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The Multispectral Imaging Science Working Group: Final Report

Volume II Working Group Reports

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The Multispectral Imaging Science Working Group: Final Report

Volume II Working Group Reports

Scott C. Cox, Editor

Proceedings of working groups sponsored
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MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

EXECUTIVE SUMMARY

INTRODUCTION

Multispectral imaging techniques can be used to obtain unique new information about the surface characteristics of the Earth. They also represent powerful tools for studying a wide range of physical processes that occur at or near the Earth's surface. The utility of multispectral imaging techniques is continually evolving with technological advances leading to improvements in the measurement capabilities of orbital sensors. This in turn expands the quality and quantity of information that can be derived from orbital multispectral surveys. For example, the Thematic Mapper (TM) successfully launched into space on Landsat 4 is a major advance over the earlier Landsat Multispectral Scanner in terms of the width and number of spectral channels that are available, their distribution throughout the visible and infrared spectrum, and its spatial resolution. The measurement capabilities of the TM are expected to result in major improvements in our ability to classify and monitor croplands, determine changes in land use patterns, map geological variations in the Earth's crust, and manage our water resources.

NASA is engaged in a long-term program of continuing research to evaluate the utility of multispectral imaging techniques for basic and applied studies of the Earth. Laboratory and field investigations conducted in the past have indicated that further improvements in the resolution, sensitivity, and frequency of orbital multispectral surveys will substantially enlarge our current observational capabilities, and open new avenues of Earth related research. Recent advances in detector array and focal plane technology, optical designs, and signal processing methods will enable us to realize some of these desired measurement capabilities in the next generation of experimental orbital sensors. In light of these technological advances and the impending launch of the Thematic Mapper, NASA chartered a Multispectral Imaging Science Working Group in March, 1982 to initiate a dialogue with remote sensing researchers that would provide long term guidance for its R and D efforts during the mid-nineteen eighties. This Working Group consisted of four Earth science panels representing the disciplines of botany, geography, geology, and hydrology, and two technology-oriented panels concerned with sensor design and data reduction.

The Working Group science panels were initially asked to summarize current knowledge of the spectral and spatial characteristics of the Earth's surface; to specify desired multispectral measurement capabilities based on this knowledge; and to identify critical gaps in our understanding of the remote sensing process that should be the focus of future research efforts. The technology panels were asked to evaluate current technological trends; to specify multispectral imaging and data handling capabilities that are achievable during the present decade; and to identify generic problems in instrument design and data reduction that should be the objects of future study. Each panel held a meeting to discuss these topics, and the outcome of these meetings is summarized here. A series of future Working Group meetings are currently planned which will provide a continuing forum for the discussion of NASA's Research and Development efforts in developing and applying multispectral imaging systems to the study of the Earth.

Remote sensing research data needs in the four terrestrial science areas have certain commonalities which can be stated as follows:

- Higher spatial resolution is needed to address specific research problems.

- Finer spectral resolution will be needed before optimum band locations to address specific problems can be determined.

- Exact time or times of observations are problem dependent.

- Radiometric accuracy needed is dependent on the dynamic ranges of the spectral signatures being observed.

The differences in research requirements are research problem oriented. Urban land use requires the highest spatial resolution. The highest temporal resolution requirements occur in botany and geobotany when observations at a certain time, i.e., during plant flowering or at the onset of senescence are required. The narrowest spectral bandwidths are driven by research requirements in geology with attempts to identify chemical characteristics of materials. Narrow spectral bands are also needed in botanical investigations to improve crop type and phenology discrimination.

The following table summarizes different thresholds in desired measurement capabilities developed by the four Terrestrial Science discipline areas:

	A	B	C
Spatial Resolution	3 meters	10 meters	30 meters
Temporal Resolution	1 time/ 2 or 3 days	1 time/month	1 time/year
Spectral Band Widths	5 nm	20 nm	100 nm
Radiometric Calibration VIS/NIR/SWIR	Absolute	Relative	Relative
TIR	Absolute	Absolute	Relative

Column A represents the desired capability which satisfies the most stringent research requirements. In other words, a hypothetical sensor with Column A characteristics would satisfy all terrestrial science research needs. Column B is a compromise in which most data requirements for Terrestrial Science research are met. Obviously, this middle ground would mean this data would not satisfy cartographic mapping needs at 1:25,00 scale, but could be useful in botany. Column C is really a lower limit where data is already being collected, specifically with the Landsat 4 TM. In this case, systems which such characteristics do not improve our research capabilities. Realistically, this chart does not define 3 sensor systems but rather should be used in evaluating trade-offs between spatial resolution and spectral band width, etc.

Discussion in the Image Science and Information Science discipline areas indicate that technology developments either well in-hand or near at-hand can support the development of research instruments to provide important remotely sensed data in the Terrestrial Science discipline areas. Use of area array technology or programmable filters can provide the spectral flexibility required in an experimental instrument. On-board computation techniques can be used to select specific bands and spatial resolutions. Advances in computer technology can be applied to facilitate data handling and data dissemination.

Each of the Terrestrial Science Working Groups emphasized the need to understand the effects of the atmosphere and viewing direction on spectral signatures. The use of off-nadir viewing approaches to obtain more frequent coverage of the Earth's surface will further increase the atmospheric effects on signals. The research suggested by the working groups emphasize the fact that remotely sensed data is only one of the tools that will be applied to solve a problem, so that laboratory and field data will also be required to adequately support research endeavors.

IMAGING SCIENCE

Satellite remote sensing has proven to be an extremely valuable tool for monitoring and investigating the Earth's ocean and land resources on a global scale. In particular, recent advances in solid-state detector arrays and sensor systems technology have made possible substantially better spectral, spatial and radiometric resolution. Data acquired from laboratory and field spectrometers, aircraft spectrometers, and the recent Shuttle Multispectral Infrared Radiometer (SMIRR) experiment have demonstrated the utility of high resolution spectra for disciplines such as geology, agriculture, botany, and hydrology. Additionally, data from aircraft instruments such as the Thematic Mapper Simulator (TMS) have demonstrated the enhanced classification accuracies and improved lithological mapping obtainable with spatial resolutions in the 5-30 meter range. The recent successful launch of the Landsat 4 Thematic Mapper with improved spatial, spectral and radiometric resolution will provide additional data to confirm or reject aircraft sensor findings.

While a significant data base is beginning to emerge from these laboratory, field, and aircraft measurements, the designs of spaceborne solid-state sensors to exploit this capability from space are still in their early stages of definition. The Multispectral Imaging Science Workshop was organized to provide a forum for the discussion of the current state-of-the-art in sensor technology, identify critical issues and provide long-range guidance for NASA's research and technology development efforts in this rapidly evolving area.

Current State of the Art

During the two-day Imaging Science workshop, a comprehensive overview of the state-of-the-art of remote sensing and supporting technology was presented. Two generic spacecraft sensor concepts were described. The first was a multispectral pushbroom sensor employing linear array technology. Four alternative designs for such a sensor, developed through recently completed study contracts, were presented. Each of the alternative sensor designs used multispectral linear array (MLA) sensors operating in six spectral bands, including two bands in the short wave infrared (SWIR) spectral region. These sensors also incorporated capabilities for stereo and crosstrack pointing. A second concept which was presented was the imaging spectrometer (IS). The IS incorporates a dispersive element and area (two dimensional) arrays to provide both multi-spectral and multi-spatial data from the same array simultaneously. The spectral bands, band width, and spatial resolution can be chosen by on-board, programmed readout of the focal plane. Technology developments to provide the foundation for implementing both MLA and IS concepts into hardware in the late 1980's were reviewed. These include visible multispectral linear arrays, Pd-silicide Schottky barrier and HgCdTe SWIR linear and area arrays and on-board data processing-compression schemes. In most cases, the technology is presently available or is nearly in hand. Results presented suggest significant progress in critical detector array technology: Pd-silicide Schottky barrier technology is now at a level of demonstrated performance and maturity that make it an attractive and lower risk alternative to the high performance photovoltaic HgCdTe hybrid arrays for broad spectral band SWIR applications. In addition, 32 X 32 element HgCdTe hybrid arrays have been fabricated and will be incorporated in an aircraft instrument, the Airborne Imaging Spectrometer (AIS).

Another key technology area discussed at some length was very large scale integration (VLSI) and the associated technology of computer aided design (CAD) of these devices. The importance of VLSI evolves from the significantly greater data volumes implied by the Terrestrial Science panels' data needs because VLSI will be required for on-board data compression and processing, as well as on the ground for parallel processing of the multispectral, spatial, temporal data acquired with the sensor. Increasingly complex VLSI circuits will be required to meet these future requirements with CAD becoming an essential design tool.

An important step in anticipation of spaceborne sensors is NASA's on-going aircraft remote sensing program and the aircraft instrument work now underway at GSFC and JPL. This work is an appropriate starting point for what should be viewed as complementary developments. Several aircraft instruments currently under development for research and technology validation in remote sensing were reviewed including the Linear Array Pushbroom Radiometer

(LAPR-II), Linear Array Pushbroom Radiometer-Short Wave Infrared (LAPR-SWIR), Airborne Imaging Spectrometer (AIS), Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and Thermal Infrared Imaging Spectrometer (TIMS). It was thought that emphasis needs to be placed on flexibility in meeting the requirements of many applications and disciplines with reliability and cost being key considerations. In addition, careful assessment should be made of the data quality achievable with such factors as sampling, modulation transfer function (MTF), spectral response uniformity, polarization, etc., taken into consideration.

Critical Issues

The results from the Terrestrial Science panels clearly indicate the need for a new generation of aircraft sensors which can provide well-calibrated, narrow-band spectral data from the visible through thermal infrared spectrum. Furthermore, because of the diverse nature of the spectral requirements expressed by the discipline panels, an airborne instrument with either programmable or selectable spectral bands and bandwidths is desirable rather than the fixed filter type airborne scanners and simulators which exist today. An advanced aircraft instrument and a concerted program of data acquisition are needed to develop measurement techniques. In addition, the data base is needed to investigate the utility of high spectral and spatial resolutions. Furthermore, a need for an airborne instrument which provides variable spatial resolution in multiples of the smallest Instantaneous Field of View (IFOV) for parametric tradeoff studies of the effects of spatial resolution on science classification, adjacency effects, cartographic, lithologic and land use research was also expressed.

While the imaging spectrometer approach utilizing area arrays appears to have greater potential in satisfying the diverse research requirements because of its spectral progammability, further work should be conducted on the use of more spectrally versatile MLA systems. Several conceptual designs for programmable spectral filters for linear arrays systems have been identifed and developed by the MLA study contractors during the MLA Shuttle instrument studies. Both approaches have advantages and disadvantages and it is not clear, at present, which is the better. In fact, it may turn out that one is more suitable as an aircraft research instrument and the other as a space system.

To provide a rationale for future space borne sensors, spectral signature studies need to be vigorously pursued using instrumentation that can be easily tuned spectrally; at present, the most promising approach seems to be an aircraft-mounted, imaging spectrometer. The result of this research should be the identification of several sets of system spectral responses, probably with some responses common to more than one set, that would be optimum for several applications. We then need to answer the question: Is a versatile MLA focal plane spectral design capable of providing a small number of spectral response sets a more cost effective and reliable solution than the imaging spectrometer approach, which can provide a larger number of response sets by electronic spectral tuning?

The presentations given at this workshop suggest that a substantial technology base already exists in detector arrays, optics, data processing, and instrument design. Other countries, for example, have exploited the availability and relative maturity of this technology and are currently developing Shuttle and satellite remote sensing instruments. What is needed now, in our case, is a set of definitive and bounded mission scenarios to focus the existing enabling technology and on-going developments. Several top level candidate research mission scenarios have been generated during the past year by GSFC and JPL. These scenarios have been the basis for the MLA instrument and imaging spectrometer designs. Additional work needs to be done to iterate the instrument designs and configurations after better defined mission scenarios and science requirements are developed.

BOTANY

Botanical sciences have made significant advances in the past decade in the use of remotely sensed data. This working group embarked on a course to determine the next step in the development of remote sensors for vegetation mapping and monitoring.

Current State of Knowledge

The optical properties of leaves dominate the spectral response of living plants when the remote sensing data is taken using nadir or near nadir look angles. When not obscured by plant canopy, culms, leaf sheaths, heads of grasses, twigs, and limbs and trunks of trees also contribute to spectral response. In the visible region of the spectrum (0.40 to 0.75 μm) chlorophylls and other pigments absorb incident light and reflectance is low. The near infrared (0.75 to 1.35 μm) is characterized by high reflectance and transmittance and low absorptance as a result of leaf mesophyll structure. The dominance of the optical properties of water in plant tissues and a partial influence of leaf structure manifests itself as strong water absorption bands at 1.45 and 1.95 μm, Figure 1. Wavelength regions between 2.5 and 8.0 μm have not been thoroughly investigated because until now, technology has not allowed acceptable signal to noise (S/N) ratios and the mix of reflected and emitted energy in the signals makes interpretation difficult. Broadband thermal emission of plants has been investigated in the 8 to 14 μm wavelength region, but multiple wavelength thermal bands have not been evaluated.

In the absence of total canopy closure, the background -either soil or water- must be measured in wavelengths where there is ample contrast between vegetation and background. Soil is less reflective than green vegetation at approximately 0.72-1.1 μm and more reflective at approximately 0.35-.7 and 1.4-2.3 μm. The resulting contrast is valuable for distinguishing plants from soil and for assessing leaf density. Reflectance from water covers in the visible and near infrared varies according to the amounts of suspended sediment.

Desired Capabilities

Thermal emission wavelengths have not been used extensively in conjunction with shorter wavelengths for classification. Energy balance processes must be considered in the development of an understanding of canopy thermal response. For instance, water availablity to plants for transpir-

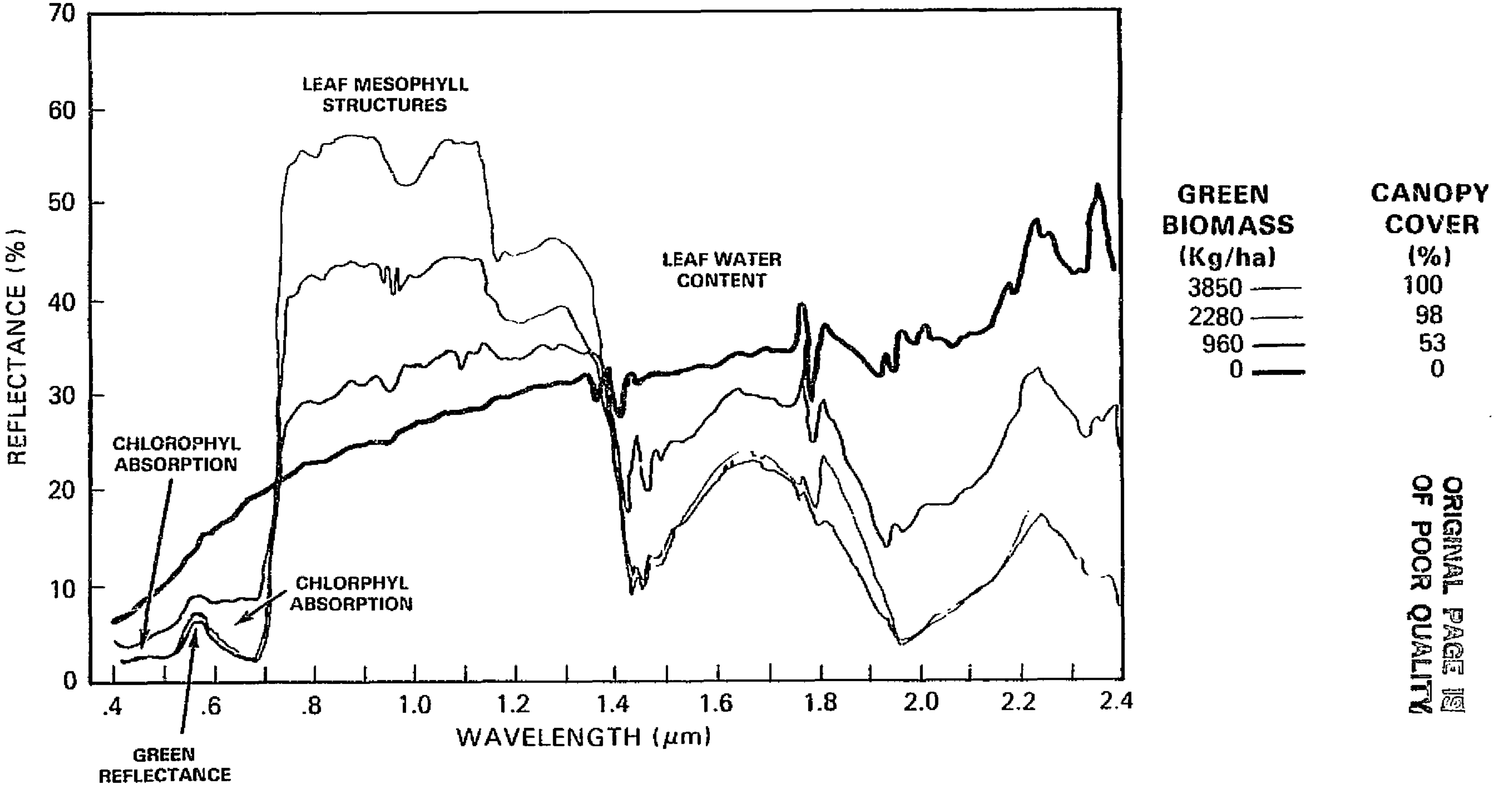


FIGURE 1. SPECTRAL SIGNATURES FROM PLANT CANOPIES SPECTRAL REFLECTANCE FOR ALFALFA CANOPY DENSITIES

ation, instantaneous isolation, near-canopy water vapor pressure of the air and atmospheric attenuation must be understood. A measurement capability in a minimum of two bands in the 8 to 14 μm interval and models using simultaneous solutions of equations defining responses would improve confidence in radiometric temperatures and their correspondence to thermometric temperature and would aid in determining the utility of thermal measurements.

Spectral measurements of the complete Bidirectional Reflectance Distribution Function (BRDF) of vegetation and soil should be undertaken. No analytic development for the prediction of scene radiance is possible without knowledge of the BRDF since the BRDF is a function of physical and biological scene attributes and represents the lower boundary condition of any atmospheric radiative transfer problem. Limited spectral measurements of individual components of the BRDF have been obtained in the field. In many cases, the field of view has been very wide and few measurements have been taken with off-angle viewing geometries. In addition, BRDF determinations must be obtained for important renewable resource scene elements such as soil and vegetation.

Several research problems were defined by the Botanical Science Working Group. They were:

1. Definition of what constitutes a scene element class must occur. In an element class such as "wheat", growth stage, phenology, condition and planting practice must be considered.

2. Statistically sound experimental designs must be formulated relative to spatial and temporal sampling.

3. Appropriate field measurement techniques must be developod.

4. Analysis techniques must be developed which allow extraction of the BRDF from under the scene radiance measurement integral.

In addition to the characterization of the BRDF, several other critical areas of spectral measurement have been identified. For example, the polarization properties of various scene element classes need to be measured.

Spectral measurements in narrow wavelength bands (1 to 2 nm) need to be made in the 0.35 to 2.5 μm wavelength region. The existence of spectral "fine structure" in vegetation may be determined by collecting laboratory leaf spectra and by using it in conjunction with multidimensional plant canopy radiation models. Additional measurements in the 1.1-2.5 μm region are critical in order to assess their utility for vegetation mapping and monitoring.

Concurrent with laboratory and field spectral measurements, target biophysical variables should be measured in the field. The biophysical variables include plant geometry as well as traditional variables such as growth stage, green leaf biomass, soil type, etc. These variables are crucial for the successful modelling of the electromagnetic behavior of vegetation. Additionally, requirements exist to define the magnitude of the influence of temporal and spatial variations of environmental control parameters on the temperature and spectral signature of plant canopies. Experiments performed under varied but realistic conditions over several diurnal cycles in varying climatic regimes are essential to an overall understanding of real world phenomena.

A major constraint in developing the desired measurement capabilities necessary for the next step in the identification and measurement of plants may be caused by the effect of atmospheric composition upon reflected and emitted electromagnetic radiation. An overriding measurement requirement is the determination of the variability of causative parameters affecting radiative transfer. A fruitful avenue for research could be to determine the relationship that exists between available meteorological data and atmospheric optical properties. There is also a need to obtain the variation in scene radiance over significant atmospheric paths arising from limited geographical areas, the so-called "adjacency effect."

In addition to spectral characterization of plant canopies, the spatial resolution required to characterize the size distributions of vegetation communities must be made. Current data show that 10-30 m spatial resolution data are required to reduce boundary effects, a major source of misclassification of agricultural crops. This resolution is driven below 10 m in areas of the globe where fields are small and agriculture is not mechanized. At the other extreme, resolution of 500 m to 5 km could be desired for repetitive monitoring of the global surface vegetation.

Remote sensing studies have established that a measurement frequency of 4-6 days is needed to adequately monitor the occurrence of vegetation related episodic events such as plant stress and flowering/reproductive periods. Assuming a 50 percent cloud cover probability, this translates into a 2-3 day revisit cycle. Geobotanical studies have established a 2-3 day requirement to monitor the onset of plant senescence. Differences in the onset of plant senescence is critical to the identification of metal-stressed plants. In areas of persistent cloud cover a revisit period of 1 day may be required in order to obtain an occasional cloud free image.

Based on ground-collected spectral data and a "noise free" simulation approach, 7 to 8 bit radiometric resolution is required to maintain spectral relationships. Unfortunately, radiometric resolution quantifies not only the spectral relationships of the target radiances but also the "noise" caused by the atmosphere and a sensing system. Failure to understand atmospheric interactions or to control instrument variability will limit the utility of increased radiometric resolution.

GEOGRAPHY

The field of Geography can be characterized by its broad interest in the identification, mapping, and understanding of the spatial distribution, use and interrelationship of phenomena on Earth. While these interests may lead to overlap with other disciplines, geography's concern with the spatial distribution of phenomena and the need to produce general purpose maps present problems unique to this discipline: those of topography and cultural or man-made surface cover. Topography includes the detection of landform and drainage elements, contour mapping and digital terrain analysis. Cultural features include the detection of man-made structures and changes to other surface cover classes caused by man's activities. The areas of concentration of this working group were focused on topics of concern to geographers in which Remote Sensing has played a traditional and increasing role - Land Use/Land Cover, Geomorphology and Cartography.

Current State of Knowledge

Land Use/Land Cover concerns itself with the spatial and spectral resolution requirements for photo interpretation and/or multispectral pattern recognition of cultural surface cover. Of particular interest are the recognition of man-made structures in urban and urban fringe regions. Other topics of interest include the delineation of and detection of changes in the landscape created by man's activities, such as strip mines, roads, railroads, and utility rights of way.

The Multispectral Scanner (MSS) and Thematic Mapper (TM) will provide Level I and Level II Land Cover information but Remote Sensing inputs to Level III information are currently derived from high resolution photographs. Table 1 lists pertinent Land Use Levels. Spectral inputs into Level III information extraction are currently unused in urban/surburban and critical or sensitive area analyses. Some trend analyses use MSS and high resolution areal photographic data. Geographic Information Systems that combine remote sensing data, terrain data and ancillary data are under development.

Geomorphological studies have made use of spatial and spectral information by photo interpretation and/or multi-spectral pattern recognition of geomorphic elements. Of particular interest are glacial and pariglacial landforms, eolian and coastal landforms, and karst topography. Drainage elements of particular interest include perennial and intermittent stream beds, flood plains, and alluvial fans. Man-made landform and drainage elements are also of concern.

Traditional forms of remote sensing have been extensively used as data sources for geomorphic analysis. Satellite data such as MSS has proven useful for delination of physiographic regions and TM will improve this

TABLE I

LAND USE AND LAND COVER CLASSES FROM
REMOTE SENSOR DATA: LEVELS I, II, III
FOR URBAN CLASSES

1 Urban or Built-up Land	
11 Residential	111 - 1 or less units/hectare 112 - 2 to 8 units/hectare 113 - 9 or more units/hectare
12 Commercial and Services	121 - retail and wholesale 122 - commercial outdoor recreation 123 - educational 124 - hospital, rehabilitation or other public 125 - military 126 - other public 127 - research centers
13 Industrial	131 - heavy industrial 132 - light industrial
14 Transportation, Communications, and Utilities	141 - highway 142 - railway 143 - airport 144 - port facility 145 - power line 146 - sewage
15 Industrial and Commercial Complexes	
16 Mixed Urban or Built-up Land	
17 Other Urban or Built-up Land	171 - extensive recreation 172 - cemetery 173 - parts 174 - open space/urban

Source: Anderson, et al., USGS Professional Paper 964, 1976.

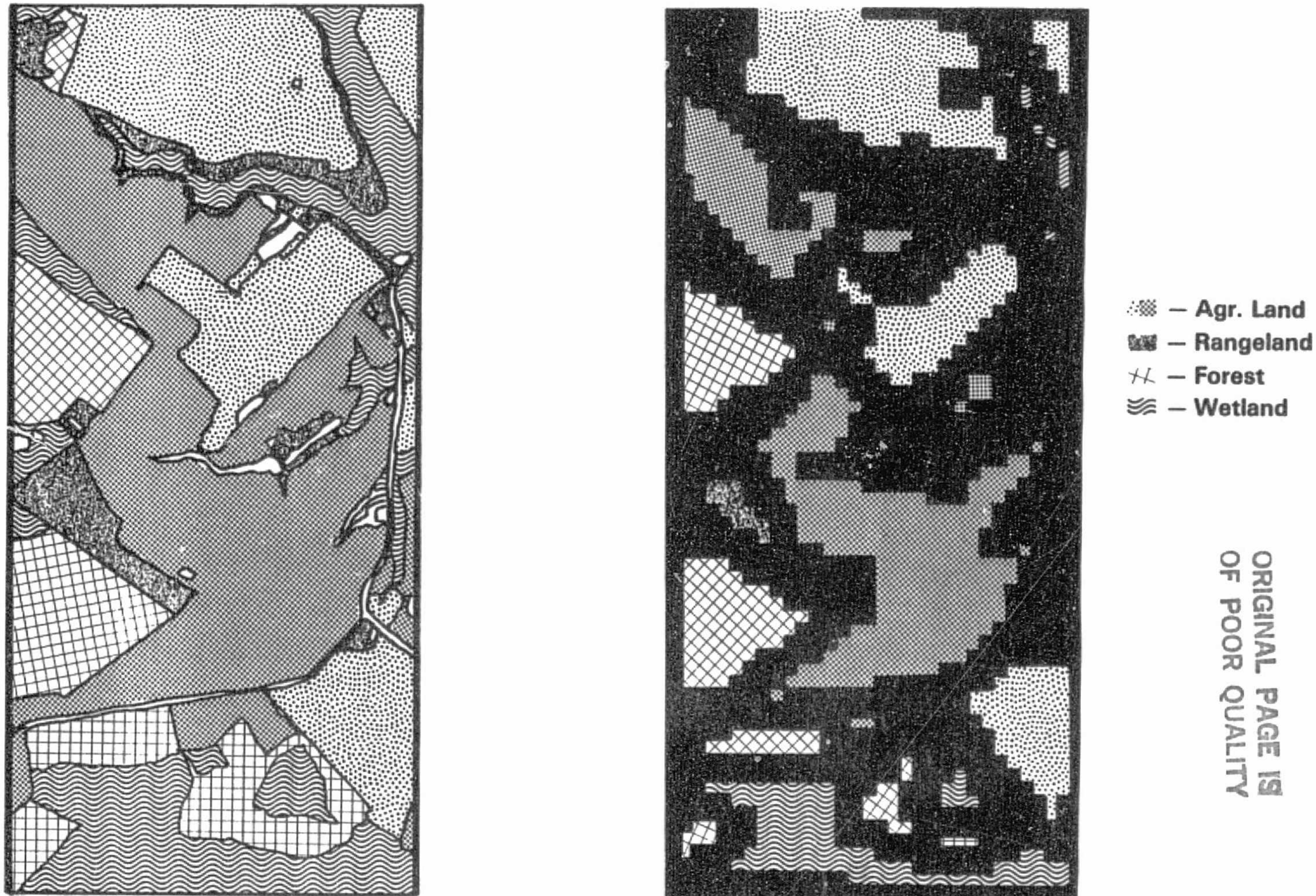
capability. High resolution aerial photography has to date provided the quantitative remote sensing data for erosional and depositional processes analysis.

The potential for precise cartographic map production from airborne and spaceborne sensors has been a major concern to geographic science. Approximately half the world is not topographically mapped at scales of 1:100,000 or larger. The MSS can provide horizontal planimetry at the scale 1:250,000 (the TM has not been tested). Five meter resolution film data from Skylab provided 1:50,000 horizontal planimetry. Topographic information is currently acquired from ground surveys and/or high resolution stereo data. Cartographic products at scales of 1:25,000 to 1:250,000 throughout the world are needed to meet requirements associated with the survey and management of natural resources, environmental planning, and the establishment of geo-referenced data bases. Data compiled by the United Nations in 1976 indicates that the demands for topographic mapping at medium to large scale cannot be met in the near future by conventional mapping techniques.

Desired Capabilities

A significant lack of fundamental research exists regarding an understanding of the interaction between spectral and spatial resolution and the consistent recognition and display of topography and surface cover. Building on work in these areas by the botanical and geological communities, a few experiments could rapidly identify promising regions of the visible and infrared spectrum and the concomitant spatial resolutions required to achieve desired levels of discrimination and identification. Figure 3 graphically illustrates the effect of resolution on the area of an image affected by boundary pixels as resolution is varied.

Basic field and laboratory spectrometer data need to be taken of man-made and mixed surface covers to develop mixing models and to ultimately understand the complex interaction of diverse cover types. Extrapolations to real situations need to be made with measurements under actual conditions that demonstrate regional, seasonal and diurnal variability. Narrow wavebands throughout the visible and infrared spectrum (0.3 to 12.4 μm) are needed to determine the existence of fine spectral structure (less than 20 nm).



All Pixels

40 Meter Boundary Pixels Removed

FIGURE 2. LAND COVER DATA, FARM AREA

Few studies have been undertaken on the spatial variability of cover types and the resolutions at which spatial features are identifiable. Furthermore, the interaction effects of spatial resolution and spectral signature mixing need to be investigated. Seasonal data acquisitions within climatic regions are also desired to assess the separability of cover types based on phenology. Finally, classification techniques that maximize the utility of high spatial resolution data must be developed if emphasis is to be placed on automated digital analysis.

Critical to all geographic requirements, but of particular concern to cartographers, is accurate registration and rectification of imagery. A satellite system involving the use of MLA sensors to meet cartographic requirements in terms of completeness of detail and geometric accuracy offers great promise for rapidly providing the data used to produce topographic maps, digital terrain information, thematic maps and image maps. In addition to map making, the growth of geo-based information systems requires ancillary data and image data to fit a common map base.

GEOLOGY

The geological community possesses substantial sophistication in the analysis and interpretation of multispectral imagery. Geologists routinely use Landsat Multispectral Scanner imagery for geological mapping in many different parts of the world. Furthermore, geologists have spearheaded efforts to improve the multispectral measurement capabilities of orbital sensors. The geological community actively campaigned for the inclusion of the 2.2 micrometer band on the Landsat 4 Thematic Mapper. It also conducted the research that led to the development of the Shuttle Multispectral Infrared Radiometer (SMIRR) experiment on the second test flight of the Space Shuttle, (see Figure 3). Most recently, geologists have explored the utility of conducting multispectral surveys at thermal infrared wavelengths to map variations in the emissivity properties of surficial materials.

Current State of Knowledge

The use of multispectral surveys to detect areal variations in the physical and chemical chracteristics of geological materials is generally

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Shuttle Multispectral Infrared Radiometer Data

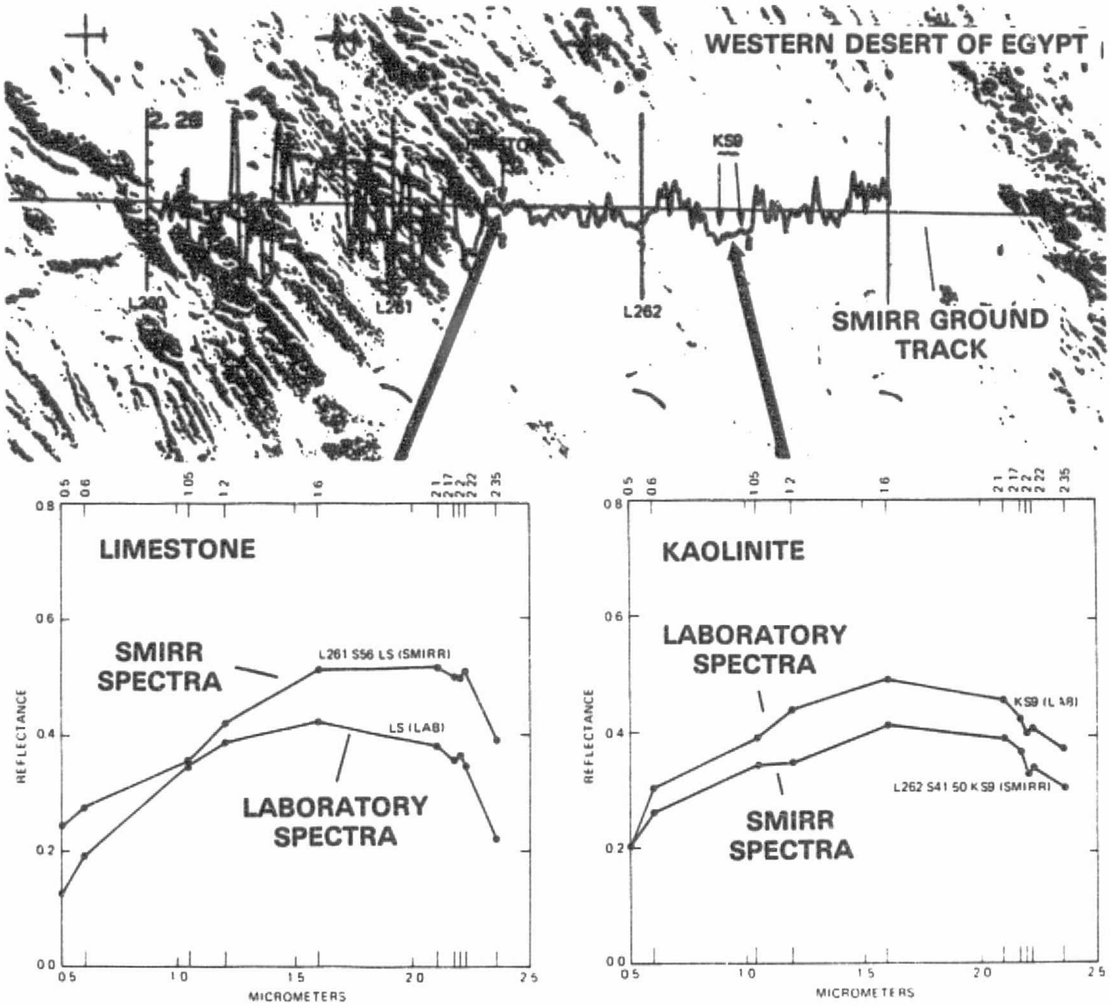

FIGURE 3. TYPICAL NARROW BAND MULTISPECTRAL MEASUREMENTS OBTAINED BY THE SMRR DURING THE SECOND TEST FLIGHT OF THE SPACE SHUTTLE

referred to as lithologic mapping. Our current ability to derive lithologic information from multispectral surveys is based largely upon previous studies of the reflectance and emissivity properties of common rocks and minerals. Laboratory measurement programs have been complemented by field investigations which employ portable, ground-based instruments and airborne scanners to survey the spectral properties of natural surfaces over progressively larger areas. The wider diversity of surficial materials encountered in field measurements tends to reduce the spectral contrast (i.e., intensity) of absorption and emissivity features associated with individual minerals. Field studies have provided insight into how the spectral "signatures" of different surficial materials are merged in orbtal multispectral surveys. Specific lithologic features that can currently be discriminated in orbital multispectral measurements include:

> Iron oxides - a group of minerals such as hematite (Fe_2O_2) and geothite ($FeO(OH)$) that typically develop through the chemical weathering of magnetite and other iron-bearing minerals. Iron oxides possess distinctive absorption features at wavelengths of 0.5-1.0 micrometers.

> Calcite ($CaCO_3$) - a common constituent of sedimentary rocks that possesses distinctive absorption features at wavelengths of 2.0-2.5 micrometers.

> Clay minerals - a wide range of mineral species including kaolinite ($Al_4Si_4O_{10}$ $(OH)_8$, alunite (KAl_3 $(SO_4)_2$ $(OH)_6$), and montmorillonite ($Al_2Si_4)_{10}$ $(OH)_2$ x n H_2O) which possess distinctive absorption features at wavelengths of 2.0-2.5 micrometers.

> Quartz (SiO_2) - a common constituent of many rocks and soils that displays distinctive emissivity properties at wavelengths of 8-12 micrometers.

Geobotanical Stress - variations in the reflectance properties of deciduous and conifer trees have been empirically correlated with enhanced concentrations of metallic elements in host soils. The phenomenological basis for this observed correlation is not well understood.

Desired Capabilities

Past use of multispectral imaging techniques for lithologic mapping has been limited largely to detecting boundaries between different soil and rock units exposed at the earth's surface. Identification of the lithologic features that are responsible for remotely sensed boundaries has generally been accomplished through comparisons with pre-existing geological maps, or field mapping studies that are specifically designed to verify image interpretations. Direct lithologic identification of surficial materials has been hindered by the size and number of measurement channels on existing multispectral scanners. Mineral species generally possess diagnostic absorption and emissivity features that extend over wavelength intervals of 5-50 nanometers, whereas the spectral bandpasses of existing scanners are typically 80 nanometers or greater. Furthermore, existing sensors generally obtain measurements in limited subsections of the 0.5-14 micrometer region. They are not designed to fully exploit the various sources of lithologic information that potentially reside in different spectral regions. The relatively large size and limited number of bands on existing orbital sensors results in ambiguous interpretations of multispectral variations.

The Geology Panel of the Working Group reached a general consensus on the desired measurement of capabilities of future orbital instruments. A high premium was placed upon improving the spectral resolution of future sensors to achieve a measurement capability of 50 nanometers or better within the visible and infrared portions of the spectrum. Spectral bandpasses of 10-20 nanometers would ultimately be desirable, but a 50 nanometer capability would represent a significant advance over the current generation of orbital sensors. Desired spectral resolution in the thermal infrared would be approximately 500 nanometers. Improvements in the spatial resolution of orbital sensors for purposes of lithologic mapping were judged to be of secondary importance. An instantaneous field of view in the range of 30-15 meters was considered desirable. Discussions of radiometric accuracy indicated that absolute sensor calibration would be desirable in the thermal infrared protion of the spectrum, whereas relative calibration would be sufficient at visible and reflected infrared wavelengths.

Critical Issues

Geologists ultimately hope to recognize and uniquely identify mineral species on the basis of their multispectral properties. Natural surfaces are typically composed of a variety of mineral species, their in situ weathering products, and diverse types of vegetation. One of the major challenges of the future is to develop methods that will enable image analysts to separate the assemblage of spectral signatures that are present in a single picture element (pixel). Future field and airborne studies should be designed to evaluate the relative utility of improved spectral and spatial resolution, and improved radiometric sensitivity for spectral deconvolution. In addition, improved theoretical models are needed that describe how the signatures of different materials are spatially averaged over pixel-sized areas.

Temporal and spatial variations in atmospheric properties and solar illumination conditions introduce variations in orbital measurements of surface radiance that confuse the interpretation of multispectral image data. Unfortunately, the effect of these confusing factors is likely to increase with future improvements in sensor resolution and sensitivity. Orbital meteorological data could, in principle, be used to correct image data on a pixel-by-pixel basis for the effects of atmospheric absorption and scattering. A series of controlled orbital experiments is required which would obtain simultaneous meteorological and multispectral data to evaluate the influence of atmospheric effects upon orbital surveys. Similarly, digital topographic data could be used to estimate sensor viewing angles and solar zenith angles within a scene on a pixel-by-pixel basis. These latter parameters could be readily incorporated in existing procedures for pixel classification and image enhancement, and they could potentially lead to improvements in lithologic identification. It is imperative that we develop new methods of data analysis and interpretation that can account for atmospheric and topographic effects, in order to fully exploit future multispectral measurement capabilities for lithologic mapping.

HYDROLOGY

Hydrology is oriented toward the solution of well-defined problems that have a direct impact on man's use of land. The Hydrological Science Working Group touched on all areas of the other Terrestrial Science Working Groups; Botany, Geography, and Geology.

Current State of Knowledge

Most of the tools used to provide information for hydrologic decision making do not give proper consideration to the temporal and spatial characteristics of important parameters controlling the processes. Indeed, many of the techniques currently used were deliberately simplified in their original development because of the absence of the type of spatial and temporal information that modern remote sensing technology is capable of providing. The use of current capabilities in multispectral imaging has provided improvements in our understanding of the hydrologic sciences that have led to development of improved techniques in the areas of snow and ice monitoring, the simulation of rainfall/runoff relations, basin characterization, surface water inventories and water quality monitoring. However, needed improvements in these techniques require a major commitment in multispectral imaging research to resolve some critical gaps in our scientific understanding before the hydrologic community will be in a position to make significant improvements in these techniques. Major scientific problems concerning the bridge between hydrologic process behavior and the information content provided by sensor resolution, wavelength, band-width, frequency of coverage, timing of data availability, and format of data delivery must be solved.

Desired Capabilities

Because of the diverse nature of hydrologic problems, 16 areas of further research were defined. Although not in priority order, they provide insight into the problems that exist in current models and point to areas in which developing remote sensing technology could fill significant gaps in the knowledge of hydrologic processes. The 16 research areas are:

- Definition of spatially distributed evapotranspiration rates for large areas;
- Flooding dynamics of wetlands;
- Definition of the temporal/spatial distribution of soil moisture dynamics over large areas;
- Determination of snow water equivalent;
- Definition of runoff and sediment yield from ungauged watersheds;
- Determination of spatial/temporal distribution of storm rainfall;
- Relationship between remotely measured surface roughness and hydraulic roughness of land surface and stream networks;
- Definition of hydrologic properties of soils and surficial materials;
- Interpretation of active/passive measurements of fluorescence and polarization of water and its contained substances;
- Determination and modeling of three-dimensional characteristics of water bodies;
- Interpretation of spectral emissivity of land and water surfaces;
- Determination of the relationship between texture of terrain surfaces and hydrologic response of watersheds;

- Discrimination between sediment and chlorophyll in water;
- Improving the determination of hydrologic land cover as related to the modeling of runoff processes;
- Improving irrigation management strategies; and
- The role of barrier island dynamics in coastal zone processes.

Several common threads concerning spatial, spectral and radiometric resolution, temporal frequency, etc., have become apparent. Concerning spatial resolution, many hydrologic phenomena are small scale, requiring spatial resolution below 10 meters; examples are texture versus hydrologic response and flooding dynamics of wetlands. Exceptions to this statement are large scale phenomena; the spatial and temporal distribution of rainfall is a critical research area requiring spatial resolution on the order of 100 meters.

From the standpoint of spectral band requirements, the diversity of hydrologic phenomena makes generalization difficult, as the entire spectrum from .4-14 μm is of interest. However, on the issue of spectral band width, discussion has indicated a desire for .2 μm bands throughout the .4 to 14μm range. Calibration should be relative throughout the mid-ir and absolute in the thermal from 4.5 to 14μm. Microwave measurements were judged to be necessary for a complete understanding of hydrologic phenomena.

Hydrologic phenomena are dynamic in nature with the frequency of occurrence varying from short lived events such as rainfall distribution to long duration phenomena like stream networks persistence. In many instances the temporal frequency of these events is not well understood and time series analysis of remotely sensed data is required.

In conclusion, the requirements that have been discussed are based on the best assessment of desired capabilities by the hydrology team. They are first approximation of capabilities whose utility should be verified from aircraft or space borne experimental sensors, and by no means should be construed as operational requirements.

INFORMATION SCIENCE

This panel confined its deliberations to consideration of meeting the information requirements suggested by the Discipline Panels: Botany, Geography, Geology and Hydrology and thus placed the findings of those panels in perspective. Consideration of Information Science couched in the interests of the discipline sciences was placed in parallel with mission design, thereby focusing on critical developments confronting Remote Sensing over the next decade. Information Extraction Science, as discussed includes data handling, concentrated on the following topics:

- Help identify the bounds of practical missions;
- Identify potential data handling and analysis scenarios;
- Identify the required enabling technology; and
- Identify the requirements for a design data base to be used by the disciplines in determining potential parameters for future missions.

