Utility Programs

As already mentioned in several different connections, the major part of the programming effort required to cope effectively with large image arrays (four orders of magnitude larger than binary character arrays and about two orders of magnitude larger than most biomedical pictures) must be devoted to conceptually trivial matters such as: the decomposition and reconstitution of pictures; edge effects; efficient packing and unpacking routines for the various modes of point representation; variations in the basic byte and word sizes between different machines; aspect-ratio and other format changes among scanner, analog-to-digital converter, internal processor, and output devices; tape and disk compatibility; storage-protect and filing devices to ensure the preservation of valuable "originals" without undue accumulation of intermediate results; diagnostic routines permitting inspection of the actual values of relatively small segments at given image coordinate locations; left–right, up–down, black–white confusions; and myriad other frustrating details.

To avoid having to reprogram all these ancillary routines for each new function to be performed on the pictures, it is desirable to set up a procedure-oriented language or system within the framework of which new programs can be readily incorporated. Such a system may provide the necessary interface with the special-purpose hardware, allow access to a library of subroutines, supervise extensive runs in the batch mode on large computers, and offer special image-oriented debugging and diagnostic facilities in a time-shared mode of operation [125], [85].

Since most functions to be performed on a picture are local operations in the sense that the values of only a small subset of all the picture elements need be known in order to compute the value of an element in the output picture, the provision of a generalized storage policy is essential for the efficient performance of arbitrary window operations. For instance a window of size $n \times m$ may take n disk accesses if the image is stored line by line. A worst case example is a horizontal edge-finding operation on an image stored by vertical scans. With large images in such cases it is usually worth rewriting the array in an appropriate format before proceeding with the calculation; flexible means for accomplishing the reshuffling must be a part of any image-processing system worthy of the name unless an entire image can be accommodated in the fast random-access memory. A valuable discussion of the computational aspects of two-dimensional linear operations on very large arrays (up to 4000 by 4000 elements) is presented in [99].

Among the best known image-processing systems are the various versions of PAX developed in conjunction with the Illiac III, and later rewritten for the CDC 3600, IBM 7094 and System/360, and also for the Univac 1108. In PAX, images are treated as stacks of two-dimensional binary arrays. Arithmetic operations on integer-valued image elements are replaced by logical operations performed in parallel on the corresponding components (such as the 2^3 level) of several picture elements. Planes are defined in multiples of the word size of the machine, but aside from a few such restrictions, PAX II is conveniently imbedded in Fortran IV, with the debugging facilities of the latter available in defining new subroutines. Both a conversational mode and batch demand processing have been implemented at the Computing Center of the University of Maryland. The major subroutines are designed for the definition of planes, masks, and windows, logical functions of one or more planes or windows, neighborhood operations, area and edge determination, preparation of mosaics, tracing of connectivity, creation of specific geometric figures such as circles and disks, distance measurements, grey-scale overprint, grey-scale histograms and normalization, superimposition of grids, noise generation, moment-of-inertia operations, translation, rotation and reflections, and include as well a number of basic "macro" operations intended to facilitate expansion of the program library [149], [170], [30], [101], [102].

Other examples of comprehensive programming systems described in the literature are Purdue's LARSYSAA [116], [202], [203], General Motors' SARF [192], and the University of Kansas KANDIDATS [76]. Such systems are generally difficult to evaluate because the publication of interesting research results developed with the system (as opposed to contrived examples) tends to lag indefinitely behind the system description. Furthermore, very seldom is there any indication of the breakdown between the amount of effort expended in the development of the system and the time required to conduct given experiments.

D. Special-Purpose Digital and Hybrid Systems

At a time of continually waning interest in special-purpose processors for pattern recognition, there are two main arguments for their use in remote sensing. The first is the inability of even the largest digital computers to cope with element-by-element classification at a speed approaching the rate of collection of the data; an airborne MSS typically spews out 10^8 samples/h while the 360/44 can ingest only about 10^5 bytes/h on a ten-class problem [133]. The second argument is based on the need for on-board processing owing to the excessive bandwidth requirements for transmitting data from a spaceborne platform.

An example of a hybrid classification system is the SPARC machine at the Infrared and Optics Laboratory of the University of Michigan [130]. SPARC has 48 analog multipliers operating in parallel, and performs quadratic maximum-likelihood decisions on 12-component vectors at the rate of one every 10 μs.

Because of the difficulty of calibrating the machine, requiring manual setting of the potentiometers corresponding to the entries in up to four previously computed 12×12 class-covariance matrices, exact duplication of results is almost impossible and the machine is therefore of marginal utility in strictly experimental investigations. A successor featuring direct digital control and an interactive display capability is on the drawing boards [132], [133].

The proposed NASA–ERTS data processing facility makes use of optical correlation techniques against chips containing easily identifiable landmarks for registering the data, and special digital hardware for point-by-point correction of vignetting in the vidicons and other systematic errors [71], [138].

So far, no on-board satellite image processor has been installed, but a feasibility study based on several hundred photographs of clouds and diverse lunar terrain features concludes that an acceptable classification rate can be attained [45].

Another study, using photographs of six "typical" terrain features, proposes a simple adaptive processor based on coarsely quantized average intensity levels, spatial derivatives, and bandpass spatial filter output [100]. Electrooptical preprocessing techniques using image intensifier tubes are described in [83].

The highly circumscribed test material used in these experiments leaves some doubt as to their relevance to the output of currently available spaceborne sensors.

In spite of the commercial availability of relatively inexpensive FFT hardware and long shift-register correlators, there appears to have been no attempt so far to apply these devices to digital image processing for remote sensing.

E. *Interactive Processing*

Interactive processing in remote sensing does not necessarily imply the kind of lively dialogue between man and machine envisioned by early proponents of conversational systems and already realized to some extent in computer-aided design and information retrieval, and in certain areas of pattern recognition (see paper by Kanal elsewhere in this issue).

The prime objective of on-line access to the imagery is to provide an alternative to laborious and error-prone off-line identification, by row and column counts on printouts or interpolation from measurements on hardcopy output, of features which are easily identifiable by eye yet difficult to describe algorithmically without ambiguity. Examples of such features are landmarks—such as mountains, promontories, and confluences of rivers—for use in accurate registration of photographs, and the demarcation of field boundaries for crop-identification studies based on multispectral recordings.

Even a system without immediate visual feedback, such as a graphic tablet on which a facsimile rendition of the digitized image can be overlaid, is considerably superior to keying in the measured coordinate values. One step better is the displacement of a cursor on the display under control of a tablet, joystick, or mouse. The ideal is direct light-pen interaction, but this is not easy to implement on a high-resolution digital display. For really accurate work, a zoom option on the display is necessary for accurate location of the features of interest, but the amount of computation required is prohibitive in terms of response time [84].

A thoroughly tested system for locating nonimaging sensor data in relation to a closed-circuit television display of simultaneously obtained photography is described in [55] and [58]. The accuracy of the computer-generated overlays is shown to be better than 0.5° by reference to salient landmarks [54].

There has also been discussion of on-line design of spatial filters, decision boundaries, and compression algorithms. Here again, however, the waiting time between results is lengthy, and the operator must transmit so little information to the machine—typically just a few parameter values—that batch processing with high-quality hardcopy output is preferable in many instances. With multiprogrammed systems, the difference between on-line and off-line operation tends to blur in any case, with the distinction sometimes reduced to whether one enters the necessary commands at a terminal in the office or at a nearby remote job entry station.

Another possible desideratum is a display browsing mode, allowing inspection of large quantities of images. Here also, however, reams of hardcopy output, with on-line operation, if any, confined to pictures of interest, may be preferable.

It would thus appear that the most appropriate applications of interactive concepts, in the context of remote sensing, are 1) the debugging of program logic, where small image arrays may be used to keep the response time within acceptable limits, and 2) the entry of large quantities of positional information, where practically no computation is required and no viable off-line alternatives exist.

IV. Image Restoration and Registration

The need for exact (element-by-element) superimposition of two images of the same scene upon one another arises in the preparation of color composites, chronological observations, and sensor-to-sensor comparisons. The spatial, temporal, and spectral aspects of image congruence are discussed in [3]. Here we shall attempt to categorize the types of differences which may be encountered between two pictures of the same scene on the basis of the processing requirements necessary to produce a useful combined version. Only digital techniques are presented; the advantages and disadvantages of optical techniques are discussed elsewhere in this issue by Preston, and in [165], [166].

Geometric distortions in electronically scanned imagery are due to changes in the attitude and altitude of the sensor, to nonlinearities and noise in the scan-deflection system, and to aberrations of the optical system.

Photometric degradation (occasionally also referred to as "distortion," with questionable propriety) arises due to modulation transfer-function defects including motion blur, nonlinear amplitude response, shading and vignetting, and channel noise.

The atmospheric effects of scattering and diffraction, and variations in the illumination, also degrade the picture, but these effects are in a sense part of the scene and cannot be entirely eliminated without ancillary observations.

Once the pictures to be matched have been corrected for these sources of error, resulting in the digital equivalent of perfect orthophotos, the *relative* location of the pictures must still be determined before objective point-by-point comparisons can be performed. In reality, this is a chicken-or-egg problem, since the pictures cannot be fully corrected without locating a reference image, but the location cannot be determined accurately without the corrections.

Tracking and ephemeris data usually provide a first approximation to the position of the sensor at the time of exposure, but for exact registration more accurate localization is required. In operator-aided systems, such as the operational NESC mapping program, the landmarks are located by eye, while in fully automatic systems some correlation process is usually employed. A compromise is preliminary location of the landmarks by the operator, with the final "tuning" carried out by computer [191] in a manner analogous to the widely used track measurement programs for bubble-chamber photographs, described by Strand elsewhere in this issue.

A major difficulty in multispectral correlation or matched filtering of perfectly corrected images is the existence of *tone reversals*, or negative correlations, between spectral bands. This phenomenon, however, constitutes the very essence of most of the spectral discrimination techniques described in Section V.

Many of the current image restoration and enhancement techniques are intended to facilitate the task of visual interpretation. These matters are discussed in detail in the July 1972 special issue of the *Proceedings of the IEEE*, and in [96]. Difficulties arise because the transformations required to reveal or emphasize one set of features may, in fact, degrade features desirable for another purpose, yet such techniques have consistently produced visually startling results in Mars images [176]. An excellent discussion of the necessary compromises is offered by Billingsley [20].

A. Mathematical Formulation

The registration problem is cumbersome to state mathematically in its entire generality, but the following formulation may help in understanding the work currently in progress.

The scene under observation is considered to be a two-dimensional intensity distribution $f(x, y)$. The recorded image is another (digitized) two-dimensional distribution $g(u, v)$. The image is related to the "true" scene $f(x, y)$ through an unknown transformation T:

$$g(u, v) = T(f(x, y)).$$

Thus in order to recover the original information from the recorded observations, we must first determine the nature of the transformation T, and then execute the inverse operation T^{-1} on the image.

When independent information is available about T, such as calibration data on distortion and degradation, or a model of atmospheric effects, or attitude data concerning the angle of view, then the two operations may be separated.

Often, however, only indirect information about T is available, usually in the form of another image or a map of the scene in question. In this case, our goal must be to transform one of the pictures in such a manner that the result looks as much as possible like the other picture. The measure of similarity is seldom stated explicitly, since even if the two pictures are obtained simultaneously, the details perceptible to the two sensors may be markedly different. Thus for instance, in registering photographs of the same scene obtained simultaneously through different color filters we would want shorelines and rivers, but not the intensity levels, to correspond. On the other hand, if the photographs are obtained years apart with the purpose of observing the erosion of the shoreline or the shift in drainage patterns, then we must expect changes in the location of such features. Seasonal variations also give rise to problems of this type.

In some studies it is assumed that except for the effect of some well-defined transformation of interest, the image of a given scene is produced either by the addition of independently distributed Gaussian white noise, or by multiplication by exponentially distributed noise. While these assumptions lead to the expected two-dimensional generalization of the familiar formulas of detection, estimation and identification theory, they bear little relation to the observed deviations in many situations of practical interest.

The case of known (or derivable) T is sometimes known as image restoration, as opposed to the classical registration problem where T must be obtained by repeated comparison of the processed image with some standard or prototype. This dichotomy fails, however, when the parameters of T are obtained by visual location of outstanding landmarks followed by automatic computation of the corrected image.

B. Single-Point Photometric Corrections

To make any headway on either problem, at least the form of the unknown transformation must be known. We can then parametrize the transformations and write $g(x, y) = T_c(f(x, y))$ to indicate that the true value (grey level) of a point with coordinates (x, y) depends only on the observed value at (x, y). The components of $\boldsymbol{c}$ specify the regions where a given correction factor is applicable.

Examples of such degradation are the vignetting due to the reduced amount of light reaching the periphery of the image plane in the sensor, and the shading due to sun-angle in the TIROS and ESSA vidicon data. Since the combined degradation is quite nonlinear with respect to both intensity and position, the appropriate correction factors are prestored for selected intensity levels on a 54 by 54 reference lattice, and the individual values in the 850 by 850 element picture are interpolated by cubic fit. Camera warmup time through each orbit, as well as the sawtooth effect owing to the non-uniformly reciprocating focal-plane shutter, are taken into account, but contamination by the residual images on the photocathode is neglected. The final output is claimed to be photometrically accurate (or at least consistent) within 5 percent, which is sufficient for the production of acceptable montages for visual inspection [26], [24].

