COMMERCIAL APPLICATIONS AND SCIENTIFIC RESEARCH REQUIREMENTS FOR THERMAL-INFRARED OBSERVATIONS OF TERRESTRIAL SURFACES

AUGUST 1986

(NASA-TM-89704) COMMERCIAL APPLICATIONS AND SCIENTIFIC RESEARCH REQUIREMENTS FOR THERMAL-INFRARED OBSERVATIONS OF TERRESTRIAL SURFACES (NASA) 150 p CSCL 08B

N88-16179

Unclas

G3/43 0118977

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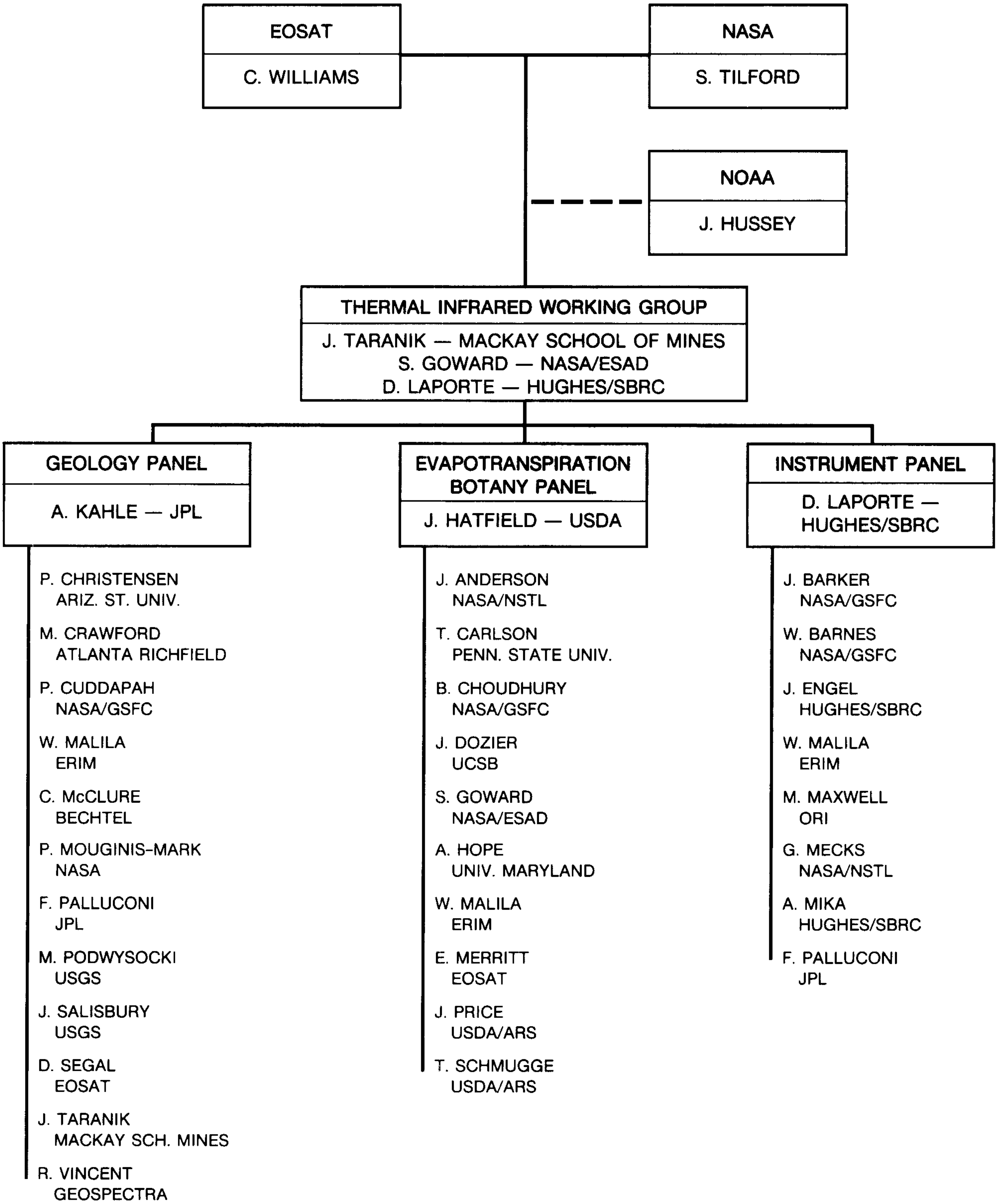
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COMMERCIAL APPLICATIONS AND SCIENTIFIC RESEARCH REQUIREMENTS FOR THERMAL-INFRARED OBSERVATIONS OF TERRESTRIAL SURFACES

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SUMMARY

In the spring of 1986 the EOSAT Company and NASA Headquarters organized a workshop to consider (1) the potential value of space-acquired multiband thermal remote sensing in terrestrial research and commercial applications and (2) the scientific and technological requirements for conducting such observations from the Landsat platform. The workshop defined the instrument characteristics of three types of sensors that would be needed to expand the use of thermal information for earth observation and new commercial opportunities.

1. *Geoscientists recommended that the Thematic Mapper be modified for the Landsat-7 instrument to include five thermal bands: four bands in the 8 to 14 μm region and one band in the 3 to 5 μm region.*

2. *Bioscientists concurred with this recommendation and further recommended that the Landsat-7 platform also support a wide-field sensor with a minimum swath width of 2750 km and a spatial resolution of 1 km for daily repeat coverage. Spectrally, the wide-field instrument would cover at least Thematic Mapper bands 1, 3, 4, and 5. Coverage of all Landsat 5 Thematic Mapper spectral bands, as well as the newly proposed thermal bands was considered highly desirable.*

3. *Instrument engineers evaluated the above requirements and concluded that the following instrument performance parameters could be attained in the Landsat-7 time frame:*

3.53 - 3.93	0.29	0.012	120
8.20 - 8.75	0.38	0.007	60
8.75 - 9.30	0.38	0.006	60
10.20 - 11.00	0.43	0.006	60
11.00 - 11.80	0.46	0.006	60

4. *Geoscientists also recommended a thermal-infrared profiling spectrometer for the Landsat-7 platform that would have 20 bands in the 3 to 5 μm region and 40 to 50 bands in the 8 to 12 μm region. The spectrometer would have a spatial resolution of 120m and NEΔTs from 0.1 to 0.3K.*

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Thus, three separate instruments are proposed for Landsat-7:

- *A Thematic Mapper with a modifed focal plane to provide multiband thermal channels*
- *A wide-field instrument with 1 km ground resolution, covering the Thematic Mapper spectral bands, and*
- *A thermal-infrared imaging spectrometer*

It is clear that a collaborative effort by NASA and EOSAT will be needed to achieve the successful implementation of the proposed sensor system.

Potential Scientific and Commercial Applications of Multiband Thermal Data

GEOLOGY

- *Global assessment of terrestrial geology*
- *Monitoring dynamic geologic phenomena*
- *Assessment of global and regional patterns of volcanic activity*
- *Exploration for minerals and energy*
- *Evaluation of groundwater resources*
- *Engineering site evaluation for resource development*
- *Evaluation of geologic hazards for civil-works siting*
- *Monitoring the effectiveness of land reclamation*

HYDROLOGY

- *Regional estimates of evapotranspiration rates*
- *Evaluation soil moisture status*
- *Mapping and monitoring of continental snow cover*
- *Water shed monitoring and management*
- *Flood forecasting and erosion assessment*

VEGETATIVE SCIENCES

- *Monitoring of growth and stress phenomena*
- *Regional to global assessments of crop yield*
- *Monitoring of drought conditions in remote locations*
- *Mapping of global vegetation types*
- *Fire detection and monitoring*
- *Urban heat island detection and monitoring*

Supporting Research Requirements for the Thermal-Infrared

Geology

Geoscientists have been comprehensively studying the characteristics of rocks, rock-weathering products and soils in the thermal infrared for over 30 years, and a base of general knowledge exists on what can be measured. However, the following research needs must be addressed if geologic applications of thermal-infrared techniques are to be signficantly expanded:

- *Development of a computer-accessible spectral library for well-characterized samples of rocks, rock-weathering products, and soils.*
- *Determination of the chemical and mineralogical factors affecting spectral signatures, such as element substitution, solid solution, order/disorder and phase changes.*
- *Evaluation of the spectral effects of surface stains and coatings, including their thickness, composition, and morphology.*
- *Development of spectral-mixing models to enable estimates of mineral abundances to be made.*
- *Investigation of the directional effects of spectral emissivity to establish the optimum illumination and observation geometry.*
- *Documentation of the influence of micro-meteorological, diurnal, and seasonal effects on the spectral contrast of reststrahlen bands.*
- *Documentation of the effects of vegetative cover and moisture on basic thermophysical properties of rocks, rock-weathering products and soils.*
- *Determination of the effects of atmospheric transmission and emission on thermal-infrared spectroscopic measurements on the earth's surface.*
- *Determination of the relationships among spectral emission, reflection, and transmission in the thermal-infrared.*

Biophysical Sciences

Little research has been conducted on some of the most fundamental phenomena related to understanding what properties of vegetation, water, and soils can be measured in the thermal-infrared. Specific research issues that must be addressed if applications of multiband thermal-infrared technology are to be significantly expanded include:

- *Development of a means of obtaining absolute, accurate, land-surface temperatures in the presence of atmospheric effects and variations in surface emissivity.*
- *Determination of the spectral emissivity properties of vegetation, mixtures of vegetation with soil, and vegetation with varying soil moisture.*
- *Determination of the biophysical attributes of land materials, such as stomatal and aerodynamic resistances, soil moisture dynamics, and stress-response mechanisms as they relate to the equilibrium temperature of the earth's surface.*
- *Development of an improved understanding of the effects of diurnal and annual cycles of energy and mass balance of various land-cover types and their effects on land thermal emission.*
- *Development of analytical techniques for interpreting local biophysical phenomena from data acquired at different times by instruments with different fields-of-view:*
- *Development of methods of using combined observations from the solar and microwave regions to improve our knowledge of land and biophysical conditions.*

Recommendations

1. *The highest priority recommendation is to expand the capabilities of the Thematic Mapper instrument for Landsat-7 to include the five thermal bands recommended by the Geoscience and Bioscience Panels. Because the commercial market is not yet developed for this data, the Government should take a leadership role in developing the instrument and should support the initial scientific investigations with its data.*

2. *The next priority is to include a wide-field multispectral scanner on the Landsat-7 platform with 1-km IFOV and a 2750 km swath width, covering the Thematic Mapper spectral bands. This instrument appears to have immediate commercial application and the commercial operator of the Landsat System should take a leadership role in its development. However, the Government should support initial scientific investigations with its data.*

3. *A thermal-infrared imaging spectrometer should be developed as a fundamental research tool to expand basic knowledge of what can be measured in the thermal-infrared. The Government should take a leadership role in developing this instrument and in supporting scientific investigations with its data.*

4. *Fundamental research in the thermal-infrared needs to be significantly accelerated and actively supported by the Government if new applications of multiband thermal-infrared techniques are to be developed for an expanded commercial marketplace.*

FOREWORD

Recent studies with multiband thermal data suggest that this data may significantly increase the scientific and commercial value of satellite-acquired observations in analyzing the earth's land areas. Therefore, NASA and EOSAT organized the Thermal-Infrared Working Group, comprising distinguished aerospace remote-sensing scientists, to evaluate alternatives for multiband thermal data collection on Landsat-7.

The Thermal-Infrared Working Group had two main tasks:

- *To provide the insights needed to guide near-term development of advanced sensor technology that will increase the commercial and scientific utility of Landsat data.*
- *To identify longer-term, high-risk, unproven technology and experiments that are more appropriately supported by the government.*

A three-day workshop was held at EOSAT headquarters in Lanham, Maryland, February 5, 6, and 7, 1986. The workshop was attended by 46 persons from government, academia, and industry, and they were asked to do the following:

- *To document what is measurable with multiband thermal-infrared techniques in the 3 to 5 μm and 8 to 14 μm portions of the spectrum.*
- *To document which bandwidths, band locations, radiometric resolutions (NEΔTs), and spatial resolutions are optimal for the greatest number of possible uses.*
- *To document atmospheric effects on satellite-acquired thermal-infrared data, and to identify methodologies for minimizing atmospheric degradation of satellite measurements.*
- *To document thermal-infrared models needed for analyzing thermal-infrared.*
- *To evaluate options for acquiring multiband thermal-infrared data, and to prioritize these options from the viewpoints of both operational- and scientific-experimentation users.*

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The panels from two disciplines, geology and evapotranspiration/botany, first met separately and then presented their recommendations to the workshop as a whole. The recommendations from the two panels were then studied by an Instrument Concepts Panel, and that panel summarized instrument tradeoffs in a meeting held 25 March 1986. This report contains the findings of these meetings.

This highly successful efforts marks the beginning of a new process of joint government/industry program evaluation to ensure the development of significant new commercial activities for the industrial sector of the national economy, and it also will more clearly define the government's appropriate role in fundamental research.

CONTENTS

1 HISTORICAL PERSPECTIVE

Broadband Thermal Mapping

Thermal-infrared remote-sensing techniques were first available for civilian applications in the 1960s. Aircraft scanners, initially used for broadband temperature surveys, measured thermal emittance from the earth's surface in the 3 μm to 5 μm portion of the spectrum. These first instruments were designed for military reconnaissance purposes, and they utilized automatic gain control and data recording directly on film. Quantitative measurements of radiant spectral emittance were not possible until the 1970s when blackbody-calibrated scanners were developed and their data was recorded in a manner enabling digital analysis. Subsequent developments in detector technology allowed the 8 μm to 14 μm portion of the spectrum to be utilized for broadband ground-temperature mapping in the early 1970s.

Early investigations with broadband thermal-infrared data revealed that thermal radiance largely depends upon the amount of solar energy absorbed by landscape cover types and on changing local environmental conditions. Variations in atmospheric water vapor, aerosols, and temperature can be significant over distances of only a few tens of kilometers, and these atmospheric variations make it difficult to obtain accurate ground measurements of temperature. In fact, except for thermal mapping of discharges in water bodies and temperature surveys of houses in urban areas, few routine applications of thermal data were possible with aircraft data because of the lack of models that could be used to understand local environmental effects on thermal measurements.

In the late 1970s several satellite missions were utilized for broadband temperature mapping of the earth's surface. Most of these satellites were used for global climate and weather research, and ground spatial resolutions ranged from 0.5 km to over 8 km. The Heat Capacity Mapping Mission (HCMM) launched in April 1978 was the first satellite specifically designed for experimentally investigating the thermal properties of the earth's land areas. HCMM was placed into a nearly circular Polar orbit at an altitude of 620 km. The satellite carried a scanning radiometer, which obtained broadband measurements of spectral radiance in the solar-reflected (0.55 to 1 μm) and the thermal-emitted (10.5 to 12.5 μm) portions of the spectrum. HCMM made its reflected and emitted spectral radiance measurements from 500m and 600m ground areas respectively. The Noise Equivalent Temperature Difference (NEΔT) was 0.4K at 280K, which was excellent for most applications. Data was acquired to evaluate how cover types on the earth's surface responded to diurnal heating by the sun.

HCMM was designed to evaluate the combined effects of near-surface composition and environmental conditions as manifested in the surface. However, the 600-meter ground resolution of HCMM limited the use of the data for most nonrenewable-resource applications. Although several renewable-resource applications seemed feasible with HCMM data, they were difficult to quantify because of calibration problems and difficulties with data production from the experimental HCMM data system (Short and Stuart 1982).*

The Landsat-3 Multispectral Scanner included a thermal band in the 10.4 to 12.5 μm portion of the spectrum. Unfortunately, sensor problems limited the utility of its thermal data. Landsat-4 and -5 have a thermal channel on the Thematic Mapper that utilizes the 10.4 to 12.5 μm portion of the spectrum. This channel has a 120-meter ground resolution and a NEΔT of 0.12K. However, the potential applications of Landsat thermal data have not been extensively investigated because of instrument and ground processing limitations, the low frequency (16 day) of repeat observations, and the marginal contrast in thermal emissions observed between differing surfaces at the observing times (9:45 a.m. and 9:45 p.m.). Moreover, the 120-meter spatial resolution, while significantly better than that of HCMM, is still considered too coarse for many applications.