Specific analysis approaches are a function of the discipline involved, and therefore no attempt was made to define any specific data analysis developments that may be required. In addition, it was recognized that a number of generic data handling requirements exist whose solutions cannot be typically supported by any single discipline. The areas of concern were therefore defined as:

- Data handling aspects of system design;
- Enabling technology for data handling, with specific attention to rectification and registration; and
- Enabling technology for analysis.

Within each of these areas, the following topics were addressed:

- State-of-the-art (current status and contributing factors);

- Critical issues; and

- Recommendations for future research and/or development.

It is instructive to examine two areas of concern, data handling and analysis. For brevity this summary focuses on the current state-of-the-art and critical issues to be faced in the near future, and outline some future research recommendations, a number of which are tentively identified.

Data Handling

The technology of data handling is dominated by commercial interests with large volume production. The established trends are:

- Computer memory costs are decreasing rapidly;

- Processing capabilities are increasing; microprocessors are becoming practical for small scale remote sensing data analysis; and

- Magnetic tapes are the present storage medium. For some purposes, digital video disks will be practical.

Finally, special purpose Very Large Scale Integrated circuits are only beginning to become available, but there is no commercial development interest in these for Remote Sensing because of low volume. The NASA Office of Space Science and Applications is not currently supporting this activity, but indications are that for on-board processing VSLI is a research area with potential large scale benefits.

The potentially wide variety of research scenarios places differing demands on both the sensors and analysis capabilities; it is evident that the designs of research systems must satisfy the scenarios. Although there are many operational type considerations in the design of reserch systems, it is likely that research systems will bear little resemblance to operational systems and the distinction between the two must be maintained.

Data being gathered for scientific research may allow research heretofore not practical or possible. As some of these developments will be slow in maturing, some continuity of data may be important. In turn, larger quantities of data will exacerbate problems in acquisition, archival and dissemination (by the system) and in registration and analysis (by the user). Because of larger data volumes, tradeoffs between better data quality transmitted to the ground and that provided by ground processing must be evaluated. In a related scenario, tradeoffs could be made concerning direct data broadcast to the users or the archiving of unprocessed data. Finally, increasing demands for higher spatial resolution and more spectral bands will multiply data handling problems. Large scale and Very Large Scale Integrated (VLSI) circuits must be developed to provide the data manipulation capability which will make possible the on board processing, improved ground data handling, and increased complexity of data analysis.

Analysis

Multispectral analysis methodologies are now mature for low-to-moderate dimensionality analysis (e.g., supervised and unsupervised pixel by pixel classification). The methodology for spatial analysis is now maturing for the extraction of micro spatial structure (texture, edges). However, characterizing higher order spatial structures is still at a primitive state. Furthermore multi-temporal analysis is ad hoc in its methodology with rapid maturation of phenologic stage analysis in agriculture the most advanced. Several critical issues have been identified which will pace the future development of multispectral information extraction techniques. First, the atmosphere is recognized as having an effect on the data which will be more critical as the more sophisticated analyses are performed in the future.

This must specifically be addressed in the sensing and the associated data handling. Second, a recurring problem is that all disciplines are faced with the mixed material pixel problem. Neither the general nor the specific effects of smaller pixels or the additional spectral bands is yet known. The related problem of registration affects all disciplines. This will be exacerbated with the smaller pixels of the future. Finally, and most importantly, disciplines are anticipating the availability of off-nadir data. This will increase atmospheric and registration problems and further research is needed to determine the extent of the effects and the possibilities of overcoming them.

RECOMMENDATIONS FOR INVESTIGATION

The following broadly-stated recommendations are developed in the body of the report. Specific experiment definition must await the outcome of experiment definitions by the discipline teams.

Analysis

- Conduct experiments with parameters exceeding expected mission parameters to determine sensitivities to lack of meeting them in an operational system and to determine any potential interactions.

- Determine the need for and utility of absolute radiometric calibration. What accuracy of calibration is useful?

- Study complete system characterization from the discipline point of view to determine practical limits on requirements and to provide a model for evaluating parameter variations.

- Promote cross-discipline fertilization in model development and usage.

- Promote research in the conversion of analysis concepts to software.

Enabling Technology

- Provide end-to-end system analysis to the disciplines to facilitate development of their loss-in-utility functions and thus allow better overall system design.

- Determine from the disciplines the ancillary data that is required for them to accomplish their analysis, the desired form for that data, and then provide the necessary data.

- Investigate the effects and utility of on board processing in relation to problem analysis.

- Investigate alternate computer and system designs and the use of VLSI as they affect the data analyst.

- Determine the requirements for comprehensive data sets and begin collecting the required data.

- Push the development of a comprehensive geographic information system to facilitate the use of multitype, various scale data.

- Promote the development of modular hardware and software systems to allow wider technology interchange and minimize duplicated efforts.

- Develop data analysis/networking systems that allow distributed or non-local processing and foster science cross-pollination.

IMAGING SCIENCE PANEL

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

JOINT MEETING WITH

INFORMATION SCIENCE PANEL

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MULTISPECTRAL IMAGING SCIENCE WORKING GROUP
JOINT MEETING WITH
INFORMATION SCIENCE PANEL

INTRODUCTION

Satellite remote sensing has proven to be an extremely valuable tool for monitoring and investigating the Earth's ocean and land resources on a global scale. The development of the next generation of remote sensing systems, starting with the evolutionary Landsat-D system and followed by systems developed around entirely new sensor concepts and technologies, will further increase the quantity and quality of satellite acquired remote sensing data. In particular, recent advances in solid-state detector array and sensor technology will make possible substantially better spectral and spatial resolution. Data acquired from laboratory and field spectrometers, aircraft spectrometer, and the recent Shuttle Multispectral Infrared Radiometer (SMIRR) experiment have demonstrated the utility of high resolution spectra for disciplines such as geology, agriculture, botany, and hydrology. Additionally, aircraft data from aircraft instruments such as the Thematic Mapper Simulator (TMS) have demonstrated the enhanced classification accuracies and lithological mapping obtainable with spatial resolutions in the 20 meter range. Finally, laboratory, field, and aircraft studies have shown that the short wave infrared (1–2.5 μm) and thermal infrared (8–14 μm) regions possess interesting diagnostic spectral features which can be used for identification of specific classes of rock types and minerals.

While a significant data base is beginning to emerge from these laboratory, field, and aircraft measurements, the designs of spaceborne solid-state sensors to exploit this capability from space are still in their early stages of definition. The Multispectral Imaging Science Workshop was organized to provide a forum for the discussion of the current state-of-the-art of sensor technology, identify critical issues and provide long range guidance for NASA's research and technology development efforts in this rapidly evolving area.

The Multispectral Imaging Science and Information Science Workshop was held May 10, 11, 12, 1982. The first half of the first day consisted of formal presentations given by the panel chairman of the four science discipline groups. Each of the four respective chairmen summarized the results of their discipline workshop including the current state of knowledge with respect to high resolution spectral and spatial measurements, results from laboratory and field studies, critical gaps in the understanding of the basic mechanisms associated with the interaction of the incoming radiation with the Earth's surface cover, desired spatial and spectral requirements from both aircraft and future spaceborne sensors, and recommended experiments and research to test and validate the utility anticipated from future enhanced capability spaceborne remote sensing systems.

After the discipline panel Chairman's presentation, the remainder of the first day and one half of the second day was devoted to presentations on the current state-of-the-art of solid state sensor technology by individuals from the NASA centers, other agencies, universities and industry. Papers were presented on solid state sensor design concepts, IR detector array and focal plane development status, supporting NASA technology efforts, calibration techniques, NASA aircraft programs and on-board data processing/compression approaches and issues.

The various discipline teams had provided an overview of their objectives and requirements to the Imaging Science and Information Extraction groups, and these groups were tasked to address how the science could be accomplished in terms of current technology and-or the future thrust and trends of sensor systems, detectors, and information handling techniques. This report is a summary of the state-of-the-art and recommendations developed during the workshop and is based upon the presentations, discussions with panel members, and the written material prepared by the panel members. Further details on all the topics can be found in the comprehensive set of submitted papers contained in the appendix.

FOREIGN EARTH OBSERVATION PROGRAMS

There are significant activities outside the United States of America in developing earth observation capabilities using solid state pushbroom sensor technology. The U.S.S.R. launched a "METEOR" spacecraft in June of 1980 into a nominal 600 Km altitude orbits carrying 5 earth observation sensors. One sensor incorporated 3 solid state VIS/NIR bands with an Instantaneous Field of View (IFOV) of 30 m with 30 km swath width. The other electro-mechanical sensors had a large number of visible/near infrared (Vis/Nir) and infrared bands with IFOV's of 80,, 170, 240 and 1,000 m and swath widths of 85, 600, 1,400 and 2,000 Km.

The German Ministry of Research and Technology is developing a Modular Optoelectronic Multispectral Scanner (MOMS). It is scheduled to fly on the Shuttle Pallet Satellite (SPAS-01) in March of 1983. This two band, Vis/Nir sensor has an IFOV of 20 m and a swath width of 140 Km from Shuttle altitude of 276 Km. This sensor has 6192 pixels per line and uses 2 lens per spectral band. The system has provisions for on-board correction of gain and offset and can store 30 minutes of data on the recorder.

The French are developing the SPOT Satellite to be launched in 1984 with an 832 Km altitude orbit, 98.7° inclination sun synchronous orbit with a 10:30 AM equator crossing time. Two High Resolution Visible (HRV) imaging sensors will fly on each spacecraft. Each have a 60 Km swath width and can be pointed off nadir $\pm$ 525 Km. Each HRV has two modes of operation; the multispectral mode provides 3 VIS/NIR bands at 20 m IFOV with 3,000 pixels/line and the panchromatic mode provide one broad spectral band at 10 m IFOV with 6,000 pixels/line. Commercial sales of products are planned with film products at a scale of 1:400,000 and digital products with radiometric calibration, geometric and terrain relief compensation applied. Two spacecraft are under development and a life of 2 to 3 years is planned for each.

The Japanese are developing the Marine Observation Satllite (MOS-1) for land and ocean observation which is scheduled to fly in 1985. In addition to the ocean sensors the spacecraft will carry a Multispectral Electronic Self

Scanning Radiometer (MESSR) having 4 spectral bands in the VIS/NIR with an IFOV of 50 m and a swath width of 200 Km when all sensor heads are used. The orbit planned is 909 Km altitude, 99.1^{o} inclination, sun synchronous with an equator crossing time between 10 and 11 a.m.

SPECTRORADIOMETRIC CALIBRATION

For the purposes of this discussion, the community of remote sensing data users can be divided into two groups:

1. Users requiring relative, but not necessarily absolute, spectroradiometric sensor calibration. These include workers in computer-aided scene classification, cartographers, image processors, photointerpretrs, and people concerned with composing large mosaics.

2. Users requiring absolute spectroradiometric calibration. These include physical scientists concerned with relating ground-measured parameters and/or atmospheric characteristics to the spectral radiance at the entrance pupil of the space sensor.

There are two reasons for converting the digital value to radiance: first, in multitemporal sensing, to account for any documented changes of radiometric calibration with time; second, to test or utilize physical models in which the ground reflectance and atmospheric effects are measured and/or calculated over identical spectral passbands as employed by the space sensor.

Inadequately corrected relative detector-to-detector response causes stripping and information loss in the imagery. Relative radiometric response occurs when the outputs from all detectors in a band are equal or can be adjusted during preprocessing to be equal when the incident spectral radiance is constant across the sensor's field of view. (Note that the number of detectors in a band can be as few as six for the multispectral Scanner System (MSS) on Landsat and as many as 18,500 on future MLA systems.) Stripping often can be completely removed by the histogram equalization method; thus, relative radiometric precision can be high even though the accuracy involved may be low. In this equalization procedure the histogram of each detector output is compared with that of every other detector, after a large number of data samples (~2x 10^5) have been recorded. It is assumed that, if the scene is spatially and spectrally random, the histograms for a large number of samples will be identical. If the histograms are not identical, adjustments are made during the preprocessing step. This procedure can be repeated for scenes of different average radiance, and the relative responses can then be equalized over the dynamic range of the detectors.

The utilization of verification of physical models usually requires the use of data calibrated in an absolute sense. Until recently the highest in-orbit absolute radiometric accuracy has been little better than ten percent. This low accuracy has been due to: (a) the fact that the calibration in orbit has often been for the focal plane only, not for the complete system; (b) the loss in accuracy accompanying the transfer of calibration from the standard source at the national laboratory to the factory or laboratory site; (c) the use of source-based calibration procedures.

RESEARCH IN RADIOMETRIC CALIBRATION

Research plans should, in this decade, aim to reduce the uncertainty in absolute calibration of a space sensor to:

$\pm$ 1 percent of the full scale signal level when the calibration is performed on-board with the sun as reference.

$\pm$ 2 percent of the full scale signal level when the calibration is performed with reference to a large uniform ground site at which appropriate atmospheric measurements are made.

The $\pm$ 1 percent on-board system calibration is needed to verify the accuracy of the $\pm$ 2 percent calibration procedure. The main reasons for pursuing the $\pm$ 2 percent method are:

The substantial savings it represents in system design and fabrication costs if it can replace the on-board method.

The capability then will have been established for accurate intercalibration of all aircraft and space remote sensing systems.

The calibration program should be primarily concerned with:

1. Exploiting the order of magnitude improvement in absolute radiometric accuracy resulting from the development of self-caibrated detectors at the National Bureau of Standards.

2. Refining the measurement and modeling of earth surface reflected radiances and atmospheric radiative transfer.

Important additional questions that should be addressed are:

1. Whether technological and/or natural variability considerations limit the accuracy to which the absolute calibration can be made.

2. The benefit of data having better absolute radiometric accuracy for remote sensing applications.

PLATFORM CONSIDERATION

It is necessary to know the instantaneous position of the spacecraft and the instantaneous line of sight between each specific detector and its conjugate area on the Earth's surface in order to associate the output of that detector with the area on the Earth's surface from which the reflectance or radiation originated.

The platform-sensor system center of mass position and velocity plus the three angles which describe the instantaneous orientation of a set of platform body-fixed axes with respect to a geocentric inertial frame (say, equinox and equator of a particular epoch) and their rates of change or angular velocities constitute the system state description. If the platform and sensory system can be assumed to approximate a rigid body to within some allowed error budget of, say, fractions of a microradian at all frequencies of concern plus some calibrated, fixed offset, then knowledge of these six state variables plus the center of mass position and velocity state variables would suffice for a dynamic description of the platform-sensor system. However, this is not the present state of affairs.

Earth remote sensing satellites can be tracked over short arcs to one meter to tens of meters accuracy depending on tracking system complexity. Orbit prediction models employed over a few days after orbit determination by tracking yield position accuracies of hundreds of meters to a kilometer or so. Continuous near real time tracking using the pending Global Positioning System will yield position accuracy of 10 to 100m and velocity accuracy of 1 to 10cm per second. Orbit adjustment is accomplished by well-developed thruster technology and is limited mainly by orbit estimation capability. This category is well-developed in basic knowledge and understanding, models are available for input to system design procedures, and future advancements call for evolutionary engineering improvements.

Earth remote sensing satellite platform attitude angles have been measured by horizon sensing and controlled to tenths of a degree. LANDSAT-D is designed for attitude measurement and control by star tracking, Kalman filter gyro drift estimation and reaction wheels to $\pm$ 175μrad bounds. (High Energy Astronomy Observatory-2 was controlled to $\pm$ 10 to 25μrad and estimated to better than 10μrad while Space Telescope is designed to achieve $\pm$ 35nrad rms pointing error. These show potential possibilities for Earth sensors.) Typical low frequency platform attitude control is limited to a bandwidth on the order of 0.02 Hz.

Vibration and thermal warping effects offset sensor boresight attitude with respect to platform attitude. Thermal effects are low frequency, large (50 to 100 μrad per degree C or more), and can be measured with respect to platform axes on board. High frequency vibrational effects are serious; registration and rectification success depends on their determination and attenuation. The problems of vibrational excitation of high frequency sensor attitude upsets became evident in the LANDSAT-D design and resulted in the incorporation of a triaxial angular displacement sensor with a bandwidth from 2 to 125Hz, mounted on the Thematic Mapper. General awareness that the remote sensing platform, its subsystems, the sensors, and their subsystems must be viewed as a complete and interactive system for attitude and attitude rate estimation and control is recent. This category of true sensor instantaneous boresight estimation and tight broad-band control of the platform-sensor system can profit from fundamental experimental research and creative engineering design.

A reduction of any errors in developing the system state description will have an immediate impact on both the utility of the remote sensing data for cartographic applications and on registration and verification processing.

Platform considerations and issues are discussed in greater detail in the final report of the NASA-sponsored working group, chaired by R. Holmes of the General Motors Research Institute: Fundamental Research Panel-Electromagnetic Measurement and Signal Handling of Remotely Sensed Data.

ONBOARD DATA PROCESSING

Summary of SOA

On-board data processing can be done either by compact general purpose hardware and software or by custom structured digital hardware. Capabilities of general purpose processors for space flight have expanded dramatically in recent years, but do not yet match small ground systems because of the radiation hardening, environmental, and reliability problems associated with space flight. On the other hand, substantial progress has been made in space survivability of custom-structured designs by DoD technology programs. While these advances, especially in radiation hardening, are being applied to G.P. architectures, a second limiting area, software creation and validation, remains a major difficulty for on-board processors. The engineering solution-of-choice currently favors custom architectures for well-defined on-board high data rate processing requirements.

On-board data compression techniques, trades, and potential hardware implementations were reviewed in two papers presented at this workshop.

Adaption of the noiseless coding data compression techniques, originally developed for the planetary probes, to the imaging spectrometer appears to be encouraging. However, it is clear that compression exceeding about 2.4:1 will be difficult to achieve without some signal degradation. The degree of achievable compression will depend, to a large extent, on the entropy of the scene and the acceptable signal degradation. Adaptive rate controlled data compression schemes such as the RM2 and the BARC schemes, presented by R. Rice of JPL, will require further study before their potential usefulness for the high data rate multispectral sensors can be established. The compression ratio also has to be traded off against the complexity of the on-board design, particularly with respect to the amount of buffer storage and number of arithmetic operations per pixel. Higher level data compression approaches such as cluster compression algorithm and the principal components approach, which exploits band to band correlations were briefly discussed. However, it is unlikely that these schemes will be implemented before the simpler and more direct compression approaches such as DPCM and its variants become flight hardware.

Potential Applications in Remote Sensing

A number of the sensor-specific processing and correction functions can be transferred from the ground segment to the spacecraft. This shift would permit lower cost proliferated ground systems, especially for operationally and commercially oriented remote sensing systems. Functions suitable for on-board processing include radiometric calibration, geometric correction, relative registration (either thru archive control or ex post facto correction), absolute registration, ephemeris generation, and simple band ratio classification. The last item may be commandable in the types of ratios to generate. Information adaptive data compression is also suitable for on-board processing.

Recommendations for Research and Development

The technology for space environment operation of high speed special processors is being heavily funded. Remote sensing should follow and adapt these efforts to the unique requirements of remote sensing. Specific architectures and validation of design approaches suitable for remote sensing should be pursued. Calibration and data comparison are likely to yield advances most rapidly. For the very high data rates of advanced systems, parallel architectures will be needed in most areas of onboard processing. Data flow and management will be a major issue in such structures and must be addressed. Commandable and mission-adaptive processing will also be of substantial importance.

MULTISPECTRAL LINEAR ARRAY CONCEPTS

The Multispectral Linear Array (MLA) concept provides the potential for significant advances in remote earth sensing technology beyond the current Thematic Mapper (TM) capabilities. As requirements for higher spectral, spatial, and temporal resolution continue to climb, the TM approach of using a mechanical object plane scan mirror has become increasingly diffficult to handle as larger mirrors and higher scan frequencies encounter the laws of inertia. The MLA does not encounter this problem since the image plane scanning is done electronically and is only limited by electronic frequency sampling rates and the size density of the arrays. Manufacturing techniques continue to offer higher size density and larger arrays. Techniques for sampling at ever increasinq rates continue to evolve along with the higher density solid state arrays.

An MLA sensor operating in the pushbroom scan mode can meet demanding research requirements in a number of discipline areas. A pushbroom mode sensor provides:

a. Long dwell time which permit high spatial resolution and radiometric sensitivity.

b. Fixed detector array and optics which result in improved geometric properties.

c. Compact optics which allow a pointable field-of-view to conduct atmospheric effects and stereographic experiments.

MLA sensor definition studies and supporting technology developments in selected critical areas such as the SWIR focal plane are in progress. Science studies are being initiated to establish objectives for the land observing research mission and to convert these scientific objectives to a set of required MLA sensor parameters. Laboratory and field research program are being conducted to provide a base of expertise in the reduction and analysis of MLA sensor data.

In order to achieve the optimum results from the MLA concept the following recommendations are suggested.

1. Perform studies to provide an improved science basis for earth resource applications of future MLA type sensors.

2. Continue to develop and demonstrate focal plane array technology for the visible near infrared, shortwave infrared, and thermal infrared spectral regions.

3. Design and fabricate new field test instruments, conduct evaluation tests and provide data for scientific assessment.

4. Perform on-going engineering studies fabrication and test in technical areas critical to MLA instrument development such as beamsplitter, wide field optics, large spectra filters, etc.

5. Analyze parameter interactions (MTF, calibration, quantization, spectral response ...), development of error budgets, performance of related trade-off studies and evaluations of resulting data product quality.

6. Develop statistical characterization of scene and development of optimal data compression techniques.

7. Analyze off-nadir (stereo, cross-track) image acuracy requirements and development of related data processing techniques.

These recommendations should involve a broad cross section of organizations from research, engineering, industry, and the user communities. In this way a responsive system will continue to develop to an eventual routine use of the MLA from space with wide and varied applications.

With the current technology base and the trends of development suggested above, the MLA should be the logical choice as an efficient, routine remote sensing system through the next decade and beyond.

Requirements

The requirements placed on a remote sensing system by the various discipline users' observational needs suggest a system that will have a multiplicity of known spectral bands. In many cases certain bands are of value to numerous users, but only rarely do particular disciplines such as hydrology or geology select the same group of bands.

Spatial resolution requirements can vary widely between the various researchers. Optimization of spatial resolution vs. data rate requirements will necessitate tradeoffs between the two and this must be approached within the framework of the information to be derived and the analysis technique to be used. The most stringent requirement for spatial resolution could be the design goal, but that will not necessarily produce the most efficient and productive system. Research is needed here to determine the lowest spatial resolution acceptable, the data manipulation that can enhance observations, and the optimum optic to detector capability.

Temporal coverage adds an additional variable to the requirements of an MLA sensor in space. As an example, the lithologist does not require the same temporal resolution as a hydrologist concerned with the flash floods. Studies will be needed to determine the optimized temporal resolution from the standpoint of global coverage repeat rates, orbital altitude and inclination, geosynchronous vs. solar synchronous vs. varying sun angle, and combinations of spacecraft to give broad coverage.

Since these combined requirements predict extremely high data rates to achieve the broad applications capability inherent to MLA, it is urgent that research to determine the minimum number of data points required for each application. Along with these studies, schemes must be developed to efficiently extract meaningful information out of the extremely large data stream.

STATE-OF-THE-ART IN MLA TECHNOLOGY

An MLA sensor system is currently under study at GSFC's Advanced Land Observing System Study Office, and several designs have been studied by industry that will meet the baseline requirements. MLA Shuttle instrument designs are also being studied.

One of the system presently under study is planned to be a technology validation and observational research mission to provide a basis for future satellite based land remote sensing system demonstration to be carried on the Space Transportation System (STS) and is expected to provide scientific basis for selection of MLA sensor systems for satellite based land remote sensing. In the configuration under study the MLA will fly in near earth orbit at an inclination of approximately 40°. Stereo and cross track pointing capabilities will be incorporated.

MLA baseline parameters for this system are as follows;

- Spectral bands
  - 3 visible
  - 1 SWIR
  - Expandable to 12
- IFOV
  - 10 meters (visible) — 20 meters (SWIR)

- Swath Width - 60 km
- Cross track pointing of $\pm 30^{0}$
- Stereo

Imaging Spectrometer

Imaging spectroscopy for the remote study of the Earth's surface is the technique of measuring and analyzing the reflected and emitted radiation, as simultaneously as possible, at many spectral wavelengths (10's - 100's) for many spatial elements (100's - 1000's). The value of the technique has been demonstrated for several fields such as geology, meteorology, agriculture, oceanography and botany (e.g. rock-type, minerology, crops, forests, water vapor, identification and distribution). Imaging spectroscopy presents the greatest opportunity for advancement in routine space remote sensing capabilities by the late 1980's, given the existing and nearly-existing technology base.

At present, the laboratory and field studies and the instrumentation and data handling experience are not sufficient to define precisely which spectral bands, how many bands, and which instrument design are best suited for space application. Therefore, a long-term research program is required to develop this promising technique to the point of routine use. The emergence of detector array technology and the rapid advancements in electronics, which make increased computing capability available at low cost, enable the development of aircraft instruments now and the establishment of a strong technical base from which to investigate future space-borne utilization.

This research and technology program should involve a variety of approaches and organizations (research and engineering). The emphasis should be not only on developing the technique and the associated technology, but also on developing a broad and knowledgeable developer and user community. The goal is to develop the technique for eventual routine use from space with wide application. An analogy for this approach is that of a pyramid built from the base to the point; the base blocks are the various research and development efforts recommended here leading to the point of space application, but with the broad base of a knowledgeable community of scientists and engineers to support the transition.

A series of specific recommendations is listed below.

- A research program should be carried out to develop imaging spectroscopy for routine use. This program should include:
  - Laboratory and field study of the optical properties of natural materials and their relationship to subsurface materials.
  - Laboratory, theoretical, field, and flight studies directed at defining and removing the effects of the atmosphere on remote measurements.
  - Development and experimental use of several designs of measurement instruments by several groups.
  - Use of these instruments in the field and from aircraft to develop and verify measurement techniques and instrument designs and to develop an experienced experimenter and user community.
  - Use the data from the experimental instruments to drive data handling and analysis technology and to prepare for routine use of this high data rate technique.
  - Monitor and participate in the development of key technologies and test them in the experimental instruments.
  - Experimental flights of two or three instrument and experiment designs on space platforms.

- A supporting technology development program should be conducted to advance the key technologies needed in future imaging spectroscopy applications including:

  - Development and characterization of advanced detector arrays for use in aircraft and eventual space flight instrumentation and the provision of useful devices to the research community.

  - Investigation of key optical design and fabrication techniques with emphasis on spectral filtering and dispersing optics.

  - Investigation of instrument and ground data processing concepts and systems.

  - Pursuit of spacecraft systems technologies applicable to the eventual implementation of space-borne instrumentation.

Requirements

Differing observational requirements of the several discipline groups combine to justify an advanced capability. This is documented elsewhere in this report and in a recent National Academy of Sciences report (Report of NAS-SSB Committee on Earth Science). Several disciplines, which can be individually satisfied with a few spectral bands, require different sets of bands. Some disciplines individually have different band requirements for different applications (e.g., lithologic mapping). In many cases, the appropriate bands for each application have not been defined and more research is needed. Therefore, a wide variety of bands must be available in a measurement system.

Other measurement goals are often optimized by making the spectral bands narrow. The problem of removing atmospheric effects from multispectral data sets may necessitate additional spectral bands to characterize the atmospheric contribution. Finally, there is a need to explore the accessible spectral regions to determine the most useful bands. These needs can be met by a programmable sensor which possesses sufficient granularity in spectral band selection to exploit the known spectral signatures and to explore new spectral characteristics.

A further motivation for an advanced multispectral capability is the need to reduce the measurements to the minimum number (i.e., only return data which is absolutely required for any one application). Since each application may require different measurements, a versitile, adaptable instrument is required.

STATE OF THE ART IN IMAGING SPECTROSCOPY INSTRUMENTATION

Based on recognized needs described above, imaging spectroscopy instrumentation for aircraft flight research programs is being developed at several institutions. In addition, a variety of future imaging spectroscopy instrument concepts are under study ranging from aircraft instruments to free-flying spacecraft-borne systems. Intermediate conceptual designs suitable for space shuttle and possible space platform application have been studied. We conclude that the instrument technologies needed for aircraft instrumentation are presently available and that the devedlopment program proposed here is capable of supporting the orderly development of space flight hardware for missions in the late 1980's.

Flight testing of two aircraft instruments will begin within a year. The Mapping Reflectance Spectrometer (MRS), developed jointly by the University of Hawaii and MIT, will begin field tests this fall to provide data for research in the 0.35 - 4.0 micrometer spectral range; a series of aircraft flights have been proposed to follow. The Airborne Imaging Spectrometer (AIS) developed by JPL will be flown in conjunction with the Thermal Infrared Mapping Spectrometer (TIMS) to provide complementary data in the 1 to 2.5 and 8-11 micrometer spectral regions. The research objectives of these programs have been materially aided by previous spectroscopic investigations: The SMIRR experiment which flew on the second shuttle payload, and the airborne spectroscopic work of Dr. William Collins, of Columbia University, as well as by several laboratory and field studies.

The emergence of imaging spectroscopy is aided by technological progress, most notably in detector array technology for the visible and infrared, and low-cost electronics which make possible sophisticated processing, both within the instrumentation and in versatile data analysis systems.

Although expensive, because of their low production volume and experimental nature, linear and area array detectors are becoming available for use in instrumentation. Experimental infrared devices can be obtained only by means of development contracts. Typical costs for state-of-the-art arrays are of the order of 100K dollars. The development of array modules and mosaic focal planes for space flight instrumentation has been initiated as an important major technology development. For the short wavelength infrared, arrays of 1 by 128, 32 by 32, 64 by 64, and 64 x 128 have been described. Development of larger mosaic focal planes for space flight is focused on arrays of many thousand elements in length and on the order of one hundred elements in the spectral dimension.

Several optical and mechanical designs for imaging spectrometers have been proposed, each offering some advantages for certain applications. The conflicting requirements for small size, large field, simultaneous spectral and spatial coverage, pixel registration, etc., and the fact that none of the designs have been tested and evaluated under field conditions make it difficult at the moment to specify the optimum design for each application.

The data rates for these instruments are very high (10^7 - 10^9 bits/s) and, because of the spectral coverage, the information is diverse. The handling and analysis techniques for rapidly processing this data and quickly having it available to the user are not fully developed. Solutions involve improved data processing and handling both at the sensor and in the ground processing system; however the allocation of the functions between these locations is poorly understood. Instrument radiometric calibration is a key example. Needed development includes dedicated high-rate processing devices using VLSI and new system architectures.

CONCLUSIONS

During the two-day workshop, a comprehensive overview of the state of the art of remote sensing and supporting technology was presented. Two generic spacecraft sensor concepts were presented. One concept is the multispectral pushbroom sensor utilizing linear array technology. Four alternative designs for such a sensor, which were developed through recently completed study contracts, were presented. This multispectral linear array (MLA) sensor operates in six spectral bands including two bands in the SWIR spectral region and incorporates capabilities for stereo and crosstrack pointing.

A second concept which was presented is the imaging spectrometer (IS). The IS incorporates a dispersive element and area arrays to provide both spectral and spatial information siumltaneously. The spectral bands, band width, and spatial resolution can be chosen by on-chip programmed readout of the focal plane. Technology developments to provide the foundation for implementating both MLA and IS concepts into hardware in the late 1980's were reviewed. These include visible multispectral linear arrays, Pd-silicide Schottky barrier and HgCdTe linear area arrays and on-board data processing-compression schemes.

Results presented at this workshop and other recent meetings suggest significant progress in the critical detector array technology. Pd-silicide Schottky barrier technology is now at a level of demonstrated performance and maturity that make it an attractive and lower risk alternative to the high performance photovoltaic HgCdTe hybrid arrays for broad spectral band SWIR applications. 32 x 32 element HgCdTe hybrid arrays have been fabricated and will be incorporated in an aircraft instrument, the Airborne Imaging Spectrometer (AIS).

Another key technology area discussed at some length at this workshop was very large scale integration (VLSI) and the associated technology of Computer Aided Design (CAD) of these devices. The importance of VLSI evolves from the significantly greater data volumes implied by the Science Panel's data needs. To handle the large data volumes, VLSI will be needed for on-board data compression and processing, as well as on the ground for parallel processing of the multispectral, spatial, temporal data acquired with the sensor. To design the increasing complex VLSI circuits required, CAD will be essential.

The aircraft instrument work now underway at GSFC and JPL is an appropriate starting point for what should be viewed as complementary developments. Emphasis in both cases needs to be placed on flexibility in meeting the requirements of many applications disciplines, reliability, and cost. Careful assessment needs to be made of the data quality achievable with such factors as sampling, MTF, spectral response uniformity, polarization, etc., taken into account. Both approaches should be pursued with appropriately realistic guidelines and objectives.

Ongoing aircraft measurement programs and the designs of proposed airborne instruments for research and technology validation were presented. Several aircraft instruments currently under development for research in remote sensing were reviewed including the LAPR-II, AIS, AVIRIS, and TIMS. The results from the disciple panels clearly indicate the need for a new generation of aircraft sensors which can provide well calibrated narrow band spectral data from the visible through thermal infrared spectrum. In addition, because of the diverse nature of the spectral requirements expressed by the discipline panels, an airborne instrument with either programmable or selectable spectral bands and bandwidths is desirable rather than the fixed filter type airborne scanners and simulators which exist today. An advanced aircraft instrument and a concerted program of data acquisition is needed to develop the measurement techniques and a data base to explore the utility of high spectral and spatial resolutions. A need for an airborne instrument which provides variable spatial resolution in multiples of the smallest IFOV for parametric tradeoff studies of the effects of spatial resolution on scene classification, adjacency effects, cartographic, lithologic and land use research was also expressed by segments of the disciple groups.

While the imaging spectrometer approach utilizing area arrays appears to have greater potential to satisfy the diverse research requirement because of its spectral programmability, further work needs to be conducted on the use of more spectrally versatile MLA systems. Several conceptual designs for programmable spectral filters for linear arrays systems have been identified and developed by the MLA study contractors during the MLA Shuttle instrument studies. Both approaches have advantages and disadvantages and it is not clear at present which is the better. In fact, it may turn out that one is more suitable as an aircraft research instrument and the other as a space system.

Spectral signature studies need to be vigorously pursued using instrumentation that can be easily tuned spectrally; at present the most promising approach seems to be an aircraft mounted imaging spectrometer. The result of this research should be the identification of several sets of system spectral responses, probably with some responses common to more than one set, that would be optimum for several applications. We then need to answer the question: is a versatile MLA focal plane spectral design capable of providing a small number of spectral response sets, a more cost effective and reliable solution than the imaging spectrometer approach which can provide a larger number of response sets by electronic spectral tuning.

The presentations given at this workshop suggest that a substantial technology base already exists in detector arrays, optics, data processing, and instrument design. Other countries, for example, have exploited the availability and relative maturity of this technology and are currently developing Shuttle and satellite remote sensing instruments. What is needed now, in our case, is a set of definitive and bounded mission scenarios to focus the existing enabling technology and on-going developments. Several top level candidate research mission scenarios have been generated during the past year by GSFC and JPL. These scenarios have been the basis for the MLA instrument and imaging spectrometer designs. Additional work needs to be done to iterate the instrument designs and configurations after more defined mission scenarios and science requirements are developed.

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BOTANICAL SCIENCES TEAM

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

COMPTON TUCKER

BOTANICAL SCIENCES TEAM

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

April 14-15, 1982 at ORI

CO-CHAIRMEN: C.J. Tucker (NASA) and C.L. Wiegand (USDA)

MEMBERS: G. Badwhar (JSC), B. Cibula (NSTL), E. Crist (ERIM), C. Daughtry (LARS), R. Fraser (GSFC), D. Kimes (GSFC), D. Pitts (JSC), B. Rock (JPL), C. Schnetzler (GSFC), S. Ungar (GISS/GSFC)

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EXECUTIVE SUMMARY

BOTANICAL SCIENCES TEAM –
MULTISPECTRAL IMAGING SCIENCE
WORKING GROUP

Significant improvements in the orbital ability to remotely sense vegetated targets will result from 1) an understanding of, and compensating for the atmospheric effects upon radiative transfer; 2) having an appropriate spatial resolution for the mission in question; 3) obtaining data at a temporal frequency of 2-3 days; 4) having narrow spectral bands to maximize vegetation-background material contrasts or plant stress responses; and, 5) the inclusion of additional spectral bands.

The wavelength regions between 0.35 -14 μm which are important sources of spectral information from vegetated areas are, with one or two exceptions, well established and documented. Bands centered at 0.44, 0.55, 0.66, 0.85, 1.65, and 2.2 μm are important in the reflective region of the spectrum. The ~ 3.5-3.9 μm region is important for fire detection while the 10.5-12.5 μm region is important to detect thermal features. Spectral band selection should result in narrow spectral band intervals in order to maximize the vegetation-background material spectral contrast and emphasize plant stress responses while maintaining signal to noise requirements. Narrower spectral bands will also minimize atmospheric absorption effects in certain wavelength regions. Additional research is needed to determine the existence/importance of high resolution spectral information; to understand the bidirectional reflectance distribution function; and to determine the importance of polarization.

The spectral properties of vegetation must be considered simultaneously with atmospheric attenuation. This concurrent consideration usually eliminates areas where atmospheric attenuation is appreciable such as the 0.75-0.78, 0.90-0.97, 1.1-1.18, 1.3-1.55, 1.8-2.1, 2.3-3.5, 4.0-10.0 μm regions. In addition, the atmosphere is the most limiting factor facing vegetational remote sensing and one where significant research must be conducted. For example: the spatial and temporal horizontal and vertical distribution of absorbing aerosols, cloud droplets, ice crystals, ozone, trace gases, and water vapor is not well known; coordinated measurements of scene radiance for a variety of atmospheric conditions in conjunction with ground and aircraft experiments have not been made; the utility of placing sensor bands in areas of the spectrum where the atmosphere dominates (i.e., "atmospheric sounder" bands) has not been evaluated for water vapor, optical depth, cirrus clouds, etc.; the inclusion of a pointable lidar to obtain atmospheric scattering information has not been evaluated; and additional research is needed on agricultural and non-urban aerosols and their height profiles.

The atmosphere also determines the effective noise equivalent change in reflectance ($NE\Delta\rho$) for a given spectral band and its dynamic range. For example, it would be impractical to talk of a $NE\Delta\rho$ of 0.25 percent when the atmospheric variation alone is ± 0.5 percent. The ability to make orbital spectral measurements with a $NE\Delta\rho$ of 0.5-1.0 percent is currently thought to be the best which can be achieved. Additional research in this area will be performed with the thematic mapper which was launched on Landsat-4 in July, 1982.

Spatial resolution requirements are widely divergent. The requirement of 10-30 m for small spatial frequency objects is completely different from the large-scale monitoring needs on the order of 500-5000 m. The particular spatial resolution needed for a given mission is determined by the spatial frequency distribution of the material(s) in question. Increasingly smaller spatial resolutions have been shown to increase the chance of classification error in many cases due to better sampling of the within scene-element spectral variability and the adjacency effect contribution from adjacent pixels via atmospheric scattering. Additional research is needed to compile the spatial frequency distributions for other cover types and classes, to further evaluate the adjacency effect, and establish the within-class spectral variability. The impact of 10-30m data on the data rate and processing requirements must be evaluated also.

The dynamic nature of vegetated surfaces requires spectral data collection at 4-6 day intervals to detect episodic events (onset of stress, recovery from stress, etc.); to monitor crucial physiological periods such as flowering and fruit development; and, to note the onset of senescence for geobotanical investigations. Assuming a general cloud probability of P = 0.5, this then becomes a 2-3 day interval. There is a research requirement to obtain spectral data at hourly intervals from the same target(s) viewed under different illuminating conditions to evaluate the advisability and need for nonsun-synchronous orbits.

Sensor variability must be minimized by the control of detector response variability and by close spectral acceptance matching. Failure to control detector radiometric and spectral variability will limit increased radiometric resolution.

INTRODUCTION

Remote sensing imaging technology advances of the past decade make possible high spectral and spatial resolutions from orbital altitudes. In addition, research involving the interaction of electromagnetic radiation with plant canopies has made significant progress. This report, a summary of the Botanical Sciences Team meeting of the NASA Multispectral Imaging Science Working Group held in mid-April, 1982, documents the improvements in vegetation monitoring and mapping which would result from increased spectral and spatial resolutions. Areas where the existing knowledge is incomplete are also identified.

Several areas which we considered have previously been covered in detail by Smith, et al. "Description of Research Issues - Scene Radiation and

Atmospheric Effects Characterization," NASA document (1980). We have taken the liberty of including appropriate portions of this NASA document in the spectral and atmospheric sections.

This report is organized into two major and three minor sections. The two major sections are devoted to the spectral properties of vegetation and the atmospheric effects upon remote sensing of vegetation. The minor sections involve spatial resolution, radiometric resolution, and frequency of obervation requirements.

The spectral properties section includes consideration of the bidirectional reflectance distribution function and associated plant canopy radiation modeling needs, polarization, high resolution spectra, and plant canopy biophysical sampling.

The atmospheric effects section includes consideration of how the atmosphere influences the electromagnetic radiative transfer from plant canopies. These considerations play a crucial role in spectral, spatial, and radiometric resolutions for remote sensing of vegetation.

It was the concensus of the Botanical Sciences Team that significant improvements in the orbital ability to remotely sense vegetated targets will result from the following: understanding and compensating for atmospheric effects upon radiative transfer; having an appropriate spatial resolution for the mission in question; obtaining data at a temporal frequency of 2-3 days; having narrow spectral bands to maximize vegetation background material contrasts; and, the inclusion of additional spectral bands.

SPECTRAL PROPERTIES OF VEGETATION

The spectral response of living plants is dominated by the optical properties of leaves, although culms, leaf sheaths, and heads of grasses and twigs, limbs, and trunks of trees also contribute when they are not obscured by foliage. In the visible (0.4 to ~ 0.72 μm) region chlorophylls and accessory pigments absorb most of the incident light and reflectance is low (Allen et al. 1969; Gates et al., 1965; Gausman et al. 1970; Kumar and Silva, 1973; Tucker and Garratt, 1977). The ~ 0.72 to 1.35 μm region, where leaf cellular structure is important, is one of high reflectance and transmittance and low absorptance (Gausman, 1974). This wavelength region is referred to either as the "reflective infrared" or near-infrared plateau. The 1.35 to 2.5 μm region is partially influenced by leaf cellular structure but is dominated by the optical properties of water in the plant tissue. There are strong water absorption bands centered at 1.45 and at 1.95 μm with reflectance peaks between, below, and beyond them (Allen et al., 1969; Gates et al., 1965; Thomas et al., 1966; Tucker, 1980). Thermal emission of plants and other scene components occurs in the 3 to 14 μm region. The wavelength region between 2.50 and 8.00 μm has not been widely used because few detector systems have these wavelengths, signal to noise (S/N) ratios are low, and the mix of reflected and emitted energy in the signals is difficult to interpret.

The backgrounds against which plants are observed are soil, bedrock, plant litter, and, in some cases, water. To map, monitor, and classify vegetation, wavelengths must be used where there is ample contrast between the vegetation and the background. Soil and most bedrock materials are typically much less reflective than green vegetation at ~ 0.72-1.10 μm and much more reflective at ~ 0.35-0.70 and ~ 1.40-2.30 μm, making these wavelengths valuable for distinguishing vegetation from the soil background and for assessing vegetation green leaf density (Colwell, 1974; Richardson et al., 1975; Tucker and Miller, 1977; Wiegand et al., 1974).

To classify (identify ecologically meaningful native plant communities, distinguish among crops, or vegetation-related land uses), it is necessary to time the measurements to take advantage of differences in stages of development that affect ground cover, leaf area index, shadows, moisture content, and/or pigmentation. To estimate production, defined as yield/ha, the land area occupied by a given vegetation category must be known with sufficient accuracy and there must be a way to judge the yield/unit area against historical or direct sampling data. LACIE provided considerable sampling experience to satisfy preset production accuracy criteria. Mapping may be done in the classification or production applications, but vegetation green leaf density and its distribution can be mapped automatically from the spectral observations with fast table look-up procedures based on the global characteristics of green vegetation and soil. Obviously, better spatial resolution is required to follow the behavior of individual fields than for synoptic assessment.

Vegetation indices are used to monitor vegetation development, physiological condition and stress, forage production, and grain yields. The indices are ratios, differences, sums/differences, and linear combinations of the visible and reflective infrared region that reduce the information about green leaf vegetation and the soil background, respectively, to a single, numerical index. They can be calculated using radiances, reflectance factors, or digital counts and they relate well to canopy characteristics such as chlorophyll concentration, leaf area index, percent cover, dry-green biomass, and plant water content. (Kauth and Thomas, 1976; Kimes et al., 1981; Richardson and Wiegand 1977; Tucker, 1979).