If the preflight calibration does not yield a sufficiently accurate description of the response of the post-launch system, as was the case with the early Mariner pictures, then the correction may be based on the average grey-scale distribution of many pictures on the assumption that the true distribution is essentially uniform [156].

Spectral calibration of digitized aerial color photography can be performed on the basis of the measured reflectance characteristics of large ground calibration panels [52].

Single-point photometric corrections have also been extensively applied to airborne multispectral imagery. A comprehensive discussion of the various factors contributing to variations in the output of the multispectral scanner, including the crucial non-Lambertian reflectance characteristics of vegetative ground cover, is contained in [112]. This study also offers an experimental evaluation of various normalization methods based on *relative* spectral intensities, and a formula for eliminating channel errors resulting in "unlikely" observations. A followup study [113] describes interactive techniques based on visual examination of certain amplitude averages. Good examples of the importance of amplitude preprocessing in extending the range of multispectral recognition are shown in [88], [188].

A more theoretical approach to automatic derivation of the complicated relation between sun-angle and look-angle is presented in [43] and an analysis of scattering phenomena in different layers of the atmosphere in [172].

C. Multipoint Photometric Correction

This class of operations may be symbolized as

$$g(x, y) = T_c(f(n(x, y)))$$

where $n(x, y)$ denotes a *neighborhood* of the point (x, y). In the simplest case, the corrected value at (x, y) depends on the observations at two adjacent points:

$$g(x, y) = T_c(f(x-1, y), f(x, y)).$$

Such linear filtering operations (the properties of the filter are characterized by $\boldsymbol{c}$) are common in correcting for motion blur (the convolution of the true video with a rectangular pulse corresponding to the length of the exposure), for loss of resolution due to modulation transfer function (MTF) rolloff, for periodic system noise, and for scan-line noise [18], [156], [179], [157], [50], [10], [217], [184], [177].

The desired filtering operation may be performed directly in the space domain as a local operation [179], [10], [11], [156], with typical operators ranging from 3 by 3 neighborhoods for motion blur to 21 by 41 elements for more complex sources of low-frequency noise, by convolution with the fast Fourier transform [80], [50], [2], [186], or through optical techniques [96]. In processing speed the local operators show an advantage as long as only very-high-frequency effects are considered and they are also less prone to grid effects in the final results [184], [7]. Optical processing has not yet been used on an operational basis on nonphotographic imagery, principally because of the difficulty of interfacing the digital and optical operations [95].

D. Geometric Distortion

Geometric distortion affects only the position rather than the magnitude of the grey-scale values. Thus

$$f(u, v) = f(T_c(x, y))$$

where T_c is a transformation of the coordinates.

If the transformation is linear, the parameter vector contains only the six components necessary to specify the transformation, i.e., $\boldsymbol{c} = (A, B, C, D, E, F)$ where

$$u = Ax + By + C$$
$$v = Dx + Ey + F$$
$$f(u, v) = f(Ax + By + C, Dx + Ey + F).$$

Important subcases are pure translation ($A = E = 1$, $B = D = 0$), pure rotation ($C = F = 0$, $A^2 + B^2 = D^2 + E^2 = 1$), and change of scale ($A/B = D/E$, $C = F = 0$). From an operational point of view, the transformation is specified by the original and final location of three noncollinear points. In executing a linear transformation on the computer, it is sufficient to perform the computations for a small segment of the image in high-speed storage, and transform the remainder, segment by segment, by successive table lookup operations. Aside from the saving in high-speed storage requirements, this technique results in approximately a tenfold decrease in computation over direct implementation of the transformation.

Along the same lines, a projective transformation is specified by eight parameters, which may be derived from the location of four pairs of picture elements. The execution of this transformation is, however, more complicated, since the relative displacement of the picture elements is not uniform throughout the frame.

It is important to note that owing to the quantization of the coordinate axes, the actual computation of the corrected image is usually performed in reverse in the sense that the program proceeds by determining the *antecedent* of each element or set of elements in the new image. Were the transformation performed directly, one would be faced with the possibility of the occurrence of gaps in the case of dilations and the superposition of several elements in the case of contractions. Since the computed coordinates of the antecedents do not in general fall on actual grid points, it is customary to adopt a nearest neighbor rule for selecting the appropriate element, though local averages are sometimes used instead.

Translation, rotation, and perspective transformations occur in practice owing to changes in the position and attitude of the sensor platform, while scale changes are frequently required by format considerations in input–output. The most bothersome distortions cannot, however, be described in such a simple form. Properties of the transducer itself, such as pincushion distortion, barreling, optical aberrations, and noise in the deflection electronics are best characterized by their effect on a calibration grid scanned either prior to launching or during the course of operation. In addition, fiducial marks are usually etched on the faceplate of the camera in order to provide *in situ* registration marks.

The expected sources of distortion in ERTS-A RBV imagery are discussed in quantitative terms in [136] with particular reference to correction by means of analog techniques such as optical projection and rectification, line-scan modulation, orthophoto correlation, and analytically (digital computer) controlled transformation of incremental areas. Because of the nonuniformity of the distortions over the entire format, and the possibility of tone reversals from object to object in the spectral bands, only the last system is accorded much chance of success.

The precise measurement of the location of the 81 (9×9 array) fiducial marks (also called reseau marks) on the faceplate as well as on the output image of a number of return-beam vidicons destined for the ERTS-A satellite is described in detail in [137]. It is shown that to provide a frame of reference for eventual correction of the imagery to within one-half resolution element, the vidicon parameters must be established to the accuracy shown in Table I.

The detection of the fiducial marks in the ERTS vidicon images, with experiments on simulated pictures derived from digitized Apollo photographs, is described in [11], [16], [129]. The basic technique is "shadow casting" of the intensity distributions on the x and y axes of the picture. This is shown to correspond, for the selected fiducial-mark geometry, to matched-filter detection.

The actual correction, by interpolation between the grid coordinates of the distortion on extraterrestrial images, is reported in [156], on TIROS vidicon data in [26], and on ATS spin-scan cloud-camera pictures in [28]. The correction of geometrical distortions may be efficiently combined with the production of rectified orthophotos (equivalent to a 90° angle of view) [156] and with the generation of standard cartographic products such as Mercator and Polar Stereographic projections [27], [23], [29].

TABLE I

CALIBRATION REQUIREMENTS FOR PARAMETERS OF THE RETURN-BEAM VIDICON FOR ERTS-A (from [137])

Parameter	System Accuracy	Calibration Accuracy
Reseau coordinates	± 10 μm	± 3 μm
Lens:		
Focal length	+270 μm −980 μm	±20 μm
Principal point	± 65 μm	± 5 μm
Radial distortion	± 30 μm	± 5 μm
Electronic distortion	±750 μm[a] (about 125 TVL of 6 μm each)	± 5 μm
Orientation between cameras	$\pm 7.0 \times 10^{-4}$ rad (about 2.4 ft)	$\pm 1.5 \times 10^{-5}$ rad (about 3 in)

[a] Recent data indicate that the 750-μm value may be too high. However, the complete RBV-transmission-EBR system has not been tested yet.

A fast algorithm suitable for digital computers equipped with MOVE BYTE-STRING instructions has been reported in [217], [10], [11]. This algorithm is intended for the correction of small distortions, such as those due to the camera characteristics, and is based on the fact that relatively large groups of adjacent picture elements retain their spatial relationship in the corrected picture. The program computes the maximum number of adjacent elements that may be moved together without exceeding a preset error (typically one coordinate increment). Experimental results [17], [129] show that the boundaries between such groups are not visually detectable.

When the imagery is intended mainly for visual use rather than for further computer processing, the technique of "gridding" offers an expedient alternative to mapping [27]. With this method the picture elements are left in their original location and the positional information is inserted by the superposition of latitude and longitude coordinates over the image. Since only the locations of selected image points need be computed for this purpose, the method is quite rapid and is extensively used with the specially modified output devices of the National Environmental Satellite Center.

E. Automatic Determination of Anchor Points

Finding corresponding points in two pictures of the same scene can be accomplished by correlating a "window function" from one picture with selected portions of the other picture. If the two images differ only by a shift or translation, then only a two-dimensional search is involved. If, however, a rotation and a change of scale are also necessary, then the time required for exhaustive search exceeds all practicable bounds.

Once one window function has been adequately matched, the location of the maximum value of the correlation function usually gives a good idea of where the search for the next window function should be centered, even if the transformation is not quite linear.

In terms of our earlier formulation, we are trying to evaluate the parameter vector $\boldsymbol{c}$ under the assumption that both $f(x, y)$ and $g(x, y)$ are available and that parameters representative of the entire image can be derived by establishing the correspondence of selected subimages. This usually involves maximization of a similarity function subject to the constraints imposed by the postulated transformation.

The similarity function to be maximized may take on several forms. If, for instance, we take two $m \times m$ images $\boldsymbol{Y}_1$ and $\boldsymbol{Y}_2$ considered as vectors in an m^2-dimensional space, then an $n \times n$ window function $\boldsymbol{V}_1$ and the trial segment $\boldsymbol{V}_2$ may be considered as projections of $\boldsymbol{Y}_1$ and $\boldsymbol{Y}_2$ onto the n^2-dimensional subspaces spanned by the coordinates corresponding to the elements in the two subimages. Reasonable choices for the similarity function are as follows

1) $$\boldsymbol{V}_1 \cdot \boldsymbol{V}_2$$

2) $$\frac{\boldsymbol{V}_1 \cdot \boldsymbol{V}_2}{\boldsymbol{Y}_1 \cdot \boldsymbol{Y}_2}$$

3) $$\frac{\boldsymbol{V}_1 \cdot \boldsymbol{V}_2}{|\boldsymbol{V}_1| \cdot |\boldsymbol{V}_2|}.$$

The first of these functions suffers from the defect that false maxima may be obtained by positioning the window function over some high-intensity region of the target picture. Normalizing the entire image 2) does not circumvent this difficulty completely. Alternative 3) is thus usually chosen, representing the angle between the window function and the trial segment considered as vectors, in spite of the fact that this procedure requires renormalization of the trial segment for each displacement.

A good account of the problems encountered in an experimental investigation of this problem, viewed as "one of determining the location of matching context points in multiple images and alteration of the geometric relationship of the images such that the registration of context points is enhanced," is given in [3], [4]. Both 14-channel multispectral images obtained one month apart and digitized Apollo-9 photographs were tested. Window functions ranging in size from 4 by 4 to 24 by 24 picture elements and located at the vertices of a grid were used to obtain least squares estimates of a "generalized spatial distance" incorporating the translational, rotational, and scale parameters of the required transformation. The information derived at each vertex was used to center the search space at the next vertex at the most likely values of the parameters. The actual correlation function was the correlation coefficient[2]

$$\phi(k, l) = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} f(i + k + s, j + l + s) g(i, j)}{\sum_{i=1}^{n} \sum_{j=1}^{n} f^2(i + k, j + l) \sum_{i=1}^{n} \sum_{j=1}^{n} g^2(i, j)}$$

where the image f is of size $m \times m$; the window is of size $n \times n$; $s = (m - n)/2$; and k and l range from $-s$ to s.

The average values were previously subtracted from f and g to yield zero-mean functions; $\phi(k, l)$ is then bounded by -1 and $+1$. In order to circumvent the problem of tone reversals, experiments were also conducted on gradient enhancement techniques designed to extract significant edge information from the images, but this is of less value than might be expected, owing to the noisy nature of the data. The computation was carried out by means of FFT routines, which are shown to yield an average improvement of an order of magnitude in speed over the direct method. The displacements determined by the program are of the order of 2–3 elements in the multispectral data and 10 elements in the photographs; safeguards are included to reject maxima obtained under certain suspect circumstances (for instance on patches of uniform intensity).

[2] The formula is given in this form in [4]; the more customary formulation has a square root in the denominator.

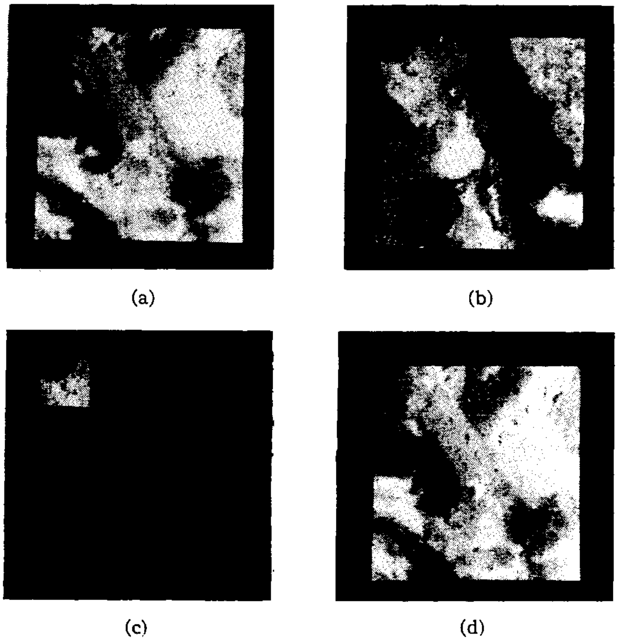


Fig. 6. ITOS-1 registration experiment. A 32 by 32 window function (c) extracted from the top left corner of picture #1 (b) is tried in every possible position of the search area (a) by means of the sequential similarity detection algorithm. The position of the best match determined by the algorithm is shown in (d), where the window function is inserted into the search area. Note the discontinuities due to the change in cloud coverage between the times of exposure of the two pictures.