Multiband Thermal Mapping

Laboratory research on the spectral emittance of rocks and minerals in the thermal infrared indicated a considerable potential for nonrenewable resource applications in the early 1970s. Airborne remote-sensing investigations established the feasibility of multiband thermal mapping from airborne platforms in the mid-1970s. In 1979 Kahle and Rowan (1980) analyzed 6-channel multiband data from the Bendix 24-channel scanner and demonstrated that the silicate mineralogy of rock units could be evaluated. In 1980, NASA Headquarters organized a Workshop on Geological Applications of Thermal Infrared Remote Sensing Techniques at the Lunar and Planetary Science Institute to evaluate recent research results with multiband thermal data and to consider the feasibility of a new multiband thermal instrument. This workshop discussed the specifications for the Thermal Infrared Multispectral Scanner (TIMS). TIMS was funded as a $2 million instrument development project, and the first TIMS data was acquired over Death Valley in 1982 (Kahle and Goetz 1983; Gillespie et al., 1984). Since that time, data from sites throughout the United States and Australia have been acquired, and the great potential for use of multiband thermal data has been demonstrated for a wide variety of applications.

There has been little evidence of spectral features in the radiance from vegetative canopies and soils. As illustrated in Section 5, TIMS data acquired of vegetated landscapes consistently shows blackbody (or graybody) spectral emissions; however, recent laboratory measurements of longwave reflectance from plant leaves by Salisbury (see Section 5) has shown strong spectral structure. Further research will be needed to evaluate the potential of multiband observations in the study of vegetative canopies. Little or no work has been accomplished for soils; however, it is anticipated that some spectral structure will be present. The composite of graybody vegetation and a spectrally selective emitting soil may allow estimation of ground cover in a complementary fashion to that provided by visible and near-infrared measurements.

*References are compiled in Section 7.

The potential near-term value of multiband thermal-infrared observations in vegetation/hydrology research lies in derivation of absolute surface temperatures from sensor brightness measurements through effective corrections for atmospheric attenuation and for surface nonunity emittance. Little experimental work has been completed, but the theoretical calculations of Wan (1985) suggest that correction for atmospheric effects can lead to a 1K accuracy in land surface-temperature determinations from satellites under clear-sky conditions. The need for this level of accuracy stems from the desire to use this data for analysis of biophysical processes such as photosynthesis and evapotranspiration, where the satellite-derived surface temperature is but one of several variables that must be accurately measured to evaluate process rates.

2 POTENTIAL COMMERCIAL AND SCIENTIFIC APPLICATIONS

Nonrenewable Resources

Remotely sensed image data is analyzed by scientists trained in geology to develop information about landscapes. Landscape information is interpreted to develop information about rock types, rock sequences, the geometric attitudes of rock assemblages, structural discontinuities in rock assemblages, and the geodynamic evolution of the region under study. This geologic information is used to develop crustal models that are used to assess resource potential, explore for resources, to design resource production and distribution facilities, and to monitor the effectiveness of procedures for minimizing the impact of disturbances of the landscape on the environment.

The primary use of remotely sensed data by resource explorationists has been to map geologic structures. Topographically related landscape patterns (landforms and drainage) are interpreted to delineate structural discontinuities and the geometric attitudes of rock assemblages. Landscape cover types (rocks, rock-weathering products, soils, vegetation, water, culture, and mixtures) that can be spectrally discriminated with remote-sensing measurements can be analyzed to develop geologic information on rock types, their geometric relationships, and geologic models.

Broadband Thermal Techniques

Broadband thermal-infrared image data has been particularly useful for geological applications in terrain having low relief and thin cover with soils or unconsolidated materials. Differences in the thermal inertia of rock types, evaporation of contained moisture from porous and permeable rocks, and differences in moisture content of rock and soil materials related to structural discontinuities (faults) have been detected by broadband thermal mapping techniques in semiarid to arid physiographic environments when other techniques are not able to detect such phenomena. This is important, since many of the world's most productive oil and gas fields occur in large, low-relief basins.

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Broadband thermal data has also been utilized for mapping thermal-inertia differences of rock materials related to hydrothermal alteration. Volcanic rocks that have been altered by mineralizing fluids (hydrothermal alteration) often have diurnal thermal signatures different from unaltered rocks. Dense crystalline volcanic rocks that have been altered to clays often have a much lower thermal inertia than the original materials. Introduction of silica in porous and permeable low-thermal-inertia rock materials may increase the thermal inertia of those rock materials, thus allowing silicification to be mapped from broadband thermal imagery.

Multiband Thermal Techniques

One of the most important parameters in classification of rock materials is silicate mineralogy. Silicates are the fundamental building block minerals that form rocks. Igneous rocks that form below the earth's surface range in composition from granite (containing abundant quartz and sodic feldspars and minor hornblende and biotite) to gabbro (containing no quartz, calcic feldspars, and minor amounts of pyroxenes, amphiboles, and olivine). The extrusive equivalents of these rocks are rhyolite and basalt.

Rocks forming at the base of the oceanic crust and within the mantle (ophiolite complex) range in composition from gabbro to eclogite and are often associated with olivine-rich rocks. Ophiolites and layered complexes of mafic rocks often contain platinum group metals and chromite. These strategic minerals are now the subject of global exploration for supply alternatives. Reflected solar radiation and backscattered microwave radiation are not influenced by mineralogic differences in these igneous rocks. However, the nature of the silicon-oxygen bonding in the principal silicate minerals causes characteristic emission spectra in the 8 to 14 μm portion of the spectrum.

Research with TIMS data has now demonstrated conclusively that spectral emissivity variations can be detected that will allow major variations in igneous rocks to be evaluated. In addition, hydrothermally altered igneous rocks should be better discriminated using multiband thermal techniques because, in the reflected part of the spectrum, silica has no significant spectral variations in reflectance while clay minerals and iron oxide minerals do show these variations. The addition of multiband thermal-infrared techniques should significantly improve discrimination and evaluation of hydrothermal alteration zones.

A global data base of multispectral thermal-infrared image data should also be a valuable tool for evaluating sedimentary rock sequences in basins containing hydrocarbons. Discrimination of quartz sandstones, carbonates, bedded gypsum/anhydrite and shales would significantly improve the analysis of facies and interpretation of depositional environments for quantitative modeling of basin sedimentation. In addition, multispectral thermal imagery could be useful in the search for surface alteration related to hydrocarbon microseepage. Reported chemical changes associated with hydrocarbon microseepage include the alteration of gypsum to calcite, the reduction and mobilization of iron oxide, and the recementation of elastic sedimentary rocks with calcite, pyrite, and montmorillonite.

Multiband thermal mapping techniques would have their greatest potential application where the total areal vegetative cover is less than 40%. On a global basis, such areas have climates that include tropical and subtropical steppe, middle latitude steppe, tropical and subtropical desert, and middle latitude desert. Some highland areas, the Sierra Nevada, Sierra Madre Oriental of Mexico, Peruvian and Chilean Andes and Altiplano, Hindu Kush, Tibetan Plateau and Himalayas, and the Brooks Range in Alaska are also areas where vegetation cover is sparse enough to permit emittance variations in rocks and soils to be evaluated. Approximately one-third of the earth's land masses could be evaluated geologically using multiband thermal techniques. Many of these areas have not been investigated comprehensively by geologists and are of considerable interest in the search for strategic materials.

The greatest limitations on expanding the use of thermal-infrared data for nonrenewable-resource applications have been insufficient ground spatial resolution and the lack of global, repetitive, calibrated data. Global availability of high-spatial-resolution broadband-thermal data should significantly increase the number of commercial applications and the overall utility of Landsat data. The addition of multispectral thermal bands represents the development of an entirely new dimension in earth-resource satellite data. At the present time, a small number of scientists are prepared to analyze this new data, but the market for the data has not been developed. Anticipated major geoscience applications of this new data set include:

- *Global assessment of mineral and energy resources.*
- *Exploration for base and precious metals in poorly mapped, remote, semiarid-to-arid areas having sparse (less than 40%) vegetation.*
- *Exploration for hydrocarbons and energy minerals in poorly mapped, remote, semiarid areas having sparse (less than 40%) vegetation.*
- *Engineering site evaluation for resource development and production.*
- *Evaluation of groundwater resources in temperate-to-arid regions.*
- *Evaluation of geologic hazards for civil works siting.*
- *Monitoring the effectiveness of reclamation of lands previously involved in resource extraction.*

The geologic community for broadband and multiband thermal data consists of the following:

- *Oil and natural gas industries*
- *Private consultants to the oil and natural gas industry*
- *Metal-extraction and metal-manufacturing companies*
- *Energy minerals companies*
- *Private consultants in mineral and energy-mineral exploration*
- *Construction materials industries*
- *Engineering and construction firms*
- *Private geological engineering consultants*
- *State geological surveys*
- *State departments of minerals and energy*
- *State departments of conservation and environment*
- *Universities and research institutes*
- *Defense intelligence community*
- *U.S. Bureau of Land Management*
- *U.S. Bureau of Mines*
- *U.S. Department of Commerce*
- *U.S. Department of Energy*
- *U.S. Environmental Protection Agency*
- *U.S. Geological Survey*

In summary, improved spatial resolution and the addition of several bands will significantly increase the geologic utility of thermal-infrared data from Landsat satellites. This increased utility should lead to an expanded market and a competitive edge in the international marketplace. Because only a small number of geoscientists are prepared to analyze such data today, a research and development effort should begin now to develop simulated satellite-acquired multiband thermal data. Such data should be given wide distribution to all segments of the user community. Consideration should be given to developing standardized data-reduction procedures that will produce standard multiband thermal products that can be easily analyzed on personal computers with color monitors.

Applications to the Study of the Earth as a Planet

NASA has the mandate to study the Earth as a planet, and multiband thermal data may contribute significantly to improving our fundamental understanding of continental landforms, recent tectonism, and volcanism. Such research will also support commercial applications because it will lead to the development of improved crustal models.

Specific research and fundamental questions that can be approached using this capability, suggested by Peter Mouginis-Mark (NASA, Land Processes Branch), include making regional-to-continental-scale maps of rock chemistry, particularly with respect to the abundance of silica. This knowledge would provide us with the opportunity of investigating several topics relating to the origin and evolution of the continents and the weathering of these rocks. Examples of these studies might include addressing the following questions:

Was the chemical evolution of the early Earth (over 2-billion years ago) the same as is occurring today by the process of plate tectonics?

Here, an analysis of the ancient Archean Cratons of Canada, South Africa, Australia, and Siberia could be intercompared to see how diverse the rock types (primarily volcanic rocks) were for each structural (tectonic) setting. Subsequently, the more recent continental blocks, such as the Arabian and Icelandic, could also be compared.

What can be learned, on a continental scale, about the mountain-building process associated with island arc formation and the creation of mountain belts such as the Andes?

An especially rewarding experiment might be to study the spatial and temporal distribution of volcanic rocks within South America along the Andes Mountains. A large number of granite plutons (silica-rich remnants of exposed differentiated magma chambers) are located here that provide insights into the cores of volcanoes similar to the ones currently active in the Andes.

In addition, by mapping the silicate distribution associated with different volcanoes, it might be possible to study the spatial variation in the way the subducted Pacific Plate is being reassimilated into the mantle as it dives beneath the South American Plate. For instance, we know that high silicate rocks (and, hence, explosive volcanoes, because of the amount of entrained volatiles) are associated with rapidly dewatering subducted sediments, whereas in different tectonic settings (slower subduction rates) one would expect to find more mafic rocks. However, there has been no regional survey of silica content and, as a result, models for plate reassimilation have not been developed. The thermal-infrared bands being proposed here for the Landsat-7 instrument would allow us to initiate this study.

Typically, it is assumed that a one-time collection of data over a site is sufficient for geologic research. However, if we assume that a key element of our effort to understand the dynamics of the Earth lies in developing models describing atmosphere/soil/vegetation interactions, then more frequent collections could aid in the validation of these models. Currently, it is impossible to know if these models are valid in a predictive sense for more than a few years into the future, and we do not have the long-term historic data collection necessary to do retrospective studies. However, preserved in the geologic record is much of the information needed to understand recent climatic change and more transient phenomena, such as sand-dune migration, river flooding, frequency of volcanic eruptions, etc.

By using satellite-acquired thermal-infrared information, it would be possible to investigate stable vs. unstable dunes or to track the fall-out from desert-wide sand storms by identifying the evolving weathering products and vegetation on the sand sheets and stable dunes. Similarly, it would be possible to map the distribution of flood waters over time by monitoring the recent sediments that are deposited after the waters recede or to search for volcanic ash deposits at various stages of weathering. The regional scale required makes a spaceborne sensor the only instrument capable of achieving these science objectives.

In addition to the above-mentioned scientific research opportunities afforded by a spaceborne thermal-infrared sensor, the temperature-measuring capabilities of the instrument would permit us to evolve a technique for predicting volcanic hazards worldwide. For instance, Peter Francis (Lunar and Planetary Institute), using the thermal band of the Landsat-5 Thematic Mapper, has discovered anomalously warm summit crater lakes on volcanoes in the Andes that have been presumed to have been extinct for millions of years. It is possible that these warm temperatures indicate the onset of new activity. Similarly, Anne Kahle and David Pieri (JPL) have used the airborne Thermal Infrared Multispectral Scanner to map hot spots on the near-surface crustal structure of Kilauea Volcano (Hawaii) as indicators of shallow magma reservoirs beneath it and this summer are trying the same experiment in Italy. These kinds of studies on a worldwide basis may provide a tool for predicting volcanic hazards, since pre-eruptive magma movement frequently takes place days to weeks before major, life-threatening, eruptions.

Ecology, Hydrology, and Renewable Resources

Much of the commercial and scientific value of satellite-acquired thermal-infrared observations that could be realized in the biophysical sciences and in renewable-resource assessments has not yet been achieved. This is primarily because of the lack of space-acquired thermal-infrared measurements appropriate for these uses. However, the potential of these measurements in ecological and hydrological research as well as in renewable-resource assessments is great. Thermal emissions from land represent the net product of the manner in which vegetation, soils, water, snow, and ice use absorbed sunlight in evapotranspiration, photosynthesis, atmospheric heating, and changing states from solid to liquid to gaseous phases. These biophysical processes determine the availability of water in the environment, which, in turn, affects the ability of the environment to sustain life and encourage growth.

Over the last 30 years, researchers have repeatedly shown in field studies that radiometrically measured surface temperatures can be used to evaluate the status of land biophysical conditions. Studies have been conducted on soil moisture status, evapotranspiration, plant stress, snow mapping, water-temperature assessment, and urban effects on climate. In each case thermal-infrared measurements have proven to be of great value in the assessment of these phenomena. The only satellite-based research program that effectively supported investigation of thermal-infrared observations in biophysical analysis was the Heat Capacity Mapping Mission (HCMM). It proved less successful than anticipated (Short and Stuart 1982) because of:

1. *An insufficient repeat observation cycle (5-16 days)*
2. *Poor sensor calibration*
3. *Inability to correct for atmospheric attenuation*
4. *Low spatial resolution (600 meters — inadequate for agricultural field delineation)*
5. *Lack of timely data availability*

Only limited attention has been given to the Landsat Thematic Mapper thermal-infrared measurements because the time of day they are acquired is considered inappropriate for biophysical analysis. Investigators are only now beginning to look at data from the Advanced Very High Resolution Radiometer (AVHRR). Studies currently underway in the NASA Interdisciplinary Science Land Climatology program should, in the near future, provide a better assessment of AVHRR thermal-infrared measurements for land biophysical analysis. Because of the lack of space missions focused on the use of thermal-infrared measurements in renewable-resource assessments and the biophysical sciences, there has been no sustained research effort supported to develop the knowledge needed to accomplish a successful mission.

Specific phenomena of scientific and commercial significance that would be observed with high-quality, multispectral, thermal-infrared data include:

- *Growth and stress phenomena in natural vegetation and arable crops*
- *Soil moisture status and evapotranspiration rates*
- *Land effects on climate and weather*
- *Surface wind fields*
- *Distribution and intensity of fires*
- *Extent and condition of snow cover*

However, two specific requirements must be met to capture the commercial and scientific value of thermal-infrared observations in renewable-resource assessments and analysis of the hydrosphere and biosphere:

1. *A means must be developed to derive accurate surface kinetic temperatures from the observations. An accuracy of ± 1.0ºC or better is needed.*
2. *A means must be developed to collect observations at a temporal frequency greater than that provided by the Landsat Thematic Mapper. The daily observations acquired by the AVHRR serve as a model of the repeat coverage needed.*

A solution to the first requirement may be achieved by carrying out well-calibrated (better than 0.5ºC) multispectral thermal-infrared observations. Over oceans, the three-band thermal-infrared sensor on AVHRR provides sufficient information to correct for atmospheric attenuations. This approach is effective because the ocean surface is a uniform spectral emitter with an emittance of nearly one. Over land, emittance variations, topography, and high-spatial-frequency atmospheric variability reduce the accuracy of this approach. The inclusion of additional spectral bands, particularly in the 3.0 to 5.0 μm, 8.0 to 9.5 μm, and 10.0 to 12.5 μm spectral regions may provide a means of accounting for both surface emittance variability and atmospheric attenuation. Further research will be required to establish the accuracy and precision of this multispectral approach. However, without multiple spectral thermal-infrared bands, no ability to derive accurate surface temperatures is possible.