Bands centered at 0.45, 0.55, 0.66, 0.85, 1.65, and 2.2 μm are candidates to map, monitor, and classify vegetation (Allen et al., 1970; Tucker, 1978; Wiegand et al., 1972). However, energy in the solar spectrum is low at wavelengths longer than 1 μm and these wavelengths are susceptible to low S/N ratios with narrow-band sensors. Thus, engineering systems for low noise in the 1.0 to 2.5 μm region is mandatory for narrow-band sensing systems.

Thermal emission wavelengths have not been used extensively in conjunction with the reflective wavelengths for classification (Kumar, 1980). To understand thermal responses, energy balance processes as opposed to reflectance phenomena must be considered. Water availability to plants for transpiration, instantaneous insolation, near-canopy water vapor pressure of the air, and atmospheric attenuation need to be considered (Ehrler et al., 1978). Two or more wavelength bands within the 8 to 14 μm interval and simultaneous solutions of equations defining responses could help to improve confidence in radiometric temperatures as well as their correspondence to thermometric temperature. In any case, the reflective wavelengths should corroborate the thermal findings and vice versa. For example, midday surface temperature and ground cover, as deduced from the reflective wavelengths, are inversely related provided the soil behind the vegetation is dry (Kimes et al., 1980).

Recent research using the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-6 and NOAA-7 has shown that the 10.4-11.4 and 11.4-12.4 μm regions are also useful as a means for detecting clouds (including faint cirrus clouds). The 3.5-3.9 μm AVHRR band has also been shown useful for monitoring fires in forested areas (Matson and Dozier, 1981). Because fire is a major influence upon vegetation, this wavelength region should also be included.

The majority of in situ spectral measurements in the 0.35 to 2.5 μm region have been made in the nadir mode. They have not included polarization measurements; they have not been of fine (i.e., 0.001-0.002 μm) spectral resolution; they have been made principally in the 0.35-1.1 μm region; and, they have not adequately sampled target biophysical variability.

Some areas which need to be addressed include:

(1) The complete bidirectional reflectance distribution function (BRDF) of vegetation and soils must be made. The BRDF is the fundamental property of scene elements which governs scene exitance (Kasten and Raschte, 1974; Nicodemus, 1978). It is an intrinsic property of the surface, independent of irradiance conditions. It is a function of physical and biological scene attributes. The BRDF is also the basic quantity to have if one is interested in atmospheric phenomena, since the BRDF forms the lower boundary condition of any atmospheric radiative transfer problem. Thus, it is seen that no analytic development for the prediction of scene radiance at the individual pixel level, or beyond, is possible without a knowledge of this function.

Limited spectral measurements of individual components of the BRDF have been obtained in the field; for example, nadir-direction measurements of spectral reflectance have been obtained for a limited number of solar zenith angles (Bauer, et al., 1979; Bunnik and Verhoef, 1974; Rao, et al., 1979; Ungar, et al., 1977). In many cases, the field-of-view is very wide. Very few measurements have been taken with off-angle viewing geometries. In fact, these vertical and off-angle measurements are estimates of components of the bidirectional reflectance distribution function in that one is really measuring an integral of the BRDF times the complete irradiance field including both diffuse sky light and solar illumination (Robinson and Biehl, 1979).

In essence, there are very few data available, particularly in the reviewed literature of the complete BRDF of any scene element class (Smith and Ranson, 1979).

BRDF determinations must be obtained for important renewable resource scene element classes, such as soil, vegetation categories, and so forth. These measurements are needed to develop empirical characterizations of scene exitance in terms of attributes and to support theoretical modeling. While, at first glance, it seems astounding that such measurements have not been obtained, a closer examination of the considerations involved in such measurements provides some insight and indicates subsidiary research problems to be investigated.

(i) First, because the BRDF is associated with scene element classes, a careful definition of just what constitutes the scene element class must be formulated. That is if one is examining the class "wheat," immediately questions about stage of growth, phenology, condition, planting practices, and spatial scale of sampling must be considered.

(ii) Statistically sound experimental designs must be formulated relative to spatial and temporal sampling. In many instances, it is very difficult to find sufficiently large homogeneous areas to rapidly carry out a complete set of BRDF measurements.

(iii) Appropriate field measurement techniques must be developed which allow measurements to be obtained which are insensitive to short term irradiance fluctuations and can be appropriately calibrated. These techniques must also include a measurement of the complete irradiance field.

(iv) Analysis techniques must be formulated, perhaps based on some theoretical considerations, which allow one to extract the BRDF function from under the measurement integral of scene radiance; and further remove atmospheric considerations which would be important if such measurements were obtained from an aircraft system.

(2) Polarization properties of scene exitance for scene element classes are needed. In the mid to late sixties, several interesting experimental measurements of polarization for vegetation canopies, soils, and other categories were obtained by Coulson, et al., (1965), and by Egan (1970). The extent to which the atmosphere contributes to polarization also needs to be examined.

(3) Spectral measurements with narrow wavelength intervals (i.e., 0.001–0.002 μm) need to be made of scene elements in the 0.35–2.5 μm wavelength region. With the exception of Collins (1978) and Ungar, et al. (1977), no other in situ narrow-interval spectra from vegetation have been reported. The existance of spectral "fine structure" in the spectral response of vegetation needs to be determined. We suggest that narrow wavelength-interval laboratory leaf spectra be collected, correlated with leaf anatomy and physiology and used in existing one and multi-dimensional plant canopy radiation models. This approach would resolve the issue if "fine structure" does exist, and if so, to what extent is it obscured by the plant canopy variability of soil, shadows, stems, litter, flowers, etc. Table 1 lists the principal areas of fine spectral structure that may be of value in the descrimination and monitoring of vegetation.

(4) Additional measurements are needed in the 1.1–2.5 μm wavelength region. In particular, preliminary evidence suggests the usefulness of the ~1.1–1.3 μm region for vegetation mapping and monitoring purposes.

(5) Concurrent with additional field and laboratory spectral measurements must occur measurements of target biophysical variables. These include plant canopy geometry, individual leaf reflectance and transmittance, and the more traditional variables such as growth stage, green leaf biomass, soil type, etc. The role of plant canopy geometry is crucial for successful modeling of the electromagnetic behavior of vegetation canopies. A discussion

TABLE 1. POSSIBLE SPECTRAL REGIONS WHERE FINE STRUCTURE MAY EXIST IN THE 0.4 – 14.0 μm REGIONS

Wavelength (μm)	Type of Feature	Possible Value
.440–.500	Absorbance	Detection of changes in chlorophyll/carotenoid ratios (related to stress).
.650–.700	Absorbance	Detection of chlorophyll states as well as tannin and anthocyanin content. Initial stress detection.
.700–.750	Reflectance	Senescence detection. Dead or dormant vegetation.
.800–.840	Absorbance	Possibly related to leaf anatomy and/or state of hydration.
.865	Reflectance	Height of feature may be useful in species discrimination.
.940–.980	Reflectance	Shifts in peaks may be related to leaf anatomy and/or morphology. May be useful for species discrimination.
1.140–1.200	Reflectance	Height of this feature very useful for species discrimination of senescent forest species. A ratio of this feature with the one at 1.645 μm offers a good indication of moisture content and thus stress.
1.630–1.660	Reflectance	An indication of moisture content of leaf. May also be an indicator of variation in leaf anatomy. May be useful for species discrimination. An indicator of leaf moisture content when used as a ratio with the 1.270 μm data above.
2.190–2.300	Reflectance	An indicator of moisture content. May also be of value in species discrimination.
3.000–5.000; 8.000–14.000	Reflectance/ Emittance	Little is known concerning the value of thermal IR data in the study of vegetation. This is an area that needs further study.

of this biophysical attribute is indicative of general considerations for all such parameters.

The special role of canopy geometry rises from the dual role it plays in analytical representations. First, because it represents the vehicle by which the individual scatterers are positioned throughout the media, a description is required either to calculate bulk-media average electromagnetic parameters or to build up composite scattering, emitting and absorbing behavior from individual element response. It may be easier to relate biophysical attributes to electromagnetic parameters at the individual-leaf level and then develop canopy-level distributions than to produce a direct sampling of the biophysical attribute, e.g., water in ignorance of the governing canopy geometry distributions which are being implicitly sampled. The second important role of canopy geometry arises because of changes in the status of vegetative condition. For example, stress is often manifested in a rearrangement of canopy structure. The detail to which canopy geometry must be specified depends upon the particular modeling approach used, whether cross-polarization response is required and so forth. For bulk-media approaches, average values may be adequate while for discrete scatter theories, detailed specifications may be more appropriate.

The first research issue in determining canopy geometry distributions and their variability in both the spatial and temporal domains is to clearly define the concepts and determine their applicability to the wide range of vegetation types encountered, including multicomponent vegetative structures (forest canopies, for example). The second research issue is to review and possibly develop further mathematical descriptions that have been used to characterize canopy structure. A third research issue is to review and probably develop further measurement techniques to characterize canopy geometry. Finally, there is the central problem of establishing the distributions for the targets of interest using well-established statistical methodologies for obtaining robust statistical estimates.

By canopy geometry, we mean individual canopy subelements, e.g., leaves, stems, morphology, component slope distributions, and the composite description of the spatial arrangement of the elements, usually referred to as canopy architecture. A considerable amount of theoretical work has been done by ecologists, plant geographers, and agronomists. Mathematical descriptions of canopy architecture are available from Idso and deWit (1970). Both traditional direct measurement techniques and indirect methods using light attenuation considerations, e.g., Norman, et al. (1979), are available. More recently, Smith and Berry (1979), Vanderbilt, et al. (1977) and Brach and Tejer (1980), have described more rapid and perhaps more appropriate techniques for remote sensing purposes. There is some evidence that only a finite number of distributions, perhaps convolved in different combinations, may be required to characterize broad classes of vegetation. For example, Idso and deWit (1970) characterize low-lying varieties such as crops and natural grassland into five broad types. However, the characterization of herbaceous and woody canopies has not been seriously addressed other than through broad parameterizations such as stem density and diameter at breast height (dBh).

The availability of experimental measurements is very limited. For all practical purposes, canopy geometry characterization has not been emphasized in remote-sensing field measurement programs. In the short term, a few carefully selected test cases should be conceived for simple vegetative media that seem appropriate to the existent models, e.g., relatively homogenous crop canopies at medium to high LAI. Extensive sampling, probably using the diffraction technique of Smith and Berry (1979) and the light attenuation approaches of Norman et al. (1979), should be made for LAI and leaf-slope distributions. An analysis of the variability in inferred distributions as a function of sample size, sampling volume, and so forth, should be made. Leaf morphology, i.e., shape and size, has been studied using both simple measurements of length, width, and boundary curve analysis. Another recommended approach is diffraction analysis as it has been applied by Ulaby, (1981) for determining corn leaf angle distribution. To a limited extent, laboratory evaluation of measurement techniques can occur simultaneously with the field characterization studies.

In a larger time-frame, the mathematical description or measurement of canopy geometry must be refined and expanded to handle the multi-component cases, heterogeneity which may require complete xyz specification, and evaluation on a broad range of canopy architectures.

The specification of the geometry parameter distributions can help guide the required sampling constraints for other biophysical parameters. The measurement, including sampling considerations, characterization, and definition of these other biophysical attributes involves the same research issues as for canopy geometry. That is, we are dealing with media for which very little is really known a priori about the underlying nature of the variable distributions or about their stability.

This information about the natural variability of biophysical parameters is fundamental to the design of experimentation to support modeling and empirical characterization. This requirement is common to all of the research objectives defined in the scene characterization and atmospheric effects category.

(6) There is a need to define the magnitude of the influence of temporal and spatial variations of environmental control parameters on the temperature and signatures of surface features.

The interpretation and measurement of thermal data for scene elements offers some particular difficulties because of the close coupling of the media to time dependent and spatially variant control factors. It is likely that integration times required to obtain meaningful measurements of the thermal signatures of categories will vary in a complex way with different types of scene elements under consideration. For example, the thermal response characteristics of an expanse of exposed bare soil are certainly different from those of a dense corn field. In some cases, it is not clear that a single static measurement of the thermal properties of scene elements is even meaningful.

Significant efforts have been undertaken, primarily by non-remote sensing specialists, to examine the dependence of the temperature of selected surface features on meteorological conditions. This is particularly true for agriculture applications, and to a lesser extent, forest environments. Studies of rangelands and other natural vegetative coverings is essentially nonexistent. Concurrent measurement of thermal exitance from a multitude of view angles is, however, limited. What measurements have been taken have usually been analyzed through empirical characterizations (Heilman, et al., 1976; Kimes, et al., 1980; Millard, et al., 1980), and parameters required for process-oriented modeling objectives have usually not been obtained.

The influence of temporal and spatial variations in wind fields and temperature gradients as well as other control variables needs to be examined for a whole range of vegetative and nonvegetative scene elements. It is important that experiments be performed for several conditions representing different but realistic scenarios, (for example, open, distributed, and continuous tree or crop canopies on flat or hilly terrain surfaces). Several diurnal cycles need to be sampled for different climatic variations. Such experiments are very costly and time consuming. The utilization of automatic recording instruments can facilitate this task.

(7) There is a requirement to obtain basic measurements of spectral emissivities and other electromagnetic parameters of scene elements.

In order to apply or develop analytic representations of the thermal behavior of renewable resource categories, the fundamental electromagnetic parameters must be determined.

There are isolated values available in the literature of measurements of such parameters for a variety of vegetation elements. Principally, the work of Gates, et al. (1965), should be noted. For other than vegetative scene elements and cultural features, very little data are available. The few measurements reported in the literature are used again and again in subsequent studies. The statistical distribution of these measurements and their variability with respect to different categories is not known. There is even difficulty in the interpretation of the measurement on emissivities for components of scene elements. When one examines an assemblage of components making up a particular category, (for example, a forest canopy composed of twigs, leaves, needles, understory of various assorted sizes and shapes, moisture conditions, and so forth), it is not always clear what should be measured.

There is a need to perform some fundamental laboratory measurements of basic components of interest for both vegetative and nonvegetative media. Experimental techniques must be carefully developed and examined for possible applicability to field conditions. Ultimately, a sufficient sampling must be undertaken for realistic field conditions in order to assess the variability of these parameters. Furthermore, the condition of the samples must be carefully documented.

(8) There is the need to develop relationships between thermal characteristics of scene elements and the more usually inferred or measured physical parameters.

A major problem in applying, evaluating, or extending existing models is our inability to use realistic input descriptors for a spectrum of materials and our lack of knowledge concerning the dynamic nature of these inputs. In order for applications of thermal modeling to develop the statistical distributions of scene radiance as a function of informational characteristics of scene elements, we need to describe changes in thermal properties with the changes in physical properties or with the biological characteristics of the media under consideration.

A reasonable understanding of the important thermal properties of materials that are required in order to predict the exitance exists (Kahle, 1977; Kimes, et al., 1979). Such a list would include the spectral emissivities and absorptivities of scene components, thermal conductivities, convection coefficients, and albedo factors. The dependence of these parameters on other descriptors of the media is not well understood.

Both laboratory and field experiments will be required to measure these parameters for the wide spectrum of conditions of scene elements of interest in the renewable resources program. The dependence of conductivity on moisture content in soils is one example. Carefully controlled experiments must be designed and measurement techniques may need to be developed.

ATMOSPHERIC EFFECTS UPON REMOTE SENSING OF VEGETATION

This section deals with the consideration of the variations introduced by atmospheric composition upon reflected and emitted electromagnetic radiation from vegetation and the associated background materials.

The principal causes of atmospheric attenuation of infrared radiation are absorption and scattering by molecular constituents and scattering by aerosols. The principal gas absorbers in the 1-15 μm region are CO_2, H_2O, and O_3. The superposition of absorption bands by these and other gases such as N_2O and CH_4 limits clear windows to regions: 8-9 μm, 10-12 μm, 3.5-4 μm, and narrow windows near 1.6 μm and 2.2 μm.

Absorption by O_3, N_2, and O_2 is very strong below 0.3 μm and windows are usually restricted to regions beyond 0.34 μm. The region between 0.4-1.0 μm is reasonably free of gaseous absorbers. However, some strong bands exist which should be avoided when conducting remote sensing experiments:

.6884	μm O_2
.7621	μm O_2
.9419	μm H_2O

A wide ozone band of moderate optical depth (.045) covers the region between .5-.7 μm, but is less than the Rayleigh scattering component at all wavelengths. Rayleigh scattering is due to the gaseous molecules and is most intense at low wavelengths (.38 μm) falling off (proportional to λ^{-4}) as wavelength is increased. Mie theory describes scattering by particles in the atmosphere when the diameter approximates the wavelength of the scattered light. Under Mie scattering most energy is scattered by a particle in two directions: back toward the source and away from the source. Therefore, under Mie scattering, one will "see" a halo around a source, and will see increased brightness in looking "down sun." Generally speaking, most aerosols and naturally occurring airborne materials do not absorb significantly in the visible regions of the spectrum, the one major exception being smoke. Beyond 1 μm both water and ice exhibit absorption which must be considered as a major effect on remote sensing, however, at longer wavelengths larger optical depths are required to produce equivalent attenuation. Vertical and horizontal variability of scatterers causes major uncertainty in algorithms designed to correct for atmospheric effects. Variable components include aerosols (.1-1 μm), active condensation nuclei (.1-10 μm), dust (1-100 μm), water droplets (.1-4.000 μm), and ice crystals (.1-200 μm).

The Botanical Sciences Team unanimously agreed that atmospheric effects strongly influence or dominate many spectral, spatial, and radiometric considerations for vegetational remote sensing. Specifically:

(1) There is an overriding measurement requirement to determine the variability of the underlying causative parameters affecting radiative transfer.

Specifically, these parameters include the spatial and temporal distributions of the absorbing gases such as ozone, water vapor, oxides of nitrogen, sulphur dioxide, and of the aerosols and cloud droplets as well as crystals. Furthermore, size distribution and the absorption characteristics of these non-molecular components should also be considered. For most applications, the shape of the aerosol particles is probably a factor of very low significance, but such is not the case with ice crystals which are generally aligned along the prevailing wind directions in the cirrus clouds.

The large scale distributions of many of these quantities have been of keen interest to several disciplines of the atmospheric science (e.g., atmospheric chemistry and optics, remote sensing of the atmospheric composition, and effects of dust on climate). DOD, NOAA, and NASA have several ongoing efforts which are applicable to our investigations. (Pitts, et al., 1977; Slater, 1980; Turner, 1979). The NASA Tropospheric Environmental Quality Remote Sensing program is relevant particularly in the areas of anthropogenic aerosols and salt particles. To some extent, these effects are also applicable to several mesoscale regions.

For remote sensing applications, much more attention on various characteristics of these parameters must be focused at the microlevel, and probably also at the mesolevel. Their variability on a scale of 1-1000 m is not understood. Some of the most important parameters are the absorption properties of aerosols which are generally inferred from the complex part of the refractive index of aerosol material. Some information about this aerosol parameter is readily available, but further measurement, especially in the agricultural regions of great interest, are strongly recommended.

(2) The relationship between available meteorological data and atmospheric optical parameters needs to be established.

A considerable effort has been put forth towards establishing relationships between several meteorological parameters such as air mass and relative humidity and some of the atmospheric optical parameters listed earlier. The Air Force Geophysics Laboratory and the Atmospheric Sciences Laboratory at White Sands, New Mexico, have sponsored such studies. The applicability of these efforts to many of the renewable resource target areas of interest to NASA, particularly at the microscale level required, remains limited.

A fruitful avenue proposed is for a NASA-sponsored basic research program in this area which would complement efforts of other agencies in the focusing of attention on the ground-level spectral measurements of the downward solar and total sky radiations. The use of ground-level and satellite-borne lidar systems should also be explored. Such measurements can then be correlated with air mass, relative humidity, and other atmospheric parameters. Regular measurements of total (not spectral) solar radiation are obtained at many Weather Bureau stations and some other locations. However, they are generally taken in the areas of least interest to agricultural remote sensing.

(3) There is a need to obtain the variation in scene radiance over significant atmospheric paths and arising from limited geographical areas, on the order of tens of meters, as a function of surface pattern. Vast quantities of aircraft and satellite measured radiance data exist and are continuously being obtained. These data can be used to partially satisfy this requirement.

The overriding requirement is to coordinate the measurement of scene radiance variation for a variety of atmospheric conditions with ground and aircraft experiments for which more detailed information on atmospheric parameters can be estimated.

The atmospheric effect that originates from the effect of nearby fields on the radiance above a given field (adjacency effect), is shown to affect the upward radiance, and thus cause reduction of the apparent resolution of satellite imagery acquired from space, and alter spectral responses (Kaufman and Fraser, 1981) resulting in misclassification of the surface fields. Although the conclusions are drawn from theoretical analyses, some experimental evidence of the existence of the adjacency effect shows the degradation of imagery acquired from space. But the same adjacency effect, in the presence of a sharp discontinuity in the surface reflectance, has the potential of serving as a tool for measuring the optical characteristics of the atmospheric aerosols. Radiances measured above such a discontinuity can be used to estimate the atmospheric optical thickness, single scattering and vertical scale height of the aerosols. Such data can then be used to correct the satellite data (to remove the atmospheric effect from the imagery), (Kaufman and Fraser, 1982).

In order to evaluate the actual importance of the radiative interaction between the surface nonuniformity and the atmospheric scattering, experiments have to be performed, in which all the physical quantities that take part in this phenomena are measured. These quantitites include: the horizontal pattern of the surface bidirectional reflectivity, the aerosol optical thickness, vertical profile of the volume extinction coefficient, scattering albedo and phase function, and the outgoing radiance at the top of the atomsphere (Kaufman and Fraser, 1982).

(4) The required atmospheric parameters necessary for understanding and simulating the remote sensing effects in the thermal regime are needed.

The remote sensing of renewable resources using the thermal regime will necessitate repetitive sampling of scene exitance, possibly over diurnal cycles, in order to determine the state or condition of terrestrial materials. This temporal sampling necessitates a clear understanding of the concomitant variability in the underlying aerosol distributions and profiles. Also, many of the remote sensing applications involve measurements of limited spatial extent. Thus, the variability of the underlying parameter structures required to simulate atmospheric effects must be determined at these scales.

Significant thermal work involving atmospheric considerations has been performed relative to climatic scales. Study of cloud effects is notable. The utilization of existing meteorological satellites has provided a significant background experience in large scale thermal characteristics of the atmosphere. The inversion of satellite radiance data in order to estimate underlying parameters has also been investigated.

In the near term, there is a need to perform some joint experimental programs involving both detailed surface characteristics and atmospheric considerations. For such areas, (agricultural regions during phenology cycles corresponding to dense vegetative cover and in the atmospheric window regions), fairly simple experiments can be designed to obtain the required parameters at the spatial and temporal scales required. During other portions of the phenological cycle when bare soil is exposed and dust generation occurs or in areas of potential pollution, more detailed measurement procedures and sampling will be required. For near point sources or line pollution sources, there will be a requirement to sample the two-dimensional variability of underlying absorbing aerosols as well as the simple vertical profiles.

SPATIAL, RADIOMETRIC, AND FREQUENCY OF OBSERVATION CONSIDERATIONS

SPATIAL RESOLUTION

Spatial resolution refers to the fineness of detail represented in an image; that is, the minimum size of objects on the ground which can be separately distinguished using multispectral imaging data. Just as the user of maps needs to know their scale, so the user of remotely sensed images needs to know the size distribution of the materials which they are interested in monitoring, mapping, or classifying.

Size distributions have been compiled in a survey form for the major U.S. government agencies (Inter-agency Task Force, 1979). These data show a bimodal distribution with the need for 10-30 m spatial resolution data, principally in the agricultural area, where field boundaries are a major source of misclassification and with a need in the large-area vegetation monitoring or climate area for spatial resolution of 500 m-5 km because of the need to repetitively monitor the terrestrial land surface. Additional target size distributions are needed to further assess the extent of spatial resolution requirements (Pitts and Badhwar, 1980).

It has been documented that as the spatial resolution decreases the percentage of classification error increases for some cover types. Clark and Bryant (1977), Thompson, et al. (1974), Langrebe, et al. (1977), and Kan, et al. (1975) have all reported these findings for urban land use types, crop types, and forest types. This results from several sources having the ability to resolve the spectral variation present in almost every cover type (as the resolution increases new classes become evident) and the adjacency effect caused by atmospheric scattering and the sensing system point spread function increases (Townshend, 1980; Fraser and Kaufman, 1981). Increasing spatial resolution then represents a "threshold" where improvements in this measuring capability result in the ability to measure increased variability within a given cover type and an increasing relative contribution from adjacent terrain.

Data from Landsat-D's thematic mapper and multispectral scanner and from the French SPOT solid-state satellite should provide an excellent means to document the extent of this trade-off between spatial resolution, within field variation, and the adjacency effect.

The increasing within-cover-type spectral variability with finer spatial resolution suggests that future classification techniques based upon this "textural" information may be possible and must be investigated. The degree to which multitemporal registration will be affected by finer spatial resolution systems also needs to be addressed.

RADIOMETRIC RESOLUTION

Radiometric resolution for remote sensing of vegetation involves the conversion of remotely sensed spectral radiances into some type of output signal from the sensor system in question. Usually this output signal is converted from an analog voltage to a digital binary word for telemetry to ground stations. The full range value is selected as the maximum radiance value which the sensor system will experience for the band in question under various illumination conditions. The interval between quantizing levels is simply the maximum radiance value divided by the number of quanitizing levels minus one.

A previous effort to address the question of satellite sensor system radiometric resolution has approached this problem by using aircraft multispectral scanner data (Morgenstern, et al., 1976). The procedure used for this type of radiometric resolution investigation involved using a simulation classifier and a set of scene cover-type spectral responses for an agricultural data set collected by an aircraft multispectral scanner. These data were employed to define decision boundaries for the various scene components. Pixels in the simulated scene were randomly generated from each of the spectral response distributions and were subsequently classified. Radiometric sensitivity was simulated by adding corresponding amounts of noise to the covariance matrices of the spectral responses. This simulation concluded that a noise equivalent change in reflectance (NE$\Delta\rho$) of 0.5 percent to 2.0 percent resulted in an overall decrease in classification accuracy from 87 percent to 80 percent, a classification accuracy decrease from 53 percent to 37 percent for highly stressed corn, and a classification accuracy decrease from 94 percent to 85 percent for soybeans. These simulation results addressed the specific question of how field center classification accuracy was affected by changes in NE$\Delta\rho$. The authors caution that actual classification or mensuration accuracy is a complex function of many factors, only one of which is field center accuracy (Morgenstern, <u>et al.</u>, 1976). Tucker (1980) investigated radiometric resolution requirements using ground-collected spectral data and a "noise-free" simulation approach. He reported that 7 to 8 bits were required to maintain spectral relationships for thematic mapper bands 3 and 4.

NE$\Delta\rho$ refers to the change in target spectral reflectance necessary to result in a spectral radiance value which is quantized by the sensor system in question into a higher or lower output signal vis-a-vis an "unchanged" or noisless target spectral reflectance. Where

$$\mathrm{NE}\Delta\rho = \frac{\text{(scene radiance)}}{\text{(Mean sensor signal)/(rms sensor noise)}} \cdot \frac{1}{\frac{2\ \text{(scene radiance)}}{2\rho}} \qquad (1)$$

$$\mathrm{NE}\Delta\rho = \text{NE radiance} \cdot \frac{2\rho}{2\ \text{radiance}} \qquad (2)$$

with ρ = spectral reflectance of target

NE = noise equivalent of sensor (i.e., generally electronic and quantizing noise)

rms = root mean square

The NEΔT thus represents the ability of a sensor system to detect a minimum change in target spectral reflectance (or NEPT for thermal channels). The smaller the numerical value for the NEPT or NEPT, the more sensitive any sensor system is to changes in target spectral radiances. Several factors besides quantization levels impact upon a sensor system's NEPρ performance. These factors include the intensity of the target incident spectral irradiance (solar zenith angle and atmospheric conditions) and the nature of the sensor system's optical and electronic design.

Target spectral radiances are in part reflected upward and, with the addition of atmospheric backscattered spectral radiances, both impinge upon the sensor's detectors at the satellite system's orbital altitude. In general the spectral radiances are converted by the detectors into an output signal (current or voltage) which is amplified and passed through a low-pass presample filter. The low-pass filter controls (1) the rms electronic noise; and (2) the high frequency aliasing due to targets smaller than a resolution element. The Nyquist theorem states that the total information in a band limited signal can be reconstructed if sampling occurs at 2 times the highest frequency component. Therefore, the low-pass presample filter minimizes the effect of high spatial frequency targets which can appear "aliased" as lower frequencies within the filter bandpass.

Electronic sampling then occurs to obtain voltage (analog) values for each pixel which are representative of the scene radiances. This sampled voltage is next converted from an analog level into a digital value by the analog/digital converter. This is a straightforward task where the input voltage is converted into the binary representation of the voltage level to which it most closely corresponds. The various bands for the system in question are multiplexed and encoded serially into a data stream which is telemetered directly or recorded for subsequent telemetry to ground receiving stations.

Radiometric resolution is thus faced with preserving spectral reflectance/radiance differences present in the scene as these target radiances propagate through the atmosphere, impinge upon the sensing system's detectors, and are subsequently quantized into digital counts. Atmospheric variability is introduced by atmospheric composition, atmospheric refraction, and by the "contamination" of adjacent pixels via the previously discussed adjacency effect. Instrumentation variability must be minimized by the control of detector response variability and by close spectral acceptance matching. Failure to adequately control detector variability will severely limit increased radiometric resolution.

The areas of previously suggested atmospheric effects research should provide the $NE\Delta\rho$ which is needed to provide maximum radiometric resolution. These results, coupled with the desired dynamic range for vegetated targets (i.e., < 5 percent reflectance in the visible and >70 percent reflectance in the near infrared) and the range of illumination conditions (i.e., equator at noon on the equinox and Siberia in the winter) will determine the radiometric resolution required for future multispectral imaging orbital systems.

FREQUENCY OF OBSERVATION

Remote sensing of vegetation studies have established that a measurement frequency of 4-6 days is needed to adequately monitor the occurance of episodic events like agricultural plant stresses and recovery from them as well as the crucial flowering/reproductive periods. When the probability of clouds ($P = .5$) is included, this requirement is increased to every 2-3 days. (Tucker, et al., 1980). Geobotanical studies have established that a 2-3 day sampling frequency is needed to record the relative onset of plant senescence as metal-stressed plants enter senescence sooner than non-stressed plants of the same species and locale (Labowitz et al., 1982). Studies of cloud distributions in selected tropical areas show that daily observations are needed in areas like the Amazon Basin of Brazil to obtain occasional cloud-free images.

These needs translate into two satellite data observation cycles: every 2-3 days when occasional clouds are considered and daily for other selected areas where cloudy conditions are usually the norm.

There is a need to collect data at hourly intervals from targets viewed under different illuminating conditions to evaluate the need for nonsun-synchronous orbits. The need to have a 2-3 day repeat frequency results in either many satellites (and an important calibration requirements among them) or having fewer satellites with each having a large swath width. For example, 3 NOAA-6 or NOAA-7 satellites in orbit simultaneously would provide data globally at 3-4 day intervals. However, in this case the atmospheric pathlength and directional reflectance differences must be understood to make use of this potential data source.

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GEOGRAPHIC SCIENCE TEAM

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

NEVIN BRYANT

EXECUTIVE SUMMARY: GEOGRAPHIC SCIENCE

INTRODUCTION

The field of Geography can be characterized by its broad interest in the identification, mapping, and understanding of the spatial distribution, use, and interrelationship of phenomena on Earth. Such a wide-ranging pursuit of knowledge naturally leads to overlap with the other Discipline Panels, with the result that the set of concerns was restricted to topography and cultural surface cover. Topography includes the detection of landform and drainage elements, contour mapping and digital terrain analysis. Culture includes the detection of manmade structures and changes to other surface cover classes caused by man's activities. Three panels were formed to address the geographic science issues: Land Use/Land Cover, Geomorphology, and Cartography.

Each panel developed a position statement on basic scientific rationale, the state-of-the-art, the potential contributions of multispectral imaging systems with extended spectral and spatial capabilities, and generic experiments to exemplify the quantum increase in utility anticipated from future remote sensing systems.

LAND USE/LAND COVER: Land Use/Land Cover forms an important component of a geographer's analysis of spatial patterns and their dynamics is the study of land use: "man's activities on the land which are directly related to the land," and land cover: "the natural and artificial constructions covering the land surface." There are two fundamental scientific rationales for the study of Land Use/Land Cover (LU/LC). LU/LC is a basic earth surface phenomenon of value in understanding the Earth's planetary systems. In addition, LU/LC is the surface expression of the critical interface between man and his activities and the Earth's physical system. As a result, LU/LC has long been recognized as an important area of geographic study.

The MSS and TM provide Level I and Level II information. Levels of LU/LC information obtained from remote sensing data have been described in the U.S. Geological Survey Professional Paper 964. Remote sensing inputs to Level

III information is currently derived from high resolution photographs. Multispectral data for Level III information extraction is currently unavailable for use in urban/suburban and critical/sensitive area analyses. Some trend analyses use MSS and high resolution areal photographic data. Geographic Information Systems that combine remote sensing data, terrain data and ancillary data are under development.

GEOMORPHOLOGY: Geomorphology studies the form and composition of the land and the processes which shape those forms. Land capability and suitability for any particular use is influenced by geomorphology. An understanding of processes involved in terrain development is integral to the quantitative study of landform and drainage elements (termed Terrain Analysis). There is a need for internally consistent areally extensive data that can be integrated with other environmental data for the quantitative analysis of process. In fact, a number of landform types that are characterized by limited areal and temporal expression often indicate destabilized conditions. Remotely sensed data can provide information which may lead to an improved understanding of processes influencing landforms and associated elements.

Traditional forms of remote sensing have been extensively used as data sources for geomorphic analysis. MSS data has proven useful for delineation of physiographic regions. TM will improve this capability. High resolution areal photography has provided the quantitative remote sensing data inputs required for process analyses.

CARTOGRAPHY: The demand for cartographic products at scales of 1:25,000 to 1:250,000 continues to increase throughout the world to meet requirements associated with the survey and management of natural resources, environmental planning, and the establishment of geo-referenced data bases. However, data compiled by the United Nations (1976) indicates that the demands for topographic maps at medium to large scale cannot be met in the near future by conventional mapping techniques. A satellite system involving the use of MLA sensors to meet cartographic requirements in terms of completeness of detail and geometric accuracy offers great promise for rapidly providing the data with which to produce topographic maps, digital terrain information, thematic maps, and image maps.

Approximately half the world is not mapped topographically at scales of 1:100,000 or larger. The MSS can provide horizontal planimetry at the scale 1:250,000. The TM has not been tested. Five meter resolution film data from Skylab was shown to provide 1:50,000 horizontal planimetry. Elevation information is currently acquired from ground surveys and/or high resolution stereo imagery.

REQUIREMENTS: It is evident from the Geographic Science Discipline's deliberations, that there exists a lack of significant fundamental research regarding the interaction between spectral/spatial resolution and the consistent recognition and display of topography and cultural surface cover. Fortunately, a few key experiments should rapidly identify promising sections of the visible and infrared spectrum, and the spatial resolutions required to achieve the desired levels of element descrimination and identification.

Table 1, Summary of Geographic Science Data Gaps, provides a prioritized summary of data gathering and analysis products required.* It should be noted that the most urgent needs are confined to land use/land cover and geomorphology research areas rather than cartography. This reflects the intensive feasibility study efforts undertaken by NASA (Stereosat) and the USGS (Mapsat) in recent years, which have resulted in a more complete understanding of requirements for viable future missions.

Table 2, Candidate Experiments, summarizes those research areas which promise to achieve the greatest contribution from future remote sensing missions. Table 3 summarizes the data requirements to undertake each experiment. The undertaking of these experiments, each with a high probability of successful execution, should dramatically improve the time scale where man has a better understanding of the Earth resources and trends in the habitability of our planet.

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*The first three priority areas can be pursued immediately, as they require the application of existing technology to geographic science experiments.

Table 1

PRIORITIZED SUMMARY OF GEOGRAPHIC SCIENCE DATA GAPS

1. BASIC SPECTROMETER DATA (NOTE EXPERIMENTS in Table 2)
   - SYSTEMATIC VARIATION IN SPATIAL RESOLUTION
   - NARROW WAVEBANDS; 0.3 - 12.4 MICRONS
   - VARIOUS CLIMATIC REGIMES AND ENVIRONMENTAL CONDITIONS
   - VARIOUS SEASONS
2. SPATIAL FREQUENCY INFORMATION ON COVER TYPES
3. ANALYZE INTERACTION OF SPATIAL RESOLUTION, TARGET HETEROGENEITY, AND SPECTRAL SIGNATURES FOR COVER TYPES
4. DEVELOPMENT OF CLASSIFICATION APPROACHES THAT MAXIMIZE UTILITY OF HIGHER RESOLUTION DATA
5. TIME SERIES DATA ACQUISITIONS WITHIN CLIMATIC REGIMES TO ASSESS BOTH SEPARABILITY OF COVER TYPES AND LAND COVER CHANGES
6. ACCURATE REGISTRATION AND RECTIFICATION
   - GIS DATA BASE DEVELOPMENT
   - ANCILLARY DATA INTEGRATION
   - STEREO AND OFF-NADIR DATA ACQUISITIONS
7. DATA FROM VERY STABLE PLATFORMS FOR CARTOGRAPHIC APPLICATIONS

Table 2

SUMMARY OF CANDIDATE EXPERIMENTS

I. LAND USE/LAND COVER

- URBAN/SUBURBAN LEVEL III LAND USE DESCRIMINATION
- URBAN VS. RURAL COVER TYPE DESCRIMINATION AND CHANGE DETECTION
- SURFACE MINING OPERATIONS DESCRIMINATION & RECLAIMATION MONITORING

II. GEOMORPHOLOGY

- PROCESSES INFLUENCING PERIGLACIAL LANDFORMS
- "CATASTROPHIC" EVENTS EFFECT UPON LANDFORMS
- SEMIARID AND ARID LANDFORMS SPECTRAL AND SPATIAL CHARACTERIZATION AND ASSOCIATIONS
- DRAINAGE NETWORK AND DRAINAGE BASIN ANALYSIS

III. CARTOGRAPHY

- COMPARISON OF FILM, AREA, AND LINE-ARRAY DATA
- INTERRELATIONSHIPS BETWEEN TOPOGRAPHY, SUN ELEVATION AND AZIMUTH, AND VIEWING DIRECTION AS RELATED TO INFORMATION EXTRACTION

Table 3

SUMMARY OF DATA REQUIREMENT FOR EXPERIMENT

I. Land Use/Land Cover

	URBAN LEVEL III	URBAN VS. RURAL III	SURFACE MINING III
FIELD SURVEYS	CRITICAL	CRITICAL	CRITICAL
SPECTRORADIOMETRY	CRITICAL	CRITICAL	CRITICAL
COLLATERAL DATA	YES	YES	YES
HIGH RES. PHOTOGRAPHY	CIR & PANCHROMATIC B&W	CIR	CIR
TEMPORAL REGISTRATION	(DYNAMICS 2 PIXELS)	(DYNAMICS 2 PIXELS)	(DYNAMICS 0.5 PIXEL)
RECTIFICATION	YES	YES	YES
BASE LINE SPATIAL RES.	5M	5M	5M
SPECTRAL REQ.*	0.4-12.4	0.4-12.4	0.4-12.4
TEMPORAL RES.	TIME SERIES	TIME SERIES	TIME SERIES
TERRAIN DATA**	N/A	N/A	YES
SPECIAL REQUIREMENTS	TIR, SWIR DIURNAL ACQUISITIONS	TIR, SWIR DIURNAL ACQUISITIONS	VARIATION IN LOOK ANGLES

* SPECIFIC BANDS TO BE DETERMINED

** EITHER EXISTING DTM OR FLIGHT EXPERIMENT

Table 3 (Con't)

SUMMARY OF DATA REQUIREMENTS FOR EXPERIMENTS

II GEOMORPHOLOGY

	PERIGLACIAL	ARID	CATOSTROPHIC EVENTS	DRAINAGE
FIELD SURVEYS	CRITICAL	CRITICAL	CRITICAL	CRITICAL
SPECTRORADOMETRY	CRITICAL	CRITICAL	CRITICAL	CRITICAL
COLLATERAL DATA	YES	YES	YES	YES
HIGH RESOLUTION	CIR	NATURAL COLOR	NATURAL COLOR OR CIR	NATURAL COLOR OR CIR
PHOTOGRAPHY				
TEMPORAL REGISTRATION	N/A	N/A	0.5 PIXEL CAPABILITY	N/A
RECTIFICATION	YES	YES	CRITICAL	CRITICAL
BASE LINE SPATIAL RES.	5M	5M	5-30M	5M
SPECTRAL REQ.*	0.4-12.4	0.4-12.4	0.4-12.4	0.4-12.4
TEMPORAL RES.	3 FLIGHTS JUN-SEPT	EACH SEASON	EVENT DEPENDENT	EACH SEASON
TERRAIN DATA**	YES	YES	YES	YES
SPECIAL REQ.	NOON OVERFLIGHT	HIGH & LOW SUN ANGLES	EVENT DEPENDENT	NONE

* SPECIFIC BANDS TO BE DETERMINED

** EITHER EXISTING DTM OR FLIGHT EXPERIMENT

SUMMARY OF DATA REQUIREMENTS FOR EXPERIMENT

III CARTOGRAPHY

	SENSOR COMPARISON	INTERRELATIONSHIP ANALYSIS
FIELD SURVEYS	YES	N/A
SPECTRORADIOMETRY	N/A	N/A
COLLATERAL DATA	YES	YES
HIGH RES. PHOTOGRAPHY	B&W VISIBLE AND IR	B&W VISIBLE AND IR
TEMPORAL REGISTRATION	N/A	N/A
RECTIFICATION	CRITICAL	CRITICAL
BASE LINE SPATIAL RES.	2M	2M
SPECTRAL REQ.	VIS & NIR	NIV & NIR
TEMPORAL RES.	N/A	N/A
TERRAIN DATA	STEREO PAIRS	STEREO PAIRS
SPECIAL REQUIREMENTS	EXTREMELY STABLE PLATFORM	EXTREMELY STABLE PLATFORM

GEOGRAPHIC SCIENCE TEAM

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GEOGRAPHIC SCIENCE

INTRODUCTION

The field of Geography can be characterized by its broad interest in the identification, mapping, and understanding of the spatial distribution, use, and interrelationship of phenomena on Earth. Such a wide-ranging pursuit of knowledge naturally leads to overlap with the other Discipline Panels, with the result that the set of concerns was restricted to topography and cultural surface cover. Topography includes the detection of landform and drainage elements, contour mapping and digital terrain analysis. Culture includes the detection of manmade structures and changes to other surface cover classes caused by man's activities. Three panels were formed to address the geographic science issues: Land Use/Land Cover, Geomorphology, and Cartography. The areas of concern for each panel are summarized below:

Land Use/Land Cover

Deals with the spatial and spectral resolution requirements for photo interpretation and/or multispectral pattern recognition of cultural surface cover. Of particular interest are the recognition of man-made structures in urban and urban fringe regions. Other topics of interest include the delineation of and detection of changes in the landscape created by man's activities, such as strip mines, roads and railroads.

Geomorphology

Is concerned with the spatial and spectral resolution requirements for photo interpretation and/or multispectral pattern recognition of geomorphic elements. Of particular interest are glacial and periglacial landforms, eolian and coastal landforms, and karst topography. Manmade landform elements, such as berms, dikes, and levees were considered. Drainage elements of particular interest would include perennial and intermittent stream beds, flood plains, and alluvial fans. Manmade drainage elements, such as canals, diversion channels, and spreading basins were also considered.

Cartography

Spatial and geometric resolution requirements for photographic/analog or digital photogrammetry from spaceborne sensors was the prime area of concern. Of particular concern are the impacts of National Map Accuracy requirements upon system precision to determine planimetric mapping and elevation at various scales (1:250,000 to 1:24,000). An analysis of relief effects upon off-nadir viewing was also of concern.

Each panel developed a position statement on basic scientific rationale, the state-of-the-art, the potential contributions of multispectral imaging systems with extended spectral and spatial capabilities; generic experiments use noted to exemplify the quantum increase in utility anticipated from future remote sensing systems.

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LAND USE/LAND COVER

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

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N85 11410

LAND USE/LAND COVER

Panel Members:

Richard E. Witmer, Chairman (USGS)
Jerry Clark (JPL)
Leonard Gaydos (USGS)
Robert Holz (University of Texas - Austin)
John Jensen (University of South Carolina)
Dale Quattrochi (NSTL)
Darrel Williams (GSFC)

LAND USE/LAND COVER

INTRODUCTION

Geographers analyze spatial patterns and their dynamics. An important component of that study is land use, "man's activities on the land which are directly related to the land" and land cover "the natural and artificial constructions covering the land surface." There are two basic scientific rationales for the study of Land Use/Land Cover (LU/LC): (1) LU/LC is a basic earth surface phenomenon, of value in understanding planetary systems. (2) LU/LC is the surface expression of the critical interface between man, his activities and the physical system. As a result, LU/LC has long been recognized as an important area of geographic study. There are also considerable practical rationales: (1) The demonstrated need for consistent and timely information concerning the status of land resources. (2) The need to assess trends, to monitor dynamics. (3) The need to use the information and an understanding of dynamics from building simulation models, in order to minimize impacts of conflicting LU/LC decisions.