Similar work has been reported on a pair of black-and-white Gemini photographs of Cape Kennedy, obtained thirty months apart, and on a SO 65 color-separation triplet [10]. On the black-and-white pictures, windows of size 16 by 16 and 32 by 32 elements gave fairly consistent results, but on the SO-65 IR–red, and IR–green pairs, 128 by 128 elements were necessary even with preprocessing by means of an edge-enhancement technique using the coefficient of dispersion or mean-to-variance ratio over 3×3 subregions. These experiments were carried out on a terminal-based system in a time-shared environment.

Impressive savings in processing time can be demonstrated on the basis of the observation that when two windows do not match, the cumulative distance function rises on the average much more rapidly with each pair of picture elements examined than when the windows do match [13]. The class of *sequential similarity detection algorithms*, as the method is called, was analyzed on the assumption that the deviation between two pictures in register is exponentially and independently distributed, and optimal stopping rules were derived under various conditions. The number of operations required was tabulated according to the size of the search space and the size of the window. It is shown, for example, that for a search area of dimensions 2048 by 2048 and a window size of 256 by 256 elements (much larger than in the experiments actually carried out), the direct method would require about 10^{12} operations, the FFT, 10^{10} operations, and the best of the sequential algorithms, 2×10^7 operations. The test vehicle in this instance consisted of pairs of ITOS AVCS frames obtained two days apart over the Baja California and Gulf Coast regions (Fig. 6).

Another shortcut for multiple template matching, based on prior selection of "rare" configurations, is compared to the conventional systematic search in [147].

F. Cloud Motion

An interesting twist on the registration problem occurs when the camera remains stationary and the scene shifts. This is precisely the case in attempting to determine wind-velocity vectors from changes in the location of cloud masses in the 30-min intervals between successive readouts from the geostationary ATS spin-scan cloud cameras.

An excellent account of the importance of this problem in the context of the Global Atmospheric Research Program, which requires wind-velocity measurements accurate to within 3 knots, is presented in [191]. An interactive computer facility (WINDCO) for tracing cloud motion by means of 32 by 32 element FFT correlation on a Univac 1108 computer is also described. A highlight of this paper is the thorough treatment of the computations necessary to determine the satellite orbit and attitude from least squares approximations of the measured location of landmarks appearing in the pictures. It is shown that the parameters necessary for mapping operations can be determined to an accuracy superior to the resolution of the individual picture elements.

Correlation techniques using the FFT were also applied to 64 by 64 element windows extracted from preprocessed (i.e., projected on standard map coordinates) versions of the large ATS pictures by Leese and his colleagues. They report an approximately twentyfold improvement over direct calculation of the lagged product. The metric selected was the correlation coefficient; the observed peak value was usually about 0.7. The results are claimed to be comparable to or better than visually obtained values when only a single layer of clouds is present or when the wind velocity is constant with altitude. The major source of inaccuracy, in addition to the gradual deformation of the cloud masses, is the occurrence of relative mapping errors between the two pictures [121], [122].

Essentially similar results were obtained with a binary matching technique operating on edge configurations extracted from ATS cloud pictures quantized to only two levels. This method is a factor of two or more faster than the FFT method, but is also unable to cope with multilayer cloud patterns drifting in different directions. The human observer, however, has little difficulty in separating such motion components on the basis of accelerated "loop movies" showing twenty or more successive exposures [121].

Yet another sustained attempt at generating wind-velocity maps from ATS pictures is taking place at the Stanford Research Institute. In this work the bright points (clouds) are aggregated by means of a clustering algorithm, and the ground location is determined through successively finer-grained cross correlation against preselected 20 by 20 element templates. At the last stage a directed-search technique is used, as if the cross-correlation function were monotonic, but the results are checked by means of several independently chosen starting points. The major remaining difficulties are said to be connected with changes in sun angle [73], [53].

G. Parallax Measurements

The determination of parallax from stereo photographs differs from the problems just discussed in that the displacement function may vary quite rapidly from point to point; therefore, the use of window functions based on uniform displacements is inappropriate.

Good results in estimating parallax on a single digitized low-altitude stereo pair were obtained with the assumptions that the difference in the grey levels of corresponding trial pairs of points in the two pictures is a zero-mean Gaussian process and that the departure of the displacement function from its average value over a small neighborhood is also of the same form. Since in this formulation the grey-level difference distribution is conditional upon the parallax, for which the Gaussian continuity condition gives an *a priori* distribution, Bayes' rule may be invoked to estimate the *a posteriori* dependence of the parallax on the observed video distribution.

The computation of the altitude contour lines from the parallax information is a straightforward problem in analytic geometry. Some results of applying the complete procedure to the estimation of forest-tree heights are shown in [9].

It should be noted that there exist automatic and semiautomatic photogrammetric image-correlating devices (*stereoplotters*) which recognize corresponding subsections on a stereopair of photographs and simultaneously transform and print one of the images in an orthographic projection or generate altitude contour lines. Several types of equipment are available, with electronic (scanned) or direct optical image transfer, digital or mechanical implementation of the projective parameters, manual or automatic correlation, and on-line or off-line printout [207], [98]. These sophisticated and expensive precision instruments are not, however, considered to be sufficiently adaptable to cope with the types of distortion expected from the various satellite sensors [136].

V. Classification Techniques

Experimental work in automatic classification through remote sensing may be neatly dichotomized according to whether the primary features consist of spectral or spatial characteristics. Examples of the former are largely based on the output of the Michigan multispectral scanner, while examples of the latter include aerial photographs, high-resolution photographs of the moon, and satellite cloud pictures.

The reason why the expected development of methods based on both spatial *and* spectral characteristics has not yet taken place to any significant degree is that the spatial resolution of the airborne multispectral scanner is too low to allow discrimination of most objects of interest. With multiband aerial photography, on the other hand, automatic registration techniques have not yet come far enough along to permit the preparation of digital color composites in sufficient numbers for significant experimentation.

The typical classification experiment in either domain is open to criticism on several counts. The data, collected in a single region under favorable conditions by airborne or spaceborne sensors, are *examined in their entirety by the experimenter*, who decides which areas are most representative of the region as a whole. The samples from these areas are assembled to form the training set, which is characterized by ground-truth information delineating certain categories of interest. A statistical categorizer or decision box is constructed on the basis of the statistical parameters extracted from the training set.

The classification performance is evaluated on another portion of the data (the test set), also carefully *selected to enhance the probability of correct classification*, where the location and extent of the different types of cover is known to the experimenter. If the error rate is unacceptably high, then offending portions of the test set may be included in the training set for another iteration through the whole cycle!

The details of the various experiments differ with respect to the source of data, the method of labeling the training and test sets, the number and nature of the classes to be identified, the degree of statistical sophistication of the categorizer, and the method of evaluating the results, but the general scheme of classifying samples of the test set according to their similarity to the training set remains the same.

Since it is impossible to review in detail the many dozen pattern-recognition experiments reported in the literature, we shall confine our attention to a few tasks which have been the object of sustained efforts and will examine other contributions in terms of their deviation from the specimen tasks. Rather than offer a description of each classification problem, method of collecting the data, and decision algorithm, we shall concentrate on the experimental procedure, the manner of evaluating the results, and the validity of the derived inferences. For background, the reader cannot do better than turn to the excellent discussion of these matters in relation to conventional photointerpretation in [36], which includes many fine examples drawn from Gemini pictures and coordinated low-altitude oblique aerial photography.

A. Crop Recognition

In the United States, the recognition of crop species by means of multispectral *signatures*, or distinctive spectral characteristics, has been extensively studied since 1966 with a view to providing timely information for fertilization practices, blight control, harvesting schedules, and yield forecasts [61], [90], [124]. There has been much discussion of the importance of systematic coverage throughout the growing season [167], [195], but most of the experiments reported use only data collected in a single day.

Almost all of the earlier work in automatic classification is based on data collected by the Michigan scanner at altitudes ranging from 3000 to 10 000 ft in intensively farmed areas of the Midwest, though a number of missions were also flown in the Imperial Valley agricultural test site of southern California in conjunction with the Apollo-9 experiments. As a rule only the twelve bands spanning the visible and near-IR range of the spectrum are used, because the other channels of the Michigan scanner do not produce data in register with the first twelve channels and cannot be readily transformed into the same spatial coordinate system [25].

Ground truth is generally obtained either through ground surveys or by means of color, IR, and black-and-white photography obtained during the overflights. The performance of skilled photointerpreters using the various types of imagery has been most recently evaluated in [14], with still valid ideas on the most appropriate roles for manual and automatic techniques discussed in [35] and [118].

Most of the classification experiments were performed by investigators associated with the Infrared and Optics Laboratory of the University of Michigan and with the Laboratory for Applications of Remote Sensing of Purdue University. The primary instruments for experimentation were a CDC 3600 at Michigan and IBM 360/44 and 360/67 computers at Purdue. A number of results were also obtained with the Michigan SPARC analog processor.

Extensive programming systems were developed at both installations to allow data editing, data normalization, inspection of statistical attributes of spectral distributions, selection of spectral bands, derivation of categorizer parameters, execution of classification procedures, and evaluation of results [115], [202], [112], [148], [87]. Both organizations take pride in the accessibility and ease of assimilation of their software packages as attested, for instance, in [206] and [208].

The ground swath covered in each flight by the Michigan scanner is normally twice as wide as the flight altitude. i.e.,

$\frac{1}{2}$ to 2 mi, with the flight lines varying in length from 2 to 20 mi. With a few notable exceptions [88], however, not all of the data collected are run through the training and classification algorithms, and even when all of the data are actually classified, the determination of the accuracy of classification over the entire region is usually hampered by the difficulty of entering into the computer the complete ground-truth description.

The specific fields chosen for training and for classification are usually selected for uniform appearance and for nearness to the centerline of the swath since recognition tends to be worse at oblique look-angles [113]. Sometimes the central portions of certain fields are chosen for the training set, with the remainder of the field used for checking the "generalization" capability of the categorizer [63].

The training areas are frequently augmented by including areas where "preliminary" classification runs show poor recognition rates [202], [131]. In view of the variability of widely spaced samples, this procedure usually requires the specification of several subclasses for each category of interest [131], [113]. Automatic mode determination by means of clustering algorithms has also been attempted with fair success [201], [63], [6], [65], [66].

The ratio of the size of the training set to the size of the test set has been steadily decreasing as it is discovered that in multispectral recognition the quantity of samples collected in any given field is much less important than the judicious inclusion of small "representative" regions along, and particularly across, the flight line. Though excellent results have been obtained under favorable conditions over large areas up to 90 mi away from the training fields, even these experiments show that the experimenter must ever be on the alert to change the configuration of training and test fields should an inopportune fluff of cloud intrude on the original experimental design [88].

Much effort has been devoted to the selection of suitable subsets of the spectral channels in order to increase throughput. Among the feature selection methods tested are principal component analysis, divergence, and minimax pairwise linear discriminants. All reports agree that four to six channels perform as well as the full set of ten or twelve (and sometimes better, owing to the use of suboptimal classifiers), but, as expected, the best subset varies from application to application. Linear combinations of channels have also been used, with similar results, but the necessary computation can be justified only for problems involving a large number of categories [116], [117], [140], [64]–[66].

Theoretical attempts to relate the laboratory-observed spectral characteristics of plants to remote observations through the atmosphere are discussed in [51] and [91].

Michigan and Purdue seem to agree that quadratic decision boundaries derived from the maximum likelihood ratio based on Gaussian assumptions constitute the preferred method of classification. Almost all of the experiments discussed in this section made use of this technique, though linear decisions, sequential tree logic, potential functions, and nearest neighbor classification have been shown to yield very similar results, at least on small samples [193], [63], [158], [65], [66]. The quadratic decision rule is to choose the class (or subclass) i which exhibits the largest value

$$g(\boldsymbol{x}) = (\boldsymbol{x} - \boldsymbol{M}_i)^T \tilde{K}_i (\boldsymbol{x} - \boldsymbol{M}_i) + C_i$$

where $\boldsymbol{x}$ is a multispectral measurement vector; $\boldsymbol{M}_i$ is the class mean vector estimated from the training samples; $\tilde{K}_i$ is the class covariance matrix; and C_i is a constant related to the *a priori* probability of class i.

This decision function can be computed rather rapidly (0.3 ms per six-dimensional sample, eight classes, on an IBM 360/44) by making use of table lookup and sequential search procedures [57].

One means of improving the recognition results achieved by such methods is "per-field" classification, where the individual sample vectors are replaced by the average values of the spectral components in each field. Not only does this ease the computational requirements, but it also reduces the contribution to the error rate of weedy patches, irrigation ditches, and other irregularities [6], [14], [65]. Efforts are underway to develop automatic methods for deriving the field boundaries in order to give real meaning to these per-field figures, but while the majority of the boundary segments may be readily obtained by "local operators," linking them up in the desired topological configuration is a difficult matter [4], [213], [214].

Recognition results range from 90 to 98 percent on a single crop (wheat) versus "background" [131], [88], through 91 percent on eight classes in the same flight line, dropping to 65 percent with only four classes across flight lines [63], to 30 percent on really difficult-to-distinguish crops with training and test samples selected from different fields [70].

In comparing the classification performance of a given system to how well one might be expected to do by chance alone, the *a priori* probabilities which are obtained from the ground truth associated with the training set should be taken into account. On the above four-class problem, for instance, almost half the samples were drawn from soybeans, hence one would reach approximately 50-percent correct recognition without any reference at all to the multispectral information.