A solution to the second requirement may be achieved by including a low-spatial-resolution (1 km), wide-swath (2,750 km) sensor on the Landsat platform. This sensor should replicate the spectral coverage of the Thematic Mapper (including the multispectral thermal-infrared bands) and provide the same level of high-quality calibration (better than 0.5ºC) specified for the Thematic Mapper. This low-resolution system would provide daily repeat coverage to keep track of the dynamics of the biophysical phenomena. The Thematic Mapper would provide periodic updates of the local sources (e.g., individual crops) of regional trends and possibly serve as a calibration reference for the wide-field sensor system.

The Evapotranspiration/Botany Panel appreciates that this temporal requirement is significantly greater than that needed by the geology community and, thus, places added burdens on the observing and data-processing systems. However, it must be clearly understood that for biophysical applications much of the real informational value in remotely sensed observations is in the time domain. This fact was well established in the NASA Large Area Crop Inventory Experiment (LACIE) and Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) experiments and further confirmed with thermal-infrared observations in the HCMM experiment. Lack of this temporal coverage will significantly reduce the value of any Landsat-type observing system in biophysical research and renewable-resource applications.

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Geologic Sciences

In September 1985, the Geosat Committee met in a workshop at Flagstaff, Arizona, entitled "Remote Sensing: Goals and Directions for Research and Development." One part of that workshop focused on defining fundamental research needs for the geosciences, and a panel was specifically organized to analyze research requirements in the mid-infrared (2.5 to 25 μm) region. The major conclusions of that panel are summarized below:

- *A spectral library should be developed for well-characterized samples of rocks, rock weathering products, and soils. Spectra in the library should be computer accessible and should be acquired in a manner facilitating their intercomparison. Sample characterization data is a critical part of the record.*
- *The chemical and mineralogical factors affecting spectral signatures, such as element substitution, solid solution, order-disorder, and phase changes, should be studied.*
- *The spectral effects of surface stains and coatings, including their thickness, composition, and morphology should be determined.*
- *Spectral mixing models should be developed. More linear mixing in the mid-infrared region should allow a spectrum to be deconvolved into individual mineral abundances.*
- *The directional effects of spectral emittance should be investigated to determine the optimum remote-sensing geometries of illumination and observation.*
- *Micrometeorological and diurnal and seasonal effects on the spectral contrast of reststrahlen bands should be documented to optimize measurement timing.*
- *Carbon dioxide laser reflectance should be investigated as a remote-sensing alternative to passive measurement of spectral emittance.*
- *The basic thermophysical properties of rocks, rock-weathering products, and soils, as well as the effect of vegetation cover and moisture on these properties should be determined.*
- *The effects of atmospheric transmission and emission on mid-infrared and spectroscopic data should be determined.*

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In addition to these requirements, recent investigations with TIMS data have documented the need to assess the effects of variations in vegetative cover over consolidated rocks, unconsolidated rock-weathering products, and soils and the combined influence of topography on thermal measurements.

Geoscientists recognize the need for a strong program of longer-term, high-risk supporting research that is uncertain in its outcome to foster development of a fundamental understanding of what can be measured in the mid-infrared and the types of information that can be extracted from the measurements. This type of program will require an adequately funded program of laboratory, field, and airborne/spaceborne data collection for diverse physiographic regions of the world and should involve investigators from many different disciplines.

Biophysical Sciences

Studies of land thermal radiance emissions for biophysical applications have been constrained by minimal support for this research and limited laboratory, field, and remote observations. Some of the most fundamental questions, e.g., characterization of the spectral emittance properties of land and soil, are relatively unexplored. The capability of measuring and modeling the thermal behavior of land areas, particularly vegetated landscapes, is immature compared to capabilities in the solar and microwave spectral regions. This lack of attention appears to have occurred because of difficulties in developing thermal-infrared sensors as well as because of the perceived complexities in interpreting land thermal emissions. However, thermal radiance is a fundamental component of the land energy/mass cycle which occurs as the net product of processes determining the biophysical state and dynamics of the observed land area. Observation of this radiance, particularly in conjunction with solar-reflectance and microwave measurements, should significantly improve the knowledge of terrestrial biophysics.

Specific research issues requiring intensive investigation include:

- *A means of accounting for atmospheric attenuation in the presence of variations in surface emittance.*
- *The spectral emittance properties of various land materials, particularly vegetative materials.*
- *The biophysical attributes of land materials, such as stomatal and aerodynamic resistances, soil moisture dynamics, and stress response mechanisms, as they relate to the equilibrium temperature of land.*
- *The diurnal and annual cycles of energy and mass balance of various land covers as they relate to land thermal radiance.*
- *Analytical techniques for interpreting local biophysical phenomena from data acquired at different times by instruments with different fields of view.*
- *Methods of using combined observations from the thermal, solar, and microwave regions to improve our knowledge of land biophysical conditions.*

Investigation of these issues will require a combination of theoretical, laboratory, and field experiments and will begin to establish the range of possible observed land thermal emissions. There is a particular need to develop more accurate and efficient laboratory and field instruments to carry out high-spectral-resolution thermal-infrared measurements. Recent technological advances in thermal-infrared sensors suggest that this is possible, but no effort has been focused in this direction. Theoretical efforts need to be encouraged to develop more realistic yet simplified models that can be used to interpret the observed land thermal emissions. Available satellite thermal-infrared measurements from the Landsat and AVHRR sensors should be subjected to more intensive analysis to establish the range of observable land thermal-emission patterns. In general, there is a need to develop a research focus on land thermal-infrared observations, lacking in the research community to date.

4
GEOLOGY PANEL REPORT

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The potential for using multispectral data in the thermal infrared for geologic compositional mapping has been recognized since the pioneering laboratory spectroscopic work of Lyon in the early 1960s (Lyon 1962, 1962a, 1964, 1965). Since then, there has been only limited realization of this potential due to lack of true multispectral remote-sensing instruments. However, image data from the airborne Thermal Infrared Multispectral Scanner (TIMS) recently has verified Lyon's work.

In this report of the Geology Panel, we first discuss the known aspects of thermal-infrared spectroscopy of geologic materials as applied to remote sensing, and we also indicate those areas requiring further research. Then a discussion follows of the tradeoffs considered by the panel for the proposed instrument, including band selection (number, width, and position), spatial resolution (NEΔT or NE$\Delta\varepsilon$), time of day, atmospheric corrections, and digitization levels. Finally, we discuss the exciting possibility of the addition of a nonimaging spectrometer as a complementary addition to the proposed imager.

Background

Useful Spectral Portions of the Thermal-Infrared Region

The middle- or thermal-infrared portion of the spectrum available for geologic remote sensing extends from approximately 3 to 35 μm. The source of energy is thermal radiation from surface materials at ambient terrestrial temperatures. The useful spectral range is limited both by the amount of energy radiated and by how much of this energy is transmitted through the atmosphere. At terrestrial temperatures, the spectral radiance of a blackbody is at a maximum around 10 to 11 μm, dropping off sharply to shorter wavelengths and less sharply to longer wavelengths. The best atmospheric window lies between about 8 and 14 μm with poorer windows between 3 and 5 μm and between 17 and 25 μm. Figure 1 shows the windows in the 3 to 5 and 8 to 14 μm regions.* Interpretation of

*LaPorte 1986: personal communication.

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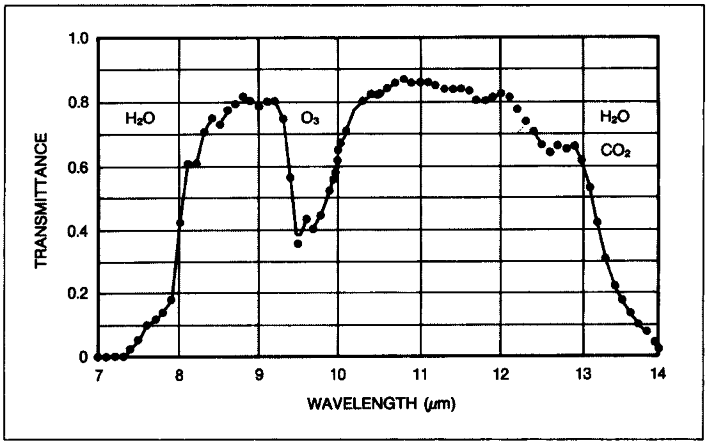
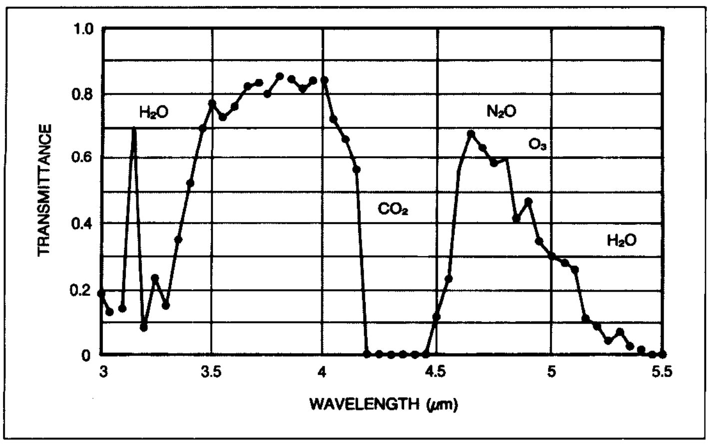
Figure 1. Atmospheric Transmission in the 3 to 5.5 μm and 7 to 14 μm Wavelength Regions for the U.S. Standard Atmosphere. (From Lowtran5)





data from the 3 to 5 μm region is further complicated by overlap with reflected solar radiation, which, although dropping rapidly in intensity, still contributes. Thus, the 8 to 14 μm region is by far the easiest spectral region to use and has received most attention to date. Fortuitously, this is also a spectral region containing diagnostic spectral information on many minerals, including the silicates, which make up the great majority of continental surface rocks.

Thermal-Infrared Spectra of Rocks and Minerals in the 8 to 14 μm Region

The thermal-infrared spectra of rocks and minerals have been studied in the laboratory for some time, and extensive reference to early work is made in the publications of Lyon (1962) and Lazarev (1972). Spectral features of minerals in the thermal-infrared region are the result of vibrational (bending, stretching) molecular motions, with the most intense features resulting from excitation of the fundamental modes. The vibrational energy, and therefore the wavelength, of these bands is diagnostic of both the anion composition and the crystal lattice structure. Thus, thermal-infrared spectra provide a direct means of identifying the composition of many silicates and other common materials (carbonates, sulfates) and of interpreting crystal structure and, therefore, the mineralogy of these materials.

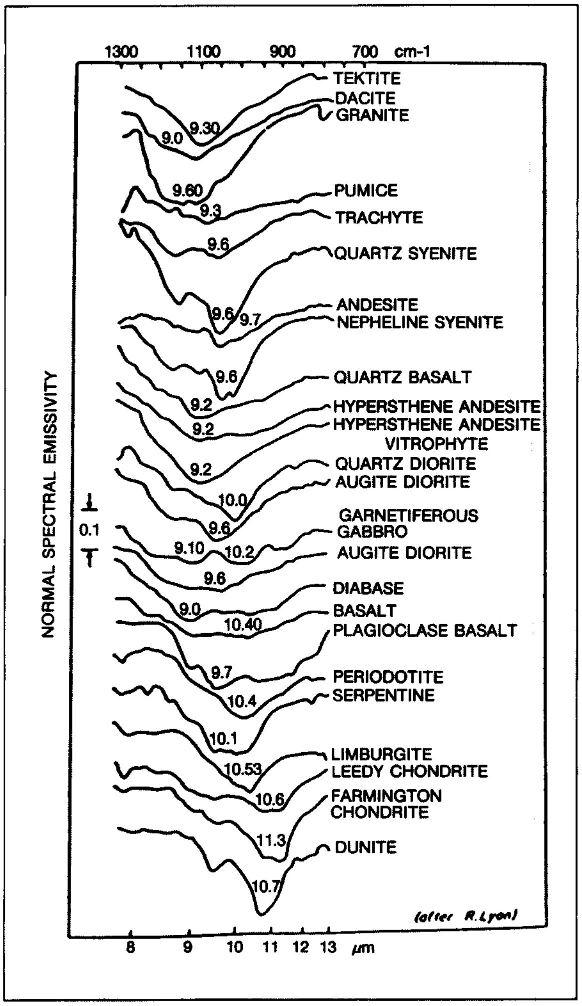
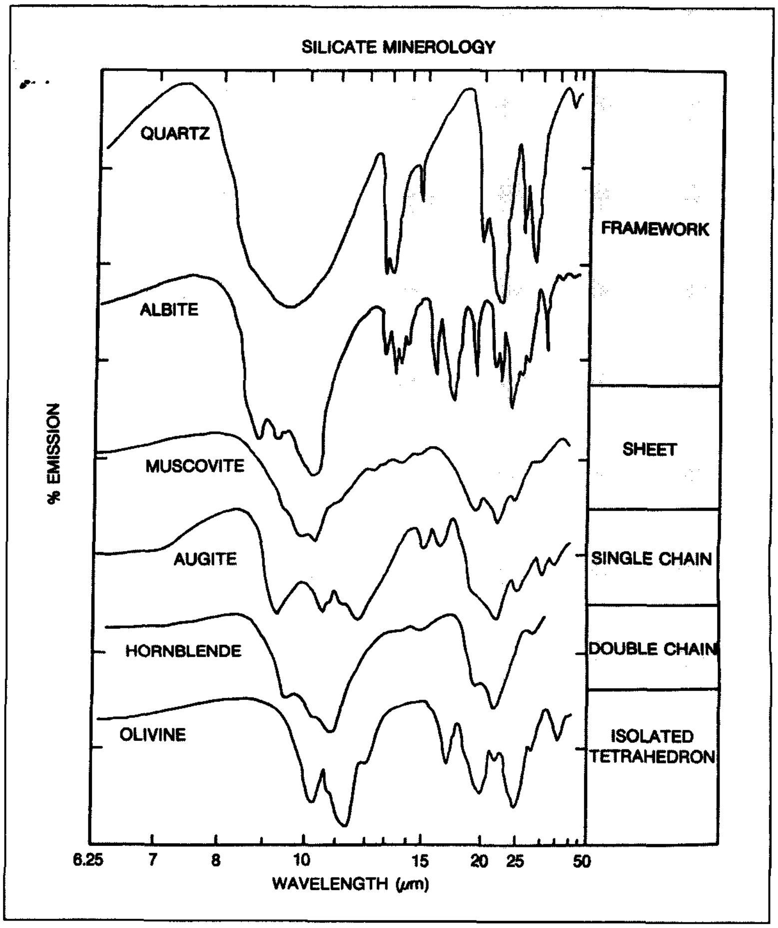


Figure 2. Emission Spectra of Various Rock Types Showing Reststrahlen Minima. (Vicker and Lyon 1967.)

A strong theoretical framework exists for interpreting observed spectral features on the basis of ion mass, bond strength, and crystal structure (e.g., Lazarev 1972; Farmer 1974; Karr 1975). Laboratory studies have documented the thermal-infrared spectral bands of many minerals and rocks (e.g., Lyon 1962a, 1964, 1965; Hovis and Callahan 1966; Goetz 1967; Vickers and Lyon 1967; Hunt and Salisbury 1974, 1975, 1976; Lyon and Green 1975; Vincent et al., 1975; Farmer 1974; van der Marel and Beutelspacher 1976) and show that the location, strength, and form of these spectral features vary systematically with composition and crystal structure. An example is given in Figure 2. The most intense absorption feature in the spectra of all silicates (the reststrahlen effect) occurs between 8 and 12 μm, and this region of a spectrum is generally referred to as the "Si-O stretching region." Typically, the absorption wavelength shifts to shorter wavelengths as the bond strength within the lattice increases (Vincent and Thomson 1972; Hunt and Salisbury 1974).

Figure 3. Thermal-Infrared Transmission Spectra of Silicate Minerals Showing the Correlation Between Band Location (Vibrational Energy) and Mineral Structure.