Level III USGS classes (Anderson et al.) are needed to provide a quantum jump in usability of LU/LC data. (See Tables 1 and 2) Presently, some Level II classes (see Table 3) can be mapped from the MSS. High altitude imagery has been used to map all Level II classes. Improved spectral and spatial resolution are needed to map Level III and it is our next logical goal.

Justification

The user community (Federal agencies, State and regional agencies, local agencies, academia, private sector, etc.), in the U.S.A. and abroad, need: (1) Consistent and timely information on the uses being made of land resources (this is an inventory function). (2) Information on present land use/land cover patterns and changes in order to assess land use trends such as: urbanization patterns and impacts, degradation of environmental quality, loss of agricultural land, surface mining and other mineral extraction, impacts on wildlife habitat, land development conflicts, impacts on critical

TABLE 1

LAND USE AND COVER CLASSIFICATION LISTING

FROM FLORIDA LEVEL III SYSTEM*

100 URBAN AND BUILT-UP

- 110 Residential, Low Density (less than two DUPA*)
  - 111 Single Family Unit
  - 112 Mobile Home Units
  - 119 Low Density, Under Construction
- 120 Residential, Medium Density (two-five DUPA*)
  - 121 Single Family Unit
  - 122 Mobile Home Units
  - 123 Mixed Units
  - 129 Medium Density, Under Construction
- 130 Residential, High Density
  - 131 Single Unit (six and over DUPA**)
  - 132 Mobile Home Units (more than six DUPA**)
  - 133 Multiple Dwelling Units Low Rise (two stories or less)
  - 134 Multiple Dwelling Units High Rise (three stories or more)
  - 135 Mixed Units
  - 139 High Density, Under Construction
- 140 Commercial and Services
  - 141 Retail Sales and Services
  - 142 Wholesale Sales and Services (except warehousing associated with industrial use)
  - 143 Professional Services
  - 144 Cultural and Entertainment
  - 145 Tourist Services (hotel, motel)
  - 146 Oil and Gas Storage (except where associated with industrial use)

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*From Land Use, Cover, and Forms Classification Manual, State of Florida, Dept of Transportation, 1978, pp. 38-43.

**DUPA Dwelling Units per Acre

147 Mixed Commercial and Services
148 Cemeteries
149 Commercial or Service Under Construction

150 Industrial
151 Food Processing
152 Timber Processing
153 Mineral Processing
154 Oil and Gas Processing
155 Other Light Industrial
156 Other Heavy Industrial
159 Industrial Under Construction

160 Extractive
161 Strip Mines
162 Sand and Gravel
163 Rock Quarries
164 Oil and Gas Fields
165 Abandoned Mine and Fields
166 Reclaimed Land
167 Holding Ponds (mining, dredging, etc.)

170 Institutional
171 Educational Facilities
172 Religious
173 Military
174 Medical and Health Care
175 Governmental
176 Correctional
179 Institutional Under Construction

180 Recreational
181 Swimming Beach
182 Golf Courses

183 Race Tracks
184 Marinas and Fish Camps
185 Parks, Zoos
186 Community Recreational Facilities
187 Stadiums
188 Historical Sites
189 Other Recreational (riding stables, go-cart tracks, skeet ranges, etc.)

190 Open Land
191 Undeveloped Land within urban areas
192 Inactive Land with street pattern but without structures
193 Urban Land in transition without positive indicators of intended activity
194 Other Open Land

200 AGRICULTURE
210 Cropland and Pasture Land
211 Improved Pasture
212 Unimproved Pasture
213 Woodland Pasture
214 Row Crops
215 Field Crops

220 Tree Crops
221 Citrus Groves
222 Fruit Orchards
223 Other Groves (pecan, avocado, coconut, mango, etc.)

230 Feeding Operations
231 Cattle
232 Poultry
233 Hogs

240 Nurseries and Vineyards

- 241 Tree Nursery
- 242 Sod Farms
- 243 Ornamentals (perennial) - Shrubs
- 244 Vineyards
- 245 Floriculture (annual)

250 Specialty Farms

- 251 Horse Farms
- 252 Dairy
- 253 Kennels
- 254 Mariculture (fish farms)
- 259 Other

300 RANGELAND (Less than 20 percent tree crown closure)

310 Herbaceous

- 320 Shrub and Brushland
- 321 Palmetto Prairies
- 322 Coastal Scrub
- 329 Other Shrubs and Brush

330 Mixed Rangeland (any combination of the above)

400 FORESTLAND

410 Coniferous Forest

- 411 Pine Flatwoods (undifferentiated)
- 412 Longleaf-Xeric Oak
- 413 Sand Pine Scrub
- 414 Australian Pine *
- 415 Longleaf-Upland Oak
- 419 Other Pine

420 Hardwood Forest

- 421 Xeric Oak
- 422 Brazilian Pepper
- 423 Oak-Pine-Hickory

*Not a true pine

424 Malaleuca

425 Temperate Hammock

426 Tropical Hammock

427 Upland Temperate Hammock

428 Cabbage Palm

429 Wax Myrtle-Willow

430 Hardwood Forest (Continued)

431 Beech-Magnolia

432 Sand Live Oak

438 Mixed Hardwood

439 Other Hardwood

440 Tree Plantations

441 Coniferous

442 Hardwood

443 Regeneration Area

500 WATER

510 Streams and Waterways

520 Lakes

521 Lakes larger than 500 acres

522 Lakes larger than 100 acres but less than 500 acres

523 Lakes less than 100 acres but greater than 10 acres

524 Lakes less than 10 acres which are dominant features

530 Reservoirs

531 Reservoirs larger than 500 acres

532 Reservoirs larger than 100 acres but less than 500 acres

533 Reservoirs larger than 10 acres but less than 100 acres

540 Bays and Estuaries

541 Opening directly into the Gulf or Atlantic Ocean

542 Not opening directly into the Gulf or Atlantic Ocean

550 Major Springs

600 WETLANDS

- 610 Hardwood Forest
  - 611 Bay Swamp
  - 612 Mangrove Swamp
  - 613 Gum Swamp
  - 614 Titi Swamp
  - 615 River and Lake Swamp

- 620 Coniferous Forest
  - 621 Cypress
  - 622 Pond Pine
  - 623 Atlantic White Cedar

- 630 Forested-Mixed

- 640 Vegetated Non-Forested
  - 641 Freshwater Marsh
  - 642 Saltwater Marsh
    - 642(1) Cordgrass (Spartina)
    - 642(2) Needlerush (Juncus)
  - 643 Wet Prairies

- 650 Non-Vegetated
  - 651 Tidal Flats
  - 652 Shorelines
  - 653 Intermittent Pond

700 BARREN LAND

- 710 Beaches Other Than Swimming Beaches

- 720 Sand Other Than Beaches

- 730 Exposed Rock

740 Disturbed Lands

741 Rural Land in transition without positive indicators or intended activity

742 Borrow Areas

743 Spoil Areas

744 Fill Areas (highways-railways)

800 TRANSPORTATION, COMMUNICATION AND UTILITIES

810 Transportation

811 Airports

812 Railroads

813 Bus and Truck Terminals

814 Major Highways

815 Port Facilities

816 Canal Locks

817 Oil, Water, or Gas Long Distance Transmission Lines

818 Auto Parking Facilities (when not directly related to other land use)

819 Transportation Facilities Under Construction

820 Communications

821 Transmission Towers

822 Communication Facilities

829 Communication Facilities Under Construction

830 Utilities

831 Electrical Power Facilities

832 Electrical Power Transmission Lines

833 Water Supply Plants (including pumping stations)

834 Sewage Treatment

835 Solid Waste Disposal

839 Utilities Under Construction

900 THIS SECTION RESERVED FOR SPECIAL CLASSIFICATION

TABLE 2

LEVEL III's SUBDIVISION OF RESIDENTIAL LAND*

I. URBAN AND BUILT-UP

11. Residential - residential land use is based on a density factor for dwelling units per hectare. Each residential area will be delineated to include houses, garages, sheds, lawn and streets. The dwelling unit per hectare density is determined as follows:

$$\text{Residential Density} = \frac{\text{structures}}{\text{hectare}} \times \frac{\text{units}}{\text{structure}} = \frac{\text{units}}{\text{hectare}}$$

Criteria: Any area of one hectare or more where dwelling units predominate is mapped as residential. The residential areas will be subdivided if necessary into the following Level III and Level IV categories:

111. one and under units per hectare
112. over one to eight units per hectare
113. over eight units per hectare

This last category will be further subdivided into single family dwelling units amd multi-family dwelling units.

1131 - single family dwelling units
1132 - multi-family dwelling units

In many cases, mobile home parks will be classified as 1131.

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*Level III subdivision of residential land, developed for cooperative land use/ land cover mapping project between U.S.G.S. and San Mateo County, California.

TABLE 3

USGS LAND USE AND LAND COVER CLASSIFICATION SYSTEM FOR USE WITH REMOTE SENSOR DATA

	Level I		Level II
1.	Urban or built-up land	11.	Residential
		12.	Commercial and services
		13.	Industrial
		14.	Transportation, communications, and utilities
		15.	Industrial and commercial complexes
		16.	Mixed urban or built-up land
		17.	Other urban or built-up land
2.	Agricultural land	21.	Cropland and pasture
		22.	Orchards, groves, vineyards, nurseries, and ornamental horticultural areas
		23.	Confined feeding operations
		24.	Other agricultural land
3.	Rangeland	31.	Herbaceous rangeland
		32.	Shrub and brush rangeland
		33.	Mixed rangeland
4.	Forest land	41.	Deciduous forest land
		42.	Evergreen forest land
		43.	Mixed forest land

TABLE 3 (Cont'd)

5.	Water	51.	Streams and canals
		52.	Lakes
		53.	Reservoirs
		54.	Bays and estuaries
6.	Wetland	61.	Forested wetland
		62.	Nonforested wetland
7.	Barren land	71.	Dry salt flats
		72.	Beaches
		73.	Sandy areas other than beaches
		74.	Bare exposed rock
		75.	Strip mines, quarries and gravel pits
		76.	Transitional areas
		77.	Mixed barren land
8.	Tundra	81.	Shrub and brush tundra
		82.	Herbaceous tundra
		83.	Bare ground tundra
		84.	Wet tundra
		85.	Mixed tundra
9.	Perennial snow or ice	91.	Perennial snowfields
		92.	Glaciers

From: U.S.G.S. Professional Paper 964, 1976. Anderson et. al.

and sensitive areas, pressures on public land. (3) Current land use/land cover information in order to minimize the impacts of events such as: catastrophic natural hazards (volcanic eruptions, floods, earthquakes, wildfire, etc.); other natural hazards (landslides, subsidence, etc.); man-induced hazards (nuclear accident, dam failure, etc.); toxic waste disposal; disruptive development (highway routing, etc.).

In order to create a usable structure for considering the enormous number of potential Level III land use/land cover situations, a matrix was created (see Figure 1) which treats several large subdivisions of the landscape (i.e., urban/suburban, rural, and critical/sensitive areas), in light of the major utility functions of land use/land cover data and information (i.e., inventory, change, simulation and modelling, and impact assessment). In this matrix, land use activities may be thought of as high contrast targets against a land cover background. Specific samples of Level III Land Use/Land Cover data needs, state-of-the art data extraction capability, capability gaps, and candidate experiments designed to close those gaps are presented for several of the intersections in the left-hand side of the matrix. Even though the rural landscape dominates Land Use/Land Cover study, it was the feeling of the panel that examination of requirements for specific Level III rural types should be left to the Botany team. Discussion of rural considerations was concentrated instead on examining problems that those cover types present in mapping Level III urban/suburban and critical/sensitive types. It should be emphasized, however, that geographic science remains extremely interested in all classes of Land Use/Land Cover, and especially in the spatial distribution of the phenomena. This contrasts with some requirements of the Botany group for analysis of remotely sensed data for statistical estimation only. Requirements the Botany group has for mapped data would dove-tail quite nicely with requirements geographers analyzing Land Use/Land Cover patterns would have.

The key to data gathering and consistent categorization of any group of Level III categories which comprise a Level II category lies in the proper identification of the discriminant function which separates the Level III classes. Figure 2 illustrates several aspects of that process. The chart presumes that the information needs for the Level III classes have been

	INVENTORY	CHANGE	SIM/MODELLING	IMPACTS
URBAN/SUBURBAN (RES. DENSITY)				
RURAL (FOREST LAND) (AGR. LAND ETC.)				
CRITICAL/SENSITIVE (SURFACE MINING)				

← INFO EXTRACTION → ← INFO ANALYSIS →

FIGURE 1. LEVEL III LU/LC RESEARCH PRIORITIES

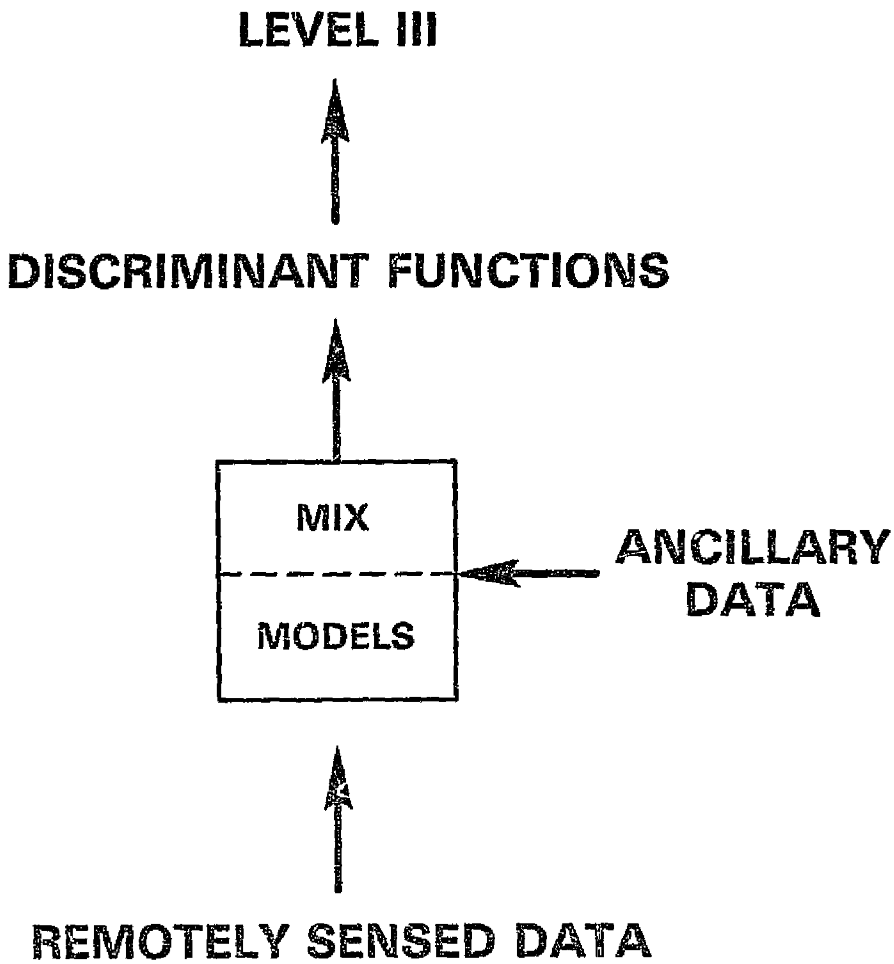

FIGURE 2. SPATIAL, SPECTRAL, RADIOMETRIC & TEMPORAL REQUIREMENTS

identified and the discriminant functions determined. Maximum use of remotely sensed data in identifying Level III classes is the goal. The critical point in the process which flows from data input through the discriminant functions to the ultimate derivation of Level III categories is the appropriate determination of the mix of remotely sensed and ancillary data sets. An example of one assessment of spatial resolutions necessary to achieve differing class levels is given in Figure 3, but it should be emphasized again that many specific Level III classes will need ancillary data.

At the present time the remotely sensed data are provided largely in the form of aerial photographs limited in regional extent. Spectral data are used very little, and the dynamics of the phenomena at Level III have been largely ignored. By and large, much ancillary data need to be added (field data, mapped data, etc.) in order to create consistent Level III classes. In doing so, Level III knowledge is gathered and can be modelled. Once the structure and process models are created, sensor systems (and their related data handling systems and product output systems) can be designed. Those systems should try to optimize the spatial, spectral, and temporal requirements needed to properly exercise the discriminant function.

Urban Suburban Landscape

Justification and Statement of the Problem. The majority of urban land use mapping in the United States and the world is based on the use of relatively large scale metric aerial photographs (scales larger than 1:50,000). Using such imagery, analysts usually extract Level III Land Use/Land Cover information for a diverse array of applications, many of which are civil engineering in nature. Consequently, such users have found the 80 meter spatial resolution data of Landsat inadequate for their urban Land Use/Land Cover mapping requirements. Even the 30 meter spatial resolution data from the proposed Thematic Mapper will not provide the needed detail. Thus, there exists a large user group in every town and county which currently discounts the NASA sponsored remote sensing program because it cannot provide the spatial resolution necessary to accurately inventory urban land use at the local level. If NASA produces a sensor which provides such data, it will tap a vast cross-section of the community which actively uses remotely sensed data.

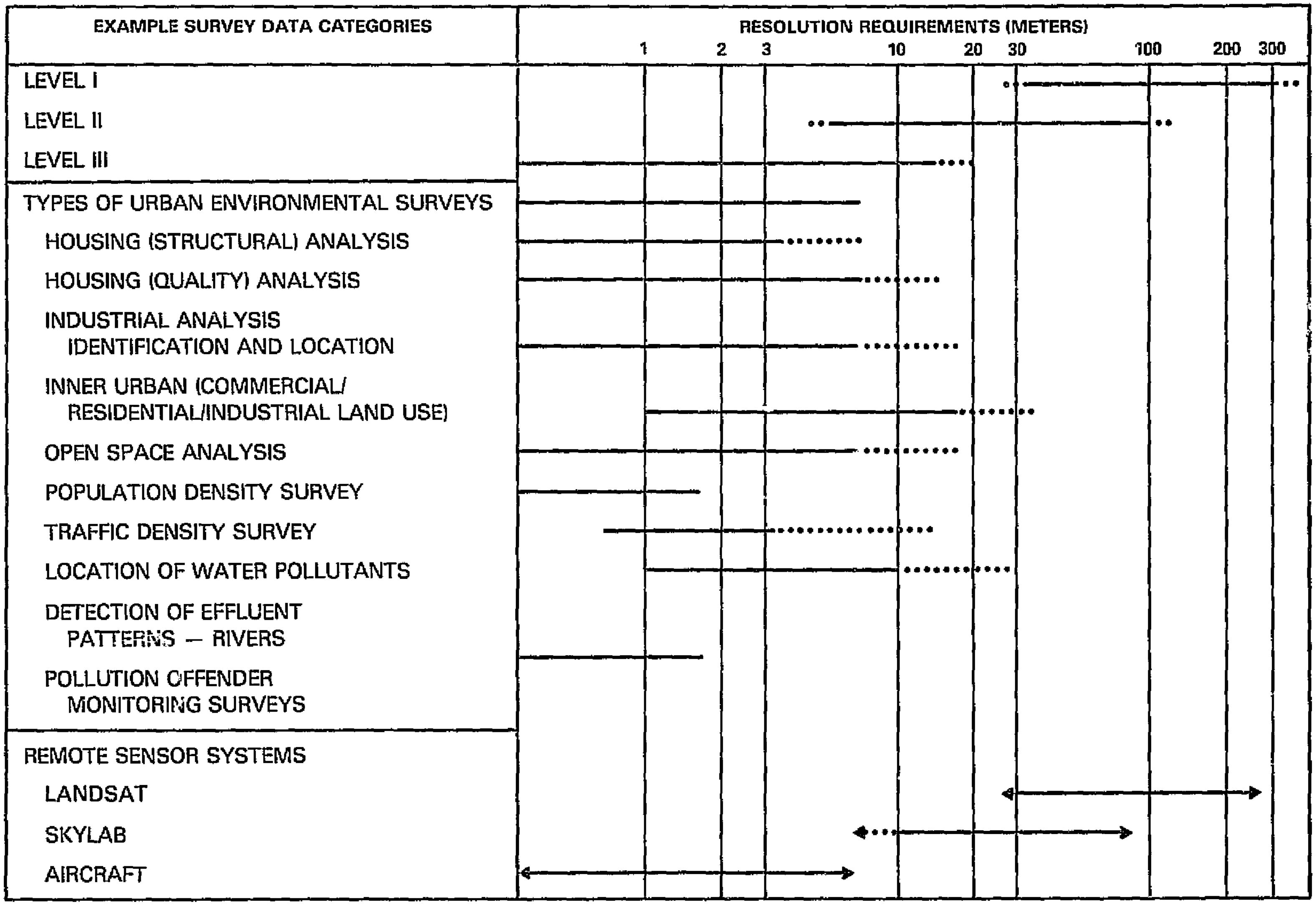

FIGURE 3. FROM: MANUAL OF REMOTE SENSING, 1975 (VOL. II)

Requirements. The Level III land use and land cover categories for the Level I "Urban and Built-up" Category represent the variables of interest. In an urban/suburban environment it has been shown that there is a need for specific spatial, spectral, and temporal resolution data. Figure 4 suggests that in order to extract Level III information with good 'completeness' that a range from 1-5 meter spatial resolution is required (Welch, 1978). Obviously, there must be sufficient object to background contrast to differentiate between the edges of dissimilar materials. This is where the spectral resolution is important. However, for urban/suburban applications it appears two or three relatively broad bands in conjunction with high spatial resolution data are sufficient for accurate Level III inventory. The temporal measurement of the Level III categories ranges from approximately hourly for transportation studies to multiple years for update and change detection studies.

State-of-the-art and Gaps in Knowledge. Level III Land Use mapping in the urban/suburban environment can currently be performed using only high resolution aerial photographs.[1] Such a methodology has imperfections including: (1) Aircraft mobilization costs; (2) Data set inconsistencies between dates, (including geometric variations between frames or dates, radiometric variations associated with sun angle, atmospherics, possible vignetting, film processing.) In spite of these imperfections, it is possible to accurately map Level III using aircraft data and manual photo interpretation techniques after applying appropriate radiometric and geometric corrections to the data. At present, we are unable to detect Level III categories from a satellite platform. In addition, given that that sensor would be a digital system we have no information on the following: The Level III urban classes are primarily composed of concrete, asphalt, wood, vegetation, glass, soil and water. Man configures these materials into unique structures which vary considerably geographically owing to diverse environments and cultural patterns. These are manifested in quite diverse urban morphologies world wide (note Figure 5) complicating our problem significantly. We currently have almost no spectra available to understand the interaction of electromagnetic radiation with these materials in an urban environment.

[1]Footnote - Another discussion of current state-of-the-art and considerations for improved sensors is included in the Geography Section of Volume III.

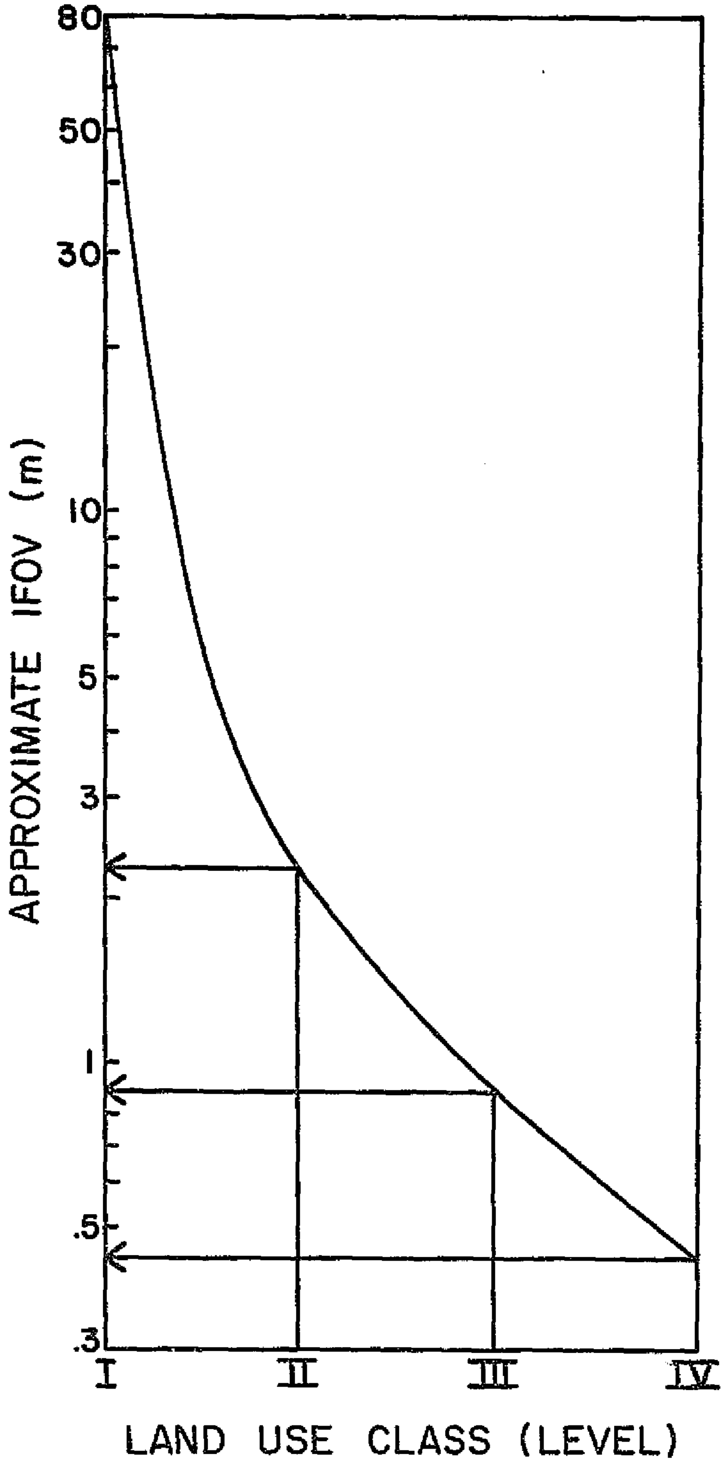

FIGURE 4. SOURCE: WELCH (1978)

Generic Experiments. Using an Area (Linear) Array sensor, systematically evaluate the following or the Level III urban categories of major metropolitan cities:

1. Investigate the significance of having various spatial resolutions, especially 5, 10, 20 and 40 meters IFOV. This is done by aggregating various column elements of the array spectroradiometer. The spectral resolution should be held constant.

2. Investigate the significance of having various spectral resolutions, throughout the 0.3-2.55 μm region, by aggregating various row elements of the array spectroradiometer. The spatial resolution should be held constant.

3. Identify where "interaction" occurs between spatial and spectral resolution using an analysis of variance approach. This would require a systematic variation of both spectral and spatial resolution using the area array system.

The above research could first be performed using aircraft platforms. Also, the research should be performed using a variety of central business districts and urban fringe areas throughout the world. This will document the geographic 'extendability' of the spatial and spectral resolution results. The above experiment should also be conducted in conjunction with some intensive spectroradiometer data collection for a few well selected test sites. The spectra would be necessary for detailed theoretical evaluation of the airborne data. Once the aircraft/spacecraft data are obtained, evaluate the utility of manual analysis, digital analysis, hybrid manual/digital techniques. Further research should be invested developing classifiers to use with improved spectral/spatial resolution data in the urban environment.

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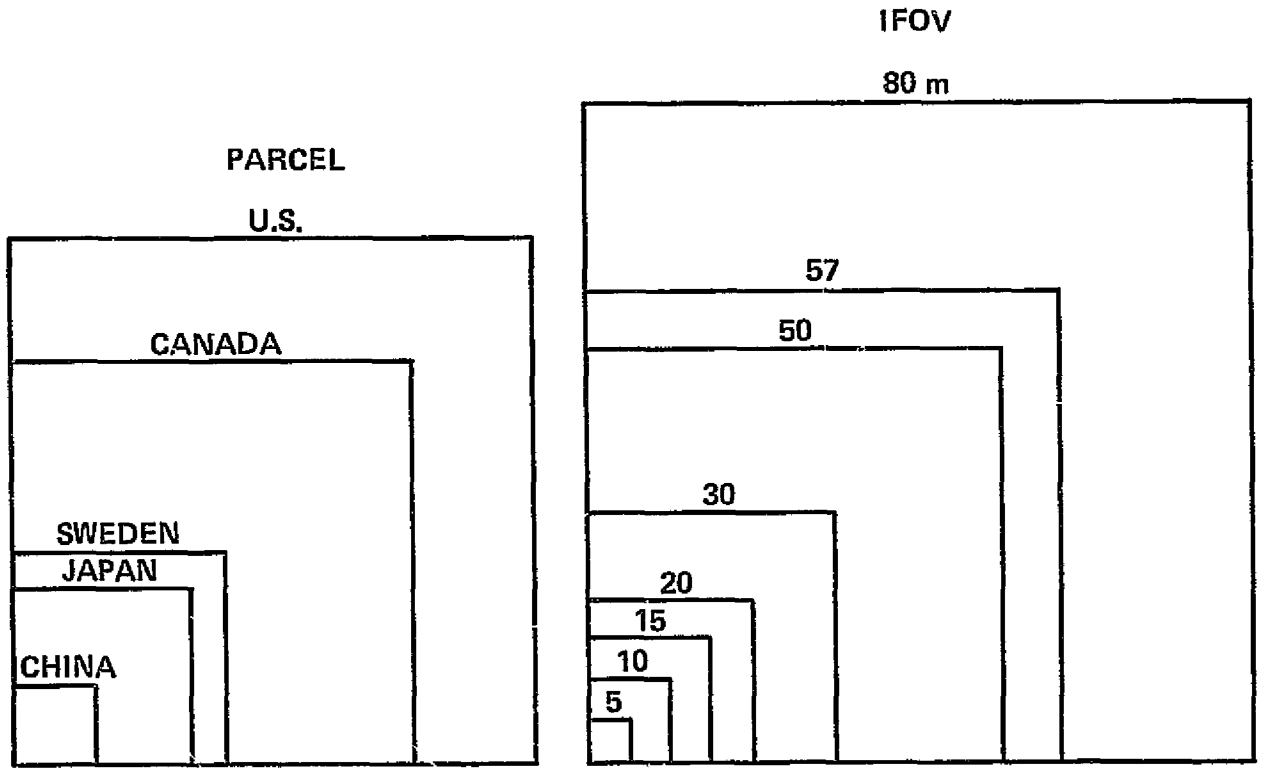

THE AVERAGE URBAN LAND PARCEL SIZES IN DIFFERENT COUNTRIES COMPARED TO IFOV's OF 5 TO 80 M. SPATIAL RESOLUTION REQUIREMENTS WILL VARY WITH GEOGRAPHIC REGION.

FIGURE 5. SOURCE: R. WELCH, UNIVERSITY OF GEORGIA

Change Detection

Justification and Statement of the Problem. Detection of land use/land cover change over time is an important analytical function because it isolates the dynamic changes affecting the character of the landscape over time (Friedman, 1979, Peplies, 1976). The detection of changes allows comparisons of the current use with past uses to help the study of development or abandonment trends. Changes in cultural features might be expressed as changes from non-urban to urban (changes expressed in gross shifts between Level I classes) or changes from one land use class to another (whether it be within the same level or between levels). The pivotal problem in the detection of change is the registration of multidate imagery, because multiple dates provide the spatial and spectral indications of land use change over changes in time. The need to register multiple dates to extract indications of change is complicated by: 1) the necessity to spatially-register common points between images, because misregistration will prejudice the change map; 2) differences in scene spectral response over time, because thematic classifications may not be comparable; and 3) the need to choose data acquired on the most useable dates, because the choice must be sensitive to seasonal changes and stage of development or abandonment.

Requirements. The requirements for sensor data used to detect or monitor change are determined by the variable spatial, spectral, and temporal attributes of imagery. Spatial variations within an image affect the success of registration between images allowing the features of one image to spatially match the features of another. Spatial variations related to the anomalous movement of the platform complicate the ability to register common features in the area. Spatial variations caused by sensor anomolies, such as systematic panorama effect and mirror-scan velocity problems (Sabins, 1978), will be sensor specific. Spatial variations caused by registration technique (image-to-image, or image-to-map base) or the method for control point selection (auto-correlation between images, or analyst choice of points between images, or analyst choice of points between image and map) will affect registration. Spatial variations between images can also be caused by choice of algorithms to geometrically reorient the imagery, such as surface fit or local anomaly corrections. Spectral variations between dates affect the possibility of producing consistent classifications between dates. Spectral variations can result from changes in atmospheric conditions and sensor calibration problems (Goetz, et al., 1975). Spectral variations will be caused by differences in seasons. Spectral variations between dates will be introduced during geometric rectification of one image to another, or during geometric reprojection of images to map base. Locally, of course, spectral variations between dates can result from changes in land use. Temporal variations, on a periodic schedule, provide the basis for change detection studies. Temporal variations can cause spectral variations because of seasonal differences, atmospheric conditions, and sensor calibration problems, as well as change in land use. Temporal variations useful for change detection depend on a periodic return of the sensor to resample the scene. With these spatial, spectral, and temporal variations in mind, sensor requirements for minimizing spatial variations include a stable sensor platform and the absence of systematic sensor anomalies. A well-calibrated sensor would minimize spectral variations.

State-of-the-Art and Gaps in Knowledge. State-of-the-art for image registration in support of change detection studies include the image-to-image method and the image-to-map base method. With the image-to-image method, two dates are registered using one image of the pair as the base image. This is the approach used for the Landsat-3 MDP registrations. The two images are registered to each other based on common points which are features identified in one image so that those feature locations become the basis for rectifying that image to match the base image. With the image-to-map base method (Clark, 1980) two dates are registered using a map base as the method for relating one to the other. Two images are registered to each other by control points that relate the image coordinate system to the map coordinate system. The image control points are converted to an image-based coordinate system analogous to the map coordinate system and projected in its map projection. A gap in the state-of-the-art is the need to recognize what loss of spectral information occurs between an image in its original form and its rectified or reprojected form.

Generic Experiments. Experiments to test the spatial, spectral, and temporal attributes of image data as they relate to change detection include:

1. Development of a geometric correction algorithm to permit local anomaly corrections within a surface fit. (This would be especially useful for simulation studies using aircraft data.)

2. Development of methods for recognizing and minimizing spectral variations between images due to atmospheric conditions, sensor gain and calibration problems, and seasonal differences

3. Study of difference in classification results in multiple dates due to the differences in registration technique

4. Determination of whether or not the change detection capabilities are controlled by the stages in the process; in other words, determine when the change, as evidenced on the ground, becomes apparent in the image.

Rural (Land Use/Land Cover)

Justification and Statement of Problem. Rural Land Use/Land Cover occurs in close association with urban/suburban areas and critical/sensitive areas. There is a need to understand the total scene components (spectral, spatial, temporal and their interactions) that exist in the urban-rural transition zone.

Over the past several years, a majority of the funding for remote sensing research with spacecraft acquired data has gone to agricultural and forestry investigations, but these investigations have not considered the potential spectral and spatial conflicts with urban/suburban or critical/sensitive areas (or enclaves of agriculture or forest within urbanized areas). In other words, agriculture/forestry researchers have only looked at their cover types of interest in rural settings which do not include urban/suburban cover types, and therefore, scientists are not aware of spectral/spatial conflicts. However, some of the most productive agricultural and forestry lands are located in areas where there is increasing pressure for: (a) urban development/expansion and/or (b) extraction of energy or mineral resources using surface mining techniques. As population grows and urban areas expand, the frequency of agriculture/forestry practices adjacent to urban areas will increase.

Requirements. The variables of interest are those rural land covers that will tend to conflict with urban land covers, especially in the spectral domain. In general, the extent of diversity of cover types (and variables) in rural areas is primarily limited to differences in the size and shape of fields, forest stands, etc. even on a global basis. However, in urban areas there is greater diversity in scene variables due to cultural differences, physical settings and the tendency of building materials to be first order derivatives of local natural materials, especially in the lesser development countries (i.e., mud huts in Africa vs. concrete, steel, aluminum, wood, etc. used in the U.S.).

Several specific examples of variables which may cause conflict in successfully differentiating rural vs. urban land use/land cover categories follows:

Rural		Urban
Water (farm ponds, etc.)	vs.	Pools
Wetlands	vs.	Dark surfaces (asphalt, etc.)
Contiguous forestland	vs.	Sporadic trees lining streets
Agricultural fields	vs.	Garden plots
Pasture	vs.	Lawns, golf courses
Range land	vs.	Vacant lots
Barren ground	vs.	Cement, vacant lots

State-of-the Art and Gaps in Knowledge. Due to the greater research emphasis over the past on agriculture/forestry cover types, and the lesser diversity of variables associated with these cover types, our ability to inventory rural Land Use/Land Cover at Level II is fairly reliable (especially for agriculture, forestry, tundra, rangeland). By contrast, our ability to inventory urban cover types with MSS data is primarily limited to Level I, with occasional subdivision into Level II categories such as residential, and commercial.

A fairly good source of *in situ* spectral measurements exists for agricultural crops and range land, but there is a paucity of spectral data for forest cover types and urban cover types. The monitoring of change in urban areas using MSS data has met with limited success, whereas several good examples of monitoring change in rural settings exist. Agriculturalists routinely use multitemporal analyses within a single growing season to predict yield. Several examples of monitoring forest insect infestation, fires, large scale harvesting of forest land, and disturbances due to surface mining exist. In a similar manner, a great deal of progress has been made in developing simulation models and assessing impacts for rural Land Use/Land Cover, particularly for agricultural crops, i.e., the models for estimating crop yields and standing green biomass. To the best of our knowledge, no such examples of simulation models or impact assessments exist for urban/suburban areas which rely on digital remotely sensed data.

In summary, a number of information gaps exist in the state-of-the-art for remote sensing of urban/suburban land use at Level II and III. These gaps include:

1. A better understanding of urban spectra and how they conflict with spectra associated with rural land use/land cover (Spectra should be collected seasonally, geographically, and in association with changing weather conditions so that their variation can be understood.)

2. A need to understand the spatial/textural relationships within urban and rural areas and between them

3. A need to develop spectral/spatial or contextual classification algorithms to more efficiently and accurately extract information from higher resolution data. (Present algorithms are mostly based on a per pixel approach which uses only one element of information (color) available in multispectral digital data. (Markam and Townshend, 1981, and Latty and Hoffer, 1981).

Generic Experiment. Additional research into spectral, spatial, and temporal differences between rural land covers and urban or critical/sensitive land covers needs to be conducted to aid in the separation of Level III classes.

Spectral. There is a basic need to compare spectral data between rural and urban or critical/sensitive cover types. Spectra have probably been collected in sufficient quantity for most agricultural and range-land types, but these should be examined to ensure that adequate representation of these types likely to be in close association with the urban area (like stressed orchards scheduled for urban development) is available. Additionally, there is a great need to acquire spectra data for urban forest cover since very little presently exists. Spectral data for all these cover types needs to be collected over wide geographic ranges, seasonal conditions, slopes, aspects and for varying examples of diverse urban morphology. Data should first be collected *in situ* and later by air using spectroradiometers. These will be quite valuable to researchers defining spectral considerations for mapping Level III types. The main object of this specific research lays in comparing spectral data collected in both rural and urban areas, determining the conflicts known to exist but which have not previously been quantified, and proposing means of resolving conflicts.

Spatial. Little attention by remote sensoring researchers has been paid to the nature of the urban/rural fringe. This region, which has continually caused problems to those working in both rural and urban regions, is poorly understood. We need to study the spatial characteristics of intermixing of urban and rural types in the fringe area in different geographic regions reflecting different settlement and growth patterns. Additionally, attention should be particularly paid to specific subclasses of both urban and rural types such as recently begun residential subdivisions and abandoned fields, that exist in this zone in a heterogenous mix. Study of the nature of the region where problems in mapping exist will aid in our basic understanding of the region and potentially suggest new ways of dealing with problems that occur. We must also study spatial characteristics of both urban and rural classes that tend to conflict at a very detailed level. The spatial aspects of the intermixing of basic classes (concrete, shingles, lawns, trees, etc.) that exist in residential neighborhoods must be researched and understood. The great diversity of residential types is an important factor here. At the same time, spatial patterns of rural classes with spectral signatures that tend to confuse with these urban types (bare ground, soil, pasture, forestland, etc.) must also be examined with an eye towards quantifying the differences. Examination of these spatial patterns is absolutely critical for designing those pattern recognition algorithms that will be able to incorporate these patterns in new discriminant functions. Improved algorithms are needed now to deal with Thematic Mapper data and will be even more important in the future. It is thought that recent advances in fields like robotics, cybernetics, and artificial intelligence may be applicable towards development of these algorithms.

Temporal. There is a special need to increase our understanding of how land changes from rural to urban or surface mining uses. We need to quantify the stages of change, discover the longevity of each, examine the spectral and spatial natures of each, and find out what rural classes these stages of development conflict with. The work of Jensen (1981) and Ellefsen (1974) have made some progress in this area, but much more work remains.

Critical/Sensitive Areas (As exemplified by Surface Mines)

Justification and Statement of the Problem. Surface mines include any type of disturbance of the surfacial land cover for the extraction of minerals or other materials. Surface mines seriously disturb the existing land cover, and causes severe environmental problems; e.g., potential pollution of surface and ground water sources, aeolian deposition of wind blown materials, erosion of soil to nearby lands, and finding alternative uses for mined lands. In addition, there can be potential flooding from deliberate or unintentional damming of water.

As spatial features, the composition of signatures internal to surface mines inhibits discrimination of land cover units within a Level III context. In monitoring reclamation states, a problem exists in the identification of reclamation progress on a micro-spatial scale.

Requirement. Need for discrimination of surface mines includes a need to monitor surface mines through time. We need to monitor and map changes from active to inactive stages. Map location and size of storage retention areas. Monitor the placement and condition of haulage roads. Map shallow and deep ponded water. Monitor the continual growth of mines; (i.e., size, shape, and direction of growth). Monitor reclamation stages; (i.e., monitor land cover units within reclaimed areas). Monitor impact on surrounding lands for soil erosion and deposition of aeolian sediments originating from the mined area. Furthermore, there is a need to measure the change in pre-mining rural and urban Land Use/Land Cover. This includes the loss of cultivated agricultural land, pasture, and forest; disruption of small drainage networks; and interruption of road network and degradation of road surfaces.

Major variables associated with surface mining can be grouped into spectral, spatial and temporal categories. Spectral elements include:

1. Higher albedos for surface mines in the longer wavelengths of visible and reflective IR

2. Reduced response of water in reflective IR bands as indices for locating ponds within mined areas

3. Spectral confusion caused by topographic shadows and shadows produced by landform components of the mine

4. Possibility of confusion between disturbed surface areas that are not surface mines

5. Regional variations in edge discrimination based on spectral response.

Specific spectral resolution properties for the visible regime include:

1. Shorter wavelengths; water penetration and turbidity measurements are possible

2. Longer wavelengths; good identification of chlorophyll content, good spectra to discriminate mined vs. non-mined areas, good soil boundary discrimination

3. Reflective IR; measure biomass on reclaimed areas, discriminating water, offers some potential for identifying plant stress

4. Short wave IR (SWIR); is good for measuring moisture stress in terrestrial vegetation, may be useful for surface water mapping (land vs. water)

5. Thermal IR; used for measuring residual heat within coal in surface mines (i.e., heat as potential incendiary); measuring soil moisture content; and measuring/mapping coal as darker material vs. other thermal emissive surface.

Important spatial elements associated with surface mining include the facts that extraction industries have relatively small size (less than 1 acre) and have irregular shapes. There is a complexity of spectral signatures within these small spatial units. Frequently there is a need for stereo coverage to determine extent and texture of disturbed areas. Finally, it is important to note that the size and shape of mines will vary with mining and reclamation activities through time.

State-of-the-Art and Gaps in Knowledge. The Application Survey Group study (1976) noted several successful applications of remotely sensed data use. These included:

1. S. Carolina Project, using Landsat as a monitoring tool for surface mining, had 99 percent correlation in a number of cases with planimetered areas from aerial photos.

2. 93 percent accuracy achieved in determining areas of strip mine affected acreage in Maryland--including monitoring progress of back-filled areas.

3. Stripped earth, partially reclaimed earth, vegetation, shallow water, and deep water successfully mapped in Ohio.

4. In Tennessee for about 50 cents/sq. mile (one-tenth cost of conventional technique) 1:250,000 scale maps accuracies better than 90 percent in most categories were developed.