Crop-recognition experiments have also been conducted on digitized samples of color and color-IR photography. These experiments are based on sample sizes ranging from minuscule to small: 59 samples used for a comparison of several different recognition algorithms [193]; a few hundred samples from carefully chosen densitometric *transects* (single scans) with six classes (including "low-reflectance," "medium-reflectance," and "high-reflectance" water!), and no differentiation between training and test data [175]; 6000 pixels of training data from 60 000-ft RB-57 multiband and multiemulsion photography, divided into four classes (corn, soybeans, pasture, and trees) with 95-percent accuracy [87]; seven fields from a dissector-digitized photograph (81-percent accuracy on dry cotton, 33-percent accuracy on wet cotton) [70]; and 50 000 samples (about 1 percent of one frame) of automatically digitized Apollo SO-65 photography [127], [5], [6]. Recognition rates on the latter material range from 30 to 70 percent, with about 3 percent of the carefully selected specimen areas used for training, and the rest for test. In comparing the results on satellite data to the performance obtained by airborne sensors on similar tasks, it must be observed that the photographs were scanned at a resolution corresponding to about 200 ft on the ground, and no photometric calibration was attempted.

The largest series of experiments to date are the Summer 1971 corn-blight surveys flown by the Michigan (and other) aircraft and divided up for processing between Michigan and Purdue. Strong United States Department of Agriculture (USDA) logistic support for these experiments was presumably based on the promising results obtained in August and September of 1970 [128], [14]. At the time of writing no published information was available on the 1971 experiments, but the results will be eventually released by the Corn Blight Information Center in Washington, D. C.

B. Terrain Classification Based on Spectral Characteristics

The entry of ground-truth information for crop classification, difficult as it is, is a relatively straightforward matter compared to the problems encountered in other types of terrain classification, because the geometry of cultivated fields tends to be quite simple, and it can be safely assumed that each field corresponds to one crop type or to a standard mixture.

In the absence of similar simplifying features in other problem areas there has been no attempt so far to enter ground-truth information into the computer with a view to objective quantitative evaluation of the results. Instead, classification maps are generated which are visually compared to maps or aerial photographs of the area. The results of such comparisons are invariably "promising."

Among applications which have been tackled so far with the help of the Michigan scanner are: the location of areas of potential sink-hole activity in Florida [130], [33]; a beautifully illustrated and ecologically captivating study of hydrobiological features within the Everglades [110]; and soils mapping in Indiana (where difficulties were encountered in attempting to extend the classification to samples located 4 km from the training set) [114], [206]. In addition, there have been innumerable other projects where prints of the unprocessed MSS output, or simple thresholded versions thereof, have so far proved sufficient for the purpose at hand, but where automatic processing may be eventually required as research findings are translated into operational requirements.

Terrain classification has also been attempted by means of digitized aerial photographs. Here also the difficulty of preparing detailed ground-truth maps for the entire area under investigation presents an insurmountable obstacle to quantitative evaluation of the results. In one study, for example, the investigators had to resort to marking isolated patches containing "marked vegetative zonation or relatively homogeneous stands of a dominant species" with 18-in plastic strips which were discernible in the photographs. This particular experiment is also distinguished by conscientious spectral calibration by means of large colored panels displayed on the ground at flight time and subsequently scanned with the remainder of the imagery [52].

For some other applications of interest, and some novel insights, the reader may consult [40], [109].

C. Shape Detection

The major methodological difference between research aimed at automating the production of land usage maps and research concerned with the classification and recognition of objects on the basis of their geometrical properties (including texture) is an inevitable consequence of the relative scarcity of objects of interest. In multispectral crop classification, for instance, every decision results in a positive contribution, but if we are looking for houses, roads, tornadoes, or eagle's nests, then many more pictures will have to be examined to obtain statistically significant results [78].

To gain some idea of the preliminary (and often unreported) manipulation necessary to obtain acceptable results in this area, we shall examine in some detail a rather extensive feasibility study intended to explore alternative designs for a satellite-based recognition system. Various aspects of this study have been reported in outside publications [44], [45], [103], [46], but most of the information presented here is obtained from an internal contract report [49].

The pictures originally selected by the contracting agency, as representative of the material the satellite-borne classifier would encounter, consisted of 311 black-and-white prints containing 198 lunar features, such as craters, rimas, and rilles, and 323 Nimbus cloud samples of various types.

One hundred and 47 of the better prints were selected for digitization on the basis of *visual examination.* In the cloud pictures, fiducial marks and certain "long black lines" were eliminated by means of a water-color retouching kit. The prints were then rotated *by the experimenters* to align the shadow directions to reduce variation due to changes in the solar illumination. The resolution of the slow-scan television camera used to convert the pictures to an intermediate analog tape was set *by the operator* on each pattern in such a way that the maximum size variation was kept below 1.5:1. The resolution was then further reduced by averaging to 50 by 50 picture elements for the lunar patterns, and 75 by 75 elements for the clouds. The dynamic range was also individually adjusted *by the operator* to let each pattern "fill" the 3-bit digital grey scale.

A file of 1000 training samples and 200 test samples was produced for both moonscapes and clouds by a digital editing process consisting of replicating individual patterns by means of translations of up to 15 percent of the effective frame size and rotations of up to 15°. To avoid letting "difficult" patterns predominate, not all patterns were replicated the same number of times. Due care was taken, however, to avoid including replicas of the same pattern in both the training and test set.

Each pattern was characterized by the output of *property filters* consisting either of intuitively designed measurements or of features derived by statistical means. Eight different classification schemes, gleaned from a literature search resulting in 167 titles, were tried on a subset of the data, but none of the eight methods (forced adaptive learning, "error correction," Madaline, another piecewise-linear method, mean-square error criterion, "iterative design," Bayes weights, and direct estimation of the distributions) proved notably superior to the others. Of greatest benefit to accurate classification, it turned out, was the "reduced aperture" technique, whereby insignificant portions of the picture are eliminated prior to the feature-extraction stage! The best combination of features, decision methods, and reduced aperture consistently achieved better than 90-percent correct classification on a half-dozen different ways of grouping the patterns into classes.

Experiments were also conducted on pattern segmentation. The data for these tests consisted of side-by-side montages of cloud patterns which had been correctly classified in isolated form. In this way it was possible to demonstrate that the *input* to the decision units on successive segments generally gives a reliable indication of the location of the boundary between the different cloud types (at least as long as the progression of segments is limited to the direction perpendicular to the boundary)!

Hardware configurations were evaluated for parallel/analog, sequential/hybrid, and sequential/digital methods of implementation. While all three configurations were capable of meeting the desired real-time operation criterion under the particular choice of assumptions, the last design showed a definite advantage in terms of *weight.*

Studies in a similar vein, but with more emphasis on parallel methods of implementation, have been conducted for several years by Hawkins and his colleagues [81]–[83]. The objects of interest here, extracted from aerial photographs, are orchards, oiltank farms, woods, railroad yards, roads, and lakes. The photographs were scanned with a flying-spot scanner under program control (PDP-7), with examples of various local feature-extraction operations, such as matched filters, gradient detection, contrast enhancement, and thresholding demonstrated by means of electrooptical techniques.

Another point of view altogether, but surprisingly similar conclusions regarding the feature-extraction stage, are represented by the M.I.T. pilot study of a semiautonomous Mars Rover. The input to this low-resolution system is provided by a stereo television system under control of a PDP-9, but the output, following a hierarchical multilayer model of the vertebrate visual subsystem, remains in the realm of conjecture [200].

A good description of the application of Golay rotation-invariant hexagonal-neighborhood logic to both local and global feature extraction, including measurements of object diameter, area, perimeter, curvature, and particle counts, is given in [108]. Experimental results are presented on two 500 by 500 arrays extracted from aerial photographs.

Diverse analog and digital methods for implementing texture measurements are considered in [204]. Haralick in a very thorough series of experiments, has classified 54 scenes (each $\frac{1}{8}$ by $\frac{1}{8}$ inch in area) from 1:20000 scale photographs into 9 classes on the basis of the statistical dependence of the grey levels in adjoining picture elements. He compared the results obtained (average 70 percent correct) to those of five trained photointerpreters using the entire 9 by 9 in photograph (81 percent correct) [76].

An early experiment to detect broken and continuous cloud cover in Tiros imagery on the basis of texture is reported in [178]. Local operators containing 5 by 5 picture elements were used for purely textural characteristics, with 15 by 15 element operators for distinction based on size and elongation. A follow-up study introduces additional criteria such as amount of edge per unit area and number of grey-level extrema per unit area [181], [182].

A good review of cloud-cover work, emphasizing the difference between classifying a given segment and producing a cloud map, can be found in [199]. This paper also presents new heuristic algorithms for delineating cloudy regions.

D. Nonsupervised Classification

Nonsupervised learning or *cluster seeking* are names applied to methods of data analysis where *only* the observed values are used explicitly to group samples according to some intrinsic measure of similarity. It is true that closer examination inevitably reveals that some additional information, such as the expected number of groups and some suitable metric, was used by the experimenter to achieve the desired results, but the nature of the ground-truth information associated with the samples enters the algorithm only in a circuitous manner.

In remote-sensing experiments this approach has been used 1) to alleviate the problem of multimodal probability distributions in supervised classification methods, 2) to circumvent the need for *a priori* selection of training samples, 3) to extract the boundaries between homogeneous regions in multispectral arrays, and 4) to condense the amount of information stored or transmitted.

Experiments showing the application of nonparametric clustering techniques to discover the "natural constituents" of the distributions characterizing the various terrain classes are described in [63] and [65] on multispectral scanner observations and in [5], [6], [87] on digitized multiband photographs. We learn, for example, that *mode estimation* yields a good approximation to the mean values of the spectral components in individual fields, or that seven different subclasses of "bare soil" were found in a certain batch of data, but there is not sufficient information presented to determine how much clustering reduces the error rate in comparison to using a single quadratic boundary per class, or alternatively, whether clustering permits the substitution of simpler boundary equations. In each of the papers mentioned the clustering procedure is conducted on an even smaller number of samples than the main supervised classification experiments, because the algorithms used so far tend to be very complicated and time-consuming, frequently involving repeated merging and partitioning of the tentative cluster assignments.

When the clustering technique is used on all of the available observations without any regard to the class descriptions, then it may be considered equivalent to a stratified or two-stage sampling design insuring the efficient collection of the ground-truth information [119], [1]. In other words, the classifier is allowed to designate the appropriate areas for the collection of class-identifying information on the basis of the data itself, rather than on *a priori* considerations. The necessary ground truth may then be collected after the analysis rather than before, reducing the risk that the areas sampled may not be typical of significant portions of the data. One of the few complete experiments testing this idea is described in [193], but the test data unfortunately contained only a few dozen digitized samples. A somewhat larger experiment on nine classes extracted from aerial color photographs by means of a trichromatic microdensitometer is reported in [189]; here the clustering was performed by inspection on two-dimensional projections of the three-dimensional measurement space pending the completion of suitable programmed algorithms. Finally, 2500 samples of high-altitude photography were classified by clustering in [87], but since the study was oriented toward other objectives, these results were not evaluated in detail.

The extraction of boundary information for registration or other purposes is even more difficult on noisy multispectral data than on black-and-white images. A comparison of gradient techniques with clustering is reported in [214], with both methods applied to congruencing data obtained at different times in [4]. A related problem is the conversion of gray-scale imagery to binary arrays by thresholding; here a clustering technique oriented towards the joint occurrence of certain gray-level values in adjacent picture elements has been shown to yield better results than thresholds based on the intensity histogram alone [180].

Both iterative and single-pass clustering algorithms have been thoroughly investigated by Haralick and his colleagues for the purpose of discovering data structures in remote-sensing observations that may reduce storage and transmission requirements for such data. The single-pass algorithms, tried on 80×80 microdensitometric samples of three-band aerial photography, are based on a chaining technique operating in either the image space or in the measurement space [74]. The iterative technique depends on preliminary mapping of the data in a high-dimensional binary space and adjusting the coefficients of prototype vectors to minimize the least square deviation; it proved relatively unsuccessful in reaching an acceptable error rate in compacting 27 000 twelve-dimensional multispectral observations of Yellowstone National Park [75]. An exhaustive experimental investigation of various aspects of the performance of the iterative clustering algorithm on five distributions (three arbitrary, and two tenuously connected with remote observations) is described at length in [46], and a theoretical analysis of the same family of algorithms is presented in [42].

VI. Conclusions

It would appear that few of the results demonstrated to date warrant our sanguine expectations regarding *automatic* processing of the output of the first generation of earth resources survey satellites. Even making allowances for the ever-accelerating march of science, some of the current preparations are uncomfortably reminiscent of the early attempts at automatic translation and "universal" pattern recognition.

The first grounds for scepticism concern the question of instrumentation. Is it really possible to measure consistently the reflectance of 4000 by 4000 distinct picture elements with satellite-borne vidicon cameras and multispectral sensors when meticulously tuned electronic scanning equipment (as opposed to mechanical microdensitometers) in image processing laboratories throughout the country yield only about one quarter as many usable points? The Michigan scanner has an effective transverse resolution of 220 lines (though the optical system is nearly five times as good), the ITOS camera system has barely 800 lines; improvements in this area have not, historically, taken order-of-magnitude jumps. Even if specifications are met, how much can we learn from 200 by 200-ft picture elements?