In silica-bearing (SiO_2) minerals, the wavelength of the Si-O absorption band decreases from 11 to 9 μm in a uniform succession for minerals with chain, sheet, and framework structures (cyclo-, phyllo-, and tectosilicates) (Hunt and Salisbury 1974; Hunt 1980) as illustrated in Figure 3.* This provides a direct means of discriminating among minerals with these structures. Additional bands occur in silicates throughout the 12 to 40 μm range, associated with a variety of Si, O, and Al stretching and bending motions.

The carbonates, sulfates, phosphates, oxides, and hydroxides are other important mineral groups. These occur frequently in sedimentary and metamorphic rocks and in areas of weathering or alteration. The spectra of representative minerals from these groups are shown in Figure 4 (from Hunt, 1980). The spectrum at the top of Figure 4 is that of calcite, which contains features typical of all carbonate minerals. It is dominated by features due to the internal vibrations of the carbonate ion. Unfortunately for our purposes, the fundamental absorption band occurs at about 7 μm, outside the atmospheric window, and cannot be detected remotely. However, there is a weaker feature, ascribed to a planar bend, centered around 11.3 μm, and, although it is weak, it can be detected. The sulfates (gypsum in Figure 4) contain an important fundamental band near 10.2 μm and a lesser one near 9 μm. Phosphates (apatite in Figure 4) also have

*Christensen 1986: personal communication (see Appendix A).

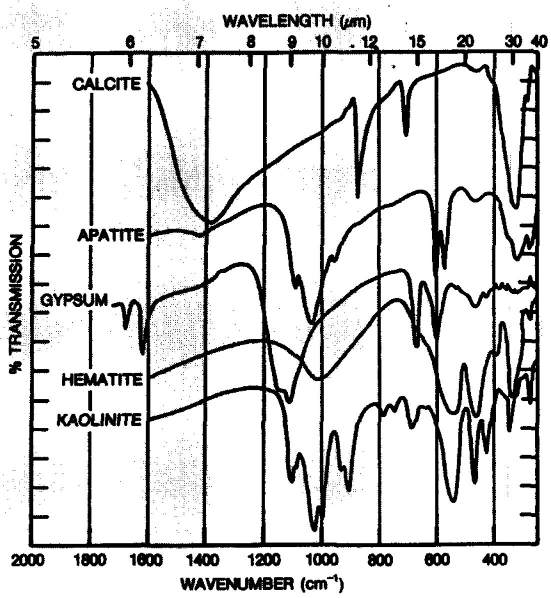


Figure 4. The Thermal-Infrared Transmission Spectra of a Representative Member of the Nonsilicate Mineral Groups Commonly Encountered in Terrestrial Remote Sensing. (Hunt 1980)

fundamentals near 10.3 μm and 9,25 μm. Features due to the fundamental stretching modes of oxides usually lie in the same region occupied by bands due to silicon-oxygen bending modes (i.e., 8 to 12 μm). The spectrum of the iron oxide, hematite, shown in Figure 4, is an example. The H-O-Al bending mode, which occurs near 11 μm in the spectra of aluminum-bearing clay minerals, is illustrated in the kaolinite spectrum of Figure 4.

In addition, in the emission spectra of very fine powders (less than 75 μm), a well-defined maximum occurs, and its location is referred to as the principal Christiansen frequency. This Christiansen peak is very obvious between 7 and 9 μm in silicates, because it occurs just prior to the onset of the intense absorption due to the silicon-oxygen stretching vibrations in a region otherwise devoid of any features. Like the reststrahlen feature, the location of this peak migrates fairly systematically to longer wavelengths as the bond stretch decreases. Its location can be used as a second means of discriminating among different rock types (Conel 1969; Logan et al., 1973). A summary of the thermal infrared spectral features of silicates is given in Figure 5.

The 8 to 14 μm region also allows us to map mineralogy, as illustrated in Figures 6 and 7. Figure 6 shows reflection spectra of the minerals quartz, orthoclase, and hornblende. When these minerals are mixed to form an artificial rock composed of 35% quartz, 50% orthoclase, and 15% hornblende, they yield the reflection spectrum shown in Figure 7. When spectra of the individual minerals are combined (weighted by the above relative amounts), a virtually identical spectrum is obtained. This shows that mineral spectra are additive in this spectral region and that rock spectra are interpretable in terms of mineral abundance. It is noteworthy that quartz will tend to dominate the spectrum of any rock in which it is present because of the relative strength of its reststrahlen band.

This spectral region also allows us to determine the composition of a rock covered with a moderate coating of desert varnish, which makes it optically opaque in the visible and near-infrared. In Figure 8, examples are shown of laboratory spectra of quartzite and quartzite covered with desert varnish.* We see the freshly broken surface of quartize and

*Christensen 1986; personal communication (see Appendix A).

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Figure 5. Diagram Indicating the Location of Maxima and Minima in Transmission and Reflection Spectra of Silicates and Summarizing Specific Vibrations Causing Them. (Hunt 1980)

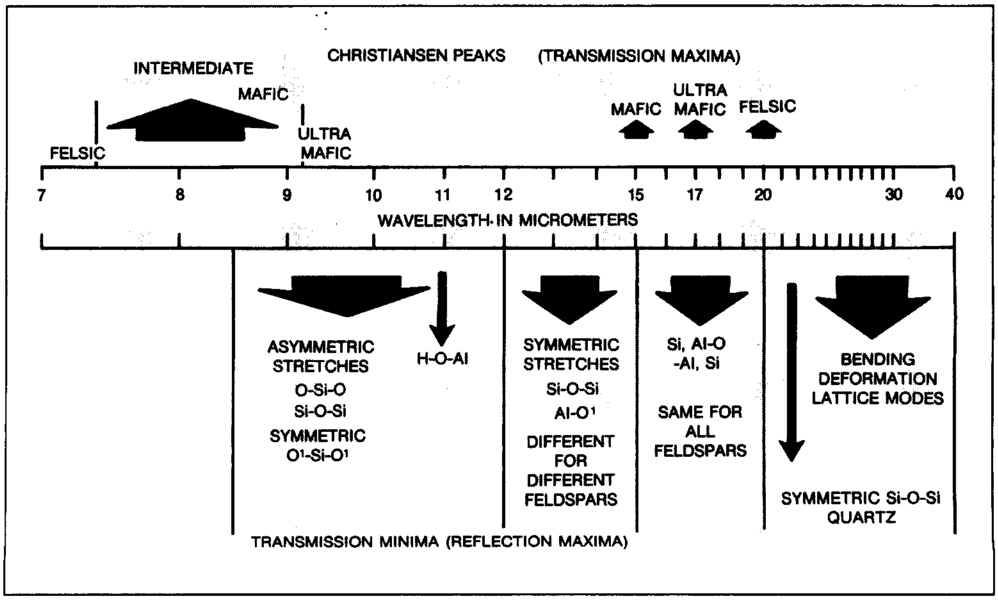
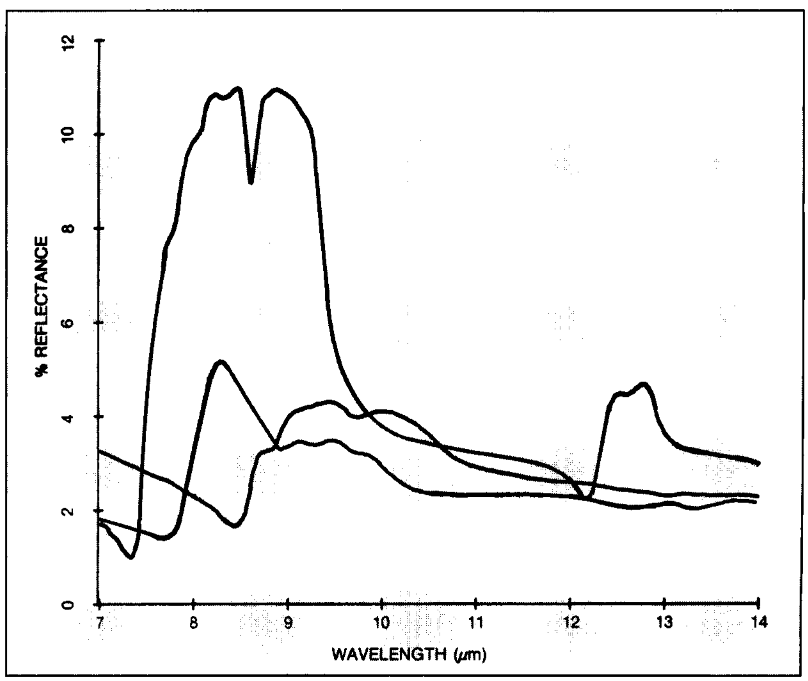


Figure 6. Reflection Spectra of the 74 to 25 μm Particle Size Range of Powdered Quartz (Black), Orthoclase (Green) and Hornblende (Red). (Spectra by J. Salisbury and L. Walter.)



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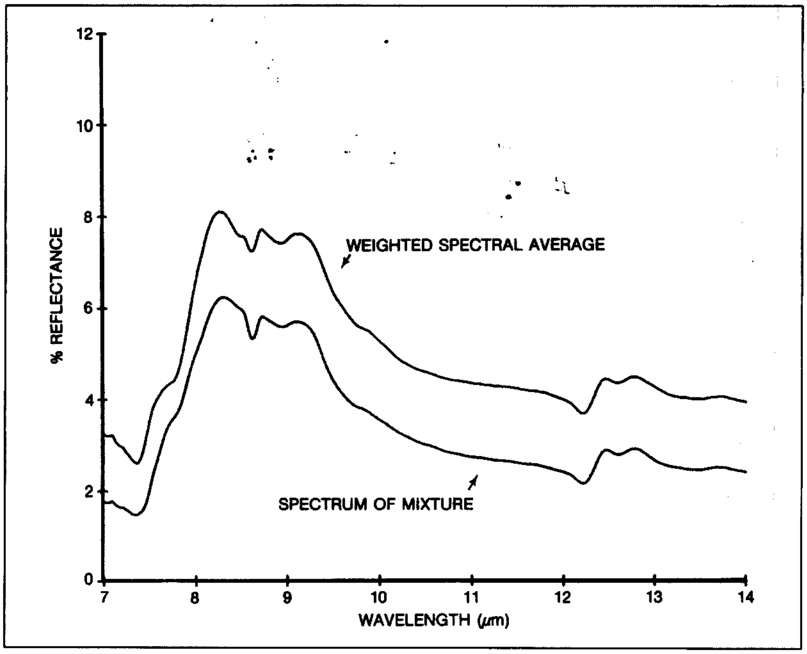

Figure 7. Reflection Spectrum of a Mixture of Quartz (35%), Orthoclase (50%), and Hornblende (15%) and a Similar Weighted Average of the Individual Mineral Spectra. (Spectra by J. Salisbury and L. Walter.)

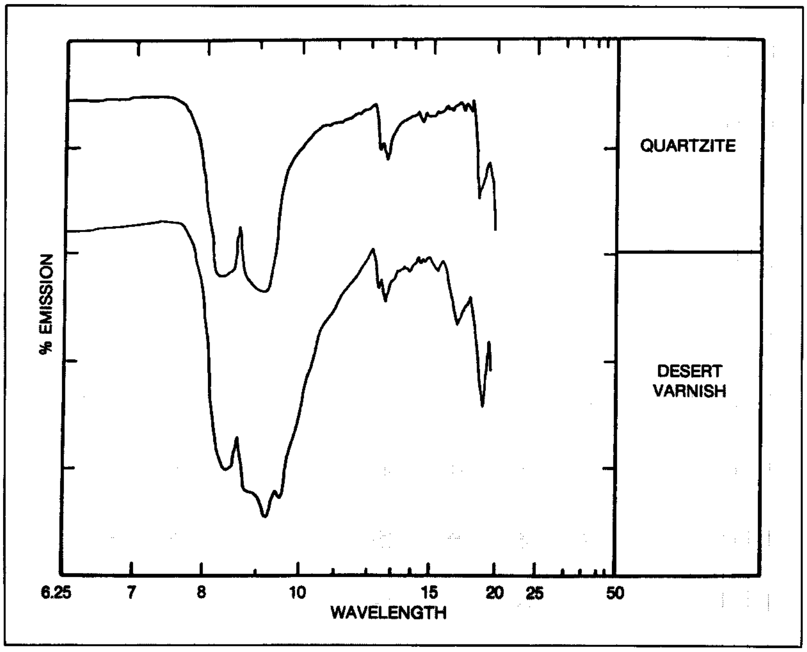

Figure 8. Laboratory Spectrum of Varnished Surface with Quartzite Spectrum for Comparison. Quartz spectral features at 8.5 and 12 μm are easily distinguished.

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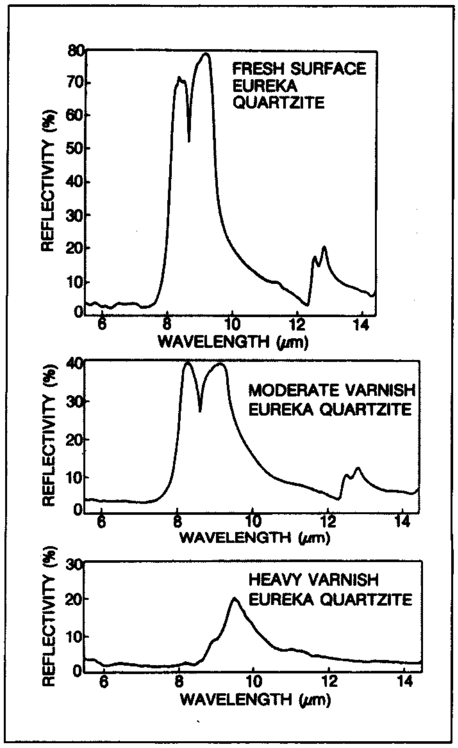
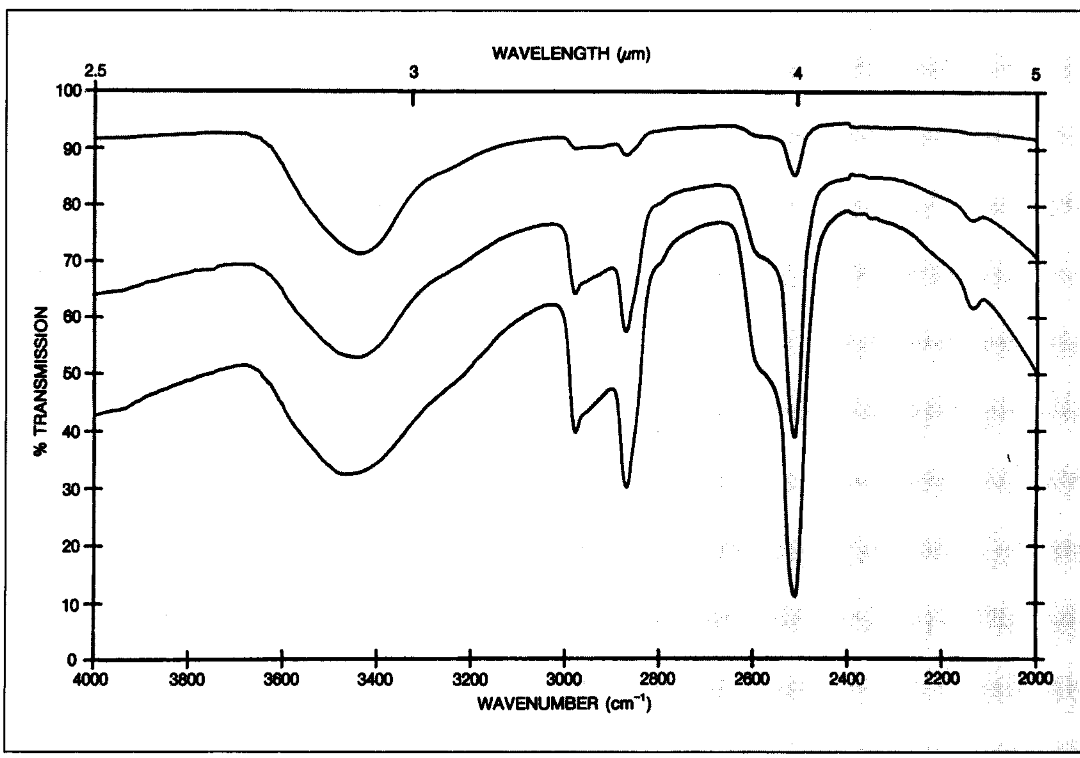


Figure 9. Laboratory Diffuse Reflection Spectra of Samples from Death Valley, California. (Kahle, in press.)