5. Coal mining study in Pennsylvania showed Landsat data may be quite useful for annual updates, although the data were of limited value for monitoring.

6. Northern Great Plains study on evaluating Landsat data for strip mining/reclamation was successful on 14 of 30 mines considered.

More recently enhanced Landsat data have been utilized to help define contrast between surface mines and non-mine land covers within the Appalachian Coal Field. Anderson, Schultz, and Buchman (1975) utilized band-ratioing as a pattern recognition tool to discriminate surface mines in Western Maryland. Two other researchers, Spisz and Dooley (1980) applied band-ratioing analysis to discriminate temporal changes in surface mining activity within a test site in Eastern Kentucky.

Several gaps remain, we need to achieve a much better understanding of spectra internal to surface mines. Particularly:

1. Effects of seasonality on spectral responses within surface mines

2. Soil moisture effects on spectral responses

3. Reflectance properties of heterogeneous materials (coal, soil, rocks, etc.)

4. Reflectance properties of vegetation on reclaimed and non-reclaimed lands (e.g., stressed vegetation, influences of disturbed soils on vegetation)

5. Spectral discrimination between mine and non-mined surface areas.

In the spatial context, there is a need to determine the spatial resolution required for delineation of land cover categories within surface mines; (e.g., coal bench, highwalls, ponds, retention areas, etc.). There is also a need to determine the spatial resolution for delineation of surface mines; specifically edge enhancement of surface mines (mine/non-mine fringe). At present, it is difficult to distinguish extractive features smaller than 1 acre in size.

Generic Experiment. Five key experiments need to be undertaken to assure advancement of remote sensing's contribution to disturbed materials analysis. They include the following:

1. Analysis of regional spectral variation between surface mined areas

2. Statistical analyses of spectral responses of surface mines within the TM mid-IR and thermal IR bands

3. Determine or quantify texture within surface mines

4. Examine the minimum spatial resolution of the appropriate sensors for discrimination of surface mines

5. Examine minimum spatial resolution of the heterogeneous land covers/land uses within surface mined areas.

SUMMARY OF DATA REQUIREMENT FOR EXPERIMENT

I. LAND USELAND COVER

	URBAN LEVEL III	URBAN VS. RURAL III	SURFACE MINING III
FIELD SURVEYS	CRITICAL	CRITICAL	CRITICAL
SPECTRORADIOMETRY	CRITICAL	CRITICAL	CRITICAL
COLLATERAL DATA	YES	YES	YES
HIGH RES. PHOTOGRAPH	CIR PANCHROMATIC B W	CIR	CIR
TEMPORAL REGISTRATION	(DYNAMICS 2 PIXELS)	(DYNAMICS 2 PIXELS)	(DYNAMICS 0.5 PIXEL)
RECTIFICATION	YES	YES	YES
BASE LINE SPATIAL RES.	5M	5M	5M
SPECTRAL REQ. **	0.4-12.4	0.4-12.4	0.4-12.4
TEMPORAL RES.	TIME SERIES	TIME SERIES	TIME SERIES
TERRAIN DATA *	N/A	N/A	N/A
SPECIAL REQUIREMENTS	DIURNAL ACQUISITIONS	DIURNAL ACQUISITIONS	VARIATION IN LOOK ANGLES

* EITHER EXISTING DTM OR FLIGHT EXPERIMENT

** SPECIFIC BANDS TO BE DETERMINED.

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GEOMORPHOLOGY

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

GEOMORPHOLOGY

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GEOMORPHOLOGY

Justification and Statement of the Problem

Gemorphology is the study of landforms. The units that are recognized are composed of earth materials shaped by movements of the earth's crust and the actions of wind and water.

The number of landform types is large because of the complexity of the process by which they are created. However, once identified, landform type reveals much about the geologic history and climate of an area and physical properties of the materials found there. Using this knowledge, it is also possible to predict soil and vegetation type and the availability and occurrence of water. This broader consideration of landform as a key element of the landscape is integrated terrain analysis. Integrated terrain analysis is performed with some purpose in mind. Terrain analysis is frequently used to predict soil mechanical properties for engineering studies by relying on established relationships between landform and soil texture. In a broader and more common use, integrated terrain analysis is used to estimate land capability for various land uses. In this application, the full range of inferred relationships between landform and other landscape elements are used to estimate soil, vegetation and hydrologic resources. The success of integrated terrain analysis varies, first, with the skill of the analyst--a great deal depends on his familiarity with the region and his ability as an interpreter--second, and more important, the degree of correlation between landform and other landscape elements which will vary from region to region. In large part, the uncertainty associated with integrated terrain analysis stems from our imperfect knowledge of the processes that create the landscape and the subsequent inability to accommodate deviations from the landscape models that are developed.

Geomorphic processes result in distinctive and characteristic assemblages of landforms. Some processes such as diatrophism and vulcanism originate within the earth while other forces, such as weathering, mass wasting, and erosion occur at the earth's surface. All involve the modification of the earth's surface by water, wind and ice. Regionally, landforms develop in a logical and sequential order (geomorphic cycle) as determined by climate, lithology and structure. On the local level, individual processes produce distinctive features which develop in response to a number of other factors including temperature, moisture, altitude, topography, and vegetative cover. The basic fact, that distinct landforms result from specific geomorphic processes, makes possible the generic classification of the land surface. A proper appreciation of the significance of these geomorphic processes in the evolution of landforms requires a better understanding of the individual landform components and the interaction of those components. The characteristics of landforms - shape, orientation, pattern and relation to other landscape variables - must be understood in terms of space and time. Knowledge of these characteristics will provide the basic input for environmental models of the static and dynamic processes which modify the earth's surface. Therefore, research requirements necessitate an understanding of geomorphic processes in various physiographic regions with special attention to the interaction and assemblage of landform components.

Two physiographic provinces which have received little study with respect to the spatial and spectral resolution requirements for detailed landform mapping and process modeling utilizing high resolution data, include arid and periglacial environments. Both environments share a number of attributes which make them especially suited to remotely acquired data. Lack of accessibility, extremely fragile ecological systems, extensive areas and extreme climatic conditions necessitate the use of multispectral imagery. Especially in arid lands, landform is highly correlated with a number of other features (e.g., soil, vegetation and water resources). Thus, once known, landform can serve as a relatively reliable indication of other features. Recent accelerated economic development in the periglacial and arid regions necessitates the acquisition of detailed landform information to provide the basis for suitability and capability studies. Erosional degradation of the landscape, resulting from fluvial processes in the arid lands and frost dynamics in the periglacial realm, dominate. Therefore, to gain a better understanding of geomorphic processes in various environments, the periglacial and arid regions have been identified as areas with critical gaps in knowledge of landforms and processes.

State-of-the-Art and Gaps in Knowledge

An exhaustive critical discussion of the nature and extent of the literature relative to the use of remote sensing in the analysis of landform and drainage elements is beyond the scope of this document. The literature on these subjects is rich and extensive. Works such as the American Society of Photogrammetry, Manual of Photographic Interpretation (1960) and Manual of Remote Sensing (1975); along with Lueders, Aerial Photographic Interpretation (1959); Rays' Aerial Photographs in Geologic Interpretation and Mapping (1960); Millers' Photogeology (1961); von Brandts' Aerogeology (1962) all provide evidence of the potential of remotely sensed data to provide the researcher information concerning landforms in their broadest context. Other works such as Keifers' "Landforms Features in the United States" (1967) and Denny, et al.'s "Descriptive Catalogues of Selected Geologic Features in the United States" demonstrate in shorter form the utility of the remote sensing approach to the study of more specific landform elements. What is apparent from an examination of this literature is the overwhelming evidence that remote sensing does indeed play an important role in the identification and analysis of landforms and drainage patterns. Yet, what is also apparent is that while the current literature is rich in documentation of the use of remote sensing for the identification of landform types (see Table 4) conventional black-and-white aerial photography is still the most common medium used. A definite sense of the spatial, spectral, temporal and functional requirements necessary to adequately analyze terrain elements and the processes acting within these elements has not been well defined. While Reeves Jr. (1975) reviews the use of remote sensing in the study of specific geomorphic process, considerable research must still be accomplished here if we are to gain a fundamental appreciation of the dynamic interaction mechanisms that affect terrain development and stability.

Terrain analysis (also variously known as land classification and integrated terrain analysis) and remote sensing have been closely linked since the concept first was applied extensively in Australia. Major publications on terrain analysis (Stewart, 1968; Mitchell, 1973; and Thie and Ironside, 1976) have dealt extensively with remote sensing techniques. Appendix B reviews the state-of-the-art in arid lands terrain analysis. Recently, a book was published dealing specifically with remote sensing and terrain analysis

TABLE 4

SENSOR COMPARISONS FOR DETAILED AREA STUDY[1]

Landform	Pan Photo	Sensor Color Photo	Color IR Photo	Thermal IR
Active Beach	Good	Good	Excellent	Good
Chenier	Good	Good	Excellent	Fair
Marsh	Fair	Good	Excellent	Excellent
Terrace	Good	Excellent	Good	Fair
Backswamp	Good	Good	Excellent	No Coverage
Natural Levees	Good	Good	Excellent	Fair
Abandoned Channels	Good	Excellent	Excellent	No Coverage
Point Bars	Good	Excellent	Excellent	No Coverage
River Bars and Islands	Good	Excellent	Good	No Coverage
Spoil Banks	Good	Good	Good	Good

[1]After Orr and Quick 1971, Courtesy U.S. Army Engineer Topographic Laboratories

(Townshend, 1981). A number of projects covering a large part of the earth's surface have been done (for example, Perrin and Mitchell, 1976) However, techniques for mapping terrain have been and are criticized for the subjective ways in which units are sometimes recognized (Hutchinson, 1981). As a result, a recognized sub-branch of terrain analysis has focused on the development of quantitative landform parameters (Mabbut, 1968). Quantitative criteria for describing landforms, developed for use with aerial photography, range from very detailed (Parry, Heginbottom and Cowan, 1968; scale of 1:5,000) to very gross (USAWES, 1959; scales of 1:400,000 to 1:5 million). Generally, these criteria were developed for rural development planning or military applications and thus have had a limited distribution. Quantitative assessment of terrain variables for specific applications use many of the same features identified for hydrogeomorphological studies. One application used remote sensing to assess trafficability in remote areas for off-road vehicles. The parameters used include surficial geology, percent of area permanently waterlogged, tree density, and micro-relief. Conventional aerial photography at 1:31,680 provided data for the first three parameters, while 1:6,000 scale was needed for accurate assessment of the last two parameters (Schreier and Lavkulich, 1978). A secondary data input to this system was from Landsat 1 digital data. Bands 4 and 7 are used to contrast vegetation and water cover, improving the overall mapping of trafficability (Schreier and Lavkulich, 1979).

Land classification in the broadest sense involves delineating areas in which a recurring pattern of topography, soils, and vegetation occurs. Remote sensing is demonstrated as a data source for structural characteristics of the topographical factor by aiding to identify stream frequency and various "ecological" factors, including vegetative cover (King, 1970). Both relief:frequency (R:F) and relief:density (R:D) curves were employed in defining land systems in a subsequent study, with frequency and density characteristics obtained from 1,125,000 photo mosaics. The relief was determined stereoscopically from 1,60,000 stereopairs (King, 1972). Land classification also has involved modeling of terrain features such as structural characteristics of diastrophic forms (fault systems and their orientation), drainage frequency, and channel patterns of width, length, variability, and sinuosity (Speight, 1977). These parameters were successfully derived from 1:400,000 aerial photography over a remote area of Papua, New Guinea. The author cites a 20-meter limit of resolution, considered to be adequate for the scale of the study of an area of 6,000 square kilometers. Because of the limited applications, restricted distribution, and various scales employed in most of these studies, no summaries of criteria have been prepared. Although there is increasing contact between groups involved in terrain analysis (witnessed by the international meetings held in Bratislava, Czechoslovakia, in 1979 and Veldhoven, The Netherlands, in 1981), it is unrealistic to expect a consensus on landform parameters.

We have a good understanding of the contribution remote sensors at various spatial resolutions can provide in enhancing our capability to recognize and locate landform and drainage elements. The present state-of-the-art in remote sensing media, i.e., Landsat MSS and aerial photographs, limit our capability to rapidly advance the understanding of geomorphic processes that operate in various environments and our understanding of associated elements in environments which interact with landform and drainage element. The Landsat MSS (and upcoming TM) spatial and spectral resolutions can be used to delineate physiographic regions, but this is a level of landform and drainage element recognition that has in most regions of the world been obtained from available topographic maps and field surveys. High resolution aerial photography has been a key tool for the more detailed analysis of those elements which provide the quantitative data needed to verify geomorphic processes. However, the limited coverage, both in terms of area covered and optimal temporal/seasonal acquisition, and the lack of a range in contrast enhancement or spectral descrimination capabilities associated with aerial photography have severely limited the ease with which alternative models of process and association could be assessed. Perhaps the best example of this dilemma in geomorphology, and its effect upon the state of the discipline was the ease with which the Davisian cycle of landform development was able to obtain supporting evidence from existing small scale maps and field surveys, and the difficulty experienced by post-World War II geomorphologists in obtaining the quantitative data needed to verify the dynamic equilibrium approach to landform development.

The delineation of regional, extensive landform elements and physiographic regions has been enhanced by the Landsat MSS systems. Review articles by Lawman and Lawrence (physiography and regional geomorpholcgy), Elson (glacial landforms), and Breed and Grow (aeolian landforms), have demonstrated this utility. As noted by Tricart (see Table 5), however, the size in geomorphological features decreases significantly, i.e., between two and four orders of magnitude in size from those geomorphic features presently delineable from spaceborne sensors.

There are several studies which have presented encouraging results for the potential of high spatial resolution (i.e., 5-20 meters IFOV) and extended and more precise spectral ranges. Landsat-3 RBV images have already demonstrated the potential for enhanced capabilities to delineate drainage networks (Dejesusporada et al., Sabins, 1981). Sabins (1978) has pointed out the utility of thermal IR, and the different emissive properties of materials, to delineate a broad spectrum of depositional landforms associated with water processes. Recent studies by geologists (Goetz and Rowan (1981)) have pointed out the ability for SWIR bands to descriminate clay types and other major parent materials, each of which one associated with depositional landforms. The saturation properties of water for NIR, well documented for Landsat's MSS in automated water body delineation, has been shown with airborne scanners to provide a similar function for the automated delineation of streams in quantitative drainage basin analysis. Finally, landforms are frequently associated with specific vegetation associations, and the flexibility in spectral band selection in the NIR and visible portions of the spectrum should assist in extended capabilities for depositional and erosional landforms delineation by enhancing the contrast between modified elements and the background data.

Generic Experiments

To fully and effectively utilize multispectral imagery for landform and process analysis, a number of areas require study. These include:

(1) The determination of the level of mapping detail for landform delineation from various spatial resolutions.

TABLE 5

CLASSIFICATION OF GEOMORPHOLOGICAL FEATURES (AFTER TRICART, 1965)

Order	Units Of Earth's Surface In KM^2	Characteristics Of Units, With Examples	Equivalent Climatic Units	Basic Mechanisms Controlling The Relief	Time-Span Of Persistence
I	10^7	Continents, ocean basins.	Large zonal systems controlled by astronomical factors.	Differentiation of earth's crust between sial and sima.	10^9 years
II	10^6	Large structural entities (Scandinavian Shield, Tethys, Congo basin).	Broad climatic types (influence of geographical factors on astronomical factors).	Crustal movements, as in the formation of geosynclines. Climatic influence on dissection.	10^8 years
III	10^4	Main structural units (Paris basin, Jura, Massif Massif).	Subdivisions of the broad climatic types, but with little significance for erosion.	Tectonic units having a link with paleogeography; erosion rates influenced by lithology.	10^7 years
IV	10^2	Basic tectonic units; mountain massifs, horsts, fault troughs.	Regional climates influenced predominantly by geographical factors, especially in mountainous areas.	Influenced predominantly by tectonic factors; secondarily by lithology.	10^7 years
		Limit of isostatic adjustments			
V	10	Tectonic irregularities, anticlines, synclines, hills, valleys.	Local climate, influenced by pattern of relief; adret, ubac, altitudinal effects.	Predominance of lithology and static aspects of structure.	10^6-10^7 years

TABLE 5 (Cont)

Order	Units Of Earth's Surface In KM^2	Characteristics of Units, With Examples	Equivalent Climatic Units	Basic Mechanisms Controlling The Relief	Time-Span Of Persis-tence
VI	10^{-2}	Landforms; ridges, terraces, cirques, moraines, debris, etc.	Mesoclimate, directly linked to the landform, e.g., nivation hollow.	Predominance of processes, influenced by lithology.	10^4 years
VII	10^{-6}	Microforms; solifluction lobes; polygonal soils, nebka, badland gullies.	Microclimate, directly linked with the form, e.g., lapis (karren).	Predominance of processes, influenced by lithology.	10^2 years
VIII	10^{-8}	Microscopic, e.g., details of solution and polishing.	Micro-environment.	Related to processes and to rock texture.	

(2) Assess and evaluate sensor wavelengths and wavebands for discriminating landforms and processes occurring in a variety of environments.

(3) Determine the temporal resolution requirements for mapping landform units.

(4) Assess available digital techniques (edge enhancement, texture) for utility in landform mapping.

(5) Develop automated digital techniques sensitive to pattern, form, texture and size.

Four experiments are recommended for geomorphic analysis and are described in detail below: assessing the effects of catastrophic events, processes influencing periglacial landforms, arid and semi-arid landform spatial and spectral characteristics analysis, and drainage basin and drainage network analysis.

1. Assessing The Effects of Catastrophic Events on Landforms

- Objective – To assess and analyze the effects of catastrophic events on the form, areal extent and temporal stability of landforms.

- Rationale/Justification – In the study of present day surface forms and sub-aerial processes, the geomorphologist follows closely the ideas embodied under the broad heading of "uniformitarianism." As such, he must consider how he may extrapolate from the present to the past and how abrupt (as opposed to uniform) rates of change could affect extrapolations. Similarly, geomorphologists must consider the degree to which the present with its abrupt and uniform changes compounded is typical of the past. For example, we know the tropical storms have a major impact upon coastal landforms. Studies of hurricanes off Florida indicate that in a fifty year period eight storms may impact South Florida. Post predictions from these observations suggest that about 160 hurricanes could have effected the area in the last 1,000 years; and, that hurricanes were commonplace in the context of the Pleistocene time when 160,000 to 320,000 may have occurred. Floods and volcanism also can be viewed within similar contexts. A major problem then in assuming present processes to be the same as those operating over a much longer time span is deciding on how much significance to attach to slow but uniform denudation as compared with the intensity of an abrupt event e.g., a hurricane, a flood, or a volcanic eruption.

- Type of Analysis - This experiment would involve both qualitative manual analysis as a first rough evaluation but would be more specifically oriented towards detailed quantitative evaluation of the type and extent and temporal stability of changes in landforms which have occurred.

- Techniques Which Might be Applied - This experiment would employ the use of both past aerial or satellite imagery topographic and other environmental with similar data derived from post event coverage by an MLA and other type systems. Both manual and automated image analysis and information extraction and display techniques including pattern recognition, and time sequential computer graphics would be employed. This experiment would be improved by the existence of post event ground reconnaissance and aerial image acquisition. A free flyer satellite would permit more flexibility for potential data acquisition and time series; however, given proper shuttle orbits effect experimentation could be carried out through a judicious combination of aircraft and sequential shuttle coverage. Collateral material either compiled pre or post event would include as a minimum topographic maps at a scale of 1:24,000 and Land Cover/Land Use maps at a scale of 1:62,500 depending upon the particular type of event under investigation. That is the type and detail of mapping coverage required for comparative analysis will depend on the intensity of the events effect on the landforms of the region affected and the aereal extent of those effects.

- Expected Results - An improved understanding of the nature of the influence of catastrophic events on the stability of landforms and the role such events have played in shaping the landforms we see around us.

2. Processes Influencing Periglacial Landforms

- Objective - To determine the spectral, spatial, and temporal characteristics of periglacial landforms and processes.

- Rationale/Justification - Accelerated development in the Arctic resulting from the recent discovery of oil, gas and mineral deposits coupled with an extremely fragile ecology, points to the need for reliable and detailed data regarding landform processes with respect to man's activities. The understanding of permafrost dynamics is of paramount importance to the study of periglacial landform processes. Environmental impacts, resulting from a disruption or disturbance of the permafrost, produce long lasting effects. Disruption of the permafrost in an area often leads to thermal degradation of the surrounding areas which may not regain equilibrium for decades.

- Types of Analysis - Initially, the interaction/correlation of landscape elements must be established. Investigate the use of multispectral imagery at various spatial resolutions to detect and identify landform units. Evaluate and determine optimal sensor wavelengths and bandwidths for discrimination of periglacial landforms and processes. Examine and document the temporal requirements for specific periglacial phenomenon (i.e., anfir's, thermal erosion, flooding).

- Techniques Which Might be Applied - Statistical analysis techniques should be utilized to correlate landscape elements. Investigate the use of available edge enhancement and texture measures for discrimination of landform units (i.e., patterned ground). Develop and test new automated techniques/algorithms sensitive to the repetitive spatial patterns of landform units based on pattern, texture, and size. Integrate (GIS) ancillary data with remotely sensed data to develop predictive models regarding processes. Degrade spatial resolution and compare information content at various resolutions (both digitally and photo interpretation).

- Expected Results - To provide an improved understanding of the spectral, spatial, and temporal characteristics of periglacial landforms and processes in order to more effectively utilize remotely sensed data in Arctic regions. Completion of the research will provide a comparison, evaluation and selection of optimal spectral wavebands for discriminating periglacial landforms; a determination of the level of mapping detail which can be achieved with each level of spatial resolution; and, identification of temporal requirements for discriminating specific periglacial phenomenon. Finally, to fully understand periglacial processes and the benefits of remotely sensed data, predictive models will be developed and tested.

3. Spatial And Spectral Characteristics Of Arid And Semiarid Landform And Their Associated Features

- Objectives - At various spatial and spectral resolutions: (1) determine what level of characterization of land form parameters is possible; (2) determine those associated elements that can be reliably predicted; (3) determine the degrees of change in terrain that can be detected.

- Rationale - Satellite scanner data, while offering a synoptic view of the landscape, has been used in only a rudimentary fashion. Improved spatial resolution will permit detection of smaller landform elements. Once identified, landform types can be linked to a number of associated features (e.g., soil, surface hydrology). Improved spectral resolution in SWIR may permit more reliable identification of soil type. Arid and semiarid environments offer several distinct advantages for the study of landform through remote sensing: vegetation is sparse and landform elements are easily detected; a number of other features (e.g., soil and vegetation) are highly correlated with landform; and finally, confounding effects of human activity are restricted. The approach and techniques developed will be applicable to other regions. However, the complexity of characterizing landforms and the reliability of their association with other features will increase in more humid environments. (See Peltier, 1962.)

- Types of Analysis - Primarily, quantitative analysis will be performed, focused on the combination of statistical models of landscape and digital scanner data. Supplementary data derived from manual air photo interpretation will be used in developing landform models.

- Techniques - Landform and associated features (soil and vegetation) will be characterized using aerial photographs and ground sampling to identify there spatial, spectral, and physical properties. All elements will be statistically correlated and used to develop a descriptive model. Stereoscopic digital data of varying spatial and spectral resolution will be acquired for the study sites. Several data sets will be developed for each test site a different resolutions. Data sets will be interpreted manually and processed digitally in parallel for comparison. Spatial processing techniques will be developed and evaluated, using x, y and z data, to recognize size, shape, texture, pattern and adjacency of landform elements. The addition of spectral data will be evaluated in its effect on accuracy in recognizing each feature.

- Expected Results - Experiment will produce: (1) detailed understanding of influence of varying spatial/spectral resultion on the ability to discriminate landforms and associated features in the study region; (2) model for use of spatial and spectral data in identifying landforms and associated features in the study region; (3) methodology for evaluating spatial/spectral resolution and identifying landforms and associated features in other climatic regions.

4. Drainage Basin And Drainage Network Analysis

- Objective - It is the purpose of this experiment to determine the degree to which high spatial and spectral resolution digital imaging sensors can aid in the identification and characterization of drainage networks and drainage basins. For drainage networks, the basic concern is to determine the ability to recognize and measure low order streams and intermittent stream beds under varying climatic conditions. For drainage basins, the principal concerns are remote sensing's ability to determine the size, shape, and land cover on small area drainage basins.

- Rationale/Justification - A major segment of fluvial geomorphology is concerned with the quantitative characterization of drainage networks and drainage basin morphometry. From these analyses it is possible to characterize the balance between erosional and depositional processes, calibrate the universal soil loss equation for a given slope or basin, model the rate of change in fluvial geomorphic processes, and calibrate hydrologic models -- particularly in the higher order basins (Chorley). The ability to automate the analysis process should permit the rapid dissemination of the techniques and models developed since 1945 to a variety of environments and conditions, thereby aiding the evaluation and calibration of models.

- Techniques - Airborne digital imaging systems have presented promising results for the ability to recognize water bodies of limited size. Analyses need to be performed to determine the ability for high spatial resolution NIR to identify perennial streams and for other portions of the visible and IR spectrum to locate intermittent stream beds by direct observation or observation of associated elements. Analyses also need to be performed to determine the ability for different portions of the visible, NIR, SWIR and TIR spectrum to identify land cover within lower order drainage basins and delineate drainage basin perimeters. Analyses also need to be applied to determine the ability for stereo imagery to obtain stream gradients and drainage basin perimeters. For all experiments, the primary objective is to determine the effect systematic reductions in spatial and spectral resolution have on the ability to discriminate small area drainage networks and drainage basins.

- Analyses - The principal goal for analyses would be to determine the feasibility of automated analysis of digital remote sensing data for input to models used to characterize drainage morphometry, soil loss, and drainage system equilibrium. Therefore, research should concentrate upon determining optional spatial and spectral resolutions for drainage elements detection and development of pattern recognition algorithms that isolate drainage element parameters effectively. Conventional techniques for drainage basin analysis from remotely sensed data should also be applied to determine the accuracy of and need for automated techniques, given the incremental improvement derived from the broader range of image enhancement to be achieved from MLA systems.

- Expected Results - Achieving automated drainage network and basin analysis, particularly for small, limited area basins, will significantly enhance the utility of existing hydrographic, soil loss, and drainage system models and on understanding of their generality in different portions of the earth.

SUMMARY OF DATA REQUIREMENTS FOR EXPERIMENTS

II GEOMORPHOLOGY

	PERIGLACIAL	ARID	CATASTROPHIC EVENTS	DRAINAGE
FIELD SURVEYS	CRITICAL	CRITICAL	CRITICAL	CRITICAL
SPECTRORADOMETRY	CRITICAL	CRITICAL	CRITICAL	CRITICAL
COLLATERAL DATA	YES	YES	YES	YES
HIGH RESOLUTION	CIR	NATURAL COLOR	NATURAL COLOR OR CIR	NATURAL OR CIR
PHOTOGRAPHY				
TEMPORAL REGISTRATION	N/A	N/A	0.5 PIXEL CAPABILITY	N/A
RECTIFICATION	YES	YES	CRITICAL	CRITICAL
BASE LINE SPATIAL RES.	5M	5M	5-30M	5M
SPECTRAL REQ.**	0.4-12.4	0.4-12.4	0.4-12.4	0.4-12.4
TEMPORAL RES.	3 FLIGHTS JUN-SEPT	EACH SEASON	EVENT DEPENDENT	EACH SEASON
TERRAIN DATA*	YES	YES	YES	YES
SPECIAL REQ.	NOON OVERFLIGHT	HIGH AND LOW SUN ANGLES	EVENT DEPENDENT	NONE

* EITHER EXISTING DTM OR FLIGHT EXPERIMENT

** SPECIFIC BANDS TO BE DETERMINED

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CARTOGRAPHY

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CARTOGRAPHY

Justification and Statement of the Problem

The demand for cartographic products at scales of 1:25,000 to 1:250,000 continues to increase throughout the world in order to meet requirements associated with:

1. The survey and management of natural resources

2. Environmental planning

3. The establishment of geo-referenced data bases.

However, data compiled by the United Nations (1976) indicates that the demands for (topographic) maps at medium to large scale cannot be met in the near future by conventional mapping techniques/programs involving the use of aerial photographs. A satellite system involving the use of MLA sensors designed to meet cartographic requirements in terms of the completeness of detail and geometric accuracy standards associated with mapping programs offers great promise for rapidly providing the data with which to produce four types of map products/and data (Ducher, 1980; Welch and Marko, 1981; Colvocoresses, 1981;). These include:

1. Topographic maps

2. Digital terrain information (X,Y,Z coordinates)

3. Thematic maps

4. Image maps.

Each type of cartographic product/data is briefly considered below in relation to current needs.

- Topographic maps - Maps at scales of 1:100,000 and larger are not available for extensive areas of the world (Figure 6). Such maps are required for development activities. There is also a universal need to revise topographic maps at scales from 1:25,000 to 1:250,000 on a periodic basis. Data provided by satellite sensor systems can be used for both compilation and revision.

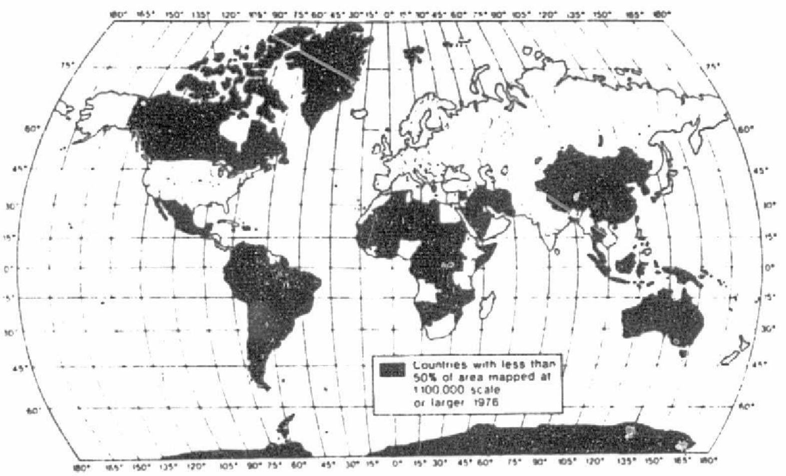
- Digital terrain data - There are exciting possibilities for generating x,y,z terrain coordinates on a global basis from satellite data. Such data can be used to generate contours and slope maps, rectify other types of satellite data (e.g., SAR), and provide Z (elevation) values for geographic data bases.

- Thematic maps - Stereo data of high spatial resolution and moderate spectral resolution should provide an efficient means of producing accurate thematic maps by both analog and digital techniques. The utility of raster image data is a function of its positional reliability and its potential for integration with geo-referenced data bases.

- Image maps - Rectified image products at 1:25,000 to 1;100,000 scale meeting planimetric map accuracy standards can be produced from satellite image data of adequate resolution (25 m IFOV). Image maps are a basic cartographic product of value to all countries. It is important to realize that a satellite program designed to acquire high revolution stereo image data suitable for producing cartographic products at scales of 1:25,000 to 1;250,000 will also satisfy the accuracy and data requirements for most other disciplines.

<u>State-of-the-Art - Mapping From Space</u>

The greatest potential for accurate topographic mapping from space is extant in metric (mapping) film cameras such as the large format camera (LFC) scheduled to orbit in the Space Shuttle, and the metric camera (MC) to be used



THE SHADED AREAS REPRESENT COUNTRIES OR REGIONS WITH 50 PERCENT OR LESS OF THEIR AREA MAPPED AT 1:100,000 SCALE OR LARGER IN 1976 (UNITED NATIONS, 1976).

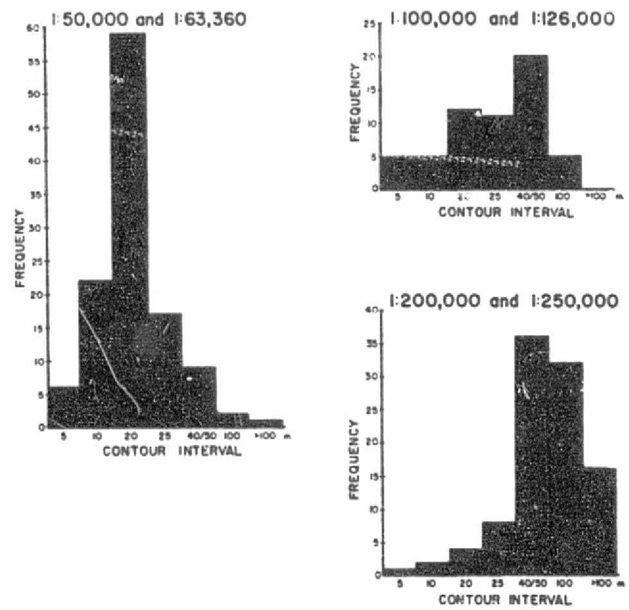


FIGURE 6. HISTOGRAMS OF CONTOUR INTERVALS FOR TOPOGRAPHIC MAPS AT SCALES OF 1:50,000, 1:100,000, AND 1:250,000 (UNITED NATIONS, 1976)

in an European Spacelab mission. These cameras with approximately a 5m (equivalent) IFOV provide the resolution and completeness of detail adequate for compilation of 1:50,000 to 1:100,000 scale maps. The geometric accuracy (RMSE x,y,z, of $\leq$ 15 M) is commensurate with a contour interval of approximately 50 m, appropriate for 1:50,000-1:100,000 scale mapping. These camera systems will provide data of a resolution and geometric accuracy as related to the production of cartographic products with reference to map accuracy standards.

State-of-the-Art Spacecraft

- General - The important spacecraft characteristics as related to the cartography problem are knowledge of the spacecraft position and attitude at the time of imaging a given pixel. The attitude control system specifications on Landsat-4 will be considered as state-of-the-art. The Global Positioning System will eventually be operational; its expected accuracies will be considered as state-of-the-art in spacecraft position.

- Attitude Control - The attitude control system (ACS) is specified to provide attitude control to within $(1\sigma) \pm 0.01°$ (36 sec), relative to inertial (stellar) space. Nadir tracking is accomplished by providing a continual pitch rate to the spacecraft corresponding to the angular orbital velocity. The nadir direction related to stellar space is calculated corresponding to the expected spacecraft position at a given instant. Error in the spacecraft position is calculated from the expected position at a given instant. Error in the spacecraft position from the expected position introduces an additional pointing error. The 0.01° applies to each axis (roll, pitch, yaw) and results in 120m (roll and pitch) ground displacement. The effect of roll and pitch is primarily a geodetic displacement; the resulting amount of image distortion will depend on the swath width used. The Landsat-4 attitude control rate limit specification is 10^{-6} deg/sec. Attitude correction is anticipated to occur approximately daily. In

Landsat, spacecraft warping between the attitude control system and the Thematic Mapper will cause some additional instrument pointing errors which are unmeasured and unknown. With the accuracy desired for cartography the attitude control must be relative to the instrument--not the spacecraft--or an active boresighting between the two is required. Since it is impossible to distinquish between roll and orbit position or between pitch and along-orbit position, the roll or pitch attitude cannot be recovered for Landsat post facto, and these positions will be grouped with the spacecraft position. Yaw remains the most intractable error source and must be obtained by calculation from the stellar attitude. No good direct yaw sensor is available.

- Ephemeris Without GPS - The along-orbit predicted position is accurate to 250m one day after ephemeris prediction, 500m after two days, and 1000m after three days. The amount to actually be encountered will depend on how far ahead the predict is made. The two-day cross-tract predict is 100 meters. Post facto orbit positions are expected to be 100m along track, 30m cross track, and 20m radial. The post-facto orbit positions are not used for Landsat image location. Orbital altitude variations above the geoid are expect to be ±25 m around an orbit, and 19km variation in the revisit to a given location. However, the two day predicted radial position accuracy is 35 meters. Line length scaling using the radial predicted value is required, and will be marginally accurate. (Depending on actual mission parameters, a change in altitude above the ground of 50-100 meters will cause the image line to vary by 1 pixel in length.)

- Ephemeris with Global Positioning System (GPS) - The GPS is being flown as an experiment on Landsat-4. The attainable accuracy with four of the Navstar satellies in view is expected to be about 15 meters in each direction in a direct ranging mode and perhaps 6 meters in a relative mode. This mode will not be available world-wide, however, until all of the Navstar satellites are in position, which will probably not occur until the late 1980's. Until that time an accuracy of only 40-50 meters can be expected. Thus, until GPS is fully operational, spacecraft (or, more exactly) image ground positions must be established by the use of ground control. Then, when and if attitude control pointing and pointing rate of the sensor can be provided, open loop (without ground control) pointing to pixel accuracy may be possible. Realistically, it should be expected that ground control will always be necessary to achieve the final geodetic accuracy desired.

State-of-the-Art: Line and Area Arrays; Spectral and Spatial Resolution

Visible CLD linear array technology is well developed, with arrays of up to 2048 elements commercially available (Ando, 1982). The HRV imager of SPOT and the Modular Optoelectronic Multispectral Scanner are examples of the current use of this technology. Silicon area arrays for use in the visible have been developed by Texas Instruments for the Galileo imaging camera and for the Wide Field/Planetary Camera of Space Telescope. These arrays are 800 x 800 elements and, like the linear arrays above, are sensitive from about 0.35 um to 1.0 µm.

Development of array technology in the shortwave infrared (SWIR) has lagged that of the visible in part to the greater technological challenges and to the only relatively recent emergence of interest in this spectral region, primarily by the military. The state-of-the-art in line arrays is in the 1.0 - 5.0 µm region is indium antimonide (lnsb). Cincinnati Electronics has delivered a 128 element live array with 250 µm pixels to the Jet Propulsion Laboratory where it has been successfully tested (Bailey, 1981) and delivery of a 512 element, 50 um pixel area is planned in mid-1982. Area arrays in mercury cadmium telluride (Hg Cd Te) of 32 x 32 elements are available from Rockwell, where work is underway on a 64 x 64 element HgCd Te CCD which will be buttable on two sides. JPC expects to take delivery of this device in late 1983 for extensive testing (Wellman, et al., 1981).

The limit in spectral and spatial resolution is partially determined by the platform on which the sensor is flown, given the practical limits in size of optics and instrument cost. From an aircraft, 10 nanometer spectral and 5 meter or better spatial (IFOV) resolutions can be achieved in the 0.4-2.5 μm regions (Wellman and Goetz, 1980; Wellman, 1981). Experience with the design of the Thermal Infrared Mapping Spectrometer (TIMS) by Daedalus for NASA indicates that 0-5 μm spectral and 30 meter spatial resolutions are the current state-of-the-art in the 8-14 μm region.

Instrument designs exist using currently (or soon-to-be) available technology for a shuttle-borne sensor capable of 10-20 nanometer spectral and 10-20 meter spatial resolution in the 0,4-2.5- μm regions (Wellman et al., 1982). In the 8-14 μm region however, 0.5 to 1.0 μm spectral and 30 meter spatial resolution systems are the current limit, due primarily to detector limitations. The same numbers apply to a free-flyer as to the shuttle although performance will be somewhat degraded at high (greater than 700 km) altitudes.

State-Of-The-Art: Landsat Data Processing

Rectification techniques for Landsat MSS have been under development for approximately ten years. The ten year period has been characterized by very slow development of the ability to deliver accurately rectified data products from a production scale system. Photogrammetric experiments have shown that the inherent quality of MSS allows rectification to approximately 10-20 meter absolute map error. However, the data delivery systems at GSFC and EROS and at application centers such as ERIM and JPL have been slower to achieve accurate rectification on a routine basis. Problem associated with MSS rectification include:

(1) Local geometric anomalies in the data associated with the mechanical scanning mechanism

(2) Large size of data sets which can prohibit the application of a thorough photogrammetric model on a production basis

(3) Difficulty in obtaining ground control for rectification (until the creation of the Goddard MDP Ground Control Point File).

The current state-of-the-art is promising. At Goddard, the MDP uses a special purpose system to achieve a high level of production with a good percentage of products meeting a reasonable accuracy standard. At ERIM, a spacecraft model is under development which can meet a high accuracy standard using six to ten highly accurate control points obtained by ground survey crews. At JPL, a general purpose software system (VICAR) is used to produce scenes, subscenes or mosaics of scenes in any map projection in an efficient manner. JPL uses the Goddard MDP Ground Control Point File for geolocation.

Extrapolation of present progress to a future MLA mission is very promising. The following points are relevant:

1. Per line data capture and per line processing are well understood.

2. Elimination of mechanical scanning and its associated geometric anomalies should make rectification much easier.

3. The new problems of butting gap and optical nonlinearity are easy to remove with ground data processing.

4. The uniform, instantaneous line capture mode of the MLA will be excellent for rectification processing.

Anticipated problems for data processing include:

1. Increased size of data sets which may produce a non-linear increase in the processing time for certain algorithms (see A.L. Zobrist, 1982).

2. Since spacecraft ephemeris and attitude will probably not be accurate for rectification purposes, GCP files will have to be developed for each mission. These may possibly be created from previous GCP files.

3. Mosaicking and map projection for production of application data sets will be necessary (See Simonett, et al, 1978)

4. Mosaicking will become more important if the data gathering swath width decreases below 180 km.

State-of-the-Art Production Of Cartographic Products 1:25,000 to 1:250,000

As shown in Table 6 a variety of products are possible to be derived from various spaceborn remote sensors. The capabilities (potentials) of each of a family of sensors is examined below. With the possible exception of space borne film cameras, the capabilities of state-of-the-art of civilian remote sensing devices are generally not adequate for the production of maps at scales larger than 1:100,000. Even this assessment may prove to be optimistic when actual data are analyzed. Maps at scales of 1:100,000 traditionally contain a level of information that may not be discernable by these systems. We believe that it is possible to design a system to meet larger scale mapping needs, however state-of-the-art components and tolerances are required in all aspects of such a system.

- Platform: Eventual operational use of remote sensing imagery for cartographic purposes will require global coverage, and, hence there is a need for polar-orbiting platforms. In addition, the precise pointing and internal consistency required will undoubtedly require the use of a free-flying satellite with minimal (or better, no) moving parts. Until such a satellite is available, it may be possible to perform some proof-of-concept experiments on other platforms, such as the Shuttle. If this is done, an instrument pointing platform and other supplementary equipment will be required to meet the stringent requirements.

- Spatial Resolution $\leq$ 5 Meter: There is currently a dearth of world-wide topographic maps in the 1:25,000 - 1:100,000 range. Welch (1982) has shown that resolutions of 5 meters or better is required. Within this must be included the optics, detector

TABLE 6

SENSOR CHARACTERISTICS APPLICABLE TO MAP REQUIREMENTS

Products \ Sensors	Film Cameras (Spacebourn)	MSS/TM	Line Arrays
Topographic Maps	1:50,000-1:100,000 50 m contour int.	X, Y position compatible with 1:250,000 mapping inadequate resolution for map compilation	X, Y position compatible for 1:50,000 mapping Z value est. 30-50 m contour interval approx. 100 m - adequate for 1:250,000 in some areas
Digital Terrain Data	X, Y, Z $\leq$ 15-20 m (rmse)	N/A	X, Y $\leq$ 20 m (rmse) Z $\leq$ 50 m (rmse)
Thematic Maps	1:25,000-1:100,000 maps developed by analog compilation. Level II Land Use (USGS) possible	1:100,000-1:250,000 maps created by digital classification. Level I and some more details possible.	1:50,000-1:250,000 analog or digital techniques could be used to delineate Level I and most Level II categories
Image Maps	1:50,000	1:100,000-1:250,000	1:50,000-1:100,000

elements, high-frequency noise vibrations, and, for multiband data, interband registration.

- Spectral Bands: It seems that one panchromatic or principal component band will capture most of the variance in a scene and is therefore the most valuable single data source. However, the additional information available through multiple spectral bands will contribute to material separation, which will be required for the mapping of thematic information. At least two bands will be required in the VIS/NIR (silicon detector) range. These may probably be fairly wide band (e.g., 0.1 μm or so), but the specific band edge locations have not been investigated for cartographic purposes. The use of additional bands in the 0.4-2.5 μm range needs to be investigated using the 5m pixels. It is expected that the planned investigations with the Landsat-4 30 meter pixels will give only a general indication due to the material mixing involved.

- Type of Coverage: Altitude (Z) information is required for the making of topographic maps and, in areas of appreciable terrain relief, for relief correction. With the small pixel size that is required, even moderate relief will displace the image content. Until and unless other methods of obtaining the Z-map are available, stereo remains the only method. It is not yet clear, however, whether a line array or framing-mode area array camera is the preferred configuration. In either case, a base/height ratio of about 1.0 seems to be ratio of choice.

- Swath Width: Minimization of relief displacement coupled with the optical problems involved in wider field optics call for a relatively narrow swath width. However, the use of a narrow width requires more swaths to cover the earth and exacerbates the resulting mosaicking problem. Further, the swath width is inversely related to the total time for complete coverage (number of swaths to cover = 40,000 km (earth circumference)/

swath width in km as the orbit time is essentially the same (~100 minutes) for all altitudes. The net result is that a swath width in the 50-90 km range appears reasonable.