In regard to the crucial question of automatic registration, very little can be said until the accuracy of the satellite attitude and ephemeris information and the magnitude of the geometric and photometric degradation are firmly established. It should be noted, however, that so far no completely automatic techniques have been developed even for the registration of weather satellite imagery, where far greater errors could be tolerated. Although it is frequently implied that the major obstacle to the implementation of digital registration methods based on correlation is the inordinate amount of computation required, none of the work performed to date indicates that the required accuracy could be attained at *any* cost.

Many of our troubles can, of course, be attributed to the lack of representative raw data. Whatever will be the significant characteristics of the ERTS and Skylab coverage, it is safe to predict that it will bear little resemblance to the digitized photographs and low-altitude multispectral observations which are currently available for experimentation. The weather satellite pictures, which are in many ways most representative, are not nearly detailed enough for most of the suggested earth resources applications. Although there have been attempts at simulating the scale and resolution of the expected data [15], these simulations did not include some of the essential features of the electronic data-collection systems, and were, in any case, largely ignored by the image-processing community.

A related source of frustration is due to our failure to take advantage of the economies of scale resulting from large well-coordinated efforts. The tendency seems to be for each research group to attempt to build its own "complete" image-processing system independently of what may be available elsewhere. Since such an undertaking exceeds the resources of most laboratories, a small part of the overall problem is selected for special attention, with the remainder treated in cursory fashion without regard for previous work on the subject. If, for instance, the selected topic is feature extraction, then the feature extraction algorithms are exercised with minimal preprocessing and normalization of the data, and without any attempt at relating the performance achieved to the manner in which the results are to be utilized. Yet chances are that, as in any large programming effort, the "interface" problems will in the end dwarf the contributions necessary to develop the individual modules.

Leaving aside for the moment the essential but so far tremulous infrastructure in image registration and restoration, we come to the more glamorous aspects of automatic data classification. Without further insistence on the many sins in experimental design (i.e., lack of separate training and test sets, and failure to select the test data *independently* of the training data), and on the widespread and arrant disregard for the statistical rules of inference governing small-sample behavior, we shall take at face value the 60-, 75-, and 90-percent recognition rates achieved on favorable test sites on a half-dozen carefully selected terrain categories or crop species. Studies of the error rates tolerable in various applications would leave little doubt that such performance levels, though perhaps not totally useless, can be reached far more economically by means of other than satellitic surveillance, but seldom in the pattern-recognition literature is there any reference to the minimum acceptable classification rates.

Perhaps an absolute standard is too much to ask. Yet, with only a handful of major test sites under study for automatic classification, are there any published comparisons of relative recognition rates obtained by *different* investigators under similar circumstances? The same photographs and printouts appear in publication after publication, but a sufficient number of conditions are changed in each study to render all comparison meaningless.

Significant progress in this area cannot be expected until sophisticated interactive systems are developed for entering ground-truth information directly in the reference frame of the digitized images. This, in turn, requires high-resolution gray-scale display devices, with attendant software facilities for pinpointing landmarks and outlining boundaries, implementing projective and other transformations, preparing mosaics, comparing the images with digitized maps, serial photographs and other prestored information, and in general, easing the burden of programming the sundry necessary details.

These observations are not meant to imply that digital methods will not play an important role in processing the torrent of data that will soon be released by the survey satellites. It is likely, however, that the computer will for a time continue to be relegated to such relatively unexciting tasks as format conversion, "cosmetic" transformations, merging the image stream and the ephemeris and attitude information, correction of systematic distortions, keeping track of the distribution list and other bookkeeping chores, while interpretation of the images is left to the ultimate user. The prototype operation is likely to be modeled on that of the successful and efficient National Environmental Satellite Center, where over one hundred frames are smoothly processed and assembled daily, with dozens of computer products distributed on a routine basis to the four corners of the globe.

The situation is more encouraging with regard to data collected by relatively low-flying aircraft. Here the scattering effects of the atmosphere are not quite so debilitating, the sensor configuration can be optimized for specific objectives, the flights can, in principle, be timed for the best combination of illumination and terrain conditions, and bore-sighted cameras and navigational subsystems can be used to ensure adequate ground location of the electronic images. The yield of usable pictures should then be sufficiently high to allow fairly sophisticated automatic analysis of the data in selected applications. An example of a plausible if modest candidate for digital processing is the bispectral airborne forest-fire detection system described in [86].

In spite of the many difficulties, the long-range objective must of course remain the eventual combination of spaceborne and airborne sensor systems with conventional ground observations in a grand design for a worldwide hierarchical data-collection system enabling more rational utilization of our planet's plentiful but by no means unlimited natural resources.

We conclude with a plea for more cohesive exploitation of the talent and funds already committed, increased exchange of data sets in a readily usable form, more collaboration and standardization in image-processing software, formulation of realistic goals, and persistence.

References

[1] R. C. Aldrich, "Space photos for land use and forestry," *Photogrammetric. Eng.* (*Special Issue on Remote Sensing*), vol. 37, pp. 389–401, 1971.

[2] H. C. Andrews, *Computer Techniques and Image Processing.* New York: Academic Press, 1970.

[3] P. E. Anuta, "Digital registration of multispectral video imagery," *SPIE J.*, vol. 7, pp. 168–175, 1969.

[4] ——, "Spatial recognition of multispectral and multitemporal digital imagery using fast Fourier transform techniques," *IEEE Trans. Geosci. Electron.*, vol. GE-8, pp. 353–368, Oct. 1970.

[5] P. E. Anuta, S. J. Kristof, D. W. Levandowski, R. B. MacDonald, and T. L. Phillips, "Crop, soil and geological mapping from digitized multispectral satellite photography," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1983–2016, 1971.

[6] P. E. Anuta and R. B. MacDonald, "Crop surveys from multiband satellite photography using digital techniques," *J. Remote Sens. Environ.*, vol. 2, pp. 53–67, 1971.

[7] R. J. Arguello, H. R. Sellner, and J. A. Stuller, "Transfer function compensation of sampled imagery," in *Proc. Symp. Two-Dimensional Image Processing* (Columbia, Mo.), pp. 11-2-1–11-2-12, 1971.

[8] R. H. Asendorf, "The remote reconnaissance of extraterrestrial environments," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 223–238.

[9] R. Bakis and P. G. Langley, "A method for determining the height of forest trees automatically from digitized 70 mm color aerial photographs," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 705–714, 1971.

[10] R. Bakis, M. A. Wesley, and P. M. Will, "Digital image processing for the Earth Resources Technology Satellite data," in *Proc. IFIP Congress 71* (Ljubljana, Yugoslavia), 1971.

[11] ——, "Digital correction of geometric and radiometric errors in ERTS data," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1427–1436, 1971.

[12] G. Barna, "Frame type imaging sensors," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 1.1, June 1970.

[13] D. Barnea and H. F. Silverman, "A class of algorithms for fast digital image registration," *IEEE Trans. Comput.*, vol. C-21, pp. 179–186, Feb. 1972; also IBM Res. Rep. RC-3358, 1971.

[14] M. E. Bauer, R. M. Swain, R. I. Mroczynski, P. E. Anuta, and R. B. MacDonald, "Detection of southern corn leaf blight by remote sensing techniques," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 693–704, 1971.

[15] D. J. Belcher, E. E. Hardy, and E. S. Phillips, "Land use classification with simulated satellite photography," *USDA Econ. Res. Serv.*, Agriculture Information Bull. 352, 1971.

[16] R. Bernstein, H. Branning, and D. G. Ferneyhough, "Geometric and radiometric correction of high resolution images by digital image processing techniques," presented at the IEEE Annu. Int. Geoscience Electronics Symp., Washington, D. C., 1971.

[17] R. Bernstein and H. F. Silverman, "Digital techniques for Earth resource image data processing," presented at the AIAA 8th Annu. Meeting, Sept. 1971; also IBM–FSD Tech. Rep. FSC 71-6017, Gaithersburg, Md.

[18] F. C. Billingsley, "Digital image processing at JPL," in *SPIE Computerized Imaging Techniques Seminar* (Washington, D. C.), pp. II 1–10, 1967.

[19] F. C. Billingsley, A. F. H. Goetz, and J. N. Lindsley, "Color differentiation by computer image processing," *Photogr. Sci. Eng.*, vol. 14, pp. 28–35, Jan.–Feb. 1970.

[20] F. C. Billingsley, "Photo reconnaissance applications of computer processing of images," in *Proc. Symp. Two-Dimensional Image Processing* (Columbia, Mo.), pp. 7-2-1–7-2-12, 1971.

[21] W. T. Blackband, Ed., "Advanced techniques for aerospace surveillance," Advisory Group for Aerospace Research and Development (AGARD), U. S. Dep. Commerce, NADO ASTIA Doc. AD 73887.

[22] P. Bock, "Space acquired data: Hydrological requirements," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 14.1, June 1970.

[23] A. L. Booth and V. R. Taylor, "Meso-scale archive and products of digitized video data from ESSA satellite," *Bull. Amer. Meteorol. Soc.*, vol. 50, pp. 431–438, 1969; also U. S. Dep. Commerce Tech. Memo. NESCTM-9.

[24] R. E. Bradford and J. F. Gross, "Conditioning of digitized TIROS and ESSA satellite vidicon data," in *SPIE Computerized Imaging Techniques Seminar* (Washington, D. C.), pp. VII 1–8, 1967.

[25] J. Braithwaite, "Airborne multispectral sensing and applications," *SPIE J.*, vol. 8, pp. 139–144, 1970.

[26] C. L. Bristor, W. M. Callicott, and R. E. Bradford, "Operational processing of satellite cloud pictures by computer," *Mon. Weather Rev.*, vol. 94, pp. 515–527, 1966.

[27] C. L. Bristor, "Computer processing of satellite cloud pictures," U. S. Dep. Commerce, Washington, D. C., Tech. Memo. NESCTM-3, 1968.

[28] ——, "The earth location of geostationary satellite imagery," *Pattern Recogn.*, vol. 2, pp. 269–277, 1970.

[29] C. L. Bristor and J. A. Leese, "Operational processing of ITOS scanning radiometer data," presented at IEEE Int. Conf. Telemetry, 1971, NESC Preprint.

[30] E. B. Butt and J. W. Snively, "The Pax II picture processing system," Univ. of Md. Comput. Sci. Cen., Rep. 68-67, 1969.

[31] G. C. Cheng, R. S. Ledley, D. K. Pollock, and A. Rosenfeld, Eds., *Pictorial Pattern Recognition.* Washington, D. C.: Thompson, 1968.

[32] L. J. Cihacek and J. V. Drew, "Infrared photos can map soils," *Farm, Ranch and Home Quart.*, Univ. of Nebr., pp. 4–8, Spring 1970.

[33] A. E. Coker, R. E. Marshall, and N. S. Thomson, "Application of multispectral data processing techniques to the discrimination of sinkhole activity in Florida," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 65–78, 1969.

[34] A. P. Colvocoresses, "Image resolution for ERTS, SKYLAB, and GEMINI/APOLLO," *Photogrammetr. Eng.*, vol. 37, 1972.

[35] R. N. Colwell, "The extraction of data from aerial photographs by human and mechanical means," *Photogrammetria*, vol. 20, pp. 211–228, 1965.

[36] ——, "Determining the usefulness of space photography for natural resource inventory," in *Proc. 5th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 249–289, 1968.

[37] R. N. Colwell and J. D. Lent, "The inventory of Earth resources on enhanced multiband space photography," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 133–143, 1969.

[38] R. N. Colwell, "The future for remote sensing of agricultural, forest, and range resources," presented before the Comm. Science and Astronautics, U. S. House of Representatives, Jan. 26, 1972.

[39] J. J. Cook and J. E. Colwell, "Michigan M7 scanner," Cent. for Remote Sensing Informat. and Analysis, Willow Run Labs., Univ. of Mich., Ann Arbor, Mich., Newsletter, 1971.

[40] M. Cook, "Remote sensing in the Isles of Langerhans," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 905–918, 1971.

[41] D. S. Cooley, "Applications of remote sensing and operational weather forecasting," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 941–950, 1971.

[42] P. W. Cooper, "Theoretical investigation of unsupervised learning techniques," NASA Contract NAS 12-697, Final Rep., 1970.

[43] R. B. Crane and M. M. Spencer, "Preprocessing techniques to reduce atmospheric and sensor variability in multispectral scanner data," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1345–1356, 1971.

[44] E. M. Darling and R. D. Joseph, "An experimental investigation of video pattern recognition," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 457–469.

[45] ——, "Pattern recognition from satellite altitudes," *IEEE Trans. Syst. Sci. Cybern.*, vol. SSC-4, pp. 38–47, Mar. 1968.

[46] E. M. Darling and J. G. Raudseps, "Non-parametric unsupervised learning with application to image classification," *Pattern Recog.*, vol. 2, pp. 313–336, 1970.

[47] A. G. DeCotiis and E. Conlan, "Cloud information in three spatial dimensions using thermal imagery and vertical temperature profile data," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 595–606, 1971.

[48] J. E. Dornbach, "Manned systems for sensing Earth's resources," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 6.1, June 1970.

[49] Douglas Aircraft Co., "Research on the utilization of pattern recognition techniques to identify and classify objects in video data," NASA Contract Rep. CR-999, 1968.