Figure 10. Transmission Spectra of Calcite, Recorded Using 1, 5, and 10 mg of Calcite in 300 mg of KBr. Increasing concentrations of calcite result in greater absorption by weak overtone bands and lower transmission. The broad water band at 2.8 μm is an artifact. (Spectra by J. Salisbury and J. Eastes.)



quartzite covered with a varnish coating approximately 50 μm thick, with the quartz signature clearly visible in both spectra. In Figure 9, we see the spectrum of Eureka quartzite — first with a fresh surface (top), then covered with a "moderate" layer of desert varnish (middle), and, finally, with a "heavy" coating of varnish in the spectrum (bottom). In the moderate-varnish spectrum, the quartz feature is reduced and a clay shoulder, due to the clay in the varnish (Potter and Rossman 1977), is added at longer wavelengths. In the heavy-varnish spectrum, the quartz feature is totally obscured, with only the varnish spectrum remaining.

Utility of the 3 to 5 μm Region

Of the atmospheric-window regions in the thermal infrared, the 8 to 14 μm band is undoubtedly the most useful for geological remote sensing; the utility of the 3 to 5 μm region being still undetermined. Referring to Figure 1, one sees that there is good atmospheric transmission between about 3 and 4.2 μm and then again from 4.5 to 5 μm, and data from this wavelength region has been used for the determination of surface temperature. However, laboratory spectral data in this wavelength region shows a paucity of diagnostic spectral features for rocks and minerals. There is a very strong molecular water band at 2.94 μm that is present in the spectrum of any mineral with adsorbed water. Hovis (1966) stated that there are strong carbonate features near 3.5 and 4.0 μm and that the sulfates and nitrites have a number of strong bands between 3 and 4.5 μm. However, examination of several collections of mineral spectra shows only a relatively weak carbonate band at about 4.02 μm, a few weak chlorite features between 3 and 4.4 μm, and relatively weak gypsum bands at 4.48 and 4.72 μm. Most mineral spectra shown in these collections are completely featureless from 3 to 5 μm.

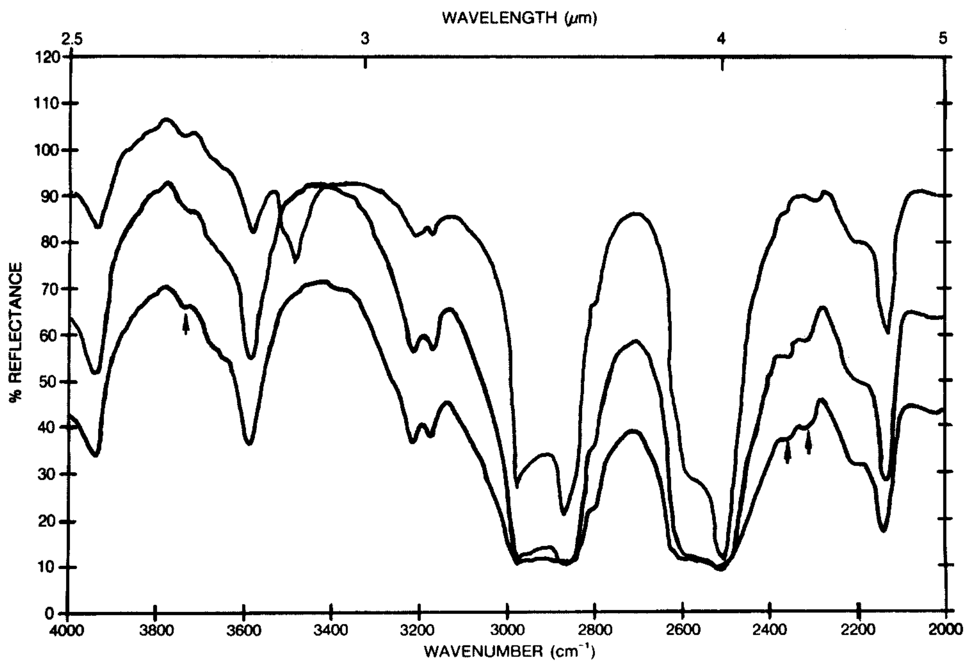
Figure 10 shows transmission spectra of calcite in the 2.5 to 5 μm region, recorded for progressively greater amounts of the mineral embedded in a KBr substrate. The top curve is the normal concentration, which results in full-scale absorption by the strong fundamental C-O stretching vibration at longer wavelengths. The much weaker overtone bands at 3.5 and 4.0 μm are barely noticeable at this concentration, but are displayed well at the higher concentrations, while still weaker overtones near 3.1 and 2.6 μm produce only barely perceptible inflections in the lowest curve.

Figure 11 (Salisbury et al., in press) shows reflection spectra of different particle size ranges of the same calcite. The interesting observation here is that all of the weak overtones are quite prominent at the coarsest particle size range and some of them (as at 3.5 and 4.0 μm) become more prominent as particle size is reduced.

Thus, some minerals, including carbonates, sulfates, and some phosphates, display spectral features that could be detected in the 3 to 5 μm window. However, problems of interpretation raised by the crossover between reflected and emitted radiation in this region are severe unless the measurements are made after sunset. As a result, use of multispectral data from the 3 to 5 μm region for geological applications is currently considered to be strictly confined to research. However, such data would be provided by the spectrometer discussed later in this section.

A single channel from 3.5 to 4.1 μm would not provide any geological information. However, it might aid in the determination of ground temperature or in our ability to correct for atmospheric variables but, because of the solar crossover, even

Figure 11. Reflection Spectra of 250 to 500 μm (Black), 74 to 250 μm (Red), and 0 to 74 μm (Green) Particle Size Ranges of Calcite. Arrows mark weak spectral features that are an experimental artifact.



these applications could be difficult. Note in Figure 12 that at reasonable values of surface reflectivity (ρ = 0.2) and surface temperature (T ≈ 300K), but with the uncharacteristic solar zenith angle of 0°, the crossover between emitted and reflected radiation falls in the center of the atmospheric window.

Much of the interest of the Evapotranspiration and Botany Working Group focused on accurate determination of surface temperature and the accurate characterization and removal of atmospheric effects. While important, both are of secondary interest to the Geology Working Group. There is much more diagnostic geologic information in spectral emittance than in the surface temperature data (including thermal inertia). Errors in atmospheric-correction and surface-temperature calculations will have only a second-order effect on the shape of the derived spectral curves when considering four or five broad bands. Atmospheric correction will be more significant for high-spectral-resolution data, but such data intrinsically enables the required corrections to be made.

Research Requirements

Spectral subjects that we consider to require more research include:

- *The emission spectra of natural surfaces (Lyon and Green 1975), including the effects of weathering products and varnishes (Potter and Rossman 1977), mixtures, temperature gradients, and particle size (Conel 1969; Aronson and Emslie 1973; Emslie and Aronson 1973; Hunt and Logan 1972; Hunt and Vincent 1968), and other environmental factors;*
- *Spectra of soils;*
- *Spectra of minerals, rocks, and natural surfaces in the 3 to 5 μm range; and*
- *The relationships among emission, reflection, and transmission spectra.*

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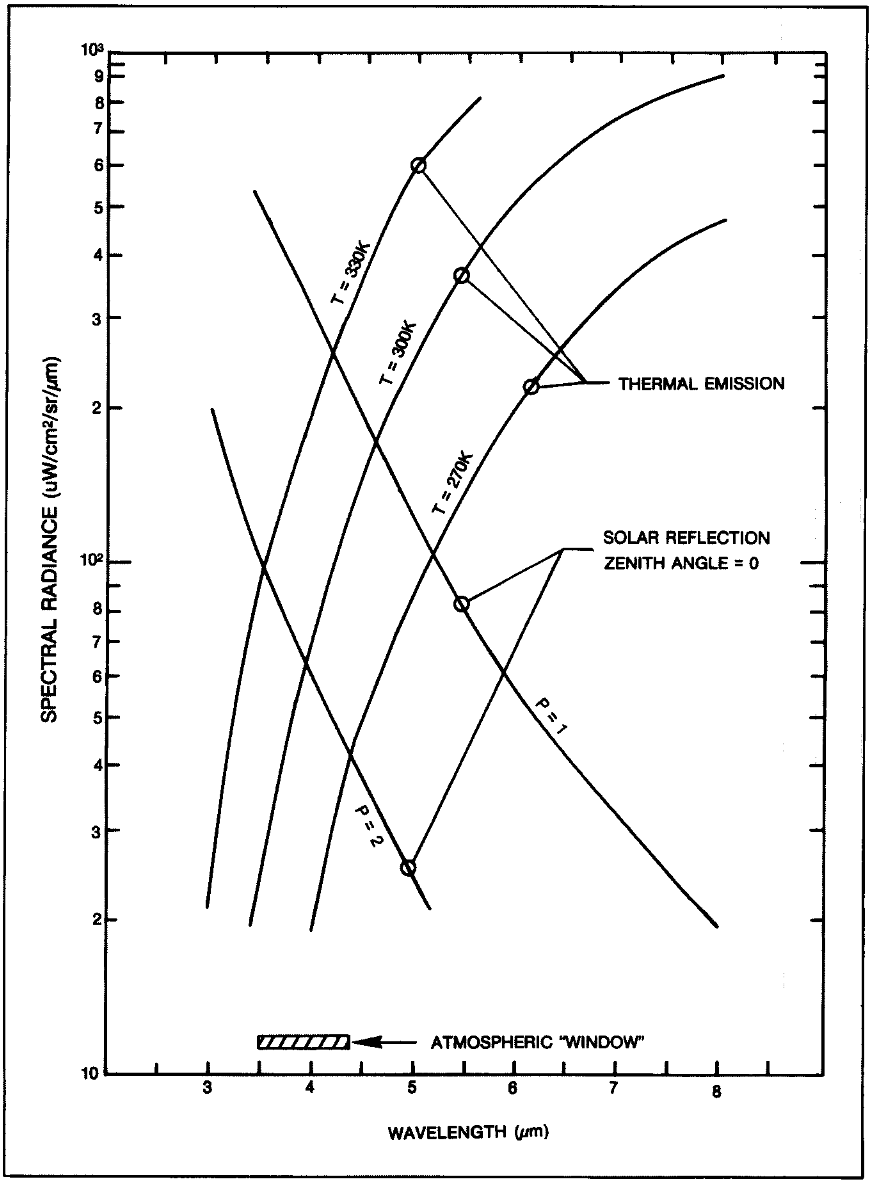
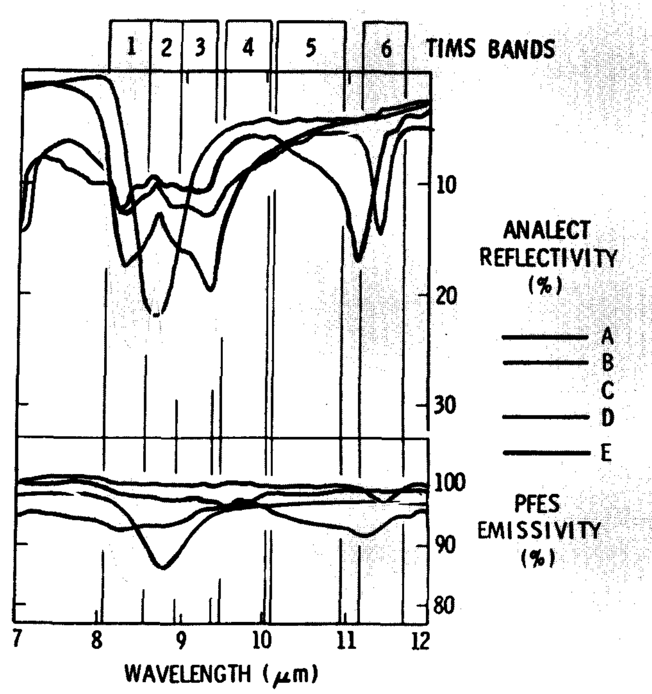


Figure 12. Illustration of the "Crossover" Effect Where Both Solar-Reflected and Terrestrial-Emitted Infrared Radiation Contribute Significantly to the Radiance Leaving the Surface.

Figure 13. Laboratory-Reflectance and Field-Emittance Spectra of the Same Natural Rock Surface from the Deadman Butte, Wyoming Area. (A) Dolostone, (B) Bentonitic Shale, (C) Orthoquartzite, (D) Marly Limestone, and (E) Bentonitic Shale. (Lang et al., 1986)



Regarding the last research need, the emission and reflection relationship is given by Kirchhoff's law, but the relationship to transmission is more complex (Hunt 1981). A comparison of laboratory reflectance data (converted to emittance) to emission data taken in the field with JPL's Portable Field Emission Spectrometer (PFES) (Hoover and Kahle, in press) is shown in Figure 13. Emission from a natural surface results in features that are subdued compared to the reflectance data, but there is a direct correspondence of features, which is not true for transmission (Hunt 1981).

Potential Nonrenewable Resource Applications

The possibility of exploiting the thermal-infrared spectral features for remote sensing of rock type from aircraft or satellite has been suggested by many authors (Vickers and Lyon 1967; Vincent and Thomson 1972; Vincent 1973, 1975). However, until the existence of the TIMS, very few tests of the technique had been possible. Hovis and others (1968), and Lyon (1972) flew nonimaging spectrometers over areas in California. They concluded that even though atmospheric effects were significant, the reststrahlen bands of silicates were observable. Two tests using a two-channel imaging spectrometer were reported. Vincent and others (1972), and Vincent and Thomson (1972) flew a scanner having a bandpass between 8.2 and 10.9 μm and another bandpass between 9.4 and 12.1 μm over a sand quarry near Mill Creek, Oklahoma and over Pisgah Crater, California. By ratioing the spatially registered images, they produced images on which they could distinguish between the quartz sand or sandstone and the nonsilicate surface material at Mill Creek. At the Pisgah Crater area, they were able to distinguish dacite from basalt and rhyolitic tuff from the surrounding alluvium. Kahle and Rowan (1980), with 6-channel thermal-infrared data from the Bendix 24-channel scanner over Tintic, Utah were able to demonstrate the power of such a data set. This led to the construction of the Thermal Infrared Multispectral Scanner (TIMS), and the results from TIMS have been extremely rewarding.

The TIMS has greatly improved our capability to do compositional mapping using mid-infrared spectral observations, and it directly demonstrates the usefulness of this spectral region in geologic applications (Kahle and Goetz 1983). Fundamental to the success of this instrument is its high radiometric resolution, having a noise equivalent temperature difference (NEΔT) of 0.1K at 300K (Palluconi and Meeks 1985). The TIMS instrument can define and map subtle variations in spectral characteristics and surface composition, distinguishing between silica-rich, clay-rich, volcanic, and carbonate rocks (Kahle and Goetz 1983; Gillespie et al., 1984; Christensen 1986; Taranik et al., 1986; Watson 1986; Miller et al., 1986; Taranik and Davis 1986; Krohn 1986; Kahle 1986; Christensen et al., 1986; Lang et al., 1986.

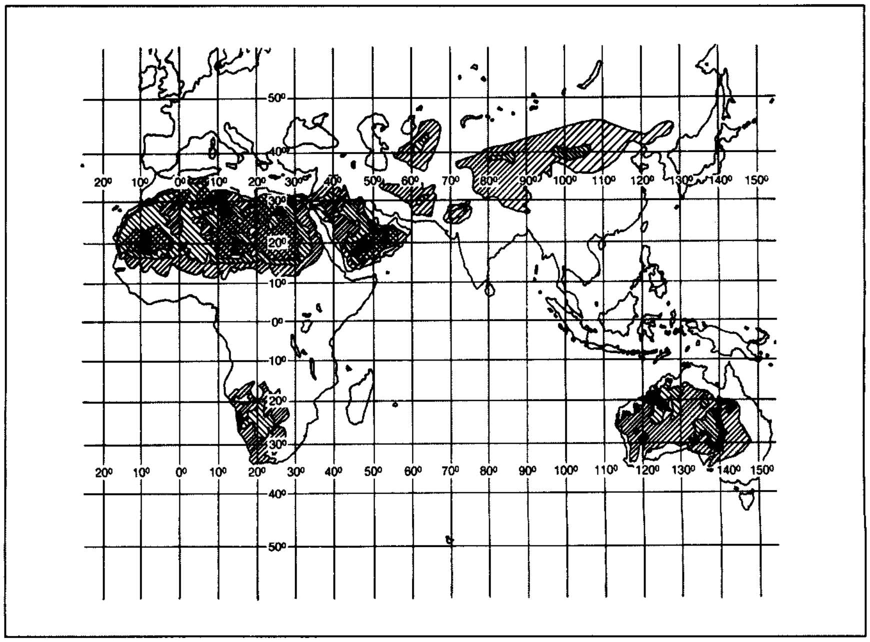
While TIMS has been an invaluable research tool, the data can be acquired only over a very limited number of sites, depending on aircraft availability and flight resources. An orbiting scanner would make this data available to the entire geologic research and applications community on a worldwide basis.