- Repeat Cycle: A 60 km swath will provide complete earth coverage in about 2 months. Increasing this to 90 km (with, of course, a suitable orbit choice) will decrease coverage time to about 6 weeks. Because multiple-season coverage will be useful in many areas, and because the multi-season set should be collected before changes of cartographic interest occur, the set should be collected within about 6 months to 1 year. This is commensurate with the swath width considerations outlined previously.

- Quantization: The small pixels required will produce more violent excursions of response due to the lesser intra-pixel material mixing (compared to the present larger pixel sensors). It has been shown that platforming (which might produce artificial contours) only becomes visible at about 5 bits or less, and only occurs in areas of gradual shading and no edges. Further, the S/N of typical sensors is perhaps 1/2 percent to 2 percent of full-scale. Thus, 6-7 bits appears entirely adequate.

- Ephemeris and Attitude: If the satellite data is to be used "open loop" with minimal (preferably zero) ground control, the location of each sensed pixel on the ground must be precisely known. This must be commensurate with the pixel size if the placement of the derived feature is to meet National Map Accuracy Standards. Although it would be desirable to control the pointing to pixel size accuracy, this may not be practical. If pixel size pointing accuracy is not achieveable, post facto recovery of attitude and ephemeris knowledge must be to pixel size precision and be relatable to each data element. This must be in the 1/2-1 arc sec range.

- Attitude Stability: The obtaining of stereo data from two looks from a single spacecraft requires that the stereo base (distance and relative attitudes) be known. Welch (1981b) has shown that a time difference between the two stations of ~ 2 msec is required. This is easily met with the normal spacecraft clock. The relative attitude must not produce errors larger than 1/2 to 1 pixel; over the ~ 90 second period required for stereo coverage. This requires attitude stability in the 10^{-6} deg/sec range expected for Landsat-4. Further, if the ephemeris and pointing accuracy outlined above are not met, ground control must be used to provide the geodetic location of the imagery. As this is laborious, especially in the undeveloped areas, the number of ground points needing precise location and needing to be visible in the images must be minimized. Thus it is desirable to extrapolate image position as far as possible from a single (or small group of control points). As shown in Figure 7, the 10^{-6} deg/sec remains the potentially largest source of this extrapolation uncertainty, if the Landsat-4 attitude control limit of ±0.01° is retained. It is desirable, perhaps absolutely necessary, to reduce the number of control points below the 10-50 points per frame currently used for Landsat. This requires that all intra-picture distortions be avoided or removed before ground control points are used for geodetic location. Although it is perhaps possible to measure <u>in vivo</u> the intra-picture distortion effects, as is being done on Landsat-4, this is intractable at best, and all sources of intra-picture distortions (vibrations, in particular) should be avoided or minimized to below about 1/4 arc sec if at all possible.

- On Board Processing: Any on-board processing will require pre-processing to remove radiometric differences between the detector elements. Because solid state detectors are extremely linear, this pre-processing can take the form of gain and offset corrections. This must be done for each detector element, requiring the necessary parameter storage and a method to

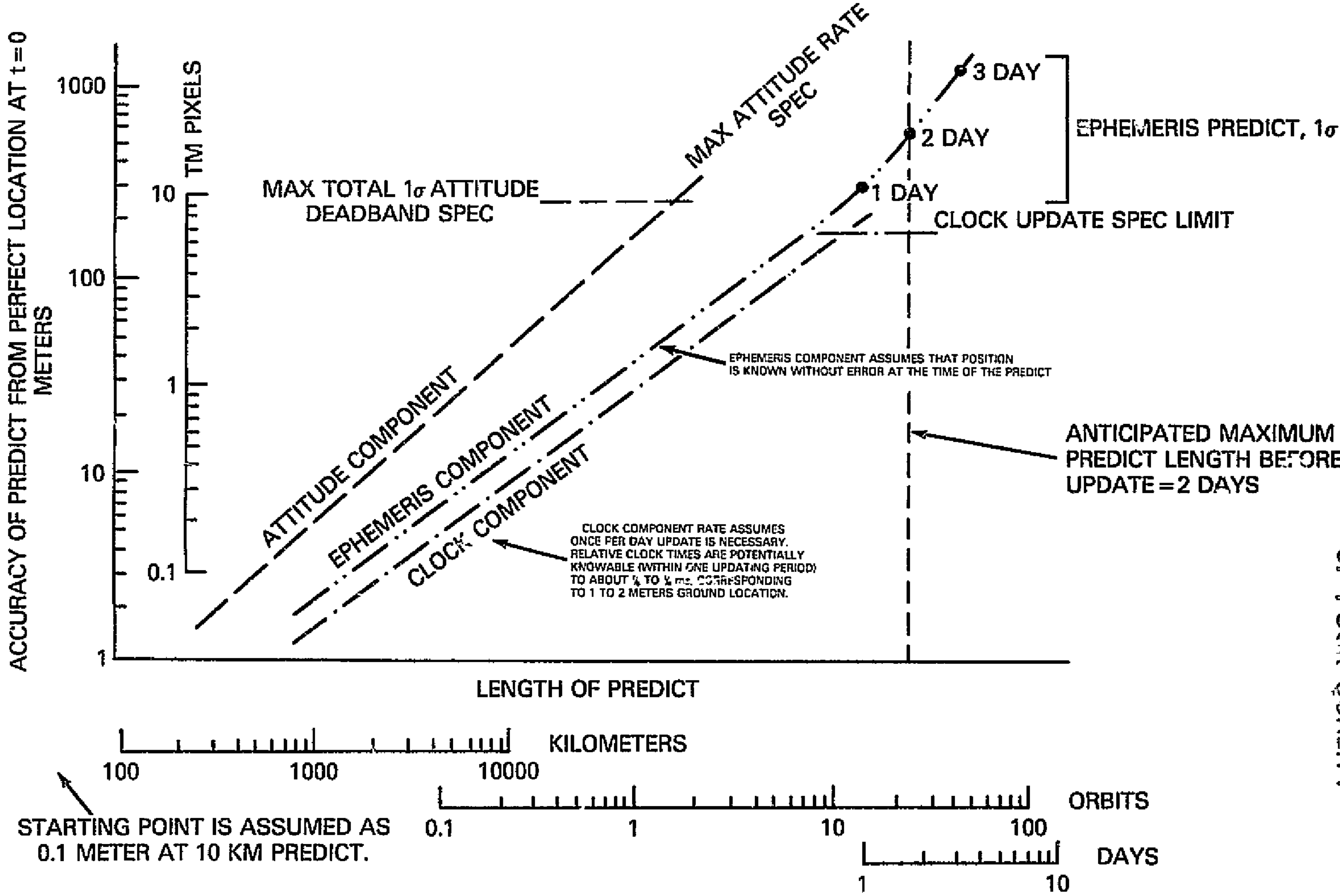


FIGURE 7. POTENTIAL LOCATION UNCERTAINTY RELATIVE TO A PERFECTLY DETERMINED POSITION AT t=0 LANDSAT D

determine detector drift during mission lifetime. Following calibration, adaptive optimum coding may be used to code the sensed data to within about 1/2 bit of the entropy content. This is appreciably more compact by about 2 times than the normal data coding, and is re-expandable on the ground to the normal form. Data compression to the 5x-10x compression range appears possible with recovery error in the range of the basic sensor S/N (1 percent or so). This possibility should be explored.

- Ground Processing - Algorithm Development: Little work has been done to date with stereo correlation of the line-array sensors. The techniques must be worked out and compared with the results obtainable with area-array data. Further, the small pixels, and corresponding large amount of data, will expand the number of pixels to be handled by 10x-100x over the present sensors. Algorithms must be developed which can handle this amount of data. The potential use of VLSI at appropriate points may be indicated. The large amount of data will quickly get out of hand unless suitable archiving, referencing, cataloging and retrieval technique are designed and implemented before the data flood begins. This may well be based on technique being developed for Landsat, but this must be investigated. This data base technology must be able to handle, and perhaps specifically be designed to include, data derived from other sources, and various pixel scales.

Gaps in Knowledge. The major gaps in knowledge regarding the use of spaceborne MLA sensor for cartographic purposes appear to be as follows:

1. The relative merits of area (frame) and line array sensor for the acquisition of stereo image data for cartographic purposes have not been determined.

2. Adequate understanding of exactly what magnitude of spatial resolution will be required for compilation of map products of scales of 1:25,000; 1:50,000, 1:100,000 and 1:250,000 to acceptable standards of completeness, and improvement in mapped detail (90 completeness) resulting from stereo (as opposed to monoscopic) viewing and from multiband (as opposed to panchromatic) data. It is evident that spatial resolution of 5 m IFOV or better are required, and that stereo, color and digital image enhancement techniques will provide additional information. However, the tradeoff or benefits gained in terms of completeness of detail at different map scales are unclear. Note Figure 8 results for the panchromatic case.

3. Accuracy to which x,y,z terrain coordinates can be derived from stereo MLA data are influenced by factors such as B/H ratio, pointing accuracy, stability of the platform and the correlation techniques employed. There is a paucity of information on use of digital correlation techniques with stereo image data generated by line or area array sensor systems. The relationships betwen basic geometry of the stereo data, the pointing and stability parameters of the spacecraft/sensor system, the number and distribution of ground control points, search window size, correlation algorithms and the accuracy of coordinate recovery (particularly z-coordinate accuracy) are not well documented and emperical experiments are virtually non-existant.

4. The interrelationships between topographic effects, sun angle and azimuth, and viewing geometry need to be investigated in relation to correlation techniques and accuracies - as related to map information and accuracy requirements.

5. Ability to extend control by means of triangulation (with stereo MLA data) and/or by use of precise spacrcraft position and altitude data for unmapped areas is poorly documented. In particular, the benefits gained from ancillary sensor such as

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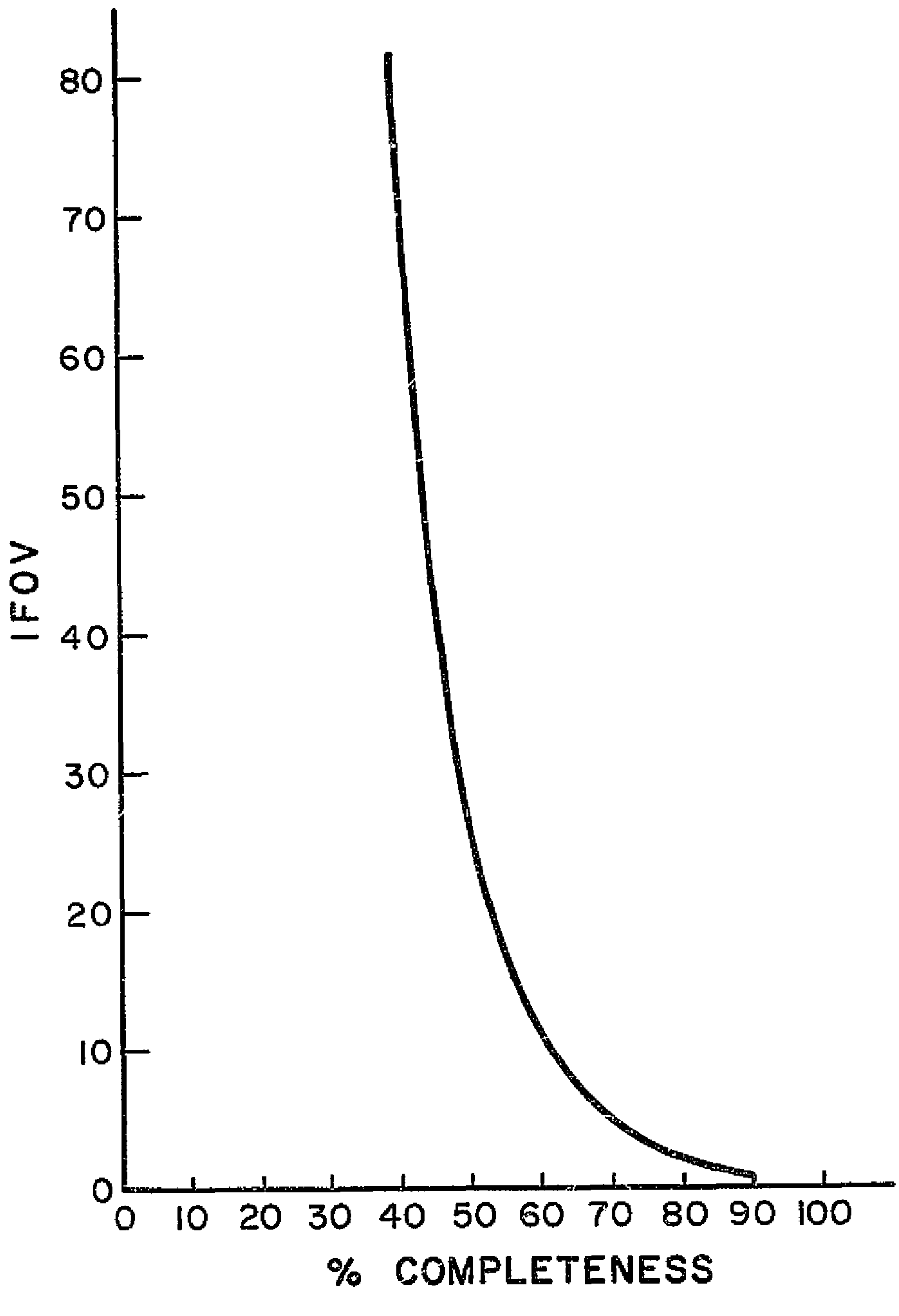

FIGURE 8. IFOV VS. COMPLETENESS

the NAVSTAR GPS, stellar cameras/trackers laser altimeter, etc., needs to be throughly investigated. Every bit of supplementary data may be required in adjustment procedure in order to ensure the derivation of x,y,z terrain coordinates to acceptable accuracies.

6. Tradeoffs between on-board and ground processing for high resolution stereo image data are unknown in terms of efficient throughput of data.

7. Inadequacies, if current ground processing techniques must be considered, in relation to the requirements for high volume data storage, retrieval and mosaicking technology needed for production of data sets There is a need for acquiring data with internal geometric consistency to minimize the non-affine warping during resampling.

Generic Experiments

The major areas for investigation of the appropriateness of spaceborne MLA sensors for cartographic purposes include:

1. Area (frame) vs. line array sensor

2. Spatial and spectral resolution requirements to ensure adequate detail (content) for cartographic products in the scale range of 1:25,000 to 1:250,000

3. Absolute positioning accuracy (x,y,z) of terrain coordinates as related to viewing geometry, spacecraft performance, ancillary data, correlation techniques, and adjustment procedures (including autotriangulation)

4. Relative accuracy of planimetric and vertical measurements (or positions) as related to pixel dimension and internal geometric consistency of the image data [Note: this may involve consideration of GIS requirements]

5. Interrelationships between topography, sun elevation and azimuth and viewing direction as related to correlation and information extraction

6. Types of processing procedures necessary to insure adequate throughput of high resolution stereo data with good internal geometric consistency.

Eventual verification of system performance and cartographic potential will require the installation of appropriate MLA sensors in a free flying spacecraft. In this regard, data from SPOT should provide considerable information on the utility of 10m and 20m IFOV and multispectral information for compiling cartographic products and, to some degree, on the possibilities for obtaining coordinate accuracies commensurate with map accuracy standards. However, SPOT with its pointable sensors and cross track stereo coverage does not appear to be an ideal sensor system for cartographic purposes.

Although a free flyer may be several years in the future, a set of preliminary MLA experiments would be possible using the Shuttle as a platform. However, the Shuttle is not an ideal vehicle due to orbital variations and platform instabilities (as compared to a free flyer). In outline, a basic shuttle experiment might involve a comparison of the following sensor (employed on the same mission) and their utility for cartographic purposes:

1. Film camera (e.g. LFC) - good resolution and geometric fidelity would provide baseline information against which area (frame) and line array could be compared.

2. Area array (framing) camera - aligned vertically and with sufficient angular coverage to provide data with a B/H ratio of approximately 0.6. [Note: it might be appropriate to devise a system which involved side-by-side camera (one film and one area array with identical formats, focal lengths, etc.]

3. Pointable line array camera. Data from this camera in combination with ancillary information used to evaluate the problems of obtaining MLA data from platforms such as the shuttle, and the data sets could be used to test algorithms for extracting coordinate data.

SUMMARY OF DATA REQUIREMENTS FOR EXPERIMENT III CARTOGRAPHY

III CARTOGRAPHY

	SENSOR COMPARISON	INTERRELATIONSHIP ANALYSIS
FIELD SURVEYS	YES	N/A
SPECTRORADIOMETRY	N/A	N/A
COLLATERAL DATA	YES	YES
HIGH RES. PHOTOGRAPHY	B W VISIBLE AND IR	B W VISIBLE AND IR
TEMPORAL REGISTRATION	N/A	N/A
RECTIFICATION	CRITICAL	CRITICAL
BASE LINE SPATIAL RES.	2M	2M
SPECTRAL REQ.	VIS AND NIR	NIV AND NIR
TEMPORAL RES.	N/A	N/A
TERRAIN DATA	STEREO PAIRS	STEREO PAIRS
SPECIAL REQUIREMENTS	EXTREMELY STABLE PLATFORM	EXTREMELY STABLE PLATFORM

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WORKSHOP ON THE USE OF FUTURE
MULTISPECTRAL IMAGING CAPABILITIES FOR
LITHOLOGIC MAPPING

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WORKSHOP ON THE USE OF FUTURE MULTISPECTRAL IMAGING CAPABILITIES FOR LITHOLOGIC MAPPING

WORKSHOP SUMMARY

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INTRODUCTION

After ten years of continuous orbital operations, many geologists have had an opportunity to examine synoptic, multicolored imagery of the earth obtained by the Landsat series of satellites. The three Landsat satellites operated in the past have carried Multispectral Scanners (MSS) which measure solar radiation reflected from the earth's surface in four distinct wavelength intervals. These spectral bands are situated in the visible and ifrared portions of the electromagnetic spectrum, specifically at wavelengths of 0.5-1.1 micrometers. Individual MSS bands possess a maximum spectral resolution of 0.1 micrometers, and they are used to measure radiation over surface areas that are 80 meters square.

Current technological advances are expected to lead to major improvements in the measurement capabilities of future orbital imaging systems. Future sensors will make use of solid state detector arrays, improved optics, and on-board signal processing to increase the number of spectral channels that can be accessed, to improve resolution and sensitivity, and to introduce greater flexibility into the process of acquiring and calibrating multispectral image data. Anticipated improvements in measurement capabilities are, in turn, expected to increase the value of orbital multispectral imagery for geologic mapping.

Geologists can extract several different types of useful information from orbital surveys of electromagnetic radiation that is reflected or emitted from the earth's surface. Many geological materials possess distinctive reflectance and emissivity properties that are related to their mineralogy, chemical composition, and physical structure. Geologists use the general term lithology to refer to these gross characteristics of rock materials. Multispectral variations in the intensity of earth radiation measured at orbital altitudes can be used to detect differences in the lithology of certain rocks and soils. The use of multispectral surveys to identify areal variations in the physical and chemical characteristics of geological materials is generally referred to as lithologic mapping.

Geologists also employ orbital imagery in a more conventional manner for geomorphological studies (i.e., terrain analysis). Aerial photography is routinely used by geologists to classify surface landforms, to map regional drainage patterns, to estimate the orientation and attitude of individual rock units, to measure displacement along faults and fractures, etc. Photogeologists interprete this type of information to detect folds and faults within the earth's crust, to determine the overall style of deformation within a tectonically disturbed area, and to project regional relationships between different rock units downwards into the subsurface. The use of orbital imagery in a more standard photogeologic manner to identify major structural features within the crust is generally referred to as structural mapping. Geological maps typically contain both lithological and structural information, and specifically display areal variations in rock lithology and crustal structure.

The Workshop on the Use of Future Multispectral Imaging Capabilities for Lithologic Mapping was held on April 20 and 21, 1982. It was one of a series of workshops conducted during the spring of 1982 by NASA's Multispectral Imaging Science Working Group. This Working Group was constituted to evaluate the utility of improved orbital imaging capabilities from the standpoint of different scientific disciplines, such as geology, botany, hydrology, and geography. The Lithologic Mapping Workshop was organized to discuss how geologists might exploit the anticipated measurement capabilities of future orbital imaging systems to discriminate and characterize different types of geologic materials exposed at the earth's surface. Potential improvements in structural mapping capabilities that could be achieved with future imaging sensors were discussed in a separate workshop organized by the Working Group's Geography team. This latter meeting was held April 29-30, 1982 in San Antonio, Texas.

The Lithologic Mapping Workshop was held on the campus of the California Institute of Technology in Pasadena, California. Approximately 25 individuals representing a variety of research agencies, academic institutions, and private companies attended the meeting. Collectively, the workshop participants possessed a broad base of experience in the use of imaging techniques for planetary exploration, terrestrial applications of remote sensing methods, and ground based geological mapping. A list of participants is included in this document.

PURPOSE OF THE WORKSHOP

The principal objectives of the Lithologic Mapping Workshop were:

1) to summarize past accomplishments in the use of multispectral imaging techniques for lithologic mapping,

2) to identify critical gaps in earlier research efforts that currently limit our ability to extract useful information about the physical and chemical characteristics of geological materials from orbital multispectral surveys, and

3) to define major thresholds in measurement resolution and sensitivity within the visible and infrared portions of the electromagnetic spectrum which, if achieved, would result in significant improvements in our ability to discriminate and characterize different geological materials exposed at the earth's surface.

The first day of the workshop was devoted to a series of formal presentations which provided critical reviews of earlier work. These presentations addressed many different aspects of multispectral remote sensing including laboratory studies of the reflectance and emissivity properties of geological materials, field measurements of <u>in situ</u> reflectance and emissivity, theoretical models of the spectroradiometric properties of extended natural surfaces, atmospheric absorption and scattering, and analysis of aerial multispectral surveys conducted over specific test sites. Discussion of these topics provided an overview of how geologists currently use multispectral imaging techniques to detect lithologic boundaries within naturally occurring geologic units.

Presentations on the first day highlighted some of the key assumptions that are commonly employed in the analysis and interpretation of multispectral imagery. In many instances, these assumptions reflect critical gaps in our understanding of how electromagnetic radiation is reflected, absorbed, and emitted at the earth's surface, how it is transmitted through the earth's atmosphere, and how it is measured by an orbital or aerial sensor system. These gaps in understanding should be the principal focus of future research efforts. The second day of the meeting was less structured and gradually evolved into a free-wheeling discussion of future sensor systems. A series of candidate experiments were proposed which placed heavy emphasis upon combined analysis of digital multispectral imagery and other data sets.

Although many scientific questions warrant further study, recent research results have underscored the importance of improving orbital multispectral imaging capabilities in the future. Previous sensors have generally acquired imagery in a limited number of spectral bands situated in specific subsections of the visible and infrared spectrum. Analysis of such data as indicated that unique types of lithological information can be extracted from multispectral measurements performed in different portions of the spectrum. Past research has demonstrated that the value of lithologic information derived through multispectral image analysis will increase with improved resolution and sensitivity in specific spectral regions, and with simultaneous acquisition of data in a wider variety of bands distributed throughout the visible and infrared spectrum.

Workshop participants were keenly aware of the need for continuing research to evaluate the utility of multispectral imaging methods for lithologic mapping in different environments. However, a strong consensus emerged during the meeting that recent experimental results provided a firm basis for specifying the desired measurement capabilities of the next generation of imaging sensors, without recourse to further research and experimentation. Workshop participants agreed that they were currently able to specify desired measurement capabilities in different portions of the spectrum that would be challenging from a sensor design standpoint, but also commensurate with anticipated technological capabilities.

CURRENT LITHOLOGIC MAPPING CAPABILITIES

Our current ability to derive lithologic information from multispectral surveys is based largely upon previous studies of the reflectance and emissivity properties of geological materials. Laboratory measurements of the spectral properties of rock materials are typically performed on small samples under rigorously controlled conditions. Laboratory measurement programs have tended to concentrate upon pure crystalline materials in the past. More recently, laboratory studies have been performed on clay minerals, silica glasses, and mineral mixtures that are commonly encountered in nature.

Laboratory studies have been complemented by field research programs which employ portable, ground-based instruments and airborne scanners to survey the spectral properties of natural surfaces over progressively larger areas. The wider diversity of surficial materials encountered in field measurements tends to reduce the spectral contrast (i.e., intensity) of absorption and emissivity features associated with individual minerals. Field studies have provided insight into how the spectral 'signatures' of different surficial materials are merged in orbital multispectral surveys.

Laboratory and field studies provide the conceptual foundation for the analysis and interpretation of multispectral imagery. These studies have conclusively demonstrated that certain types of lithologic variations can be detected in multispectral surveys of naturally occurring geological materials. The remainder of this section highlights the current state-of-the-art, with specific reference to lithologic features that can potentially be discriminated in multispectral visible and infrared imagery.

Iron Oxides. Reflectance variations at wavelengths of 0.5-1.0 micrometers have proven to be useful for discriminating a variety of iron oxides that commonly form on rock and soil particles in semi-arid environments. Geologists use the general term limonite to refer to a group of brown ferric oxides that typically develop through the chemical breakdown of magnetite and other iron-bearing minerals. Limonite consists of minerals such as hematite (Fe_2O_3) and geothite ($FeO(OH)$), and it can be detected in Landsat MSS imagery. Iron oxides may be produced by surface weathering phenomena, and by subsurface chemical reactions between iron-bearing minerals and heated, corrosive groundwaters. Subsurface hydrothermal alteration commonly accompanies the emplacement of certain types of mineral deposits, such as copper porphyry bodies and lead-zinc vein deposits. Under certain circumstances, limonite occurs in association with hydrothermally altered rocks, and it can provide an important guide to regional mineralization.

Clay Minerals. Variations in spectral reflectance at wavelengths of 2.0-2.5 micrometers have proven to be useful for discriminating certain clay minerals that commonly occur in semi-arid environments. Clays are sheet silicate structures which possess hydroxyl (OH) ions in their crystalline lattice. They typically form on the surface of rocks through chemical modification of a rock's primary mineral constituents. Variations in the clay mineralogy of natural surfaces have been detected in aerial and orbital multispectral measurements performed at wavelengths of 2.0-2.5 micrometers.

Airborne radiometer measurements have been obtained with an instantaneous field of view 20 meters square and a spectral resolution of 8 nanometers (see article by W. Collins). Orbital radiometer measurements at comparable wavelengths were obtained by the Shuttle Multispectral Infrared Radiometer (SMIRR) flown on the second test flight of the Space Shuttle. The SMIRR possessed five bands in the 2.0-2.5 micrometer region, and it performed measurements with a maximum spectral resolution of 20 nanometers and an instantaneous field of view 100 meters in diameter. Multispectral variations observed in radiometer surveys have been used to discriminate different clay species, such as montmorillonite ($Al_2 Si_4 O_{10} (OH)_2 \times nH_2O$) alunite ($KAl_3(SO_4)_2(OH)_6$), and kaolinite ($Al_4 Si_4 O_{10} (OH)_8$). As described above, clay minerals can be produced by chemical weathering processes at the earth's surface and by subsurface hydrothermal alteration. Multispectral surveys in the 2.0-2.5 micrometer region can potentially be used to distinguish hydrothermal clay minerals from other clay species. This capability could, in theory, be used to map variations in the intensity and extent of regional hydrothermal alteration.

Quartz. Emissivity variations at thermal infrared wavelengths of 8-14 micrometers have proven useful for detecting the presence and relative abundance of quartz (SiO2) in surficial rocks and soils. Quartz is a common constituent of many geological materials. Multispectral thermal infrared surveys performed in sedimentary terranes provide a means of distinguishing silicate rocks such as shales and sandstones from non-silicate rocks such as limestone ($CaCO_3$) and dolomite ($CaMg(CD_3)_2$). They can also be used to detect subtle lithologic variations between sedimentary rocks containing varying proportions of quartz (e.g., sandstones, siltstones, claystones, etc.). Multispectral infrared surveys conducted in igneous terranes provide a means of differentiating certain plutonic rocks such as monzonites and quartz monzonites, latites and quartz latites, etc. The ability to detect variations in the occurrence and abundance of quartz also has implications for mineral exploration. Quartz crystals are commonly found in the cracks and fractures that served as conduits for hydrothermal fluids during the emplacement of certain types of mineral deposits. Rocks which are impregnated with these quartz veins are said to be "silicified", and they are commonly used as ore guides when prospecting in hydrothermal mineral districts.

Geobotanical Stress. Past research has tentatively suggested that mineral induced stress can be detected in heavily vegetated areas on the basis of multispectral variations in leaf reflectance. The reflectance of most natural forms of chlorophyll increases markedly over the 0.68-0.70 micrometer wavelength interval. Analysis of multispectral radiometer data acquired in vegetated areas has suggested that the increase in leaf reflectance in the near infrared may shift to somewhat shorter wavelengths with increasing soil concentrations of metallic elements. Correlations between leaf reflectance and soil geochemistry have also been observed at wavelengths of 1.65 micrometers. Multitemporal measurements of oak leaf reflectance over the course of a natural growing season has revealed a strong positive correlation between leaf reflectance and soil metal concentration during the early fall. This observation tentatively suggests that early onset of autumn color (i.e., leaf senescence) may occur in areas of mineral induced stress. The use of botanical indices such as plant distribution, density, or vigor to detect lithological variations in underlying geological materials is generally referred to as geobotanical mapping. The limited experimental results of the past have not demonstrated that multispectral surveys can be routinely used for geobotanical mapping in heavily vegetated areas. However, they do suggest that further study of the reflectance characteristics of natural plant canopies at wavelengths of 0.5-2.0 micrometers is warranted.

NEAR TERM RECOMMENDATIONS CONCERNING FUTURE ORBITAL IMAGING CAPABILITIES

Past use of multispectral imaging techniques for lithologic mapping has been largely limited to the discrimination of different types of rocks and soils. Observed variations in the spectral reflectance and thermal emission of natural surfaces have been used to detect lithologic boundaries within naturally occurring geological materials. These remotely sensed boundaries separate materials of differing mineralogy, chemical composition, and/or physical structure. In most instances, however, it has not been possible to identify the specific lithological features that produce apparent boundaries in multispectral imagery solely on the basis of measured variations in surface reflectivity and emission. Identification of the lithologic features that are responsible for remotely sensed boundaries has generally been accomplished through comparisons with pre-existing geological maps, or field mapping studies that are specifically designed to verify image interpretations.

Lithologic identification of surficial geological materials has been hindered in the past by the size and number of measurement channels on existing multispectral scanners. Orbital sensors such as the Multispectral Scanner and Thematic Mapper obtain measurements in individual spectral bands which generally extend over wavelength intervals of 80 nanometers or more. In contrast, many mineral species possess diagnostic absorption and emissivity features that extend over wavelength intervals of 50 nanometers or less. As discussed above, past research has demonstrated that unique types of lithologic information can be extracted from multispectral measurements obtained in different portions of the visible and infrared spectrum. Simultaneous measurements in selected wavelength intervals distributed throughout the visible and infrared could place a wider variety of constraints on the lithology of geological materials, and potentially lead to lithologic identification of specific types of rocks and soils. Existing sensors generally obtain measurements in limited subsections of the 0.5-14 micrometer region, and are not designed to fully exploit the various sources of lithologic information that potentially reside in different spectral regions.

The relatively large size and limited number of bands on existing orbital sensors results in ambiguous interpretations of multispectral variations. For example, data obtained with the four channel MSS can be used to detect the reddish-brown limonitic stain that commonly develops on the surface of rock and soil particles. It is not possible to differentiate the individual minerals that form this surface coating on the basis of MSS measurements. Discrimination of limonitic minerals such as hematite (Fe_2O_3) and goethite ($FeO(OH)$) will be possible with the addition of the 2.2 micrometer band on the Thematic Mapper (TM). However, other ambiguities will remain in the interpretation of TM data, specifically with regard to the discrimination of clay and carbonate minerals.

In principle, it should be possible to overcome many of the ambiguities involved in image interpretation by obtaining multispectral measurements in a greater number of narrower spectral bands. Multispectral surveys conducted throughout the visible and infrared spectrum with improved spectral resolution will enable geologists to identify specific lithological characteristics of surficial rocks and soils. These characteristics may differ from the lithologic features that are conventionally noted by ground based field geologists. Consequently, it is likely that the use of multispectral imaging techniques for lithologic identification will lead to the development of a new taxonomy for labelling geological materials, one that differs from conventional systems of rock and mineral classification. This new taxonomy will be based upon the spectroradiometric properties of naturally occurring geological materials, and it will provide geologists with a means of categorizing rocks and soils through multispectral image analysis.

The ability to identify different geological materials in a consistent fashion on the basis of multispectral surveys represents a major breakthrough in the use of imaging techniques that will revolutionize geological remote sensing. The measurement capabilities of future imaging sensors that are required to achieve this breakthrough were discussed at length at the Workshop. Workshop participants were asked to identify generic measurement capabilities in different spectral regions that would enable geologists to characterize the lithology of naturally occurring rocks and soils. Workshop discussions avoided questions related to the desired number or position of specific spectral bands. Rather, a consensus was reached on the spectral resolution, spatial resolution, and radiometric sensitivity that is needed in different portions of the visible and infrared spectrum.

A series of ground rules were established at the outset of the meeting that governed all discussions of future sensor capabilities. Recommendations concerning image resolution and sensitivity were to be firmly based on the results of earlier field experiments. Furthermore, technical problems related to instrument design, data transmission and reduction, and digital analysis of large data arrays were not formally considered by the Workshop participants.

The summary recommendations of the Workshop concerning the desired measurement capabilities of the next generation of orbital imaging sensors is presented in Table 1. These recommendations specify generic measurement capabilities based on the assumption that future orbital sensors will collectively possess a large number of spectral channels distributed throughout the 0.5-14 micrometer wavelength region. These recommendations do not represent a proposal for a monolithic sensor that would obtain simultaneous measurements over the entire visible and infrared spectrum with the resolution and sensitivity specified in Table 1.

The most significant difference between the proposed imaging capabilities specified in Table 1 and the actual measurement capabilities of existing sensors is in the area of spectral resolution. A resolution of 50 nanometers is desired over wavelengths of 0.4-2.0 micrometers, complemented by 20 nanometer resolution in the critical 2.0-2.5 micrometer region. This exceeds the planned spectral resolution of the Thematic Mapper, and it approaches the spectral resolution of SMIRR at wavelengths of 2.0-2.5 micrometers. Desired spectral bands in the thermal infrared would be 0.5 micrometers wide. These bands correspond in size to spectral channels that are available on the current generation of airborne multispectral scanners.

The 50 nanometer channels required in the visible and near infrared (0.4-1.0 micrometers) should be augmented by a limited number of carefully selected, narrower bands 10 nanometers in bandwidth. These narrow bands would be positioned at wavelengths of 0.9-1.2 micrometers to detect subtle variations in iron oxide mineralogy (e.g., to distinguish goethite and hematite), and at wavelengths of 0.65-0.75 micrometers to detect mineral induced stress in natural vegetation canopies.

The 30 meter instantaneous field of view (IFOV) of the Thematic Mapper was deemed to be adequate for mapping lithologic variations in many common geological settings. Aircraft scanner imagery is generally acquired with a spatial (pixel) resolution of 15 meters. While this higher spatial resolution is superior for image analysis and interpretation, most of the lithologic variation observed in airborne multispectral surveys can also be detected in imagery that has been artifically degraded to a pixel resolution of 30 meters. The incremental advantages of acquiring multispectral imagery with a 15 meter IFOV have not been conclusively demonstrated by earlier research efforts. (The utility of higher spatial resolution for terrain analysis and structural mapping has been demonstrated in the past. However, the recommendations presented in Table 1 are made strictly from the standpoint of lithologic mapping.)

The desired radiometric sensitivity of future imaging sensors was specified as 1% of the incoming signal. Current sensors tend to have a fairly broad range of signal quantization, approaching 256 grey levels (eight bit precision) within individual channels of the Thematic Mapper. In many instances, the range of surface reflectance or emission values observed in a natural scene will not fill the full range of digital values that are potentially available. Instead, the digital values that are recorded in a specific spectral band will tend to cluster within a relatively narrow subsection of the available digital range. This results in the collection, transmission, and reduction of digital "bits" which contain no useful information.

Workshop participants recommended that the signal quantization of future sensors could be limited to seven bit precision (corresponding to 128 grey levels), if the range of observed digital values in each channel was artificially stretched to cover a broader segment of the available digital range. This would involve the use of some type of automatic gain control which would match the middle of the observed range of scene values with the middle of the seven bit grey scale available in individual spectral bands.

The noise equivalent temperature difference (NEDT) specified in Table 1 for the thermal infrared region is comparable to the sensitivity of the current generation of airborne thermal scanners. It represents roughly a factor of two improvement over the sensitivity of previous orbital sensors such as the Heat Capacity Mapping Radiometer (Heat Capacity Mapping Mission) and the Thematic Mapper (Landsat-D). Absolute sensor calibration would be desirable in the thermal infrared, but only relative calibration is required in the visible and reflected infrared regions.

Table 1

DESIRED MEASUREMENT CAPABILITIES OF THE NEXT GENERATION OF ORBITAL IMAGING SENSORS

	SPECTRAL REGION WAVELENGTH, MICROMETERS 0.4-1.0	1.0-2.0	2.0-2.5	8-14
SPECTRAL RESOLUTION	0.05um (selected 0.01 bands)	0.05um	0.02um	0.5um
SPATIAL RESOLUTION	30m	30m	30m	30m
RADIOMETRIC SENSITIVITY	1% of the incoming signal			NEDT=0.2K at 300K
RADIOMETRIC CALIBRATION	RELATIVE			ABSOLUTE

LONG TERM RESEARCH RECOMMENDATIONS

Certain technical issues emerged in the course of the Workshop discussions which could not be resolved on the basis of past research results. Topical problems requiring additional study were identified at the meeting, and they are summarized in a general fashion in this section. This research is expected to contribute to the development of advanced sensor systems during the middle of the next decade.

Laboratory Studies of the Spectroradiometic Properties of Natural Materials

Laboratory studies of the spectral and radiometric characteristics of geological materials have concentrated almost exclusively upon pure crystalline minerals and samples of fresh, coherent rock. These materials are not necessarily representative of "geological" surfaces that are actually encountered in nature. The surfaces of rocks and soils exposed to natural weathering phenomena are commonly altered into complicated assemblages of clay minerals, elemental oxides, and amorphous silica gels. In certain environments, rock and soil surfaces may be veneered with biological films generated by bacteria, algae, fungi, or lichen. Variations in the spectral characteristics of natural surfaces may, in fact, be significantly influenced by the spectroradiometric properties of these unconventional "geological" materials.

Future laboratory studies should examine the spectroradiometric properties of a wider range of naturally occurring geological materials. New methods are needed which will enable geologists to collect and carefully preserve micron thick samples of natural rocks and soils exposed in the field, and return such samples to the laboratory for detailed analysis. The physical structure and chemical nature of these materials needs to be better understood in order to determine their contribution to the observed spectral character of natural surfaces. Eventually, we should reach a stage where many of these exotic materials can actually be fabricated or cultured under laboratory conditions. This will enable researchers to investigate the effect of variable environmental conditions upon the evolution of natural geological surfaces, and ultimately to forecast the spectroradiometric properties of geological materials in different weathering environments.

Theoretical models relating the spectral signatures of individual materials to the overall spectral response of extended areas are required to make effective use of laboratory measurements in multispectral image analysis. The average reflectance and emissivity properties of natural surfaces are difficult to predict due to such factors as the microrelief of natural surfaces, multiple reflection and re-emission of radiation from different surficial materials, vertical variations in the chemical or physical nature of surficial materials, the presence of surficial films or coatings, etc. Microscale mixing models are needed which can describe the average spectral response of natural surfaces at small scales in which the contribution of component materials is highly non-additive (corresponding roughly to horizontal distances of one meter or less).

Spatial Resolution

Improvements in the spatial resolution of orbital imagery are extremely useful for structural mapping. Decreasing image pixel size permits a photo-interpreter to identify a far broader range of surficial landforms, bedding features, and drainage elements. In fact, the scale at which geological structures can be mapped from a digital image can be directly related to pixel resolution. The effect of improved spatial resolution upon lithologic mapping capabilities is not as well known. There was universal agreement at the Workshop that the 30 meter resolution of the Landsat D Thematic Mapper represented a significant advance over the 80 meter resolution of the Landsat Multispectral Scanner. In addition, Workshop participants generally agreed that it would be undesirable to obtain imagery in which individual trees or large boulders corresponded in size to an entire image pixel. (This equates to a lower bound in pixel resolution on the order of 5-10 meters.) However, relatively little is known about the incremental advantages of increasing pixel resolution beyond 30 meters for purposes of lithologic mapping.

A series of field experiments designed to obtain multispectral measurements at varying spatial resolution are needed to determine whether decreasing pixel size results in significant improvements in our ability to discriminate lithologic boundaries. These experiments should make use of portable field instruments and statistical, ground based sampling strategies. Field measurements should be directly compared with multispectral surveys obtained from helicopter, aircraft, and orbital platforms.

At scales of 5 meters and greater the spectral signatures of surficial components tend to combine in more of an additive fashion. A different class of spectral mixing models is needed at these scales to characterize the manner in which different surficial materials contribute to observed multispectral variations. These mixing models will be used to develop mathematical procedures for separating the spectral signatures of individual materials in remotely sensed imagery, and to identify the geological materials that are present within individual picture elements.

Spectral Resolution

Previous research in both the laboratory and the field has clearly indicated that high spectral resolution imaging capabilities at wavelengths of 0.4-2.5 micrometers will have a major payoff in terms of improved lithologic mapping. High spectral resolution field measurements have primarily been obtained with non-imaging radiometers. The next logical step in exploring the geologic utility of high spectral resolution imaging capabilities is to fabricate narrowband imaging sensors that can be used to collect experimental data over a variety of test sites. Airborne scanners developed for research purposes would ideally possess a spectral resolution of 20 nanometers in the visible and near infrared (0.4-1.0 micrometer wavelength region), as well as the long wavelength portion of the shortwave infrared (specifically the 2.0-2.5 micrometer region). A spectral resolution of 20 nanometers would be sufficient in the remaining portion of the shortwave infrared (i.e., the 1.0-2.0 micrometer region), and bandwidths of 0.2-0.3 micrometers would be desirable in the thermal infrared (8-14 micrometer wavelength region). Portable radiometers currently in use can generally obtain multispectral measurements with spectral resolutions that equal or exceed these recommended imaging capabilities.

Radiometric Sensitivity

There is currently a large gap between the precision of laboratory and field spectral measurements. Laboratory spectra are typically measured with twelve bit precision, whereas field spectra are usually measured with eight bit precision (corresponding to a 256 level "gray scale" in each spectral channel). Few, if any, experiments have been performed to determine the geologic utility of improved radiometric sensitivity in multispectral imagery. An expansion of the permissable range of digital values in multispectral imagery could prove useful for detecting trace amounts of spectrally distinct materials exposed at the earth surface. Such a capability could be applied to the detection of lithologic units that typically outcrop over short distances, localized concentrations of exotic clay minerals commonly associated with buried mineral deposits, or subtle spectral variations in vegetated areas that might be correlated with subsurface geological conditions. These potential applications of improved radiometric sensitivity are largely speculative, and need to be tested by a carefully structured program of field experimentation. An airborne multispectral scanner possessing high signal-to-noise characteristics and variable levels of signal quantization is needed to explore the utility of improved radiometric sensitivity.

Geobotany

Vegetation has a significant influence on the average spectral properties of natural surfaces in all but the most arid types of environments. Variations in the distribution, density, and vigor of vegetative species have been detected in the past in multispectral imagery. It may be possible to relate variations in these parameters to the lithology of underlying geological materials in certain instances.

Current appreciation of how multispectral imagery might be used for geobotanical mapping is based largely upon a limited number of field studies in which empirical correlations between vegetation characteristics and geological conditions have been observed. Laboratory experiments have also been performed to study the relationship between soil concentrations of metallic elements and the spectral characteristics of plants. Correlations between soil geochemistry and leaf reflectance have been noted in both the field and the laboratory, particularly at higher levels of toxicity.

Improved understanding of the spectral characteristics and variability of natural vegetation, and their relationship to the geological substrate is needed if multispectral imaging techniques are to eventually be used for lithologic mapping on a global basis. Future laboratory experiments should strive to simulate the full range of environmental conditions that are actually encountered in nature. In addition, a wider variety of test site studies should be conducted to test specific geobotanical hypotheses in different climatic settings.