[50] J. A. Dunne, "Mariner 1969 television image processing," *Pattern Recogn.*, vol. 2, pp. 261–268, 1970.

[51] D. L. Earing and I. W. Ginsberg, "A spectral discrimination technique for agricultural applications," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 21–32, 1969.

[52] W. G. Egan and M. E. Hair, "Automated delineation of wetlands in photographic remote sensing," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 2231–2252, 1971.

[53] R. M. Endlich, D. E. Wolf, D. J. Hall, and A. E. Brain, "Use of pattern recognition techniques for determining cloud motion from sequences of satellite photographs," *J. Appl. Meteorol.*, vol. 10, pp. 105–117, 1971.

[54] W. G. Eppler, "Accuracy of determining sensor boresight position during aircraft flight test," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 205–226, 1969.

[55] W. G. Eppler and R. D. Merrill, "Relating remote sensor signals to ground-truth information," *Proc. IEEE*, vol. 57, pp. 665–675, Apr. 1969.

[56] W. G. Eppler, D. L. Loe, E. L. Wilson, S. L. Whitley, and R. J. Sachen, "Interactive display/graphics systems for remote sensor data analysis," in *3rd Annu. Earth Resources Program Review* (NASA-MSC, Houston, Tex.), p. 44-1, Dec. 1970.

[57] W. G. Eppler, C. A. Helmke, and R. H. Evans, "Table look-up approach to pattern recognition," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1415–1426, 1971.

[58] W. G. Eppler, D. L. Loe, E. L. Wilson, S. L. Whitley, and R. J. Sachen, "Interactive system for remote sensor data analysis," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1293–1306, 1971.

[59] W. A. Fischer, "User needs in geology and cartology," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 11.1, June 1970.

[60] J. C. Fletcher, "NASA's long-range earth resources survey program," presented before the Comm. Science and Astronautics, U. S. House of Representatives, Jan. 26, 1972.

[61] H. T. Frey, "Agricultural application of remote sensing—The potential from space platforms," USDA Agricultural Information Bull. N-328, Washington, D. C.

[62] A. W. Frutkin, "Status and prospects of international Earth Resources Satellite programs," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 17.1, June 1970.

[63] K. S. Fu, D. A. Landgrebe, and T. L. Phillips, "Information processing of remotely sensed agricultural data," *Proc. IEEE*, vol. 57, pp. 639–653, Apr. 1969.

[64] K. S. Fu, P. J. Min, and T. J. Li, "Feature selection in pattern recognition," *IEEE Trans. Syst. Sci. Cybern.*, vol. SSC-6, pp. 33–39, Jan. 1970.

[65] K. S. Fu, "On the application of pattern recognition techniques to remote sensing problems," Purdue Univ. School of Elect. Eng. Rep. TR-EE 71-73, 1971.

[66] ——, "Pattern recognition in remote sensing," in *Proc. 9th Allerton Conf. Circuits and Systems Theory* (Univ. of Illinois), Oct. 1971.

[67] T. A. George, "Unmanned spacecraft for surveying Earth's resources," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 7.1, June 1970.

[68] F. A. Godshall, "The analysis of cloud amount for satellite data," in *Trans. N. Y. Acad. Sci.*, Ser. 2, vol. 33, pp. 436–453, 1971.

[69] I. L. Goldberg, "Design considerations for a multispectral scanner for ERTS," in *Proc. Purdue Centennial Year Symp. Information Theory* (Lafayette, Ind.), pp. 672–680, 1969.

[70] V. W. Goldsworthy, E. E. Nelson, and S. S. Viglione, "Automatic classification of agricultural crops from multispectral and multicamera imagery," presented at Symp. Automatic Photointerpretation and Recognition, Washington, D. C., 1971; also McDonnell Douglas Astronautics Co., Rep. WD.

[71] H. M. Gurk, C. R. Smith, and P. Wood, "Data handling for Earth Resources Satellite data," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 247–259, 1969.

[72] H. M. Gurk, "User data processing requirements," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 9.1, June 1970.

[73] D. J. Hall, R. M. Endlich, D. E. Wolf, and A. E. Brain, "Objective methods for registering landmarks and determining cloud motions from satellite data," in *Proc. Symp. Two-Dimensional Image Processing* (Columbia, Mo.), pp. 10-1-1–10-1-7, 1971.

[74] R. M. Haralick and G. L. Kelly, "Pattern recognition with measurement space and spatial clustering for multiple images," *Proc. IEEE*, vol. 57, pp. 654–665, Apr. 1969.

[75] R. M. Haralick and I. Dinstein, "An iterative clustering procedure," presented at EIA Symp. Automatic Photointerpretation and Recognition, Baltimore, Md., Dec. 1970; also in *Proc. 9th IEEE Symp. Adaptive Processes* (Austin, Tex.), Dec. 1970.

[76] R. M. Haralick and D. E. Anderson, "Texture-tone study with application to digitized imagery," presented at Symp. Automatic Photointerpretation and Recognition, Washington, D. C.; also Univ. of Kansas, CRES Tech. Rep. 182 2, 1971.

[77] R. M. Haralick, "Data processing at the University of Kansas," presented at the *4th Ann. Earth Resources Program Review* (NASA-MSC, Houston, Tex.) 1972.

[78] T. J. Harley, L. N. Kanal, and N. C. Randall, "System considerations for automatic imagery screening," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 15–32.

[79] L. D. Harmon and K. C. Knowlton, "Picture processing by computer," *Science*, vol. 164, pp. 19–29, 1969.

[80] J. C. Harris, "Computer processing of atmospherically degraded images," in *SPIE Computerized Imaging Techniques Seminar* (Washington, D. C.), pp. xv 1–5, 1967.

[81] J. K. Hawkins, G. T. Elerding, K. W. Bixby, and P. A. Haworth, "Automatic shape detection for programmed terrain classification," in *Proc. Soc. Photo-Optical Instrument. Eng., Filmed Data and Computers Seminar*, Boston, (Mass.), 1966.

[82] J. K. Hawkins and G. T. Elerding, "Image feature extraction for automatic terrain classification," in *SPIE Computerized Imaging Techniques Seminar* (Washington, D. C.), pp. vi 1–8, 1967.

[83] J. K. Hawkins, "Parallel electro-optical picture processing," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 373–386.

[84] N. M. Herbst and P. M. Will, "Design of an experimental laboratory for signal and image processing," in *Advanced Computer Graphics*, Parslow and Green, Eds. New York: Plenum, 1971.

[85] ——, "An experimental laboratory for pattern recognition and signal processing," *Commun. Ass. Comput. Mach.*, vol. 15, pp. 231–244, 1972.

[86] S. M. Hirsch, F. A. Madden, and R. F. Kruckeberg, "The bispectral forest fire detection system," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 2253–2272, 1971.

[87] R. M. Hoffer, P. E. Anuta, and T. L. Phillips, "Application of ADP techniques to multiband and multiemulsion digitized photography," in *Proc. Amer. Soc. Photogrammetry 37th Ann. Meeting* (Washington, D. C.), 1972.

[88] R. M. Hoffer and F. E. Goodrick, "Variables and automatic classification over extended remote sensing test sites," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1967–1982, 1971.

[89] F. Holderman and H. Kazmierczak, "Generation of line drawings from grey-scale pictures," Tech. Rep. Res. Group for Information Processing and Transmission of the Univ. of Karlsruhe, under German Ministry of Defense Contract T 0230/92340/91354.

[90] R. A. Holmes, "An agricultural remote sensing information system," in *EASCON '68 Rec.*, pp. 142–149, 1968.

[91] R. A. Holmes and R. B. MacDonald, "The physical basis of system design for remote sensing in agriculture," *Proc. IEEE*, vol. 57, pp. 629–639, Apr. 1969.

[92] M. R. Holter and W. L. Wolfe, "Optical-mechanical scanning techniques," *Proc. IRE*, vol. 47, pp. 1546–1550, Sept. 1959.

[93] R. Horvath and D. S. Lowe, "Multispectral survey in the Alaskan Arctic," in *Proc. 5th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 483–496, 1968.

[94] W. Hovis, "Passive microwave sensors," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 3.1, June 1970.

[95] T. S. Huang and H. L. Kasnitz, "The combined use of digital computer and coherent optics in image processing," in *Computerized Imaging Techniques Seminar* (Washington, D. C.), pp. xvii 1–6, 1967.

[96] T. S. Huang, W. F. Schreiber, and O. J. Tretiak, "Image processing," *Proc. IEEE*, vol. 59, pp. 1586–1609, Nov. 1971.

[97] H. F. Huddlestone and E. H. Roberts, "Use of remote sensing for livestock inventories," in *Proc. 5th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 307–323, 1968.

[98] T. A. Hughes, A. R. Shope, and F. S. Baxter, "The USGS automatic orthophoto system," in *Proc. Amer. Soc. Photogrammetry 37th Ann. Meeting* (Washington, D. C.), pp. 792–817, 1971.

[99] B. R. Hunt, "Computational considerations in digital image enhancement," in *Proc. Symp. Two-Dimensional Image Processing* (Columbia, Mo.), pp. 1-4-1–1-4-7, 1971.

[100] J. M. Idelsohn, "A learning system for terrain recognition," *Pattern Recogn.*, vol. 2, pp. 293–302, 1970.

[101] E. G. Johnston, "The PAX II picture processing system," in *Picture Processing and Psychopictorics*, B. S. Lipkin and A. Rosenfeld, Ed. New York: Academic Press, 1970, pp. 427–512.

[102] E. G. Johnston, M. N. Fritz, and A. Rosenfeld, "A study of new image processing techniques," Univ. of Maryland Comput. Sci. Cent. Rep. AFCRL-71-0434, 1971.

[103] R. D. Joseph, R. G. Burge, and S. S. Viglione, "Design of a satellite-borne pattern classifier," in *Proc. Purdue Centennial Year Symp. on Information Theory* (Lafayette, Ind.), 1969, pp. 681–700.

[104] ——, "A compact programmable pattern recognition system," presented at the Symp. Application of Reconnaissance Technology to Monitoring and Planning Environmental Change, Rome, N. Y., 1970; also McDonnell Douglas Astronautics Co. Rep. WD 1409.

[105] R. D. Joseph and S. S. Viglione, "Interactive imagery analysis," in *Proc. Symp. on Two-Dimensional Image Processing* (Columbia, Mo.), pp. 7-1-1–7-1-6, 1971; also McDonnell Douglas Astro-