There have been few earth-observation satellite systems with multispectral capability in the thermal infrared. The Advanced Very High Resolution Radiometer (AVHRR) has three thermal infrared channels at 3.55 to 3.93 μm, 10.5 to 11.5 μm, and 11.5 to 12.5 μm. However, this system was designed primarily for sea-surface temperature measurements and nighttime cloud detection, and neither the band choices nor the spatial resolution lend themselves to geological investigations.

An Infrared Interferometer Spectrometer (IRIS) with a spectral resolution of 2.8 cm^{-1} was flown onboard the Nimbus-4 satellite. This instrument had a large field-of-view (about 100 km), making it unusable for most geologic applications. However, spectral data from different regions of the globe was gathered by this instrument for about 10 months (April 1970 to January 1971). Based on these observations, the emissivity of quartz (SiO_2) in the 9 μm region of the window was deduced over most of the arid and semiarid areas of the globe. The results are shown in Figure 14. Apparently the strong reststrahlen band of quartz, together with the abundance of SiO_2, leads to this striking information in the spectral data when we view the earth from space even with this extremely large field-of-view. Spectral details of both the surface material and the atmospheric effects are clearly visible in Figure 15.

As a result of the valuable information obtained from TIMS data, the desire of the Geology Panel is to achieve a TIMS-like capability from orbit in order to make available high-quality multispectral thermal data to both the scientific and user communities on a worldwide basis.

Figure 14. The Global Map of the Quartz Emissivity at 9 μm Derived from Nimbus-4 Iris Data. (Prabhakara and Dalu, 1976)



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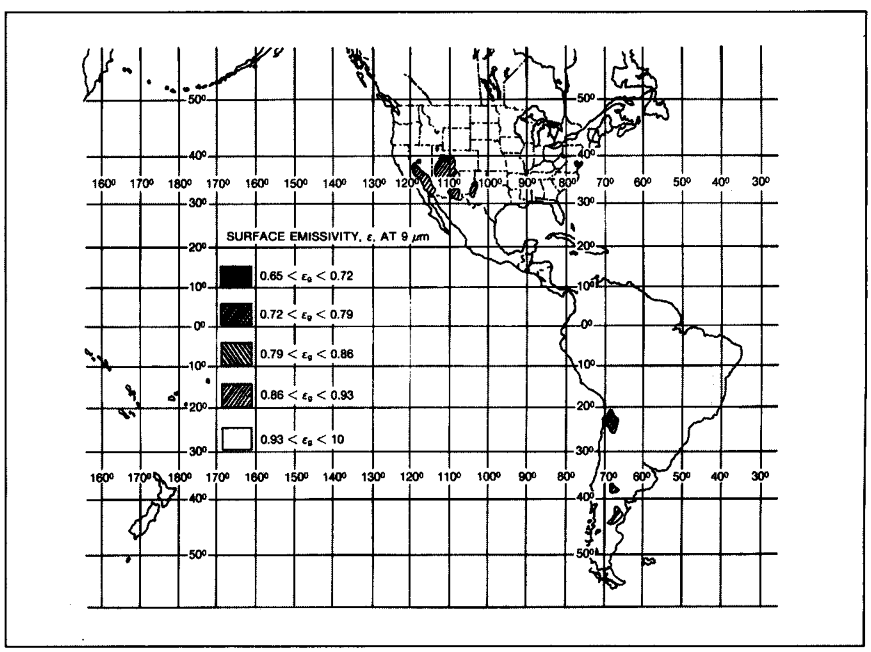

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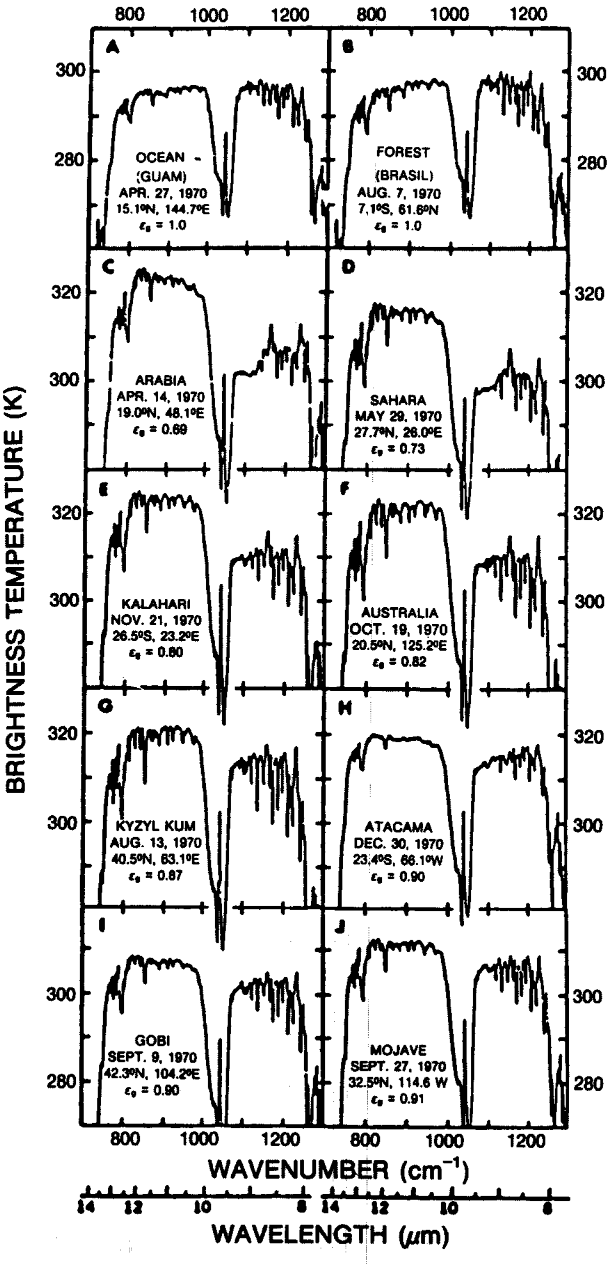
Figure 15. Nimbus-4 IRIS Brightness Temperature Spectra in the 8 to 14 μm Region. (Prabhakara and Dalu, 1976)



Evaluation of Options for Future Landsat Sensors

The Geology Panel was asked to evaluate various thermal infrared multispectral options now being considered for future satellites in the Landsat series, to suggest other options, and to prioritize tradeoffs, keeping in mind both operational and scientific research needs. The specific options suggested were:

> a. *A Thematic Mapper with a modified cooled focal plane, having one band in the 3 to 5 μm region and three bands in the 8 to 14 μm region, with a 60-meter IFOV and a NEΔT of 0.2 to 0.6K*
>
> b. *A Thematic Mapper with a modified cooled focal plane, having four bands in the 8 to 14 μm region, two at wavelengths longer than the ozone absorption band, two at shorter wavelengths, with a 60-meter IFOV, a NEΔT of 0.3 to 0.6K, and 0.5 μm bandwidths.*

Because of the availability of many excellent laboratory and field spectra and the TIMS experience, remote-sensing geologists are reasonably certain about which bands will be useful and why. Our choice is essentially option b, with the bands located as follows: (1) 8.20 to 8.75 μm, (2) 8.75 to 9.30 μm, (3) 10.20 to 11.00 μm, and (4) 11.00 to 11.80 μm.

These bands would correspond roughly to the TIMS bands as follows:

[illegible]	[illegible]
1 + 1/2(2)	1
1/2(2) + 3	2
5	3
6	4

*Band numbers correspond to the thermal-infrared bands referred to in the text, not to the Landsat band-numbering scheme.

For many TIMS scenes, particularly areas with different types of silicates present, the most useful TIMS channels are 1, 3, and 5, with 6 being used to determine surface temperature. However, in areas of ultramafic rocks, both channels 5 and 6 are used for rock identification. Only TIMS channel 6 can be used to separate carbonates from vegetation, based on the weak carbonate band centered near 11.3 or 11.4 μm.

If a fifth band were to be added in the 3.5 to 4.1 μm region, it might be used to aid in surface temperature calculations and atmospheric correction, but its existence is not considered of vital importance. The problem of reflected solar radiation in this band would probably make it only useful at night. However, recognizing the requirements of the Evapotranspiration/ Botany Panel and the need for their support of this system, our proposed system is as shown in the table on the opposite page.

If the parameters listed in the table cannot be met, the priorities are to:

> - *Widen all bands slightly*
> - *Increase NEΔT* (no more than 0.5K)
> - *Decrease spatial resolution to 90m, 120m*
> - *Reduce the number of bands by:*
>   a. *Deleting channel 5*
>   b. *Using three bands: 1, 2, (3 + 4)*
>   c. *Using two bands: (1 + 2), (3 + 4).*

The desired time of day for crossing is as late in the morning as is compatible with cloud cover.

The order of tradeoffs was determined by our experience with TIMS data, which allows at least a subjective and, in some cases, a quantitative assessment of the importance of the various factors. From a comparison of Landsat MSS, Landsat TM, HCMM, and aircraft data, we have a good subjective understanding of the need for spatial resolution for geologic problems. The Thematic Mapper resolution at 30m is much preferred over the MSS at 80m for most geologic applications.

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THERMAL-INFRARED BAND	WAVELENGTH (μm)	BANDWIDTH (μm)	NEΔT (300K) (K)	SPATIAL RESOLUTION (m)
1	8.20-8.75	0.55	0.33	60
2	8.75-9.30	0.55	0.35	60
3	10.20-11.00	0.8	0.35	60
4	11.00-11.80	0.8	0.4	60
5	3.5-4.1	0.6	0.2	60 (120)

The issue of radiometric resolution, NEΔT (or, equivalently, NEΔε), is extremely important. TIMS has an NEΔT of 0.1K or better in all channels, and it is this very good resolution that allows us to recognize the very subtle differences in rock types in our images. Comparison of field emission spectra taken at the same scene indicates that TIMS data allows us to separate rocks whose emissivities differ by only a percent or so. However, it became apparent to our panel from the discussions of John Barker of GSFC and others about Thematic Mapper thermal measurements, that merely having a good instrument NEΔT was not sufficient. It is essential that the instrument gains (or surface temperature range being sensed), the digitization of the data, and subsequent processing of the data before making it available to the user, must all be handled in a way that preserves the intrinsic NEΔT of the instrument.

In addition to our experience with TIMS, Philip Christensen has made a study of band selection, based on convolving the chosen bands (filters) with the laboratory spectra of Lyon (1964). The results of this study are included in Appendix A. It validates our band selection for rock type discrimination over other possible sets of three and four bands in the 8 to 12 μm region. The band at 3.5 and 4.1 μm was not considered in this study. The band selection is also corroborated by the studies of Malila and Suits, presented in Appendix A, which includes a discussion of the uses of the 3.5 to 5.5 μm band.

Addition of a Spectrometer for Research

The geology panel also strongly recommends the addition of a thermal infrared profiling spectrometer, which would be a nonimaging device aimed in the nadir direction or pointable within the Thematic Mapper scene. This instrument would acquire high-spectral-resolution data along a path within the imaged area. We recommend approximately 20 bands in the 3 to 5 μm range and 40 to 50 bands in the 8 to 14 μm range, with a spectral resolution of approximately 0.1 μm. We would like a ground resolution of 120m and an NEΔT of 0.1K and 0.3K.

There are several reasons for considering such an instrument. First, the six spectral channels of the existing aircraft scanner or the four or five channels of a modified Landsat Thematic Mapper substantially undersample the spectral character evident in laboratory or field spectra of terrestrial minerals and rocks. This reduces the geologist's ability, for example, to differentiate between rocks with small cation differences or between rocks with different degrees of physical replacement of one mineral by another. Second, at the scale of aircraft or satellite observation, more than one mineral or rock type is present in each individual measurement. As indicated earlier, it has been demonstrated by a number of investigators that, in the thermal infrared, the spectra of physical mixtures of minerals and the sum of the individual spectra (weighted in direct proportion to their presence in the mixture) are very similar. This indicates that, with higher spectral resolution, separating the components of a pixel containing the information from more than one mineral would be possible.

The spectrometer would not only provide valuable research information related to future thermal infrared sensors in both the 3 to 5 μm and 8 to 14 μm regions, but would also be a useful aid in determining more specific information about the composition of large, relatively homogeneous areas on the ground when simultaneously mapped by the Thematic Mapper. The synergism between an imager and a profiling spectrometer is exceedingly powerful, greatly enhancing the value of either data set taken separately. Finally, the profiling spectrometer would allow for improved atmospheric correction, because it would have sufficient spectral resolution to determine the atmospheric contributions to the sensed radiation.

There are a number of different technical approaches that could be taken to provide such a spectral profiling capability. One such instrument would be a Fourier transform spectrometer similar to the one proposed for the Mars Observer Mission. Another possibility would be a grating spectrometer for spectral dispersion on a linear array of cooled detectors.

We view this spectrometer as primarily a research instrument whose use would be directed toward a better understanding of the potential of multispectral thermal-infrared remote sensing for geologic and other applications. However, because of its combined use with the Thematic Mapper, it could also contribute to many of the operational applications of the Thematic Mapper.

Summary

The Geology Panel enthusiastically endorses the concept of a multispectral thermal-infrared capability being added to Landsat-7. From our experience with laboratory and TIMS data, we are able to conclude that the options being considered by EOSAT, with the stated performance parameters, could provide a powerful new tool for geologic remote sensing. Silicates, which make up the great majority of the earth's land surface, have diagnostic spectral features in this wavelength region, while being featureless in the visible and near infrared.

We prefer the option including four bands in the 8 to 12 μm wavelength region, two below the ozone band and two above. Specifically, our first choice of bands is: (1) 8.20 to 8.75 μm, (2) 8.75 to 9.30 μm, (3) 10.2 to 11.00 μm, and (4) 11.0 to 11.8 μm. A single band between 3.5 and 4.1 μm would be of limited use in geology, serving only to aid in the determination of surface temperature and atmospheric correction.

Preserving the intrinsic NEΔT of the instrument so the data products are not degraded by factors such as the dynamic range of the instrument (sensed temperature range), digitization levels, and ground data processing is of the utmost importance.

The geology panel also strongly urges the addition of a profiling thermal-infrared spectrometer to the satellite instrumentation, primarily for research purposes.

5
EVAPO-TRANSPIRATION/ BOTANY PANEL REPORT

Panel Chairman: Jerry Hatfield

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The primary interest of the community of users represented by the Evapotranspiration/Botany Panel lies in acquiring the ability to determine cumulative evapotranspiration and plant dry biomass (or net primary productivity) and to monitor plant stress from remotely sensed data. A secondary interest concerns use of thermal infrared data in mapping soil moisture and snow. As a result, the discussions of the Panel focused on defining the elements of a satellite remote-sensing system that would provide the most useful information germane to these interests. Little evidence currently exists that there are spectral emittance features in vegetative thermal-infrared observations, but the possibility of deriving accurate surface temperatures with multiband thermal infrared data is of great interest to the community.