New Spectral Regions

Laboratory studies have suggested that atmospheric windows in the mid-infrared at wavelengths of 3-5 and 15-25 micrometers could potentially prove useful for lithologic mapping. Thermal emission from natural surfaces in the 3-5 micrometer window is generally weaker by a factor of four or more than emission at wavelengths of 8-14 micrometers. Furthermore, very few minerals possess diagnostic spectral features in the 3-5 micrometer region. In contrast, thermal emission in the 15-25 micrometer window is generally higher, and a number of common minerals possess diagnostic spectral features at these wavelengths (notably feldspars). The principal drawback to remote sensing in this spectral region is that atmospheric transmission is low and highly variable. These spectral regions may merit greater study in the future with the advent of more flexible sensor systems which can easily obtain multispectral measurements over a broad range of wavelengths with greater radiometric sensitivity. Simultaneous measurements of atmospheric transmission will be required to make effective use of multispectral imagery acquired at wavelengths of 15-25 micrometers.

CANDIDATE EXPERIMENTS

The ability to discriminate and identify geological materials at the earth's surface is not based solely on the measurement capabilities of an imaging sensor and the reflectance and emissivity properties of surficial materials. Other factors such as atmospheric scattering and absorption, and topographic effects may limit the interpretability and, hence, the utility of multispectral imagery. Alternatively, the utility of multispectral surveys for lithologic mapping may actually be enhanced through combined analysis of visible-infrared imagery and imagery acquired at longer (microwave) wavelengths. A series of candidate experiments were discussed at the workshop which would address these issues and provide greater insight into the ultimate capabilities and limitations of multispectral imaging methods for lithologic mapping. These proposed experiments are summarized below.

Atmospheric Corrections to Multispectral Survey Data

Variations in atmospheric transmission within the 0.4-2.5 and 8-14 micrometer regions are principally attributable to variations in the distribution of water vapor within the earth's atmosphere. Atmospheric effects in multispectral surveys are frequently ignored in image analysis because they can be highly variable both within and between images of a particular area. In certain instances, "standard" atmospheric models have been used to account for variations in atmospheric transmission at different wavelengths. These models assume an average set of properties for the atmosphere as a function of latitude and season. The use of these standard atmospheric models in the reduction and analysis of remote sensing imagery has been limited, although they have proven useful in a few isolated cases. A series of controlled orbital experiments is needed to determine the extent to which atmospheric corrections can improve the geological utility of multispectral surveys. Key meteorological parameters and areal multispectral variations should be measured from orbit simultaneously at similar spatial scales. Orbital meteorological data could be used in conjunction with theoretical transmission models to correct image data on a pixel-by-pixel basis for the effects of atmospheric absorption and scattering. Meteorological parameters of potential interest include atmospheric opacity, water vapor abundance as a function of altitude, and the thermal structure of the atmosphere. This proposed experiment could potentially demonstrate the importance of simultaneous observations of surface and environmental conditions, and assist in determining the types of sensors that should be placed upon an earth-orbiting space platform.

Topograhic Corrections to Multispectral Survey Data

Variations in the spectral brightness of a natural scene can be introduced by variations in the viewing geometry of the sensor system and by variations in the source of radiation that is illuminating the scene. For example, orbital measurements of surface reflectivity performed over extended areas of uniform lithology, such as sand deserts, may vary over an appreciable range of values. These variations are related to solar azimuth (e.g. differences in the intensity of forward and backscattered solar radiation) and surface topography (e.g. the presence of sand playas, dunes, hills, etc.). Shadows are extreme examples of variations in scene brightness. Spatial variability in scene brightness can complicate the analysis and interpretation of multispectral imagery. In the past, measurements obtained in two distinct spectral channels have been ratioed to reduce topographic effects and highlight differences in the inherent spectral characteristics of surficial materials. The use of band ratioing techniques in image analysis rapidly becomes impractical as the number of measurement bands increases. A series of test site experiments should be conducted which employ digital topographic data to account for variations in the inclination and azimuth of natural surfaces in remotely sensed imagery. These parameters could be used in combination with sensor and solar ephemeris data to estimate sensor viewing angles and solar zenith angles on a pixel-by-pixel basis. In principle, these latter parameters be readily incorporated in existing procedures for pixel classification and image enhancement, and they could potentially lead to improvements in lithologic discrimination and identification. Digital topographic data would also be useful in attempting to project observed contacts between surficial rock units downward into the subsurfaces.

Combined Utility of Visible, Infrared, and Microwave Imaging Techniques for Lithographic Mapping

Radar imaging techniques differ fundamentally from visible and infrared methods in that they rely upon an artificial source of radiation to illuminate the earth's surface. Radar systems generate a series of microwave pulses which are reflected from the surface and received back at the transmitting antenna. Variations in backscatter observed within a radar image are related to surface relief and roughness, and the dielectric properties of surficial materials. Analysis of radar imagery primarily produces information concerning the morphology and physical structure of natural surfaces. For example, radar imagery obtained at different angles of surface incidence can be used to discriminate surficial materials on the basis of their roughness characteristics in much the same way that multispectral imagery obtained at shorter wavelengths can be used to discriminate materials on the basis of their reflectivity and emissivity characteristics. Information concerning the physical size and shape of surficial materials is quite different from, and complementary to the types of lithographic information that are commonly derived from visible and infrared multispectral imagery. A great deal of additional experimentation is required involving the analysis of visible, infrared, and microwave imagery collected over common test sites to gain an appreciation of the combined utility of these very different data sets for lithologic mapping.

Summary

A wide variety of topics were discussed during this relatively short two day meeting. In addition, a fair degree of agreement was reached among the workshop participants concerning the desired capabilities of future sensor systems and future research directions. One measure of the success of the meeting was the fact that none of the participants managed to speak longer than ten minutes without being barraged by questions and comments. We would like to thank all who attended for their active participation and free exchange of views. By any measure, we judge the workshop to be an unqualified success.

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HYDROLOGIC SCIENCE

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

ROBERT RAGAN

EXECUTIVE SUMMARY

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP FOR HYDROLOGIC SCIENCE

A. INTRODUCTION

The MISWG Hydrologic Science Group conducted a workshop on April 26, 27, and 28 at the Goddard Space Flight Center in Greenbelt, Maryland. The following working objectives were adopted: a) define the current state of knowledge concerning the role of multispectral imaging science in hydrology; b) identify critical areas where gaps in our knowledge limit opportunities for significant improvements in our understanding of the hydrologic processes; c) evaluate the potential of multispectral imaging sciences as tools to close these gaps in knowledge; and d) develop guidelines for a series of remote-sensing-based experiments that would help close these gaps in knowledge and, thereby, provide man with the improved scientific base necessary for better utilization of the world's water resource. The resulting documentation is intended to provide guidance for multispectral imaging programs in the hydrologic sciences with special emphasis on the visible and infrared (IR) wavelengths.

The six-person hydrology team of the Imaging Science Working Group was supplemented by thirteen scientists having expertise on the role of remote sensing in key areas of hydrology. These scientists were drawn from the USGS, USDA, NOAA, USACE, NASA, EPA, the private consulting community, and three universities. Collectively, the participants of this workshop represented the frontier in man's knowledge of the role of multispectral remote sensing as both scientific and application tools in hydrology.

The first step in the workshop was the presentation of a series of prepared briefings, each dealing with a specific area of hydrologic science. Each of these briefings addressed the four objectives outlined in the first paragraph as they related to the particular problem being discussed. After all the briefings had been presented there was a period of general discussion by all the participants. Following the general discussion, the decision was made to break into two working groups for continued discussion and development of position papers on a series of major hydrologic problem areas. The important factors developed by the working groups for each of the major problem areas identified are summarized in Section C of this document.

B. URGENCY OF REMOTE SENSING-BASED RESEARCH IN HYDROLOGIC SCIENCE

Water is a pivotal element in the quality of human life. History abounds with the chronicles of civilizations that have risen to excellence through the development and management of their water resource only to decline through the subsequent mismanagement of their limited water supplies. Too often, these declines resulted not from irresponsibility, but rather from a lack of understanding of the complex interactions among the hydrologic processes and the impacts of policy decisions on these processes.

The development and maintenance of high quality human habitation on a terrestrial scale is contingent on the resolution of increasingly complex issues related to the development and management of the limited water resource. Our knowledge of hydrologic science has allowed man to gain many benefits from his water resource. Recent developments in the multispectral imaging sciences have allowed hydrologists to advance their knowledge in some areas to a point that would allow significant improvements in the quality of development and management decisions. However, this base of scientific knowledge has many serious gaps that prohibit the evolution of critically needed tools for hydrologic decision making in an arena of a growing population having increasing expectations related to their quality of life. If these expectations for improved quality of life are to be met on anything approaching a terrestrial or even continental scale, decision makers must be supported by hydrologic information developed through techniques that far exceed the capabilities of those in use today. The working group strongly believes that multispectral imaging is rapidly reaching a point of becoming the critical tool in developing the additional scientific understanding necessary for the development of these improved hydrologic techniques.

Most of the tools used to provide information for hydrologic decision making do not give proper consideration to the temporal and spatial characteristics of important parameters controlling the processes. Indeed, many of the techniques currently used were deliberately simplified in their original development because of the absence of the type of spatial and temporal information that modern remote sensing technology is capable of providing. As stated above, the use of current capabilities in multispectral imaging has provided improvements in our understanding of the hydrologic sciences that have led to development of improved techniques in the areas of snow and ice monitoring, the simulation of rainfall/runoff and snowmelt/runoff relations, basin characterization (land use and physiography), surface water inventories, and water quality monitoring. However, improvements in both these techniques and those listed in Section C require a major commitment in multispectral imaging research if we are to resolve some critical gaps in our scientific understanding. Major scientific problems concerning the bridge between hydrologic process behavior and the information content provided by sensor resolution, wavelength, bandwidth, frequency of coverage, timing of data availability, and format of data delivery must be solved.

C. ROLE OF MULTISPECTRAL IMAGING IN MAJOR PROBLEM AREAS

The workshop identified sixteen major areas of hydrology for detailed examination with respect to the role of visual and IR imaging in improving our understanding of basic processes. No effort was made to prioritize the list nor is it all inclusive. The problems were selected as being representative of critical areas where remote sensing technologies have provided some advances in our understanding and where significant opportunities exist for the utilization of higher quality multispectral imaging to provide the additional scientific knowledge needed before new operational techniques can be developed.

This executive summary highlights key points contained in the more extensive documentation prepared by the workshop participants for each of the sixteen major problem areas. Each of the problem areas is subdivided into a series of brief comments addressing: statement of the problem; current state-of-the-art; scientific impediments to continuing advances; and suggested experiments.

- Definition of Spatially Distributed Evapotranspiration Rates for Large Areas

    Statement of the Problem - Water loss from land areas through evapotranspiration processes typically equals 50 - 100 percent of the precipitation. Evapotranspiration controls the production of biomass and its spatial and temporal behavior is defined by complex interactions among meteorological and surface phenomena.

    Current State-of-the Art - Traditional techniques designed to simulate the rate of evapotranspiration from an area of interest are constrained by their lack of sophistication, primarily imposed by an inability to define needed input data. Remote-sensing-based experiments have shown significant promise and have had some success when applied to small, relatively homogeneous areas for short time periods.

    Scientific Impediments to Continuing Advances - While there is a reasonable understanding of the role of individual components in the evapotranspiration process, we do not have the understanding necessary to synthesize the impact of the interaction of the multitude of processes involved in an area of diverse plant/soil/water complexes. We understand the transpiration of a single tree or other plant, but do not understand the role of canopy geometry on radiation and temperature distributions within a forest or plant community well enough to evolve improved approaches to large area estimates. There is a major need for research that will allow multispectral remote sensing to be used to better infer net radiation, humidity, wind velocities, and other spatially and temporally varying quantities over large areas.

Candidate Research Projects - Expand current short term experiments on small homogeneous areas that are primarily based on instantaneous measurements into large area experiments monitored by aircraft and, subsequently, high resolution geostationary platforms. Such experiments are necessary to better understand process interrelationships in nature and to define spectral/resolution/frequency requirements for the future development of dependable predictive models. Table 1 indicates the kinds of data that will be required for research in this area.

- Definition of the Temporal/Spatial Distribution of Soil Moisture Dynamics in Large Areas

Statement of the Problem - Soil moisture information is an extremely important element in the definition of important hydrologic processes and agricultural issues.

Current State-of-the Art - The soil moisture budget of large areas is so difficult to determine with conventional techniques that relatively primitive indices and other parameters are used to simulate its impact. Multispectral imaging has shown a significant level of potential for providing the critical soil moisture information and has been successful in defining this parameter in relatively small homogeneous, especially non-vegetated, areas.

Scientific Impediments to Continuing Advances - While the spectral response of isolated soils of varying soil moisture contents is fairly well understood under laboratory conditions, the application of this knowledge to the natural environment remains extremely difficult. Because soil moisture varies both temporally and spatially, work must be done to translate periodic "footprint" measurements with respect to time and space. More work needs to be done to define spectral responses as a function of moisture content, surface roughness, and vegetative cover under natural conditions.

Candidate Research Projects - Numerous small-scale and laboratory investigations are still required to fully understand the interaction mechanisms of the vegetation canopy-soil moisture complex and electromagnetic radiation. In parallel with these small-scale investigations, multispectral monitoring programs on a continuous basis must be implemented on large natural areas in order to understand the mechanics of translating small-scale phenomena into complex natural systems. Table 1 lists the kinds of data required for this research.

- Determination of Spatial/Temporal Distribution of Storm Rainfall

Statement of the Problem - The need for spatially distributed hydrologic models is widely recognized. Before the advantages offered by such models can be achieved, it is necessary to develop reliable techniques for quantifying the spatial and temporal variations of rainfall over a natural watershed.

Current State-of-the Art - Some success in defining temporal and spatial variations of rainfall has been achieved with ground-based microwave systems. Research with visible and infrared images from geostationary satellites has also shown significant promise. Reliance on traditional rain gage networks is very difficult in most areas of the world because of the sparseness of the gages.

Scientific Impediments to Continuing Advances - The problem is really one of developing sufficient understanding to translate multispectral imagery measurements into the needed rainfall information.

Candidate Research Projects - A test site should be selected that would call for the installation of a very dense rain gage network coupled with ground-based multi-frequency, active microwave measurement systems. Research aimed at development of temporal and spatial rainfall distributions would center on geostationary platforms capable of real-time multispectral imaging over a range of resolution capabilities. Monitoring of soil moisture change could also be used as a method of precipitation determination. Table 1 lists the kinds of data required for this research.

- Improving Irrigation Management Strategies

Statement of the Problem - Irrigation for crop production is one of the largest users of the world's water supply. Proper management with respect to time and spatial distribution of irrigation water can have massive impacts on crop production as well as on the quantity of water actually necessary for that production.

Current State-of-the-Art - There has been considerable success in determining the spatial distribution requirements of irrigation water through the analysis of canopy conditions using near IR aircraft imagery.

Scientific Impediments to Continuing Advances - More knowledge is needed concerning the interrelationship between spectral response and the interaction between the plant/soil system. The ability to discriminate between water induced and disease stress must be improved.

Candidate Research Projects - Long-term aircraft monitoring in a variety of spectral wave bands over a series of irrigated regions needs to be undertaken. Table 1 indicates the kinds of data required in this research.

- Determination of Snow Water Equivalent

Statement of the Problem - Snowmelt runoff is an extremely important resource making up more than 75 percent of the total water available in many areas, including most of the western United States.

Current State of the-Art - Estimating snow water equivalent and extent of coverage conventionally requires very expensive time-consuming sampling programs carried out throughout the year. Remote sensing techniques have shown tremendous promise and, indeed, have achieved operational status in the definition of extent of snow coverage in some areas. Potential for water equivalent determination is good, but must await the results of current and future research efforts.

Scientific Impediments to Continuing Advances - Before we can achieve a position of being able to estimate snow water equivalent, we must evaluate the role of mean grain size, albedo, liquid water content, and areas of active melt. The interaction of these quantities and spectral response must be better defined before significant advances can be made.

TABLE 1

SUMMARY OF DATA REQUIREMENT FOR EXPERIMENTS

WATER BUDGET PROBLEMS CENTERING ON SURFACE/ATMOSPHERE INTERFACES

	ET Rates Large Areas	Temporal/ Spatial Dist. of SM Dynamics In Large Areas	Rainfall Spatial/ Temporal Dist.	Irrig. Mgmt.
FIELD SURVEYS	Critical	Critical	Yes	Critical
SPECTRORADIOMETRY	Critical	Critical	Critical	Critical
COLLATERAL DATA	Yes	Yes	Yes	Yes
HIGH RES. PHOTOGRAPHY	CIR	CIR	B/W	CIR
TEMPORAL REGISTRATION	Critical	Critical	Yes	Critical
RECTIFICATION	Yes	Yes	Yes	Yes
BASELINE SPATIAL RES.	10M	30M-100M	100M	10M
SPECTRAL REQ.**	.4-14.0	.4-14.0	.4-14.0	.4-14.0
TEMPORAL RES.	T/S[1]	T/S	Daily	T/S
TERRAIN DATA*	Yes	Yes	N/A	N/A
SPECIAL REQUIREMENTS				

* Either Existing DTM or Flight Experiment

** Specific Bands to be Determined

[1] T/S - Time Series

Candidate Research Projects - A series of projects should be undertaken to define: 1) radiative transfer modeling strategies for snow albedo; 2) snow grain size; 3) snow water equivalent or depth through combined visible/near infrared and microwave techniques; and 4) location of active snowmelt areas. Table 2 lists the kinds of data required for this research.

- Flooding Dynamics of Wetlands

Statement of the Problem - The frequency and duration of flooding are major factors controlling the species composition of wetlands as well as the soil type, nutrient cycling and export, and sediment deposition.

Current State-of-the-Art - The role of wetlands in the ecological cycle is well understood. Although experiments were run with Landsat, it has generally been concluded that the level of classification required for wetland definition currently requires the use of aircraft mounted, high resolution sensors operating in the visible and IR bands. There has been excellent success with the aircraft mounted sensors.

Scientific Impediments to Continuing Advances - The scientific community must develop a better understanding of wetland dynamics on both a short- and long-term basis if it is to develop the classification techniques needed to improve regulation and management decision making. Information on frequency and duration of flooding is pivotal to this issue.

Candidate Research Projects - Ten or twelve sites encompassing a variety of wetland types distributed around the country should be selected for intensive multispectral image analysis. An array of sites is necessary to determine resolution and spectral band requirements for classification of the diverse vegetation defining wetlands. These experiments would have to be a minimum of three years in duration in order to define methods to determine frequency and duration of flooding as well as to quantify its impact. The techniques developed in these wetland experiments can also be used to map target-of-opportunity floods along river systems. Table 2 lists the kinds of data that will be required for this research.

- The Role of Barrier Island Dynamics in Coastal Zone Processes

Statement of the Problem - Although a very attractive recreational and economic resource, barrier islands are an extremely dynamic and ecologically sensitive system.

Current State-of-the-Art - Traditional descriptions of barrier island dynamics have come through mapping activities that are undertaken on a nonuniform, infrequent basis. Significant changes can be discerned as a result of comparing one map with a subsequent map, but little opportunity has been available prior to remote sensing to document the rate at which these changes occur. Both Landsat and aircraft remote sensing techniques have had some success at tracking barrier island transitions.

Scientific Impediments to Continuing Advances - There is a general lack of understanding of barrier islands as either hydrologic or geomorphologic processes.

Candidate Research Projects - There is a serious need for a comprehensive program that would examine both historical data as well as the remotely sensed imagery made available during the last decade to provide detailed documentation of changes occurring on a series of barrier islands at several locations along the Atlantic, Gulf, and Pacific coasts. Table 2 indicates the kinds of data required for this research.

- Relationship Between Remotely Measured Surface Roughness and Hydraulic Roughness of Land Surface and Stream Networks

Statement of the Problem - Hydraulic roughnesses of land surfaces and channels are critical inputs to the numerous hydrologic models designed to synthesize the temporal distribution of rainfall runoff.

Current State-of-the-Art - The land and channel roughness parameters are estimated visually, based on the experience of the observer. No rapid remote sensing method is available to improve the quality of these estimates.

Scientific Impediments to Continuing Advances - Terrain surface properties that are measurable require correlation to hydraulic roughness through laboratory and small-scale field experiments.

Candidate Research Projects - A series of projects should be undertaken that will start with laboratory experiments and progress successively toward field studies. A number of experiments evolving from hand-held sensor devices to towers and subsequently to aircraft mounted systems will be required before the bridge between multispectral imaging and hydrodynamic roughness can be resolved. Table 3 lists the kinds of data required in this research area.

TABLE 2

SUMMARY OF DATA REQUIREMENT FOR EXPERIMENTS

MISCELLANEOUS

	Snow Water Equivalent	Flooding Dynamics of Wetlands	Barrier Is. Dynamics
FIELD SURVEYS	Critical	Critical	Critical
SPECTRORADIOMETRY	Yes	Yes	Yes
COLLATERAL DATA	Yes	Yes	Yes
HIGH RES. PHOTOGRAPHY	VIS/B&W CIR	VIS CIR	B/W CIR
TEMPORAL REGISTRATION	0.5 Pixel	1 Pixel	1 Pixel
RECTIFICATION	Yes	Yes	Yes
BASELINE SPATIAL RES.	5M	5M	5M
SPECTRAL REQ.**	0.4-14.0	0.4-14.0	0.4-14.0
TEMPORAL RES.	T/S[1]	High & Low Tide	T/S - Historic
TERRAIN DATA*	N/A	N/A	N/A
SPECIAL REQUIREMENTS	Work in Combination With Microwave		

* Either Existing DTM or Flight Experiment

** Specific Bands to be Determined

[1]T/S - Time Series

- Definition of Hydrologic Properties of Soils and Surface Materials

Statement of the Problem - The hydrologic properties of terrain surfaces are perhaps the single most important modifier of rainfall with respect to watershed response. Infiltration rate, ground water recharge, and soil water storage are among those hydrologic properties that delay or attenuate the response at the outlet of the watershed.

Current State-of-the-Art - The hydrologic properties of terrain surfaces are traditionally defined in terms of the soil type and modifications imposed by different types of land cover. Traditionally, the soil type has been defined through very extensive ground surveys. There have been some successes, especially in non-vegetated areas, where multispectral remote sensing has provided reasonable estimates of soil type.

Scientific Impediments to Continuing Advances - Our limited understanding of spatial variability of such parameters as hydraulic conductivity of soils and, even our limited ability to measure hydraulic conductivity at a point, are major impediments to significant advances. Improvements in our understanding of the relationship between spectral response and soil characteristics such as texture is an extremely important area that needs improvement.

Candidate Research Projects - There is a real need for a series of field experiments using multispectral imagery to evaluate the hydrologic character and spatial variability of soil under a variety of conditions. Table 3 lists the kinds of data required for this research activity.

- Interpretation of Spectral Emissivity of Land and Water Surfaces

  Statement of the Problem - The temporal and spectral character of thermal IR emissivity of natural surfaces and cultivated areas is relatively undefined. Yet, emissivity is an essential consideration in any analysis of thermal imagery or radiometric data and narrow band absorption phenomena.

  Current State-of-the-Art - Laboratory measurement of emissivity is fairly well established but reliable methods for field measurement of detailed spectral emissivity remain to be developed.

  Scientific Impediments to Continuing Advances - There is a serious lack of understanding of the variations in emissivity over different terrain surface types relative to the impact on image texture characteristics and the extraction of hydrologic data from the remotely sensed data.

  Candidate Research Projects - There is a general need for both laboratory and field experimentation designed to improve our understanding of emissivity through the use of multi-band techniques. Table 3 lists the data requirements in this research area.

- Determination of the Relationship Between Texture of Terrain Surfaces and Hydrologic Response of Watersheds

  Statement of the Problem - Texture is an extremely important part of photo-interpretation of imagery of any type. It has been somewhat ignored in the digital processing of satellite data although computer-aided analysis provides an excellent medium for automated consideration of texture descriptors for extraction of hydrologic parameters.

Current State of-the-Art - Texture analysis is well established in the visual interpretation of high resolution imagery such as aircraft photography. Only a few algorithms are available to incorporate the methodology into digital image processing.

Scientific Impediments to Continuing Advances - Many questions remain concerning how dynamic are the texture descriptors with respect to such quantities as spectral band, time of day, weather and season. Also, there is no base from which to determine the correlation between texture descriptors and hydrologic parameters. Finally, the question remains as to what are the optimal measurements of texture relative to hydrologic purposes.

Candidate Research Projects - Experiments with texture parameters are needed using multispectral data obtained over selected terrain surface conditions relevant to hydrologic response. Systematic variations in scale (resolution), sun angle, energy budget history, and surface composition should be defined with respect to the selected texture parameter. Table 3 lists data requirements for this research activity.

- Improving the Determination of Hydrologic Land Cover as Related to the Modeling of the Runoff Processes

Statement of the Problem - Hydrologic modeling by governmental agencies and the private sector focuses on the definition of runoff parameters in terms of the land cover of the watershed. There are well established procedures that are very amenable to improvement through remote sensing techniques.

Current State-of-the-Art - There have been a number of successes involving the modification of existing land-cover-based hydrologic models to accept Landsat input data. With Landsat level resolution and spectral bands, there are few opportunities to advance these modeling techniques beyond those acceptable for planning level studies. The models used for design require much more detailed land cover information, probably requiring sensors approaching ten meter or higher resolution.

Scientific Impediments to Continuing Advances - Fundamental understanding of the hydrologic processes at the level of sophistication appropriate for the use of land-cover-based modeling is pretty well established. The impediments to continuing progress center on the evolution of techniques that will efficiently translate high resolution visual and thermal imagery into categories that can be entered into the design level models. The mixed pixel problem and the integration of thermal measurements to minimize misclassifications is fundamental to this need.

Candidate Research Projects - A highly instrumented test site located in a relatively large mixed land cover suburban area should be developed. The objective would be to allow a comparison between the results obtained with extremely well defined traditional models with those obtained from models having the land cover inputs defined with an array of aircraft mounted multispectral sensors having resolutions and wavelengths that are representative of those that could be orbited or placed on geostationary platforms within the next decade. Very dense rain gage and stream measuring networks would have to be established to support this effort if the results are to be reasonable. Table 3 indicates the kinds of data required in this research area.

TABLE 3

SUMMARY OF DATA REQUIREMENT FOR EXPERIMENTS

BASIC PHYSIOGRAPHY

	Roughness of Land SFC & Stream Networks	Hydrologic Properties of Soils, etc.	Emissivity of Land and Water	Texture vs Hydrologic Response	Land Cover for RO Modeling
FIELD SURVEYS	Critical	Critical	Yes	Critical	Critical
SPECTRORADIOMETRY	Yes	Yes	Yes	Yes	Critical
COLLATERAL DATA	Yes	Yes	Yes	Yes	Yes
HIGH RES. PHOTOGRAPHY	Stereo Panchrom	CIR	CIR	CIR	CIR
TEMPORAL REGISTRATION	N/A	N/A	N/A	N/A	1 Pixel
RECTIFICATION	Yes	Yes	Yes	Yes	Yes
BASELINE SPATIAL RES.	5M	5M	5M	5M	5M
SPECTRAL REQ.**	←		.4-14.0		→
TEMPORAL RES.	Seasonal	Seasonal	Seasonal		Seasonal
TERRAIN DATA*	Yes	N/A	N/A	N/A	N/A
SPECIAL REQUIREMENTS			Some Lab Study		

* Either Existing DTM or Flight Experiment

** Specific Bands to be Determined

- Interpretation of Active/Passive Measurements of Fluorescence and Polarization of Water and its Contained Substances

  Statement of the Problem - Fluorescence and polarization of natural water bodies have been little investigated. There are strong indications that measurements of these quantities can provide important information on water quality, wave patterns, and circulation.

  Current State-of-the-Art - Very limited.

  Scientific Impediments to Continuing Advances - The field is in its infancy and requires extensive study.

  Candidate Research Projects - Laboratory investigations of these phenomena on water of various types are needed to determine measurement capabilities, discriminability, and sensitivity. Such empirical studies may lead to aircraft or satellite investigations at some future date. Table 4 lists the kinds of data required for this research.

- Determination and Modeling of Three-Dimensional Characteristics of Water Bodies

  Statement of the Problem - Models for the prediction of one-, two-, and three-dimensional movement, dispersion, and fate of pollutants in water bodies have been developed. The definition of data for driving these models remains a difficult task.

  Current State-of-the-Art - Collection of data for one- and two-dimensional models of water bodies such as estuaries is relatively well developed and involves such remote sensing methods as airborne surface temperature measurements. However, extension of these measurements through the depth of the water is impractical at the present time.

Scientific Impediments to Continuing Advances - More knowledge is required concerning the penetration and resulting sensor responses of various wavelengths for waters of different quality.

Candidate Research Projects - Both theoretical and empirical laboratory research should be conducted to determine what parameters can be measured as a function of depth and at what wavelengths. Table 4 lists the kinds of data required for this research.

- Discrimination Between Sediment and Chlorophyll in Water

Statement of the Problem - The quantitative measurement of the concentration and distribution of sediment and chlorophyll in water is required for many hydrologic investigations, especially those concerned with pollutant surveys and receiving water capabilities.

Current State-of-the-Art - When occurring as individual components, sediment load and chlorophyll have both been successfully identified through remote sensing techniques. However, little information concerning the spectral response when they are combined is available.

Scientific Impediments to Continuing Advances - Because both sediment and chlorophyll occur in combination in many natural situations, it is necessary to develop a better basic understanding of their combined signal interferences and what spectral bands or combination of bands might be available to discriminate and, thereby, allow quantitative evaluation.

Candidate Research Projects - Experimentation must start, initially, in the laboratory and use waters with a range of known mixtures of chlorophyll and sediment. The laboratory sensor to be used in evaluation would have very narrow band capabilities with a potential of two hundred to five hundred separate bands. The results of these experiments would be fundamental in development of empirical models which could then be tested, first under small controlled field conditions and, subsequently, in large natural water bodies. Table 4 lists data requirements for research in this area.

- Definition of Runoff and Sediment Yield from Ungaged Watersheds

Statement of the Problem - Storm runoff and the accompanying sediment load annually produce millions of dollars in direct damage and continuing (often adverse) modifications to the fresh water ecology.

Current State-of-the-Art - Runoff modeling is a long-established hydrologic activity and modern remote sensing technologies have had a significant impact on improving the quality of the modeling process. Estimation of the accompanying sediment load has only recently started to evolve and little work relating to remote sensing has been undertaken.

Scientific Impediments to Continuing Advances - There is a major need to improve our understanding of the spatial and temporal variability of the elements that control the runoff and sediment production processes. We need to understand these processes and we need to develop scientifically based methodologies for quantifying their variabilities. Finally, significant gaps exist in the basic modeling processes themselves when one attempts to quantify the interrelationships among the various processes in natural watershed systems.

Candidate Research Projects - Test sites should be located and monitored on a continuing basis for the purpose of providing the necessary data base for productive sensitivity analyses, assessing the role of timeliness of data delivery, and the consequences of sensor resolution and spectral bands. Table 4 lists the kinds of data required for this research.

TABLE 4

SUMMARY OF DATA REQUIREMENT FOR EXPERIMENTS

WATER QUALITY

	Flores-cence	3-D Modeling of Water Bodies	Sediment/ Chlorophyll Discrimin-ation	Runoff + Sediment Yield
FIELD SURVEYS	N/A	Yes	Yes	Yes
SPECTRORADIOMETRY	Critical	Critical	Critical	Critical
COLLATERAL DATA	Yes	Yes	Yes	Yes
HIGH RES. PHOTOGRAPHY	B/W CIR	VIS, IR CIR	VIS, IR CIR	VIS, IR CIR
TEMPORAL REGISTRATION	N/A	Yes	N/A	Yes
RECTIFICATION	Yes	Yes	Yes	Yes
BASELINE SPATIAL RES.	5M	5M	5M	5M
SPECTRAL REQ.**	.4-.7	.4-14.0	Narrow Band Increments	
TEMPORAL RES.	TBD	T/S[1]	T/S	T/S
TERRAIN DATA*	No	N/A	N/A	Critical
SPECIAL REQUIREMENTS	Laboratory Studies Needed	Laboratory Research Needed	Laboratory Research Needed	Continuous Monitoring

* Either Existing DTM or Flight Experiment

** Specific Bands to be Determined

[1] T/S - Time Series

Evapotranspiration

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INFORMATION SCIENCE PANEL
JOINT MEETING WITH
IMAGING SCIENCE PANEL
MULTISPECTRAL IMAGING SCIENCE WORKING GROUP
FRED BILLINGSLEY

INFORMATION SCIENCE PANEL

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

Joint meeting with

IMAGING SCIENCE PANEL

May 10-12, 1982

A joint meeting of the two panels, Imaging Science and Information Science, was held May 10-12, 1982. It was decided that a joint meeting was appropriate, as the two activities, in concert, must respond to the desires expressed by the discipline science panels, and attempt to define the required enabling technology for the next decade. Further, the activities of the two groups interact closely, in that mission designs must consider both the flight mission and the subsequent ground data handling and analysis.

As outlined in the agenda (appendix), the initial activity was a group of presentations from the chairmen of the four discipline panels which, to a greater or lesser degree, outlined the requirements of each discipline for data sensing. This was followed by a group of presentations on various aspects of data sensing and processing, which attempted to summarize the state of the art in each area. The third activity was a synthesis of material for a panel report, based on discussions in the panels, papers submitted by the various presenters, and knowldege of the literature.

SCOPE

After much discussion, it was decided that the panel would confine its deliberations to consideration of meeting the requirements suggested by the discipline panels, but would not include apologia for the discipline programs per se. However, in view of the fact the data handling and analysis typically is left to last, it must be emphasized that due consideration of these topics must be placed in parallel with the mission design and accomplishment. Specific activity in information extraction science (taken to include data handling) is needed to:

- Help identify the bounds of practical missions

- Identify potential data handling and analysis scenarios

- Identify the required enabling technology

- Identify the requirements for a design data base to be used by the disciplines in determining potential parameters for future missions.

It was defined that specific analysis topics were a function of the discipline involved, and therefore no attempt was made to define any specffic analysis developments required. Rather, it was recognized that a number of generic data handling requirements exist whose solutions cannot be typically supported by the disciplines. The areas of concern were therefore defined as:

- Data handling aspects of system design considerations
- Enabling technology for data handling, with specific attention to rectification and registration.
- Enabling technology for analysis.

Within each of these areas, the following topics were addressed:

- State of the Art (current status and contributing factors)
- Critical Issues
- Recommendations for research and/or development.

OVERVIEW OF RESULTS

Two groups of common themes emerged during the discussions, relating to the common discipline analysis needs and to common data handling needs.

Analysis

- The atmosphere is recognized as having an effect on the data which will be more critical as the more sophisticated analyses are performed in the future. This must specifically be addressed in the sensing and the associated data handling.

- All disciplines are faced with the mixed materials in the pixels problem. Neither the general nor the specific effects of the smaller pixels or the additional spectral bands is yet known.

- Registration is a problem affecting all disciplines which will be exacerbated with the smaller pixels of the future.

- Disciplines are anticipating the availability of off-nadir data. This will increase the atmospheric and registration problems. Research is needed to determine the extent of the effects and the possibilities of overcoming them.

Data Handling

- The parameters required of either research systems or potential operational systems are not clear. System designs based on parametric analysis are required. The required parametric data are not available. A valid and potentially major activity will be gathering the required data for distribution to the disciplines and other potential users to enable parameter selection.

- The potentially wide variety of research scenarios places differing demands on both the sensors and the analysis capabilities. It is evident that the designs of research systems must satisfy the scenarios, and it is likely that these will bear little resemblance to operational systems. Expectation of operational utility from an experimental system designed for research must be avoided (e.g., Landsat).

- The data being gathered for scientific research may allow research hithertofore not practical or possible. As some of these developments will be slow in maturing, some continuity of data may be important.

- The larger quantities of data will exacerbate problems in acquisition, archival and dissemination (by the system) and in registration and analysis (by the user). Future efficient data management systems for the geographically-oriented data must avoid as much in-line processing and handling as possible.

- The tradeoffs between better data quality transmitted to the ground and that provided by ground processing must be evaluated. A possible context could be direct broadcast to the users or the archiving of unprocessed data. The potential advantages of on-board processing versus direct acquisition of adequate quality data (through, for instance, better ephemeris and pointing with sensors of implicit geometric accuracy) must be considered as part of the tradeoff.

- The increasing demands for higher spatial resolution and more spectral bands will multiply data handling problems. Large scale and very large scale integrated (VLSI) circuits will provide the data manipulation capability which will make possible the on-board processing, improved ground data handling, and increased complexity of data analysis. Although the basic technology developments will be driven by DoD and by high-volume commercial potential, the development of LSI/VLSI for the small scale NASA requirements must be supported by NASA.

This report is a synthesis drawn from the presentations and their accompanying papers, discussion with panel members, written material prepared by the panel members, open literature, and personal knowledge.

The submitted papers are attached in an appendix. They cover many of the topics in much more detail than is possible in a summary, and are recommended reading.

SYSTEM DESIGN

Current Status

- The present land remote sensing system (Landsat) is a centralized system with survey-mode data gathering, centralized processing and archive.

- A major data handling deficiency has been data delivery time.

- Data logging and cataloging are reasonably adequate.

- There is no capability for electronic transmission to users.

- There is no capability for special area extractions or projections.

- Delivery of registered data is minimal.

- There are no comprehensive data sets available from which to draw design conclusions for future missions.

Contributing Factors

- Landsat has been designed as a prime data source providing open skies data; this implies at least one complete data system and at least one distribution source.

- Data gathering rates are continually increasing, and can always outstrip system data handling capabilities.

- The system is defined as "experimental"; data handling is typically not considered the production problem which it is in an experimental system.

- During the Landsat era little attention has been paid to collecting of other data, nor to the use of non-Landsat data.

Critical System Issues

- The uninhibited increase in both data rates and data volume are putting severe pressures on the data system.

- Old data are becoming unreadable - storage media must be improved.

- Data delivery to users is too slow.

- The data are not in geographically optimum form as delivered.

- Many users still want raw data.

- Data for determining parameters for future mission designs are not available.

- Data handling problems have been consistently downplayed in system designs.

Discussion

The data handling syste for Landsats 1-3 and Landsat-4, together with the philosophy of the mission designs, are the prime sites of the data handling problem. This design philosophy (eminently successful in getting a large quantity of data gathered and beginning the development of user interest) requires that all data processed by the system be processed to completion. However, much, if not most, of the image data has not been requested by users, and only a small portion of the digitally processed data has been requested from the archive.

The impact of the system philosophy of processing all data to completion can be minimized by a brute force approach if 1) the system is truly automated and 2) the computer can keep up with the processing load. However, in the face of the ever-increasing data rates and quantity, this may not be the optimum overall system approach.

Clearly, there are two ways to reduce the archival processing load: reduce the number of scenes accepted by the archive, or reduce the amount of processing on each scene accepted. The former may not be possible if all scenes acquired must be archived to provide public access, unless the number of scenes acquired is limited to those specifically requested by users. The reduction of the processing load is clearly possible if processing-to-completion is only done upon request. The archive design for Landsat-4 MSS is of this type, but for the Thematic Mapper, with its much larger data quantity, processing to completion is to be accomplished for all scenes.

An experiment that should at least be thought through would call for careful attitude and position estimation on board, frequent annotation in the data stream of the attitude and position, and direct broadcast of the data on demand to a user with his own ground receiving station. Such a capability is currently in use with the APT terminals for reception of weather satellite data after initial data rate reduction by the system, but not for surface observation data. The improved geometric quality and footprint placement may make the data immediately useable with only a small amount of user processing; if a large central facility is still required for archive and dissemination post facto, this same improved quality will reduce the facility processing required upon data retrieval. Careful design of the total system, with due attention to the amount of ground processing required, may indicate that improved pointing , ephemeris, and geometric parameters of the flight segment may obviate much ground processing and allow alternate data delivery designs.

Hardware technology to date does not support the expeditious random retrieval which is required for efficient archive retrieval. What is required is the upcoming digital video disk or its equivalent. This medium will be relatively more permanent than the high density magnetic tapes currently being used (old tapes are becoming unreadable) and will supply the random access required for efficient archive operation. The direct broadcast mode of geometrically acceptable data may be expected to reduce the post facto archive traffic by a large factor, while still supporting the public access.

Widespread remote sensing usage will develop as (perhaps a small) part of systems which are otherwise generally useful. That is, at a county, region, or other area basis there are mapmaking, report-generating, inventorying, and other tasks which might also include remotely sensed data if such were readily and continually available and readily useable. Researchers, typically with low funding, would make use of remotely sensed data if that data were prepared in a useable form and, preferably, incorporated into a competent geographic information system. However, users may choose not to use this data if the locally required preprocessing (for example, for registration) is too extensive. Requirement suggestions were clearly stated in Simonett, 1978, as a result of the meeting on Geobased Image Formats. Most of these have been ignored to date.

Flight segment parameters (notably spatial resolution, revisit interval, and viewing conditions) will be influenced by the analysis desires of the user community. However, this community currently has little basis on which to determine important parameters. This has come about because there has been little remote sensing other than the space segments and their simulators, both of which present to the users a limited repertoire of parameters. What is needed is the development of comprehensive research remote sensing, with parameter extents which bridge all likely parameters for the near future, with adequate ancillary data. The Comprehensive Test Sites of the 70's were a potential start, but suffered from inadequate ancillary data and from inadequate funding support. In addition, they did not bridge the parameter gamut, and so served primarily as simulators.

Recommendations for Investigations

- Alternate total system architectures embracing both sensor systems and data delivery systems for different categories of users must be investigated. Such systems must include data handling issues, and may include concepts such as:

- Small scale receiving systems
- On-board preprocessing appropriate to both single-thread and multiple - broadcast systems

- A traffic study concerning acquisition processing, archiving, retrieval, and dissemination is needed.

- System design requirements to deliver optimally useable data to the users must be established.

- The user community must be provided with sufficient data to allow selection of parameters for future missions.

TECHNOLOGY FOR DATA HANDLING - GENERAL

Current Status

- The technology is established by commercial interests having large volume production. The trends are:

  - Memory costs are decreasing rapidly

  - Processing capabilittes are increasing; microprocessors are becoming practical for small scale remote sensing data analysis.

  - Magnetic tapes are the present storage medium. For some purposes, digital video disks will be practical.

- Special purpose Very Large Scale Integrated circuits (VLSI) are only beginning to become available, but there is no commercial development interest in these for remote sensing because of low volume. NASA/OSSA is not currently supporting this activity.

Contributing Factors

- Sales volume of remote sensing data not sufficient to force the technology.

Critical Issues

- Increasing data rates and volume are overloading the processing capabilities and hindering more complex processing.

- Increasing data volume and usage require better random access media.

- Information systems for the handling of geographic data are not yet adequate for the remote sensed imagery.

- Data labeling/referencing concepts for automated handling of the increasing data volumes need to be developed.

Discussion

Computer processing capability has increased tremendously over the past years, at a pace driven by commercial promises. There has been little, if any, progress driven by remote sensing interests because of the relatively low commercial promise. On the other hand, several companies now offer products for image analysis utilizing the computer technology available. These are becoming more sophisticated as the technology advances; 16 bit microprocessors now can offer capabilities formerly available only in the larger minicomputers. At the same time, larger memories and better interactive processing are being utilized by remote sensor analysts. Further progress in the mini-and microcomputer based systems will continue to occur as the computer technology improves, but no startling breakthroughs are expected.

With the advent of large quantities of digital geographically located data, digital geographic information systems are being developed. These are characteristically different from the data base management systems which are being developed for the business community in that very large data sets are involved (the images) and in that registration and analysis of multiple disparate types of data is required. The key difference for the latter is the need for spatial indexing - a relational operator not supported by standard systems. A large number of geographic information systems have been developed ad hoc by various groups. Typically each are different, designed to serve the developer, with little commonality or generality. This situation has come about because there has been no body of people to develop the various standards required to which a new system could be designed. As a result, Babel prevails. Similarly, there are few commonly accepted data labeling or referencing standards, with the result that data interchange and use of disparate data types has been unnecessarily hindered. This, in turn, has appreciably slowed the use of remotely sensed data below its potential. The adoption of the new International Landsat Tape Format will be a step in the right direction, but much remains to be done to develop it into a more general purpose geographic data standard.

Central to the attempts to use disparate data types is the problem of registering of the data - particularly image to image and image to a map (to which also, other data types are registered). This major problem has been identified in the reports of the Fundamental Research Program panels on Mathematical Pattern Recognition and Image Analysis and on Electromagnetic Measurements and Signal Handling, and treated in detail in the NASA Workshop on Registration and Rectification. This topic will be treated separately, below.