nautics Co. Paper WD 1754, Aug. 1971.
[106] H. Kazmierczak and F. Holderman, "The Karlsruhe system for automatic photointerpretation," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 45–62.
[107] H. Kazmierczak, "Informationsreduktion und Invarianz-Leistung bei der Bildverarbeitung mit einen Computer," in *Pattern Recognition in Biological and Technical Systems.* New York: Springer, 1971.
[108] S. J. Kishner, "Feature extraction using Golay logic," in *Proc. Perkin-Elmer Symp. on Sampled Images* (Norwalk, Conn.), pp. 7-1–7-8, 1971.
[109] M. C. Kolipinski and A. L. Higer, "On the detection of pesticidal fallout by remote sensing techniques," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), p. 989, 1969.
[110] M. C. Kolipinski, A. L. Higer, N. S. Thomson, and F. J. Thomson, "Automatic processing of multiband data for inventorying hydrobiological features," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 79–96, 1969.
[111] C. L. Korb, "Physical considerations in the channel selection and design specification of an airborne multispectral scanner," in *Proc. Purdue Centennial Year Symp. Information Theory* (Lafayette, Ind.), pp. 646–657, 1969.
[112] F. J. Kriegler, W. Malika, R. F. Nalepka, and W. Richardson, "Preprocessing transformations and their effects on multispectral recognition," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 97–132, 1969.
[113] F. J. Kriegler, "Implicit determination of multispectral scanner variation over extended areas," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 759–778, 1971.
[114] S. J. Kristof, A. L. Zachary, and J. E. Cipra, "Mapping soil types from multispectral scanner data," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 2095–2108, 1971.
[115] D. A. Landgrebe and T. L. Phillips, "A multichannel image data handling system for agricultural remote sensing," in *SPIE Computerized Imaging Techniques Seminar* (Washington, D. C.), pp. xii 1–10, 1967.
[116] D. A. Landgrebe, P. J. Min, P. H. Swain, and K. S. Fu, "The application of pattern recognition techniques to a remote sensing problem," Purdue Univ., Lafayette, Ind., 1968, LARS Information Note 080568.
[117] D. A. Landgrebe, "The development of machine technology processing for Earth resource survey," in *3rd Ann. Earth Resources Program Review* (NASA-MSC, Houston, Tex.), p. 40-1, Dec. 1970.
[118] P. G. Langley, "Automating aerial photointerpretation in forestry —How it works and what it will do for you," in *Proc. Ann. Meet. Soc. Amer. Forestry* (Detroit, Mich.), 1965.
[119] ——, "New multistage sampling techniques using space and aircraft imagery for forest inventory," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1179–1192, 1969.
[120] J. A. Leese, A. L. Booth, and F. A. Godshall, "Archiving and climatological application of meteorological satellite data," U. S. Dep. Commerce, Environ. Sci. Serv. Admin., Rockville, Md., Rep. to the World Meteorol. Org. Comm. for Climatol.; also ESSA Tech. Rep. NESC 53, July 1970.
[121] J. A. Leese, C. S. Novak, and V. R. Taylor, "The determination of cloud pattern motion from geosynchronous satellite image data," *Pattern Recogn.*, vol. 2, pp. 279–292, 1970.
[122] J. A. Leese, C. S. Novak, and B. B. Clark, "An automated technique for obtaining cloud motion for geosynchronous satellite data using cross-correlation," *J. Appl. Meteorol.*, vol. 10, pp. 110–132, 1971.
[123] J. A. Leese, W. Pickel, B. Goddard, and R. Bower, "An experimental model for automated detection, measurement and quality control of sea-surface temperature from ITOS-IR data," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 625–646, 1971.
[124] R. R. Legault, "Summary of Michigan Multispectral Investigations program," in *3rd Ann. Earth Resources Program Review* (NASA-MSC, Houston, Tex.) p. 37-1, Dec. 1970.
[125] S. H. Lerman, "Digital image processing at ITEK," in *Proc. Symp. on Two-Dimensional Image Processing* (Columbia, Mo.), pp. 5-5-1–5-5-4, 1971.
[126] D. S. Lowe, "Line scan devices and why use them," in *Proc. 5th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 77–100, 1968.
[127] R. B. MacDonald, "The application of remote sensing to corn blight detection and crop yield forecasting," in *3rd Ann. Earth Resources Program Review* (NASA-MSC, Houston, Tex.), p. 28-1, Dec. 1970.
[128] ——, "The application of automatic recognition techniques in the Apollo IX SO-65 experiment," in *3rd Ann. Earth Resources Program Review* (NASA-MSC, Houston, Tex.), p. 39-1, Dec. 1970.
[129] H. Markarian, R. Bernstein, D. G. Ferneyhough, C. E. Gregg, and F. S. Sharp, "Implementation of digital techniques for correcting high resolution images," presented at the ASP-ACSM Fall Convention, Sept. 1971; also IBM-FSD, Gaithersburg, Md., Tech. Rep. FSC 71-6012.
[130] R. E. Marshall, "Application of multispectral recognition techniques for water resources investigations in Florida," in *Proc' Purdue Centennial Year Symp. Information Theory* (Lafayette Ind.), pp. 719–731, 1969.
[131] R. E. Marshall, N. S. Thomson, and F. J. Kriegler, "Use of multispectral recognition techniques for conducting wide area wheat surveys," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 3–20, 1969.
[132] R. E. Marshall and F. J. Kriegler, "Multispectral recognition system," in *Proc. 9th IEEE Symp. Adaptive Processes, Decision, and Control* (Austin, Tex.), p. xi-2, 1970.
[133] ——, "An operational multispectral survey system," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 2169–2192, 1971.
[134] H. M. Maynard, L. F. Pemberton, and C. W. Swonger, "Application of image processing research to the retrieval of filmed data," in *Proc. Soc. Photo-Optical Instrument. Eng., Filmed Data and Computers Seminar* (Boston, Mass.), pp. xvii 1–10, 1966.
[135] E. P. McClain, "Potential use of Earth satellites for solving problems in oceanography and hydrology," presented at the Nat. Meeting of the Amer. Astronaut. Soc., Las Cruces, N. Mex., 1970.
——, "Application of environmental satellite data to oceanography and hydrology," U. S. Dep. Commerce, Washington, D. C., Tech. Memo. NES CTM 19.
[136] R. B. McEwen, "An evaluation of analog techniques for image registration," U. S. Geol. Survey Prof. Paper 700-D, pp. D305–D311, 1970.
[137] ——, "Geometric calibration of the RBV system for ERTS," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 791–808, 1971.
[138] E. P. McMahon, "Earth Resources Technology Satellite system data processing," in *Proc. EASCON 70*, pp. 24–27, 1970.
[139] T. M. Mendel and K. S. Fu, Eds., *Adaptive, Learning and Pattern Recognition Systems.* New York: Academic Press, 1971.
[140] P. J. Min, D. A. Landgrebe, and K. S. Fu, "On feature selection in multiclass pattern recognition," in *Proc. 2nd Ann. Princeton Conf. Information Sciences and Systems*, pp. 453–457, 1968.
[141] R. T. Moore, M. C. Stark, and L. Cahn, "Digitizing pictorial information with a precision optical scanner," *Photogrammetr. Eng.*, vol. 30, pp. 923–931, 1964.
[142] M. Mozer and P. Serge, "High resolution multispectral TV camera systems," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1475–1482, 1971.
[143] J. L. Muerle and D. C. Allen, "Experimental evaluation of techniques of automatic segmentation of objects in a complex scene," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 3–14.
[144] J. L. Muerle, "Some thoughts on texture discrimination by computer," in *Picture Processing and Psychopictorics.* New York: Academic Press, 1970, pp. 371–379.
[145] A. H. Muir, "Some shifting relationships between the user community and the Earth Resources Program," in *Proc. 7th Space Cong.* (Cocoa Beach, Fla.), pp. 2-11–2-14, 1970.
[146] L. E. Mumbower, "Ground data processing considerations for Earth resources information," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 8.1, June 1970.
[147] R. Nagel and A. Rosenfeld, "Ordered search techniques in template matching," *Proc. IEEE* (Lett.), vol. 60, p. 242, Feb. 1972; also Univ. of Maryland Comput. Sci. Cent. Rep. TR-166.
[148] R. F. Nalepka, "Investigation of multispectral discrimination techniques," Infrared and Optics Lab., Inst. Sci. and Technol. of the Univ. of Michigan, Ann Arbor, Mich., Rep. 2264-12-F, 1970.
[149] R. Narasimhan, "Labeling schemata and syntactic description of pictures," *Inform. Contr.*, vol. 7, pp. 151–179, 1964.
[150] NASA-MSFC, "Skylab in-flight experiments," Skylab Program Summary Description, June 1971.
[151] NASA, "Earth photographs from Gemini VI through XII," Washington, D. C., NASA SP-171, 1969.
[152] NASA, "Apollo-9 photographic plotting and indexing report," NASA-MSC, Mapping Sci. Lab. for Earth Resour. Div., Sci. and Appl. Directorate, Houston, Tex., 1969.
[153] NASA, NASA-MSC Earth Resour. Aircraft Program, Houston, Tex., Mission 89 Summary Rep., 1969.
[154] NASA, "Remote sensing of Earth resources: A literature survey with indexes," NASA Publ. SP-7036, 1970.
[155] NASA, "Earth resources research facility index, vol. I—Documentary data, vol. II—Sensor data," Houston, Tex., NASA-MSC-02576, 1971.
[156] R. Nathan, "Picture enhancement for the Moon, Mars and Man," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 239–266.
[157] ——, "Spatial frequency filtering," in *Picture Processing and Psychopictorics*, B. S. Lipkin and A. Rosenfeld, Eds. New York: Academic Press, 1970, pp. 151–163.
[158] R. Newman and B. Reisine, "Practical applications of sequential pattern recognition techniques," in *Proc. 7th Space Cong.* (Cocoa Beach, Fla.), pp. 2.1–2.9, 1970.

[159] V. T. Norwood, "Optimization of a multispectral scanner for ERTS," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 227–236, 1969.
[160] ——, "Scanning type imaging sensors," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 2.1, June 1970.
[161] National Research Council (Comm. on Remote Sensing for Agricultural Purposes), *Remote Sensing with Special Reference to Agriculture and Forestry.* Washington, D. C.: Natl. Acad. Sci., 1970.
[162] D. O'Handley and W. B. Green, "Recent developments in digital image processing at the Image Processing Laboratory at the Jet Propulsion Laboratory," *Proc. IEEE*, vol. 60, pp. 821–828, July 1972.
[163] K. W. Olson, "An operational pattern recognition system," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 63–73.
[164] R. F. Owens, R. W. VanDuinen, and L. D. Sinnamon, "The Socrates adaptive image processor," in *SPIE Computerized Imaging Techniques Seminar* (Washington, D. C.), pp. v 1–5, 1967.
[165] J. J. O. Palgen, "Applicability of pattern recognition techniques to the analysis of urban quality from satellites," *Pattern Recogn.*, vol. 2, pp. 255–260, 1970.
[166] ——, "Application of optical processing for improving ERTS data," Allied Research Associates Tech. Rep. 16, NASA Contract NAS-10343, 1970.
[167] A. B. Park, "Remote sensing of time dependent phenomena," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1227–1236, 1969.
[168] ——, "The role of man in an observatory/laboratory spacecraft," in *Proc. EASCON 70*, pp. 21–23, 1970.
[169] ——, "User needs in agriculture and forestry," *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 13.1, June 1970.
[170] J. L. Pfaltz, J. W. Snively, and A. Rosenfeld, "Local and global picture processing by computer," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 353–372.
[171] A. Pilipchuk, "Mechanical scanner for off-line picture digitization," Comput. Sci. Cent., Univ. of Maryland Rep. 69-92, 1969.
[172] J. F. Potter, "Scattering and absorption in the Earth's atmosphere," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 415–430, 1969.
[173] W. K. Pratt, "Semi-annual technical report of the USC Image Processing Laboratory," Univ. of South. California Rep. 411, Mar. 1972.
[174] P. K. Rao and A. E. Strong, "Sea surface temperature mapping off the eastern United States using NOAA's ITOS satellite," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 683–692, 1971.
[175] A. J. Richardson, R. J. Torline, and W. A. Allen, "Computer identification of ground patterns from aerial photographs," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 1357–1376, 1971.
[176] T. C. Rindfleisch, "Getting more out of Ranger pictures by computer," *Astronaut. Aeronaut.*, vol. 7, 1969.
[177] T. C. Rindfleisch, J. A. Dunne, H. F. Frieden, and W. D. Stromberg, "Digital processing of the Mariner 6 and 7 pictures," *J. Geophys. Res.*, vol. 76, pp. 394–417, 1971.
[178] A. Rosenfeld, C. Fried, and J. Ortan, "Automatic cloud interpretation," *Photogrammet. Eng.*, vol. 31, p. 991, 1965.
[179] A. Rosenfeld, *Picture Processing by Computer.* New York: Academic Press, 1969.
[180] A. Rosenfeld, H. Huang, and V. B. Schneider, "An application of cluster detection to text and picture processing," *IEEE Trans. Inform. Theory*, vol. IT-15, pp. 672–681, Nov. 1969; also Univ. of Maryland Comput. Sci. Cent. Rep. TR-68-68.
[181] A. Rosenfeld and E. B. Troy, "Visual texture analysis," Comput. Sci. Cent., Univ. of Maryland, Tech. Rep. TR70-116.
[182] A. Rosenfeld and M. Thurston, "Edge and curve enhancement for visual scene analysis," *IEEE Trans. Comput.*, vol. C-20, pp. 562–569, May 1971.
[183] L. Rossol, "Generation of halftones by computer-controlled microfilm recorder," *IEEE Trans. Comput.* (Short Note), vol. C-20, pp. 662–664, June 1971.
[184] H. R. Sellner, "Transfer function compensation of sampled imagery," in *Proc. Perkin-Elmer Symp. on Sampled Images* (Norwalk, Conn.), pp. 4-1–4-14, 1971.
[185] J. R. Shay, "Systems for Earth resources information," in *Proc. Purdue Centennial Year Symp. Information Theory* (Lafayette, Ind.), pp. 635–643, 1969.
[186] H. F. Silverman, "On the use of transforms for satellite image processing," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), 1971, pp. 1377–1386.
[187] D. S. Simonett, "Potential of radar remote sensors as tools in reconnaissance geomorphic, vegetation and soil mapping," in *9th Int. Cong. Soil Sci. Trans.*, vol. IV, Paper 20, pp. 271–280, 1968; also Univ. of Kansas, CRES Rep. 117-2.
[188] H. W. Smedes, M. M. Spencer, and F. J. Thomson, "Processing of multispectral data and simulation of ERTS data channels to make computer terrain maps of a Yellowstone National Park test site," in *3rd Annu. Earth Resources Program Review* (NASA-MSC Houston, Tex.), p. 10-1, Dec. 1970.
[189] H. W. Smedes, H. J. Linnerud, S. G. Hawks, and L. B. Woolamer, "Digital computer mapping of terrain by clustering techniques using color film on a three-band sensor," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 2057–2072, 1971.
[190] C. R. Smith and T. F. Shafman, "Cloud cover limitations on satellite photography of the United States," in *Trans. 49th Annu. Meeting of the Amer. Geophys. Union* (Washington, D. C.), p. 188, 1968.
[191] E. A. Smith and D. R. Phillips, "Automated cloud tracking using precisely aligned digital ATS pictures," in *Proc. Symp. Two-Dimensional Image Processing* (Columbia, Mo.), pp. 10-2-1–10-2-26, 1971.
[192] G. L. Stanely, W. C. Nienow, and G. G. Lendaris, "SARF—An interactive signature analysis research facility," in *Proc. Purdue Centennial Year Symp. Information Theory* (Lafayette, Ind.), pp. 436–445, 1969.
[193] D. Steiner, "A methodology for the automated photo-identification of rural land use types," in *Automatic Interpretation and Classification of Images*, A. E. Grasselli, Ed. New York: Academic Press, 1969, p. 235.
[194] D. Steiner, K. Baumberger, and H. Maurer, "Computer processing and classification of multi-variate information from remote sensing imagery," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 895–908, 1969.
[195] D. Steiner, "Time dimension for crop surveys from space," *Photogrammetr. Eng.*, vol. 36, pp. 187–194, 1970.
[196] R. E. Stevenson, "Oceanographic data requirements for the development of an operational satellite system," in *Proc. Princeton Univ. Conf. Aerospace Methods for Revealing Earth's Resources* (Princeton, N. J.), p. 12.1, June 1970.
[197] H. G. Stever, Keynote Address to the 13th Meeting of the Panel on Sci. and Technol., Comm. Sci. and Astronaut., U. S. House of Representatives, Jan. 25, 1972.
[198] W. M. Strome, "Canadian data-handling facility for ERTS," in *Proc. Canadian Computer Conf.*, pp. 423101–423118, 1972.
[199] J. P. Strong, "Automatic cloud cover mapping," Univ. of Maryland Comput. Sci. Cent. Rep. TR-163.
[200] L. L. Sutro and W. S. McCulloch, "Steps toward the automatic recognition of unknown object," in *Proc. Inst. Elec. Eng. NPL Conf. Pattern Recognition* (Teddington, U. K.), pp. 117–133, 1968.
[201] P. H. Swain and K. S. Fu, "On the application of a nonparametric technique to crop classification problems," in *Proc. Nat. Electronics Conf.*, 1968.
[202] P. H. Swain and D. A. Germann, "On the application of man-machine computing systems to problems in remote sensing," in *Proc. 11th Midwest Symp. Circuit Theory* (Notre Dame, Ind.), May, 1968; also *Software Age*, vol. 2, pp. 13–20, 1968.
[203] P. H. Swain, "Data processing I: Advancements in machine analysis of multispectral data," Purdue Univ. LARS Informat. Note 012472, to be included in the *4th Annu. Earth Resources Program Review* (NASA-MSC, Houston, Tex.), 1972.
[204] G. D. Swanlund, "Design requirements for texture measurements," in *Proc. Symp. Two-Dimensional Image Processing* (Columbia, Mo.), pp. 8-3-12–8-3-19, 1971.
[205] W. Swoboda and J. W. Gerdes, "A system for demonstrating the effects of changing background on automatic target recognition," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 33–42.
[206] M. G. Tanguay, R. M. Hoffer, and R. D. Miles, "Multispectral imagery and automatic classificaton of spectral response for detailed engineering soils mapping," in *Proc. 6th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 33–64, 1969.
[207] M. M. Thompson, Ed., *Manual of Photogrammetry.* Falls Church, Va.: Amer. Soc. of Photogrammetry, 1966.
[208] F. J. Thomson, "User oriented data processing at the University of Michigan," in *3rd Annu. Earth Resources Program Review* (NASA-MSC, Houston, Tex.), p. 38-1, Dec. 1970.
[209] W. R. Tobler, "Problems and prospects in geographical photointerpretation," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 267–274.
[210] D. R. Tompson, "An IBM special cartographic scanner," in *Proc. ASP-ACSM Conv.* (Washington, D. C.), 1967.
[211] M. R. Uffelman, "Target detection, prenormalization, and learning machines," in *Pictorial Pattern Recognition*, Cheng *et al.*, Eds. Washington, D. C.: Thompson, 1968, pp. 503–521.
[212] R. M. Vesper and D. N. Rosenzweig, "Sampled image laboratories and facilities," in *Proc. Perkin-Elmer Symp. Sampled Images* (Norwalk, Conn.), pp. 10-1–10-8, 1971.
[213] A. G. Wacker, "A cluster approach to finding spatial boundaries in multispectral imagery," LARS Informat. Note 122969, 1969.
[214] A. G. Wacker and D. A. Landgrebe, "Boundaries in multispectral images by clustering," in *Proc. 1970 9th IEEE Symp. Adaptive Processes* (Austin, Tex.), pp. 322–330, 1970.