Background

The use of thermal-infrared measurements for analysis of land biophysical conditions has been under investigation for several decades (Fuchs and Tanner 1966). Thermal-infrared observations have been shown to be of value in estimating soil moisture conditions, evaluating ground water, evapotranspiration studies, snow mapping, and estimating urban effects on climate (Idso et al., 1975; Tanner and Jury 1976; Cartwright 1968; Brown 1974; Dozier and Warren 1982; Carlson and Boland 1978; Goward 1981). The reason thermal-infrared measurements are of value in land analysis is that they provide an indication of the net effects of land-atmosphere interactions which is descriptive of the biophysical processes taking place at that interface. Despite the potential of thermal-infrared observations in renewable-resource assessments and biophysical analysis, it has received relatively scant attention in remote-sensing research over the last quarter century. The only exception during this time was the Heat Capacity Mapping Mission (HCMM), which produced promising results, but created no further initiatives in satellite thermal-infrared observations of land areas (Short and Stuart Jr. 1982). Only a few researchers (most from the agricultural community) have continued to pursue studies to develop

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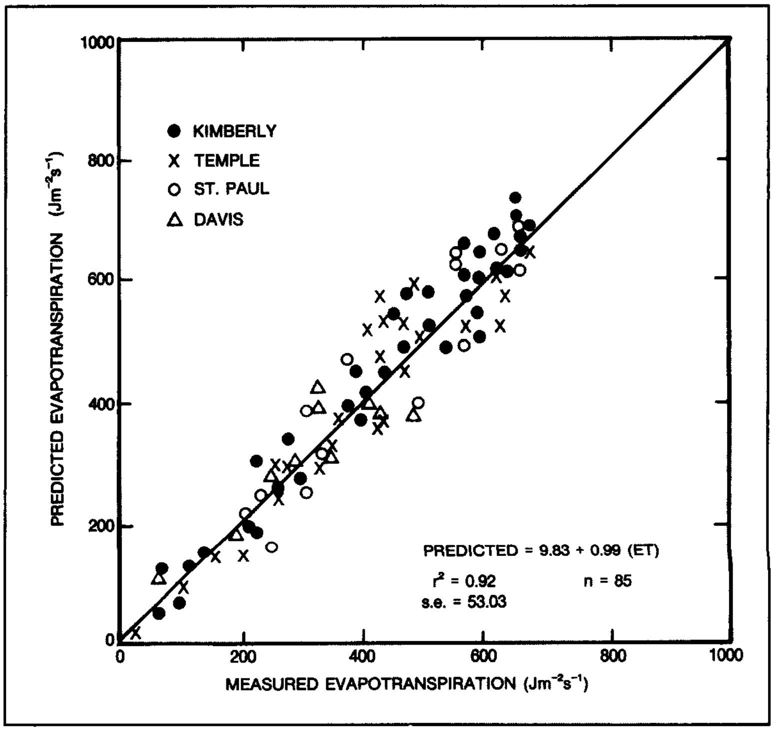
Figure 16. Correlation between Evapotranspiration Rates Estimated by the Surface-Energy-Balance Model and Measured Rates.



the potential of thermal-infrared measurements in biophysical assessments. The opportunity to convene and discuss a possible joint NASA-EOSAT initiative on thermal-infrared observations was greeted with distinct favor by the members of the Evapotranspiration/Botany Panel. Although much research is still needed to fully develop the value of thermal-infrared observations in renewable-resource assessments and the biophysical sciences, the members of the panel believe that sufficient understanding currently exists to propose a viable satellite sensor system. The following two fundamental needs must be met for a Landsat-based sensor system to be of significant value for renewable-resource assessments and scientific research in hydrology and ecology:

1. *The sensor data must permit derivation of surface thermodynamic temperatures with an accuracy of ± 1°C.*
2. *Observations must be provided that will permit near-daily updates of regional patterns of reflected solar radiation and surface temperatures.*

Potential for Thermal-Infrared Data in Renewable-Resource Management and the Biophysical Sciences

Research results indicate that thermal-infrared data has the potential for improving large-area estimates of crop yield, net primary productivity, and evapotranspiration (Idso et al., 1977; Price 1980;

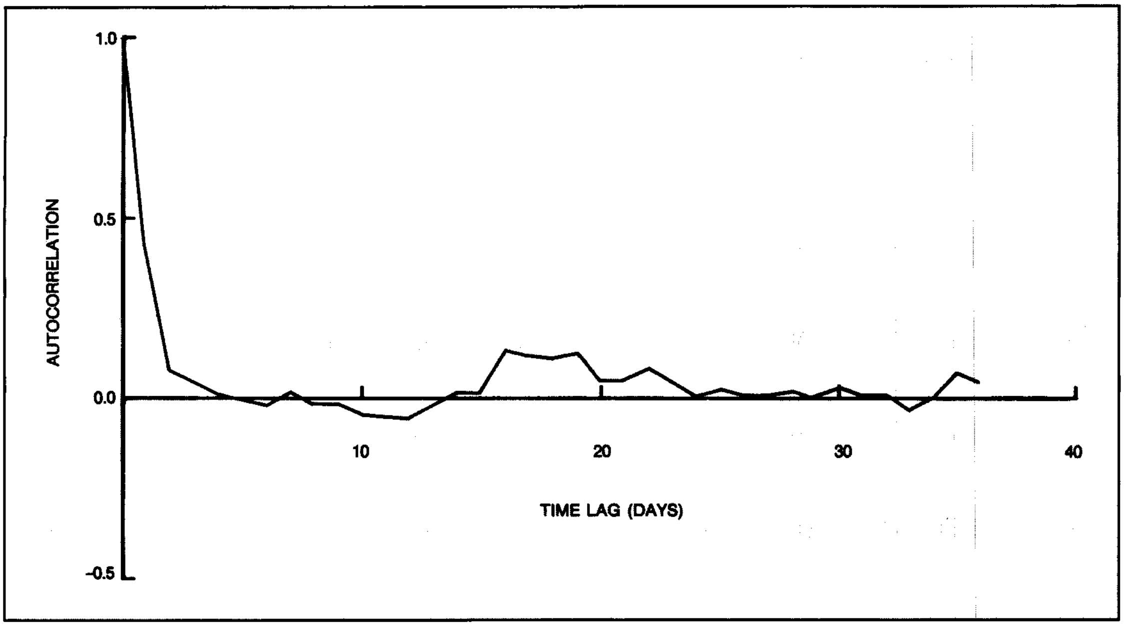


Figure 17. Evaporation Data Showing Lack of Correlation After 24 Hours.

1980; Schmugge and Gurney 1983). These results are supported by physiological observations, theoretical studies, and observations of crop yield (Ehrler 1973; Kanemasu et al., Hatfield 1983).

Evapotranspiration

The fact that plant and soil temperatures must be related to evapotranspiration rates becomes clear upon inspection of the land-atmosphere energy balance. Evaporation of water uses heat which is only released once the vapor recondenses. As long as plants and soils are well watered and not stressed, they are able to maintain relatively cooler surface temperatures because absorbed solar radiation is predominantly used to evaporate water. As the moisture is depleted, the surface warms up. Considerable research has been devoted to developing a means of employing thermal-infrared measurements to evaluate evaporation rates (Aston and van Bavel 1972; Brown 1974; Chaudhury and Idso 1985; Ehrler 1973; Idso et al., 1982; Price 1982; Reginato et al., 1985; Soer 1980; Stone and Horton 1974).

If, indeed, it is possible to estimate absolute surface temperatures accurately from remotely acquired data, this data, in conjunction with ground-acquired data (net radiation, air temperature, and wind speed), could be directly extrapolated to a regional scale with a relatively simple surface-energy-balance model. The model, which has been verified through comparative analysis with lysimeter data at a number of locations, has been reviewed by Hatfield (1984) and is ready for use by the remote-sensing community. Figure 16 shows the good correlation obtained between predicted and measured evapotranspiration rates.

The need for daily acquisition of data is documented in Figure 17. As shown, daily total evaporation with a time lag of only 1 day is poorly correlated with evaporation from the prior day. Recent work shows that the daily data input required by the model can be used to estimate daily integrated values, thus expanding the utility of one-time-per-day acquisition of remotely sensed data (Jackson et al., 1983). These ground-based studies demonstrate the utility of the approach and reveal that techniques are available to utilize satellite-acquired data when such becomes available.

Plant Stress and Chemical Status

Plants undergo stress when they are subjected to environmental limitations, such as lack of moisture, extreme temperatures, soil nutrient deficiencies and salinity, or when they are under attack by insects or disease. In any case, when plants are stressed they are generally unable to maintain normal transpiration rates and, as a result, heat up. An interesting approach to use of thermal-infrared measurements for stress evaluation has been developed. It monitors daily plant canopy temperatures and accumulates a "stress-degree-day" parameter that has been shown to be related to crop yield (Jackson et al., 1977; Jackson et al., 1981; Idso et al., 1981; Hatfield 1983).

If plant stress assessment is to be successful with thermal data, there is a need to know precisely how much cooler or hotter the plant canopy is than the ambient environment. The requirement to produce accurate surface temperatures from the satellite must be met if this use is to be successful. For many plants, leaf temperatures greater than 40°C indicate drastically diminished photosynthesis, reduced turgor pressure, closed stomata, and reduced transpiration. If this process recurs, a thermal shock may occur in the plant, resulting in significant wilting and possible plant death.

Hence, the variations in canopy temperatures from day to day and from hour to hour are important indications of the current and future health of the plant. Cycles of daily warming suggest stomata close-down, and if such cycles occur for extended time periods, wilt and plant death will eventually occur. It is possible that this cyclic pattern can be detected using thermal-infrared sensors well before the data from the visible and near-infrared regions shows any significant change. This possibility is very important to operational global and regional assessment of crops, forests, and natural vegetation.

Although it is not likely that the chemical status of plants will be able to be directly detected from remote sensors, it is possible that chemical influences on plant health might be inferred from thermal-infrared data. For example, alfalfa and cotton plants growing in saline soils have been observed to be 2 to 3°C warmer than normal plants (Howell et al., 1984). If plants with higher-than-expected temperatures are observed in apparently well-watered areas, salinity problems might be inferred. This same rationale extends to other chemically related factors; changes may be manifest in the thermal measurements before they are detectable in the visible and near-infrared, since plant temperatures represent the final result of the entire photochemical problem being addressed by the plant. Such a plant chemistry application could be extremely valuable in global vegetation assessments.

Primary Production and Yield

Vegetation net primary productivity and crop yield are intimately tied to cumulative evapotranspiration (Rosenberg et al., 1983). Empirical and theoretical research has already shown that a combination of visible and near-infrared reflected solar radiation measurements, the so-called "spectral vegetation indices," (SVI) may be used to estimate absorbed photosynthetic radiation (Kumar and Monteith 1981; Asrar et al., 1984; Sellers 1985). A strong relationship has been observed between growing season integrals of SVIs from AVHRR and net primary productivity for the North American continent (Goward, Dye, and Tucker 1985), and simple numerical models combining climate data and the satellite SVI measurements have successfully calculated continental and global net primary productivity rates (Dye 1985; Prentice 1986).

Spectral vegetation index measurements derived from reflected solar radiation measurements alone provide estimates of potential photosynthesis and minimum canopy resistance to transpiration (Kumar and Monteith 1981; Asrar et al., 1984; Sellers 1985). The inclusion of thermal-infrared measurements in a remotely sensed vegetation index will account for periods of plant stress when transpiration and, hence, photosynthetic activity are reduced.

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Varying time periods of plant stress are common occurrences in all natural plants as well as arable crops. The initial effect of drought stress reduces leaf growth, resulting in a reduction in greenness, which research results, discussed below, indicate is quantifiable using visible and near-infrared reflectances. As mentioned previously, the temperature of a stressed plant is higher than a plant not under stress. Hence, it might be possible to develop a stress index that would be a valuable supplement to the greenness index. Field observations also show a highly linear correlation between cumulative evapotranspiration and plant dry biomass (or net primary productivity). This suggests that a temperature-based index for evapotranspiration would be useful in quantifying net primary productivity. Again, it is important to recognize that evapotranspiration and plant biomass accumulation are time-dependent, and to quantify them requires repeated (at least once a day) observations.

Recent efforts have been made to examine the potential of combined solar reflective and thermal-infrared measurements in analysis of evapotranspiration rates, productivity, and yield (Gurney et al., 1983; Hatfield 1983; Goward, Dye, and Tucker 1985; Hope et al., in press; Hope 1986). Figures 18 and 19 present selected examples of the observed relationship between SVI and thermal-infrared measurements. This strong negative relationship is observed at scales ranging from field measurements to AVHRR data (Hope 1986). By combining models of vegetation canopy reflectance and thermal emissions, Hope (1986) has shown that a measure of actual canopy resistance to transpiration is derived. Hatfield (1983) has shown that it is possible to combine reflectance and thermal data in yield estimation.

The availability of high-temporal-resolution reflected-solar and thermal-infrared observations may permit development of a global vegetation monitoring system that accurately assesses regional patterns of net primary productivity and crop yield. The research to pursue this goal is underway, but it must be sustained to successfully develop this capability. Many complex questions need to be answered concerning the effects of species-specific photosynthetic and transpiration mechanisms and a means devised for characterizing other phenomena, such

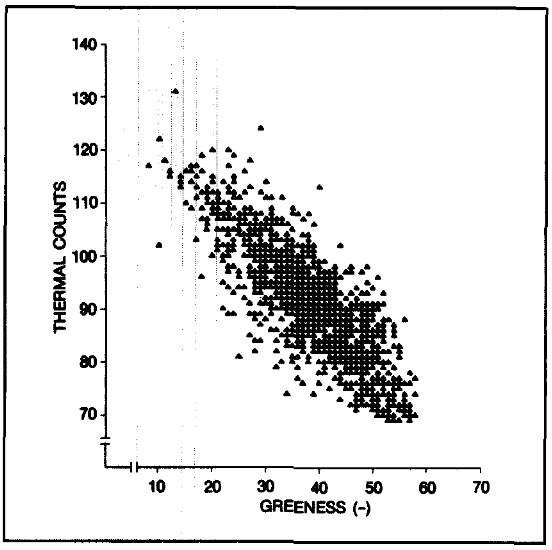

Figure 18. Correlation of the "Greenness" Index with Surface Temperature. Landsat-3 visible and near-infrared observations were converted into "Greenness" and "Brightness" features using the method of Kauth (1976). When compared to surface temperature data acquired simultaneously from Channel 2 (10.5 to 12.5 μm) of the HCMM satellite, the Greenness feature (index of vegetative cover) was highly correlated ($r = -0.812$) while the correlation between Brightness (or albedo) and surface temperature was much lower ($r = -0.163$).

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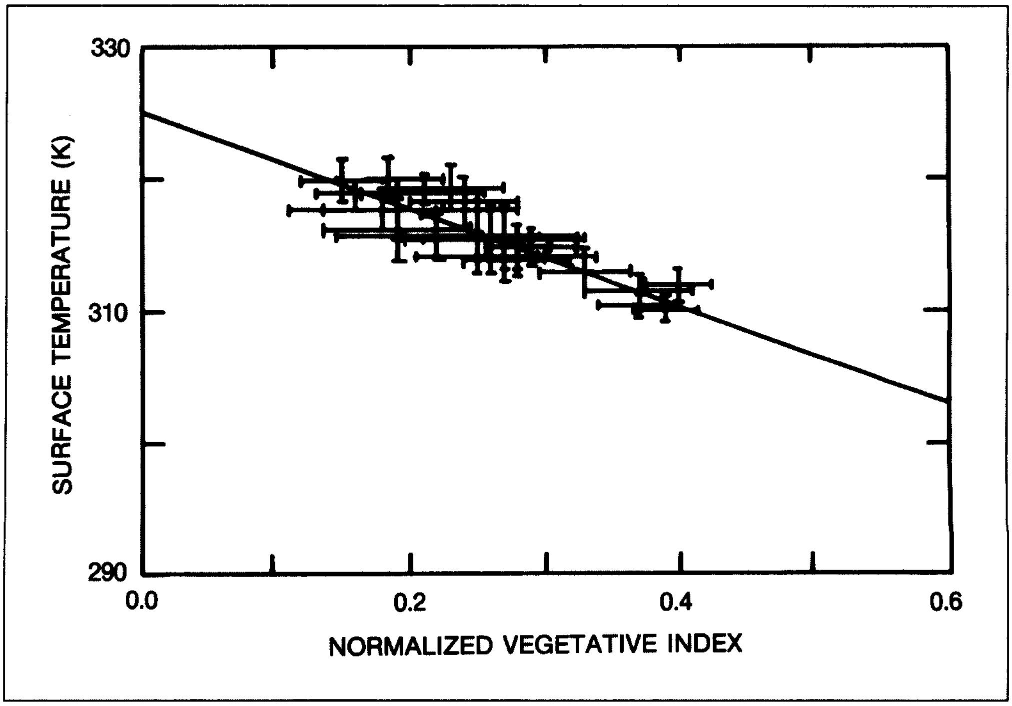
Figures 19. Correlation of Normalized Vegetation Index with Surface Temperature (provided by B. Choudhury, NASA/GSFC). In Figure 19a, a normalized vegetation index is regressed against "calibrated" surface temperatures from the AVHRR for a 10,000 km^2 area of the southern Great Plains, centered on central Oklahoma on 17 July 1982. Figure 19b shows a plot of the normalized vegetation index versus surface temperature for a single AVHRR scan line at the same location and date.

a



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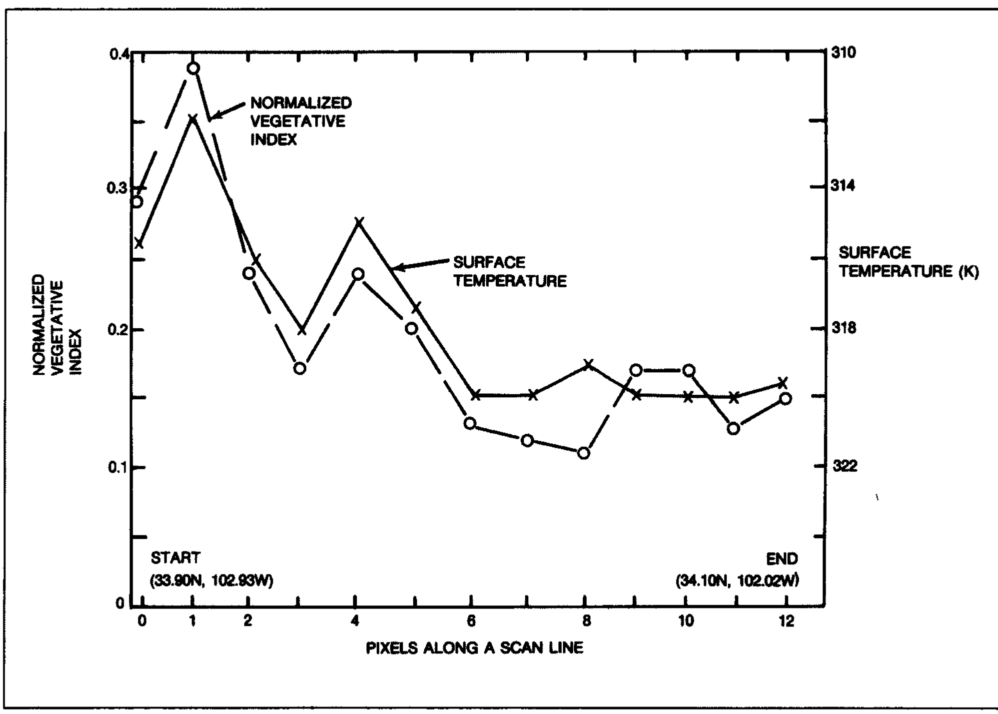


as land-surface net radiation and wind flow, before it will be possible to make truly accurate estimates of net primary productivity and yield from satellite observations. However, the development of an accurate and timely means of deriving surface temperatures is a significant step in the right direction.