At this point in time, generation of VLSI has been extremely time consuming to the point that it is only done with the vision of extremely large production runs or for relatively high cost DoD purposes. However, Mead at CIT and others have developed technology which will allow the design and fabrication of VLSI at reasonable costs. This will allow VLSI to be used in smaller production, thus making VLSI feasible for use in on-board and ground processing of remotely sensed data. A corollary to its use is that the algorithms to be implemented are those which (in ordinary hardware or software) are time consuming in operation, and which can benefit from the extreme speedup afforded by the parallel or pipeline restructuring of the computation. VLSI will be beneficial in on-board processing, ground system processing, and data analysis:

- On Board: With the multiple detectors of the pushbroom sensors, gain and offset correction of each detector will be necessary before any additional processing can be done, because many of the processes will operate best (if at all) with clean signals. Potential beneficial processes include generation of special spectral band combinations, pixel combinations for spatial resolution selection, and data compression. These all may require significant on board memory. Following data compression, the signal may be protected with Reed-Solomon coding.

- Systematic Ground Processing: For compressed data, the first steps are the removal of the Reed-Solomon coding and the expansion of the data to the full form (unless analysis can be done directly on the compressed data). Radiometric calibration will require the use of calibration tables, linear for modern detectors, but possibly nonlinear and possibly position dependent. Geometric rectification will require extensive calculations and extensive interpolations; these are the bottlenecks in current procedures. Multispectral, multitemporal mosaicked data base generation and selection of requested geographic areas will particularly benefit from VLSI.

- Data Analysis: VLSI will be beneficial in both large and small computer installations. Particularly served will be pattern recognition and other complex analysis algorithms such as multispectral classification and many filtering operations.

Although industry is developing VLSI capability (Tobias, 1981), this development is geared to special products for mass production, such as machine controllers, or to customer programmable devices such as the micro-computers. These will not serve the NASA purposes as outlined above. NASA must therefore perform VLSI design, taking advantage of the experience of NASA personnel in the required algorithms.

Recommendations for Investigation

- Given modern computer developments, especially in microcomputers, what are the tradeoffs between centralized and distributed processing?

- How can the nascent digital video disks be adapted to the remote sensing needs in archiving or other processes?

- What mass storage techniques can be devised which are not I/O bound?

- What is the 'best' data condition to be transmitted to minimize ground processing?

- What are the tradeoffs between on board and ground processing?

- What data compression techniques are applicable/acceptable?

- How to further expand the use of standard interchange formats and coding schemes to expedite the integration of various data types and to provide guidlines for generalized geographic information systems.

- How to utilize VLSI to improve data handling capabilities, both on board and on the ground?

TECHNOLOGY FOR DATA HANDLING - RECTIFICATION AND REGISTRATION

Current Status

- Registration of image to map is manual by visual overlay of map and image control points.

- Registration of image to image is by computer correlation of image control points.

- Generation of the warping function may be either by polynomial surface fit, linear interpolation between control points, or by sensor/platform parameter modeling. All methods are used with reasonable success.

- Overlay registration accuracy is generally in the 0.5 - 1.5 pixel range.

- Because of the worldwide paucity of suitable maps, ephemeris and attitude estimates must be used in many areas, with resultant geodetic accuracies in the 100 - 5000 meter range.

- The effects of the various interpolation algorithms are accepted in some communities, not accepted in others.

- The effects of single or multiple interpolations are accepted in some communities, not accepted in others.

- Large area mosaicking requires special techniques to be efficient.

Contributing Factors

- Platform attitude and location are not well enough known. The GPS will help, provided that the data system is geared to its use.

- Sophisticated military pointing systems may eventually become available, but will be expensive.

- Intraimage distortions (of, for example, the Thematic Mapper) require many control points or an accurate model to remove. In particular, vibrations in the sensors are troublesome.

- The many control points are often not available, either because of lack of suitable image areas or by cloud obscurations.

- Correlation techniques do not produce perfect registration of the control points. The best correlation method is yet to be found.

- Interpolation affects the data in known ways, but the resultant effects on subsequent analysis are quite variable, depending on the problem. It is likely that a single interpolation technique will never be acceptable to all.

<u>Critical Issues</u>

- The intraimage distortions must be eliminated from future spacecraft systems if the number of required control points is to be reduced.

- Even automated control point processing must be minimized to keep the analysis load under control.

- To produce maps open loop (no, or very few, control points) to an accuracy commensurate with the pixel resolution, ephemeris and attitude determinations must be about an order of magnitude better than that expected for Landsat-4.

- Preprocessing and correlation processing of control points need further study to determine optimum methods.

- Registration of off-nadir images is difficult.

- Aircraft instabilities exacerbate the problem in aircraft remote sensing research programs.

- Interpolation is considered a critical issue by many.

- Correction of relief distortion requires surface altitude data.

Discussion

Satellite earth orbits appropriate for remote sensing will have drift deviations from the nominal which grow at rates of tens to hundreds of meters per day. Therefore, orbit estimation is nominal at best; actual orbit positional knowledge requires frequent position and velocity measurements. It may be expected that for years ground control points will be required for precise footprint location. GPS in the early stages will be marginally accurate, and its accuracy will not approach the 10-14 meter range unless the full constellation of satellites is available.

Even with perfect knowledge of satellite position, knowledge of instantaneous pointing must be to the 0.0005 degree range to allow pixel geodetic placement without the use of ground control points.

Basic theory requires that the distortion surface produced by the various distorting factors (platform instabilities, projection to the earth, skew, sensor geometry, geodetic repositioning, and the like) be sampled at Nyquist frequency or above, to produce the grid of correction points required. The number of points may be reduced by using accurate models of some of the high order causes to reduce the order of the distortion surface. Vibrations of the type seen in Landsat-4 are the highest order causes; the Attitude Determination System has been installed to try to measure these so they can be modeled and eliminated from the corrections to be determined from the ground control points. This helps, but the proper long-range solution is to eliminate the vibrations and any sensor geometric nonlinearities.

Even after the reduction in the number of ground control points afforded by proper spacecraft design, ground control point processing will be extensive, and will require the establishment of a control point library. Even with the use of a perfect map, residual locational errors in determining the control point of the order of 5-20 meters or so may be expected. The correlation of the control point with its corresponding image point will add another error of the same magnitude.

Thus, perfect registration of the large areas of a Landsat scene, even without relief displacement effects, should not be expected, nor is it clear that this is needed by any given user. With proper reduction of the order of the distortion surface, the use of a relatively few control points may provide adequate registration for a large number of users, reducing the work load for the precision registration required for the remainder.

It has been assumed that the surface elevation data required for relief displacement correction may be obtained from stereographic line array sensors. However, because the correlation in the epipolar plane requires the correlation of a short data segment, altitude data in this direction will be severly low-pass filtered. The effect of this on the utility of the data has not been explored.

The variability of the effects of interpolation on subsequent analysis may preclude the systematic geometric corrections, and require that unresampled or specially resampled data be supplied to certain users. This requires storage of the raw data; this is now being done for the MSS, but not (officially) for the Thematic Mapper. This should be a requirement for all future missions.

Additional study is needed to determine the extent of the interpolation effects, especially with double resampling. It has recently been shown (Keyes, 1981) that the parameters currently being used for cubic convolution are <u>not</u> optimum and that better parameters without the objectionable overshoot are available.

The discussions in the report of the NASA Registration and Rectification Workshop are extensive, and are recommended reading.

Recommendations for Investigation

- What is the interaction of the registration accuracy and the number, distribution, and accuracy of control point location?

- What are the characteristics of good control points? Can active control points (e.g., Evans' mirrors or other illuminating sources) be devised for use where there are no natural points?

- How can sensor/platform models (state vector estimates) be updated by the use of control points, what are the errors to be expected, and how may be the resulting sparse set of points be extrapolated?

- What are the impacts of atmospheric refraction, terrain relief displacements, and keystoning of control points on registration of off-nadir images?

- How may the resulting geometric accuracies be verified?

- Are there suitable alternates to the current control point chips?

- Given that resampling will be needed to achieve the desired registration, what is the optimum method of resampling to preserve the information of interest?

- What is the impact of various data compression methods on correlation accuracy, in view of the fact the high frequency information, useful in the correlation, generally gets blurred in the compression?

- What is the effect of misregistration (band-to-band and temporal) on data analysis?

- For aircraft sensing, how may the distortions be measured and corrected?

- How can the highly nonisotropic altitude data obtained from spacecraft stereo sensors be handled? What is the effect of the nonisotropism?

TECHNOLOGY FOR INFORMATION EXTRACTION

State of the Art

Spectral Analysis (pixel by pixel)

- Methodology is now mature for low-to-moderate dimensionaltiy analysis (supervised and unsupervised classifications).

- Methodology is primitive for feature extraction and utilization involving high dimensionality (greater than 6-8 spectral or other data channels).

Spatial Analysis

- Methodology is maturing for extraction of micro-spatial structure (homogeneity, texture, edges).

- Methodology is primitive for characterizing high order spatial structures. Models are necessarily discipline dependent.

Temporal Analysis

- In general, methodology is ad hoc, although the agricultural temporal analysis of phenologic stages is maturing. Models are necessarily discipline dependent.

Enabling Technology

- Geometric operations and multispectral classification (especially) now require excessive amounts of computer time and are labor intensive. New more complex algorithms exacerbate the problem.

- Computer architecture is not appropriate for many problems, such as neighborhood or dispersion problems.

- Parallel architecture and VLSI technology are required for practical application of many algorithms, but are not generally used.

- Several stand-alone moderate sized systems are being marketed.

- Many users are developing small, lower capacity systems.

- Complex, multisource data bases are becoming available, but analysis methodologies lag far behind.

- Image processing/geographic information systems are beginning to improve the analysis opportunities.

Contributing Factors

- System development is slow because of limited market.

- Discipline/data technology cross-pollination is minimum.

- Sensor and data characterizations are typically inadequate.

- Integration difficulties of disparate data sets obstruct many analyses.

- Generalized modeling techniques are inadequate.

- Diversity of investigators' computers hinders intercommunication.

- Dealing with mixed pixels remains a critical issue.

Critical Issues

Spectral Analysis

- The utility of or necessity for radiometrically calibrated data is unknown.

- The utility of or necessity for greater radiometric resolution is unknown.

Spatial Analysis

- The effects on utility of high spatial resolution is unproven.

- Strategies for the use of mixed resolution data (e.g., high resolution panchromatic with low resolution spectral) are needed.

- Information extraction from more than four spectral bands is difficult.

Temporal Analysis

- There has been a lack of temporally registered data which has hindered the development of algorithms.

- General methods for time series analysis of image data to support the discipline needs are primitive. Again, agriculture phenologic analysis is maturing.

Enabling Technology

- Sensor and mission design approaches must be developed to optimally provide the data demanded by the disciplines. This will require more input from the disciplines concerning tradeoffs possible and loss factors encountered if data is less than optimum.

- Calibration and characterization data must be supplied in useable form with the image data.

- The potentials and effects of on board processing on the useability of image data must be explored.

- Inclusion of VLSI will be required to alleviate the data processing constraints which will be felt as more complex algorithms are used with the increasing sized data sets.

- New data analysis tools must be developed to facilitate information extraction. These include new approaches for extracting information from multitype data sets, generalized geographic information systems and pattern recognition.

- Comprehensive data sets for the determination of potential analysis techniques and the subsequent determination of sensing and mission parameters must be developed.

- Techniques must be developed to facilitate data interchange (e.g., format compatibility, computer-to-computer communication).

Discussion

All discipline panels believe strongly that increased data resolution and coverage - spectral, spatial, and temporal - hold great promise for yielding added information and understanding in their particular domains. Such increases, however, portend manyfold increases in the amount of data analysis computation which will be required. To be effective and practical, data analysis methods must be applicable to high-dimension data, must reduce the data dimensionality as much as possible without destroying information, and must be implemented using very high speed software and hardware technologies. Collection and analysis of laboratory and field data (including aircraft data) adequate to verify the value of all forms of increased resolution and coverage must be supported in order to guide future satellite-borne sensor development. New approaches are needed for analyzing, understanding, and modeling complex interactions among the numerous and diverse forms of data which complement the remote sensing input.

All discipline panels recognize potential value of image-oriented data bases containing data from diverse sources in addition to remote sensing. Development of quantitative methods for extracting information from such complex data structures is required, as are methods for storage, labeling, addressing, and retrieval of specific data packets upon request from the analyst.

Discipline based studies, by their very nature, tend to focus on specific research/application questions within a narrowly defined scope. The data requirements and algorithm requirements of the disciplines will be left for discussions by discipline personnel. The discussions here will be concerned with generic requirements which cross disciplines. Several topics have been identified:

- Many of the discipline-oriented studies presuppose a requirement for absolute measurements, which in turn call for absolute calibration. But absolute calibration of ground phenomena requires the removal of atmospheric effects. Thus, a main thrust must be to learn how to determine these atmospheric effects, considering attenuation, wavelength effects, and time and space variabilities. Because spatial variability occurs in distance of the order of 10's of kilometers, real time, registered atmospheric sensing will be required.

- There has been continued pressure on the system to produce increasingly finer resolution. This is driven by the "evident" better appearance of high resolution images. But there are no definitive studies on the distribution of sizes of ground objects, either natural or man-made (see also p. 78). There is no definitive estimate as to whether the supposed sensing of more pure pixels, with attendant higher variance in the data set, will help or hinder. With the data rate and quantity increasing as the square of 1/pixel size, increased resolution must be well justified.

- Increasing data notes and data quantity are occurring to meet the demands of increased spatial resolution more spectral bands, and finer quantization. Problem dependent tradeoff studies should be made to determine the optimum allocation of data bits.

- The end goal of discipline studies is to relate intrinsic target properties of phenomena to the remote sensing observables. However, most investigators have not been able to consider the complete characterization of the scene, including atmospheric components, sensor, and data reduction effects. Thus, a requirement common to all discipline areas is the understanding of how a particular remote sensing effect will ultimately be exhibited in the final data.

- The aggregate of requirements which might be met with remote sensing is quite diverse, with many conflicting requirements. In the absence of being able to satisfy all, some will remain unfulfilled. Complete system characterization of proposed systems must be made available to allow the disciplines to evaluate the utility, or lack thereof, of the proposed system. Only in this way may they understand the impact of system parameters on their studies and be in a knowledgeable position to state the deleterious effects of not meeting their requirements. This in turn, requires that suitable sensing capabilities be made available to allow the gathering of data from which to make the required decisions.

- Most discipline oriented groups require significant model development to relate remote sensing data to phenomena of interest. Although the models are necessarily discipline dependent, it may be useful to compare modeling approaches across the disciplines as applied to different spatial/temporal scales and to summarize common themes, techniques, and guidelines.

- Continually reiterated is the plea for better methods of using multi-type data, at various scales. Although analysis of multi-scale data is a problem, the overriding problem is the mechanics of overlaying and registration. This capability can be provided in a competent geographic data system if the following principles can be satisfied: 1) Store data at the resolution comensurate with its content (generally, at the resolution at which it was obtained); 2) if practical, remove the intraimage distortions so that only affine low order corrections will later be required; 3) supply with the data the precision information required to register the data during retrieval to a well understood reference (e.g., latitude/longitude or UTM); 4) store with the data all relevant ancillary information; 5) during data retrieval, reproject and rescale the data to the grid requested by the analyst, and provide the ancillary data (the analysis grid may be coarser or finer than any one of the data sets requested; interpolation up or down would be done as required to produce all data on the same grid); 6) supply the data in a standard format independent of incoming data type, with suitable annotations, to allow the analyst to use the various types interchangeably. Such a system is within the state-of-the-art, but it has not been systematically done because of lack of the cross-discipline funding required. A user-driven generalized geographic information system definition, perhaps developed by a knowledgable panel vis a vis the CODASYL approach, might set the stage for individuals to pick up the specific developments.

- Analysis methods are continually becoming more complex as the quantity of data increases. New computer architectures and the use of VLSI need to be investigated in conjunction with the analysts to develop optimum algorithms which can take advantage of the new technology.

RECOMMENDATIONS FOR INVESTIGATION

Analysis

- Conduct experiments with parameters exceeding expected mission parameters to determine sensitivities to lack of meeting them in an operational system and to determine any potential interactions.

- Determine the need for and utility of absolute radiometric calibration. What accuracy of calibration is useful?

- Study complete system characterization from the discipline point of view to determine practical limits on requirements and to provide a model for evaluating parameter variations.

- Promote cross-discipline fertilization in model development and useage.

- Promote research in the conversion of analysis concepts to software.

Enabling Technology

- Provide end-to-end system analysis to the disciplines to allow development of their loss-in-utility functions to allow better overall system design.

- Determine from the disciplines what ancillary data is required for them to accomplish their analysis, in what form. Then provide it.

- Investigate the effects of and utility of on board processing in relation to problem analysis.

- Investigate alternate computer and system designs and the use of VLSI as these affect the data analyst.

- Determine the requirements for comprehensive data sets and begin collecting the required data.

- Push the development of a comprehensive geographic information system to facilitate the use of multitype, various scale data.

- Promote the development of modular hardware and software systems to allow wider technology interchange and minimize duplicated efforts.

- Develop data analysis/networking systems to allow distributed or non-local processing and to foster science cross-pollination.

POTENTIAL SUPPORT MODES

The various investigations outlined above are those required to provide data in a timely, cost-effective manner, which is easy to use and transferrable. The investigations will also assist analysis by providing increased analysis capability, fostering analyst intercommunication, and providing some inter-discipline studies.

But the decisions of which information extraction topics to implement cannot be made until an overall research program philosophy and modus operandi are formulated. The research specifics are less important; although the sensing and platform must specifically relate to the research task data needs, the information extraction and data handling science is basically a technology development which is more or less independent of the specific discipline served.

Anything but a minor program will generate large quantities of data which are potentially useful to others besides the initial principal investigator for whom they were gathered. Efficiency of data handling and distribution is therefore important. The organization of the research tasks into a coordinated program will help assure that all of the research facets are covered and may allow decrease in data gathering expense through data sharing.

The information science support is couched in four modes:

- Support to individual principal investigator research
- Organized support to research tasks
- Support to systematic research program data system design
- Support to research data system operations

These build from a set of isolated tasks to a unified program with coordinated data support. The types of tasks which might be considered for each are listed; the list is intended to be indicative, not complete. The individual items (for example, to provide cross-discipline data sources) will need to be expanded and some made more specific as the various disciplines firm up the experiments and data requirements.

POTENTIAL SUPPORT MODES

<u>Support to Individual Principal Investigator Research</u>

Encourage PI data commonality
Assist PI data interchange
Sponsor cross-discipline research (Atmosphere studies, distribution of object sizes, interpolation, registration, off-nadir, etc.)

<u>Organized Support to Research Tasks</u>

Provide cross-discipline data sources (aircraft, shuttle, etc. instruments and flight support)
Provide coordinated data sets via geographic information systems
Facilitate cross-distribution of data (Archive? Clearing House?)
Develop VLSI for efficient data handling and analysis
Sponsor cross-discipline research (as above)

Support to Systematic Research Program Data System Design

Gather the decision data base to enable parameter tradeoffs
Perform tradeoff studies such as:

- On board vs ground processing
- Data compression techniques
- Optimum bit allocation (spectral vs spatial vs No. of bits)
- System Mode (Direct broadcast, central site, ...)
- Ephemeris vs. pointing vs. GCP for pixel location

Provide potential system configurations
Sponsor cross-discipline research yet required
Develop archival/retrieval techniques
Develop GIS, formatting, and labeling techniques
Develop VLSI and new system architecture as required
Develop system-enabling technologies such as digital video disks
Develop techniques for providing multi-type data sets

Support to Research Data System Operations

Provide an efficient archival/catalog/retrieval system
Provide efficient GIS, formatting, and labeling system
Implement new system designs (with VLSI, as applicable)
Provide system characterization

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(Papers in parenthesis are notes only.)

Omit 73
End

APPENDIX A

ORGANIZATION

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

NASA

National Aeronautics and
Space Administration

Washington, D C
20546

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MAR 8 1982

Reply to Attn of EL-4

TO: Distribution

FROM: EL-4/Chairman, Multispectral Imaging Science Working Group (MISWG)

SUBJECT: Planning Meeting of Team Leaders and Organization of MISWG

A meeting of MISWG Management Staff was held at NASA Headquarters on March 3, 1982 to finalize a schedule of activities and to discuss goals and objectives. In attendance were the following:

Dr. Ken Ando, Team Leader Imaging Science
Mr. Fred Billingsley, Team Leader Information Science
Dr. Nevin Bryant, Team Leader Geographic Science
Mr. Scott Cox, Executive Secretary
Dr. Jim Ormsby, Assistant Team Leader Hydrologic Science
Dr. Bob Ragan, Team Leader Hydrologic Science
Dr. Al Rango, Team Member Hydrologic Science
Dr. Mark Settle, Team Leader Geologic Science
Dr. Jim Taranik, Chairman
Dr. Jim Tucker, Team Leader, Botannical Science

The objectives of the Working Group were outlined by the Chairman and then discussed. The main objectives are to:

- Document the current state of knowledge with respect to high-resolution spectral and spatial measurement of the Earth's surface cover and topography.
- Identify critical gaps in scientific knowledge that must be filled before new technology can be evaluated.
- Define candidate remote sensing experiments to further develop knowledge and understanding of what can be measured.
- Evaluate technology alternatives in the light of candidate remote sensing experiments.
- Recommend technological developments which may lead to development of new measurement capabilities.
- Propose information extraction research which may lead to development of improved techniques for extracting information from multispectral data.

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The Multispectral Imaging Science Working Group will focus on measurement of spectra from the ultraviolet through infrared, while another Science Working Group will address the microwave. The Chairman stressed that the activities of MISWG are not intended as direct support of any specifically designated technology (e.g., multispectral linear array). Rather, members were encouraged to document current state of knowledge of spectra without being constrained by preconceived concepts of possible bandwidths, numbers of bands, sensitivities in bands, or spatial resolutions. Working Group members were encouraged to propose experiments in terms of needed measurements (e.g., in terms of spatial, spectral and temporal resolution) rather than in terms of technology. For example, "Based on laboratory and field research on clays, spectral measurements of rocks and soils are needed in diverse physiographic environments using measurements in the 2.2um portions of the spectruim with at least ten bands having bandwidths of not more than 0.01um".

The Chairman emphasized that the Working Group would focus on the development of remote sensing experiments aimed at developing better understanding of what can be measured with respect to the Earth's landscape characteristics (e.g., Surface cover--rocks, soils, vegetation, water, culture; and topography -- geometry of landforms and drainage). The first phase of Working Group activity (FY 84 budget phase) will not attempt to define scientific experiments for study of the Earth as a planet (e.g., develop a global catalogue of volcanic landforms).

Results from the activities of the Working Group need to be available to support development of research programs proposed for the 1984 budget. The schedule of activities for the MISWG are designed so that all activities will be completed by 1 July 82 (enclosure 1). The requirement for a general meeting was dropped and a decision was made to move directly to the terrestrial science workshops. The workshops will be held during the last half of April.

Guidelines for the workshops were the following:

- Limit should be 20 participants.
- Each participant should bring a 5 or 6 page written contribution to the workshop.
- Workshop Chairmen will be the Team Leader, but a Co-chairman from outside NASA is encouraged.
- Participants for workshops may come from government, academia, or industry.
- Team members will support the Team Leader in developing executive summaries on the workshop proceedings.
- Funds to support travel of university team members are available. However, support will not be generally provided to participants in workshops who are not team members.

- Refer to attachment 2, letter EL-4 dated 4 March 82 (enclosure 4) for additional guidance on workshops.

- Schedule of MISWG team workshops is listed in enclosure 1.

A contract with ORI Corporation will support MISWG and a listing of services is provided as enclosure 2. The charter of the Working Group was approved by Dr. Edelson on 4 March 82 and is attached as enclosure 3. A listing of key personnel is attached as enclosure 5.

James V. Taranik

James V. Taranik
Chief, Non-Renewable Resources Branch

Distribution:
Team Leader
Executive Secretary
E - Rosendahl
EL-4 Moore
EL-4 Briggs
EL-4 Welch

Enclosures

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MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

Purpose: To Define Scientific Experiments that Must be Conducted in the Visible and Infrared Portions of the Spectrum in Order to Better Define Aerospace Technology Required for Exploration of the Earth on a Planetary Scale.

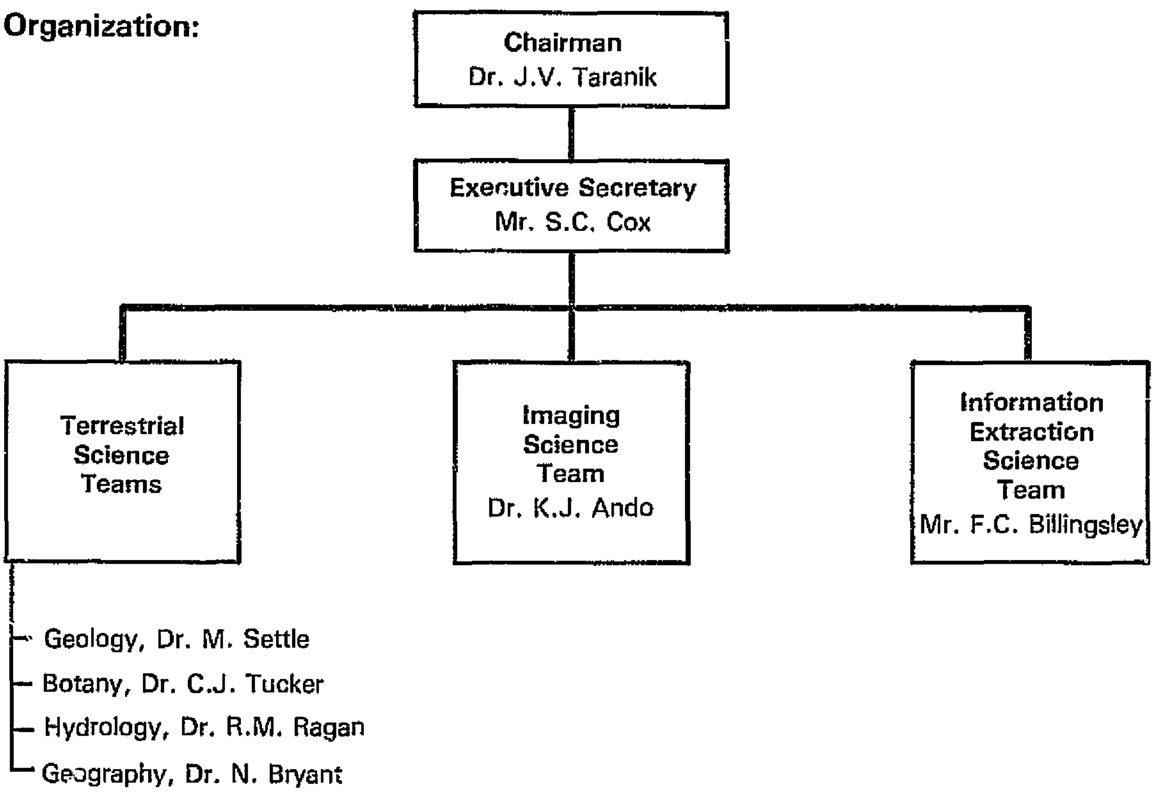
Objectives:

1. To Define Visible and Infrared Measurement Requirements for Analyzing the Earth's Surface Cover and Topography on a Planetary Basis.
2. In Light of the Defined Measurement Requirements, to Design Scientific Experiments Needed for Technology Definition.

Strategy:

1. To Develop a Scientific Rationale for the Development and Testing of Multispectral Imaging Technology in Space.
2. To Document the Current State of Scientific Knowledge and Areas of Needed Research Related to Analyzing the Earth's Surface Cover and Topography Using Spaceborne Visible and Infrared Remote Sensing Techniques.

Organization:



CHARTER

Multispectral Imaging Science Working Group

Within the last decade, solid-state multispectral technology has been developed which makes possible high spectral (0.01um) and spatial (10m or smaller) resolution imaging over wavelength intervals ranging from visible through the infrared. Such technology is replacing the optical-mechanical technology now routinely employed in aircraft and on space platforms. The high resolution of solid-state imaging systems permits new scientific information to be developed for study of the Earth on a planetary scale. There is a need to document the spectral and spatial characteristics of the Earth's surface cover and topography that should be detectable by solid-state imaging technology and to define scientific research that should be conducted to fully understand this new measurement capability. Once this understanding is attained, then various technological options for scientific study of the Earth on a planetary basis can be addressed. Management of this science working group activity has been assigned at NASA Headquarters to the Earth and Planetary Exploration Division. Headquarters will be supported by Goddard Space Flight Center which will furnish a detailee and which will arrange upport for workshops and publications.

1. Functions

The specific functions of the Multispectral Imaging Science Working Group are as follows:

(a) Document the current state of knowledge with respect to multispectral measurement of the Earth's surface cover and measurement of its topography.

(b) Identify areas where further fundamental research is needed in measurement of cover types and measurement of topography.

(c) Define a candidate series of remote sensing scientific experiments to evaluate high resolution spectral and spatial measurement of the Earth's land areas.

(d) Evaluate imaging technology alternatives in the light of candidate scientific experiments and their mesurement requirements.

(e) Recommend technological experiments which may lead to development of new techniques for acquiring, processing, transmitting, receiving, and recording solid-state imaging data.

(f) Propose information extraction experiments which may lead to new techniques for extracting new and better information from solid-state imaging data.

2. Schedule and Reporting

The Multispectral Imaging Science Working Group will meet at the call of the Chairman or Executive Secretary. The first meeting will be held in March 1982. The Working Group will cease to exist before the release of an Announcement of Opportunity or Applications Notice related to solid-state array imaging technolgy. The Working Group will report through the Chairman and Executive Secretary to the Director, Earth and Planetary Exploration Divison.

3. Membership

Membership will consist of about 30 people and will be selected by NASA from the scientific research community in terrestrial remote sensing. The chairman will be selected from NASA Headquarters and the Executive Secretary will be from Goddard Space Flight Center.

INTERPRETATION OF REMOTE SENSING DATA TO DEVELOP INFORMATION

Electromagnetic Data — Measurements of Radiated Energy from Areas of the Earth's Surface, in Certain Wavelength Bands, at Certain Bandwidths.

↓

Image Data — Arrays of Electromagnetic Data Arranged in Particular Formats, Scales and Accuracies Which May be Displayed as Variations in Brightness and/or Color, or as Digital Numbers.

↓

Remote Sensing Analysts Interpret Distributions of Brightness and/or Colors, or Digital Numbers Displayed by Image Data (Imagery), Using Pattern Recognition Models, to Develop Landscape Information.

↓

Landscape Information — Geometrical Arrangements of Topography (Landforms and Drainage) and Surface Cover (Rocks, Soils, Vegetation, Water, Culture) in Certain Scales Accuracies and Formats.

↓

Earth Scientists Interpret Geometrical Arrangements of Topography and Surface Cover, Using Models to Develop Information About the Earth.

↓

Earth Information — Resource Information in Certain Scales Accuracies and Formats, e.g. Landscape Forming Processes, Sequences of Deposition of Rocks, Geometry of Rock Sequences (Folds), Dynamic Structural Elements (Faults), Crop/Tree/Forage Type, Crop Condition, Landuse Type, Water Quality, etc.

↓

Resource Managers Interpret Earth Information Using Models to Do Something (e.g., Make Decisions, Develop Policy, etc.)

↓

Resource Application —
Develop Commodity Support Policy
Plan Stockpiles
Assess Mineral Potential
Define Exploration Areas
Assess Environmental Impact
Forecast Earthquakes
Predict Crop Production
Predict Floods
Plan Commercial Development
etc.

APPROACHES TO DEVELOPMENT OF RESEARCH PROGRAMS IN REMOTE SENSING

FUNDAMENTAL APPROACH

DETERMINE CURRENT STATE OF KNOWLEDGE

↓

IDENTIFY GAPS IN KNOWLEDGE

↓

FORMULATE SCIENTIFIC QUESTIONS

↓

DESIGN EXPERIMENTS TO ANSWER QUESTIONS

↓

DEFINE MEASUREMENT REQUIREMENTS

↓

EVALUATE MEASUREMENT TECHNOLOGY

↓

DEVELOP MEASUREMENT SYSTEM

↓

COLLECT SCIENTIFIC DATA

↓

ANALYZE SCIENTIFIC DATA

↓

DEVELOP THEORY AND MODELS

↓

UNDERSTAND WHAT IS MEASURED

↓

FINE APPLICATION TO STUDY OF THE EARTH AS A PLANET

APPLIED APPROACH

DEVELOP MEASUREMENT SYSTEM

↓

COLLECT DATA

↓

ANALYZE DATA

↓

DETERMINE WHAT INFORMATION CAN BE EXPECTED

↓

DETERMINE HOW INFORMATION APPLIES

↓

DEMONSTRATE POTENTIAL APPLICATION

↓

CREATE USER INTEREST

APPENDIX B

AGENDA

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

GEOGRAPHIC SCIENCE WORKSHOP
MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

Dates: April 28-30, 1982
Location: Mariott Hotel
711 East Riverwalk
San Antonio, TX 78205
(512)224-4555

AGENDA

I. Wednesday, April 28, 1982

Introduction

1:00 - 1:30 pm	R. Whitman N. Bryant	Objectives of Working Group Objectives and Format of Workshop
1:30 - 2:15	G. Vane	Background on MLA Systems

Justification and Requirements

2:15 - 3:00 pm	R. Witmer	Level III Land Use/Land Cover Classification of Requirements
3:00 - 3:45 pm	R. Welch	National Map Accuracy Standards for Planimetry and Elevation Determination
3:45 - 4:30 pm	J. Estes	Geomorphology (Landform and Drainage Elements Detection)

State of the Art

4:30 - 5:00 pm	F. Sabins (presented by J. Estes)	Spatial and Spectral Resolution for Landform and Drainage Element Detection
5:00 - 7:00 pm	Dinner	
7:00 - 7:45 pm	J. Clark	Spatial and Spectral Resolutions in an Urban Environment
7:45 - 8:30 pm	D. Williams	Summary of TMS Results
8:30 - 9:15 pm		Detection of Strip Mines.

II. Thursday, April 29, 1982

8:30 - 9:00 am	Organization of and Change to Working Groups
9:00 - 12:00 noon	Break out into panels for initial discussions of requirements and state of the art
12:00 - 1:00 pm	Lunch
1:00 - 2:30 pm	Panel writeups on requirements and state of the art
2:30 - 4:30 pm	Viewgraph reviews of requirements and state of the art by panel chairmen with general discussion
4:30 - 5:30 pm	Initial discussion on critical gaps in scientific knowledge and definition of candidate remote sensing experiments to further develop knowledge
5:30 - 7:00 pm	Dinner
7:00 - 9:00 pm	Panel writeups on knowledge gaps and candidate experiments.

III. Friday, April 30, 1982

8:30 - 10:00 am	Viewgraph reviews of knowledge gaps and candidate experiments by panel chairmen with general discussion
10:00 - 12:00 noon	Panels edit and expand upon general discussion for workshop documentation
12:00 - 1:00 pm	Lunch
1:00 - 3:00 pm	Panel chairmen present highlights and select key summary tables, illustrations, and graphs
3:00 pm	Executive Summary Draft (N. Bryant and R. Whitman).

Panel: Cartography (R. Welch, chairman)

Areas of Concern: Spatial and geometric resolution requirements for photographic/analog or digital photogrammetry from spaceborne MLA sensors. Of particular concern are the impacts of National Maps Accuracy requirements upon MLA system precision to determine planimetry/orthophoto mapping and elevation at various scales (1:250,000 to 1:24,000). An analysis of relief effects upon off-nadir viewing should also be made.

Panel: Land Use/Land Cover (R. Witmer, chairman)

Areas of Concern: Spatial and spectral resolution requirements for photo interpretation and/or multispectral pattern recognition of cultural surface cover. Of particular interest are the recognition of man-made structures in urban and urban fringe regions. Other topics of interest include the delineation of and detection of changes in the landscape created by man's activities, such as strip mines, roads and railroads, and utility right of ways.

Panel: Landform and Drainage Elements Detection (J. Estes, chairman)

Areas of Concern: Spatial and spectral resolution requirements for photo interpretation and/or multispectral pattern recognition of geomorphic elements. Of particular interest would be glacial and pariglacial landforms, colian and coastal landforms, and karst topography. Manmade landform elements, such as berms, dikes, and levees should also be considered. Drainage elements of particular interest would include perennial and intermittent stream beds, flood plains, and allurival fans. Manmade drainage elements, such as canals, diversion channels, and spreading basins shouid also be considered.

WORKSHOP ON THE USE OF FUTURE MULTISPECTRAL IMAGING CAPABILITIES FOR GEOLOGICAL REMOTE SENSING

Dates: April 20-21, 1982
Location: Jet Propulsion Laboratory
Pasadena, CA 91109

AGENDA

I. Tuesday, April 20, 1982

8:30 am	M. Settle	Purpose and organization of the Working Group, charter of the Geology Team, expected outcome of the meeting.
	L. Rowan	Review of the lithologic and compositional attributes of rocks and soils that have been successfully observed in past remote sensing surveys conducted throughout the visible and infrared at both aerial and orbital altitudes (e.g., Goldfield, Walker Lake, Tintic, and SMIRR results, etc.).
	R. Singer	Review of the reflectance properties of common minerals; discussion of unstudied mineral types, shortcomings of earlier analytical techniques, reflectance properties of mineral mixtures, etc.
	A. Kahle	Same as preceding with respect to emissivity properties of common minerals, specifically encompassing both the 3-5 and 8-14 micron regions; pros and cons of reflectance, transmission, and emission measurements.
1:00 pm	M. Abrams	Effects of spatial resolution upon mineral/rock type discrimination and/or identification; comparison of laboratory-field-aerial-orbital multispectral surveys performed at different spatial resolutions. To what extent does spatial averaging of different types of materials in remote sensing measurements inhibit or enhance lithologic mapping capabilities? Limitations of earlier experiments.
	W. Collins	Same as preceeding with respect to spectral resolution.
	A. Goetz	Same as preceeding with respect to radiometric accuracy - i.e., How does improved sensor calibration contribute to lithologic mapping capabilities? Is it necessary to have absolute calibration? Is the precision of the existing orbital sensors adequate?

W. Kowlick	Limitations imposed by the earth's atmosphere upon lithologic mapping capabilities. What, if any absolute limitations do atmospheric effects impose upon the resolution and/or radiometric sensitivity of orbital sensor systems?
J. Adams	Discussion of the effects of vegetation in remote sensing surveys as a source of "noise" (i.e., complicating mineral/rock identification) and as a potential "signal" (i.e., geobotanical correlations between species density, distribution, and vigor, and the geological characteristics of the underlying substrate).

II. Wednesday, April 21, 1982

Recommendations concerning future R&D experimentation that would lead to improved definition of sensor measurement capabilities for geological remote sensing.

Recommendations concerning the desired characteristics of future orbital imaging systems based on current understanding of geologic remote sensing capabilities and limitations.

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

HYDROLOGY WORKSHOP

Dates: April 26-28, 1982
Location: NASA/Goddard Space Flight Center
Building 26, Room 200
Greenbelt, Maryland 20771

AGENDA

I. Monday, April 26, 1982

8:30 - 9:45 am	Hydrology Science Team Planning Session (Ragan, Ormsby, Rango, Moore, Link, T. Jackson)
9:45 - 10:00 am	Coffee Break
10:00 - 10:30 am	Briefing to Workshop Participants and Discription of the Activity (Ragan)
10:30 - 11:30 am	Agency Activities USGS-EROS (Moore - 15 min) USDA-ARS (T. Jackson - 15 min) USACE (Link - 15 min) NASA (Rango - 15 min)
11:30 - 1:00 pm	Lunch
1:00 - 3:00 pm	Research Status Papers Hydrologic Land Use and Modeling (Feldman - 15 min) Applications to Irrigation (Miller - 15 min) High Resolution Analysis (Robinove - 15 min) Water Quality (Scarpace - 15 min) Thermal Infrared Research (R. Jackson presented by J. Hatfield - 15 min) Drainage Basin/Soil Moisture Studies (Blanchard - 15 min) Hydrologic Modeling (Huff - 15 min)
3:00 - 3:30 pm	Break
3:30 - 4:30 pm	Research Status Papers Snow and Ice Mapping (Wiesnet/McGinnes - 15 min) Cold Regions Research (McKim - 15 min) Flood Mapping (Deutsch - 15 min) Needs for USDA and EPA Models (Slack - 15 min).

II. April 27, 1982

9:00 - 9:45 am	Research Status Papers Thermal Infrared Research in Soil Moisture and Evapotranspiration (R. Gurney) High Resolution Impacts on Private Consulting (George - 15 min) Stream Channel Definition and Mapping (C. Gurney - 15 min)
9:45 - 10:15 am	Coffee Break
10:15 - 11:45 am	Discussion on hydrologic topics whether presented or not
11:45 - 1:15 pm	Lunch
1:15 - 1:30 pm	Division into Sub Working Groups
1:30 - 5:00 pm	Sub Working Group Discussions.

III. April 28, 1982

8:30 - 10:00 am	Sub Working Groups Discussions
10:00 - 10:15 am	Coffee Break
10:15 - 11:45 am	Sub Working Groups Presentations
11:45 - 1:15 pm	Lunch
1:15 - 4:00 pm	Hydrology Science Team (With selected workshop participants) Compile Executive Summary and Workshop Report
4:00 pm	Adjourn.

AGENDA

JOINT MEETING - IMAGING SCIENCE AND INFORMATION EXTRACTION SCIENCE

LOCATION:

ORI, Inc.
1400 Spring Street
Silver Spring, Maryland 20910

MONDAY, MAY 10

8:30	INTRODUCTION AND DISCUSSION OF MEETING AGENDA	Chairmen
8:45	DISCIPLINE PANEL PRESENTATION: GEOGRAPHY	Nevin Bryant
9:30	DISCIPLINE PANEL PRESENTATION: HYDROLOGY	Bob Regan
10:15	COFFEE BREAK	
10:30	DISCIPLINE PANEL PRESENTATION: BOTANY	Jim Tucker
11:15	REGISTRATION WORKSHOP REPORT	Rama Ramapryian
11:45	LUNCH	
12:45	DISCIPLINE PANEL PRESENTATION: LITHOLOGY	Mark Settle
1:30	NON-NASA SENSORS	Marvin Maxwell
2:00	MAPSAT	A. Colvocoresses
2:15	MLA SENSOR DESIGN CONCEPT	Herb Richard
2:45	COFFEE BREAK	
3:00	SENSOR TRADEOFF ISSUES	Aron Mika
3:45	VISIBLE/IR SENSOR REVIEW	John Lowrance
4:15	GSFC SUPPORTING TECHNOLOGY PROGRAM	Bill Barnes

TUESDAY, MAY 11

8:30	FUNDAMENTAL RESEARCH PANEL SUMMARY	Roger Holmes
9:15	IMAGE SPECTROMETER	John Wellman
9:45	COFFEE BREAK	
10:00	IR AREA ARRAY STATUS	John Rode
10:30	CALIBRATION OVERVIEW	Phil Slater
11:00	AIRCRAFT DATA PROGRAM	Gregg Vane, Jerry Flanagan and Jim Irons
11:45	LUNCH	
12:30	ON BOARD DATA PROCESSING	Bob Rice
1:15	ON BOARD DATA COMPRESSION	Tom Lynch
1:45	GROUND SEGMENT ISSUES	Robert Pelzmann
2:30	COFFEE BREAK	
2:45	ANALYSIS WITH SMALL PERSONAL TERMINALS	Ed Masouka
3:30	VLSI CONTRIBUTIONS TO ANALYSIS CAPABILITIES	Bob Nathan
4:15	CLASSIFICATION OF MIXED PIXELS; SPATIAL VS SPECTRAL	Phil Swain
5:00	ADJOURN	
7:00	PANEL(S) ORGANIZATION AND DISCUSSION	

WEDNESDAY, MAY 12

8:30	DISCUSSION OF PRESENTATIONS AND SYNTHESIS OF RESPONSE
12:00	LUNCH
1:00	CONTINUATION OF SYNTHESIS AND PREPARATION OF REPORT

AGENDA

MULTISPECTRAL IMAGING SCIENCE WORKING GROUP'S NASA MANAGEMENT REVIEW

LOCATION:

GODDARD SPACE FLIGHT CENTER
Building 16W, Conference Room N-76
Greenbelt, MD 20771

Thursday, June 17

8:15	Introduction and Discussion of Meeting Agenda	Scott Cox
8:30	Discussion of Working Group Activities	James Taranik
8:45	Geography Group Presentation	Nevin Bryant
9:30	Hydrology Group Presentation	Bob Reyan
10:15	Break	
10:30	Botany Group Presentation	Jim Tucker
11:15	Geology Group Presentation	Mark Settle
12:00	Lunch	
1:00	Imaging Science Group Presentation	Ken Ando
1:45	Information Extraction Group Presentation	Fred Billingsley
2:30	Break	
2:45	Discussion of Final Report Organization and Requirements	
5:00	Adjourn	

APPENDIX C

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MULTISPECTRAL IMAGING SCIENCE WORKING GROUP

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