[215] R. N. Watts, "Skylab scheduled for 1972," *Sky Telesc.*, pp. 146–148, 1970.
[216] G. R. Welti and S. H. Durrain, "Communication system configuration for the Earth Resources Satellite," in *Communication Satellites for the 70's Systems*, N. E. Feldman and C. M. Kelly, Eds. (vol. 26 of *Progress in Astronautics and Aeronautonics*). Cambridge, Mass.: M.I.T. Press, 1971, pp. 289–314.
[217] P. M. Will, R. Bakis, and M. A. Wesley, "On an all-digital approach to Earth Resources Satellite image processing," Yorktown Heights, N. Y., IBM Tech. Rep. RC-3027, 1970.
[218] C. L. Wilson, M. M. Beilock, and E. M. Zaitzeff, "Design considerations for aerospace multispectral scanning systems," in *Proc. Purdue Centennial Year Symp. on Information Theory* (Lafayette, Ind.), pp. 658–671, 1969.
[219] F. J. Wobber, "Space age prospecting," *World Mining*, p. 25, June 1968.
[220] P. Wood, "User requirements for Earth Resources Satellite data," in *Proc. EASCON 70*, pp. 14–20, 1970.
[221] E. M. Zaitzeff, C. L. Wilson, and D. H. Ebert, "MSDS: An experimental 24-channel multispectral scanner system," *Bendix Tech. J.*, pp. 20–32, 1970.
[222] B. Zavos, "Application of remote sensing to the World Weather Watch and the Global Atmospheric Research Program," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 207–220, 1971.
[223] E. O. Zeitler and R. O. Bratton, "Uses of Earth Resources data in the NASA/MSC Earth Resources research data facility," in *Proc. 7th Int. Symp. Remote Sens. Environ.* (Ann Arbor, Mich.), pp. 925–936, 1971.
[224] J. S. Zelenka, "Imaging radar techniques in remote sensing applications," in *Proc. 9th Annu. Allerton Conf. Circuit and System Theory*, pp. 975–986, 1971.

Interactive Pattern Analysis and Classification Systems: A Survey and Commentary

LAVEEN N. KANAL, FELLOW, IEEE

***Abstract*—Starting with the era of learning machines, reasons are presented for the current emergence of graphics-oriented interactive pattern analysis and classification systems (IPACS) as a general approach to practical pattern-recognition problems. A number of representative systems and their application to a wide variety of patterns are surveyed. Various aspects of alternative hardware and software implementations are commented upon and computational algorithms and mappings relevant to interactive analysis and classification of patterns are discussed.**

I. Introduction

IN THE Talk of the Town section of the *New Yorker* for December 6, 1958, "our man about town" reported on a conversation with Frank Rosenblatt, the inventor of Perceptrons [151]. The report was titled "Rival," and it reflected the anthropomorphism that was then fashionable in pattern recognition and computers.

Rosenblatt's brilliant conjectures and the colorful names for his "self-organizing" machines attracted wide attention. He had high hopes for his "artificial intelligences." They were to be replacements for human perceivers, recognizers, and problem solvers. Over the next few years there followed a flock of other "adaptive" and "learning" machines such as ADALINE and MADALINE [201], APE (see [91]), MINOS [17], CONFLEX [187], and SOCRATES [188].

Manuscript received February 12, 1972; revised July 14, 1972. This work was supported in part by the Directorate of Mathematical and Information Sciences, Air Force Office of Scientific Research, Air Force Systems Command, USAF, under Grant AFOSR 71-1982 to the University of Maryland.
The author is with the Computer Science Center, University of Maryland, College Park, Md. 20742.

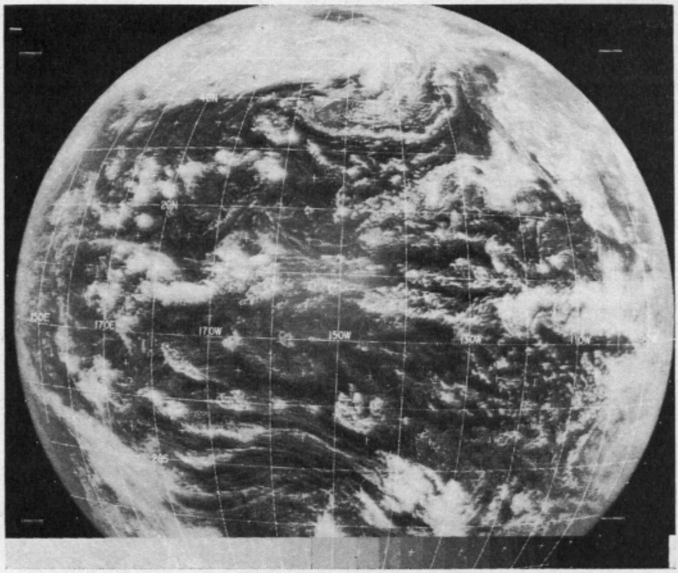
As was to become evident, the true contribution of the brilliant conjectures, catchy names and audacious claims for these machines, was not in providing a general approach to pattern recognition. Rather it was in creating an air of excitement about automatic pattern-recognition and learning machines.

Today there is greater appreciation of the complexities of what is called pattern recognition. But the excitement continues, as does the urge to look for relatively general theoretical and experimental approaches and models which are applicable to a wide class of problems. Aspects of the structural-geometric or linguistic-statistical models for pattern recognition that have recently aroused interest are presented elsewhere [94]. Here we survey graphics-oriented interactive pattern analysis and classification systems, for which we use the abbreviation IPACS. IPACS represent responses to demands for generality in the experimental domain.

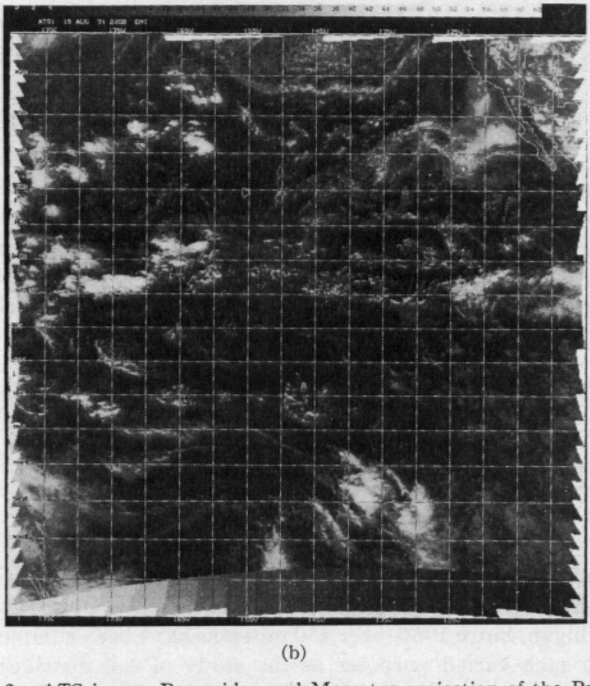
Computer-driven interactive graphic displays together with input devices such as the light pen, the Rand tablet, the Sylvania tablet, the mouse, and joy sticks, have improved man–computer communication in recent years. In addition to displaying relationships in two or three dimensions (using perspective) for human inspection, the graphics terminal provides a high data-rate communication link to the computer, enabling dynamic control and manipulation of programs by means of line drawings, as well as character codes or function buttons.

Section II discusses the impact of interactive display technology on approaches to pattern-recognition problems. Section III lists some existing IPACS and gives an idea of the

Fig. 1. ESSA-9 mosaic of North America. Traces of the reconstruction from the separate video frames are evident from the fiducial marks. The deviation of the overlay from the true coast lines shows a registration error carried into the mapping program. A programming error, since corrected, may be seen in the checkerboard in NW corner. Note gray wedge and annotation.



(a)



(b)

Fig. 2. ATS image. Raw video and Mercator projection of the Pacific Ocean from the first ATS. These illustrations were obtained through the courtesy of the National Environmental Satellite Center.

Fig. 3. Digitized Apollo photograph. This photograph of central Arizona was digitized at a resolution corresponding to 4200 lines on a drum scanner and was then recorded on film using the same device. The fiducial marks were introduced in the digital data for testing certain reseau detection algorithms [10], [11].

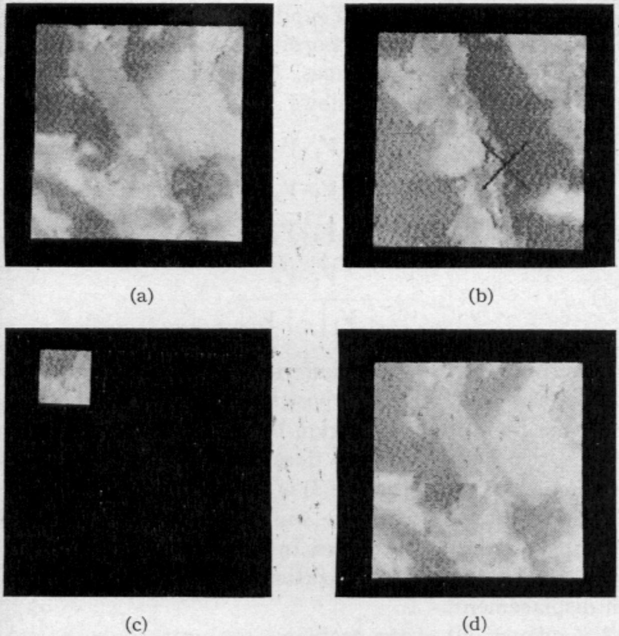


Fig. 6. ITOS-1 registration experiment. A 32 by 32 window function (c) extracted from the top left corner of picture #1 (b) is tried in every possible position of the search area (a) by means of the sequential similarity detection algorithm. The position of the best match determined by the algorithm is shown in (d), where the window function is inserted into the search area. Note the discontinuities due to the change in cloud coverage between the times of exposure of the two pictures.