Soil Moisture

The knowledge of soil moisture content is a key element in many techniques for assessing vegetation production on a global basis, estimating watershed runoff and river flow, and determining soil stability. Remote sensing in the thermal-infrared may provide a way of determining soil moisture content accurately, but this information is needed on a daily, or twice daily, basis for utility (Price 1980; Idso et al., 1975). As indicated earlier, a knowledge of soil moisture content would also provide information on evapotranspiration, an essential element in many global and regional crop assessment systems and natural vegetation studies.

Soil moisture content assessments are also important in river basin water management and snow pack runoff assessments, and remotely sensed data would be of importance in obtaining such information from areas difficult or impossible to traverse.

Plant Identification

Figure 20 (provided by J. Anderson, NASA/NSTL) shows the apparent lack of spectral aracteristics, chtypical of plant canopies in the thermal infrared. However, evidence that plant leaves may have characteristic spectra in the thermal-infrared region has recently been uncovered. The measurements, completed by J. Salisbury (USGS), are shown in Figure 21. These "diffuse" reflection spectra (i.e., retaining a specular component) of leaves were made with a specular reflectance attachment using a gold-coated sandpaper standard, courtesy of M. J. Bartholomew (JPL). They are of dried leaves and were made using a Spectrotech DRIFTS attachment and a mirror standard. They resemble specular reflectance spectra, having the same order-of-magnitude reflectance.

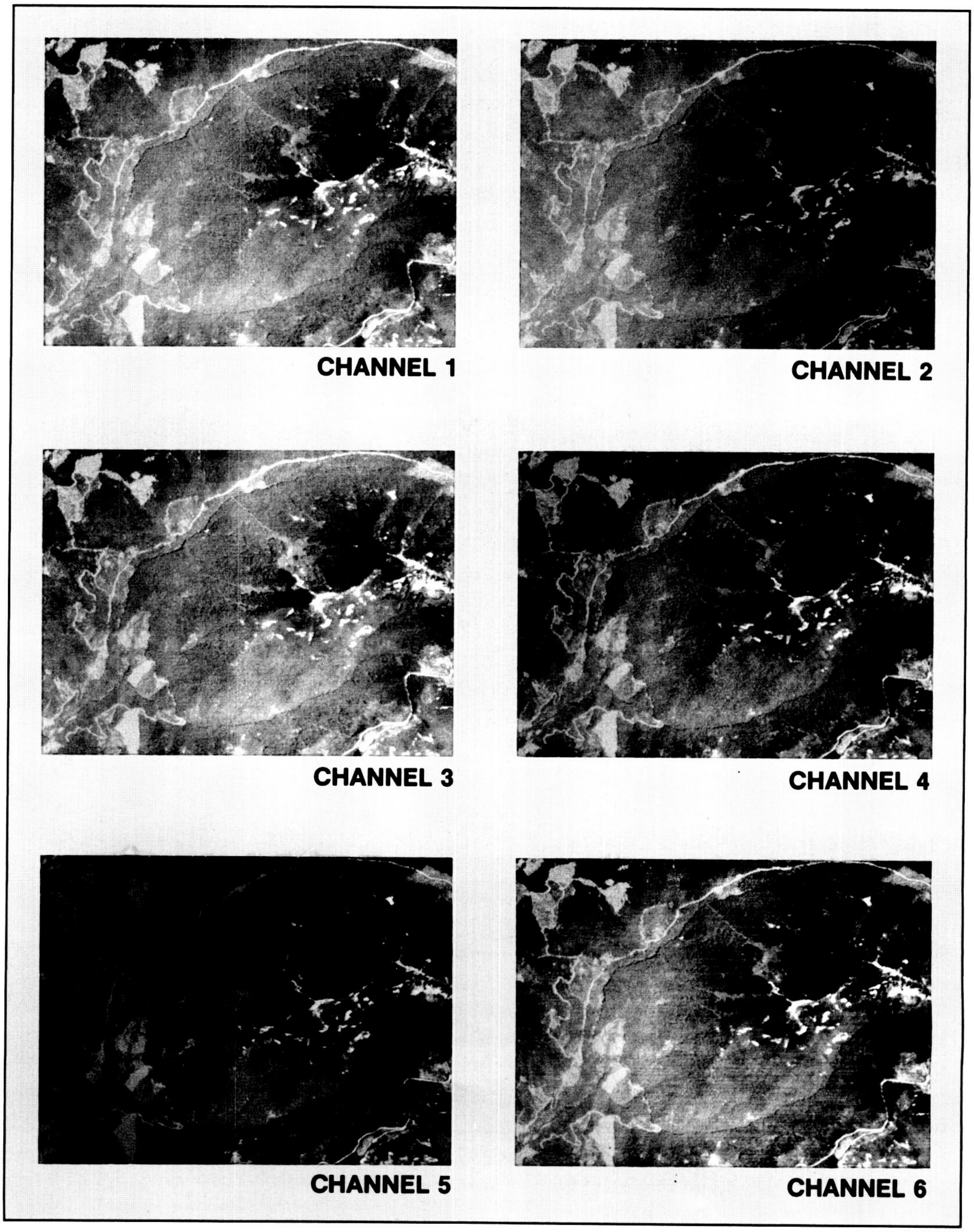
It is hypothesized that the leaf cuticle may be responsible for the observed differences. However, how individual leaf signatures translate to entire canopy response is not known. In any event, these findings open up a new area of research into the potential use of thermal-infrared leaf spectra for characterizing vegetative species.

Wind Streaking

As research into the potential utility of thermal-infrared data proceeds, new observables have been discovered. One of these, referred to as "wind streaks" is shown in Figure 22 (provided by S. Goward, University of Maryland). These observations were collected in a corn and soybean farming area in Webster County, Iowa at approximately 1:00 p.m. local time on August 30, 1979 in support of the NASA AgRISTARS research program. The sensor was the NASA NS001 Thematic Mapper Simulator, flown on the NASA C-130 aircraft at 25,000 feet, with a nominal ground resolution of 30m. The road grid is spaced at 1-mile intervals, and some distortion of the grid is apparent from the motion of the aircraft.

Figure 22a is a color composite of Thematic Mapper bands 2, 3, and 4; soybeans appear bright red and corn, brown. Figure 22b shows the thermal infrared (10.4 to 12.5 μm) image and the "wind streaks" running diagonally across the image. These are frequently observed in the daytime in high spatial resolution thermal-infrared images of vegetated landscapes. The streaking is apparently the result of convective sensible heat transfer

Figure 20. Data from Six TIMS Channels Acquired on a Daytime, August 1985 Flight Over the H. J. Andrews Experimental Forest East of Eugene, OR.



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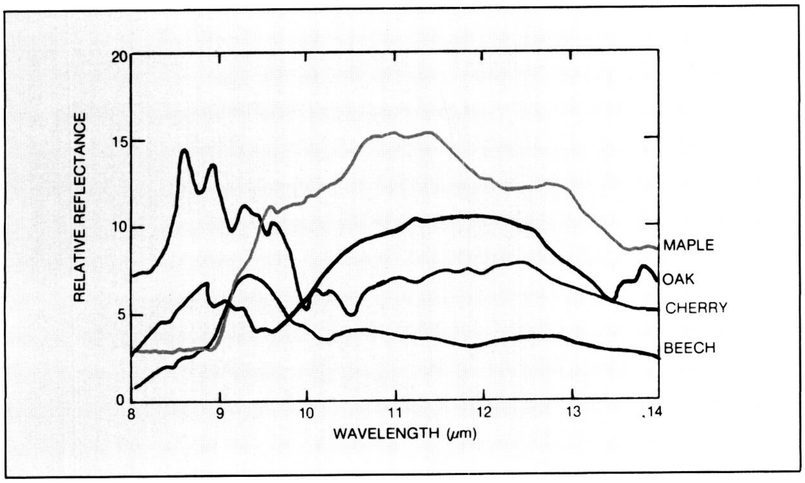
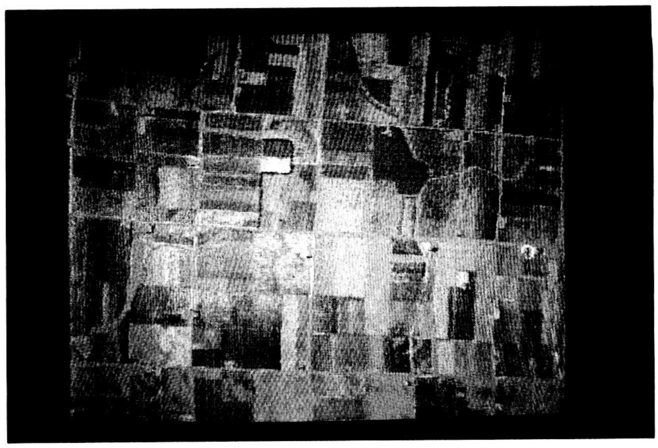


Figure 21. Reflectance Spectra of Dried Leaves.

Figure 22. Wind Streaks in a Corn and Soybean Farming Area in Iowa.



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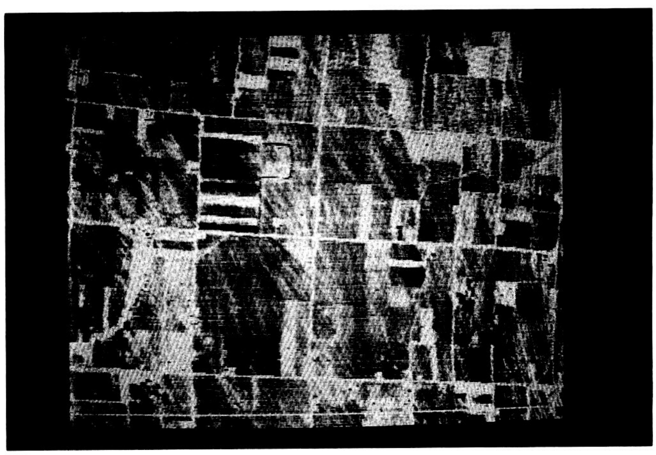

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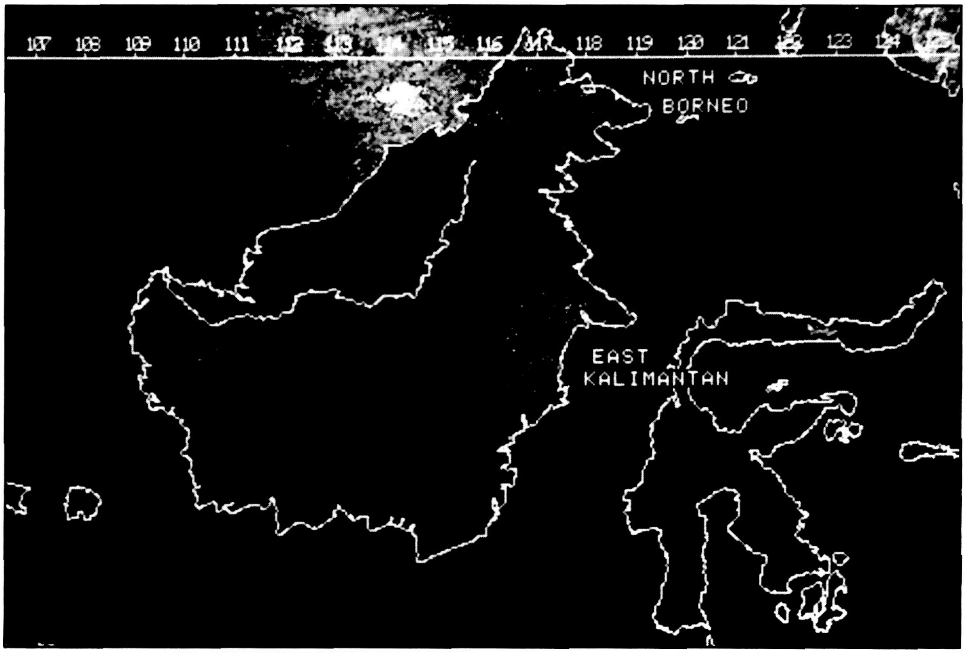
Figure 23. Fires Observed by the NOAA-7 AVHRR Channel 3 (3 to 4 μm) During Serious Drought. Note specular reflectance of solar radiation off of the ocean surface northwest of the island.



at the boundary layer. Little investigation of this phenomena has been reported; however, similar phenomena were observed at regional scales in HCMM images (NASA 1982). Hatfield et al. (1982) have shown that variability of surface temperature within a field may be related to the distribution efficiency of irrigation water, providing a management tool for agriculture.

Forest Fire Detection

The ability of the Landsat sensor to detect forest fires is well known. However, the infrequency of its coverage renders it unsuitable for monitoring fast changes, such as the ones associated with fire disturbances. With frequent coverage, this capability could also be used to alert local authorities of fires in remote areas, preventing devastating damage such as occurred in Borneo in 1982-1983 (Malingreau, 1985). Figure 23 (provided by J. P. Malingreau, NASA/GSFC) is imagery from the AVHRR instrument aboard the NOAA-7 satellite, acquired April 10, 1983 after local information on the fires had been received.

Renewable-Resource and Biophysical-Science Applications Based On Satellite-Acquired Data

While the 16-day repeat coverage of the current Landsat satellite series and the time of day of the observations limit the use of its thermal-infrared data for renewable-resource purposes, the NOAA Advanced Very High Resolution Radiometer (AVHRR), because of its wide-angle, daily (2:00 p.m. local time) coverage, has been widely investigated as a possible means of monitoring biophysical phenomena, including evapotranspiration and crop stress. Currently, there are several uses of Landsat data in the category of vegetative monitoring. The AVHRR has sensors that detect visible, near, and thermal infrared radiation. The orbital period of the two satellites currently in operation is 102 minutes, resulting in 14.1 orbits per day. The satellite has a scan angle of $\pm$ 55.4^0 from nadir and a pixel resolution at nadir of 1.1 km. Past applications based on AVHRR data include a wide range of topics (Yates et al., 1986).

Applications in hydrology include mapping and monitoring continental snow cover (Matson and Wiesnet 1981; Wiesnet and Berg 1981; Dewey and Heim Jr. 1982), mapping of snow cover for river basins (Bowley et al., 1981), monitoring of river floods (Wiesnet et al., 1974), and monitoring of lake basins (Schneider et al., 1985).

Applications in the vegetative sciences include monitoring and discrimination of global vegetation (Tarpley et at., 1984; Tucker et al., 1984; Justice et al., 1985; Tucker et al., 1985; Goward, Dye, and Tucker 1985). Other uses of AVHRR data have included fire detection and monitoring (Parmenter 1971; Matson and Dozier 1981; Miller et al., 1983), urban heat island detection (Matson et al., 1978), dust and sandstorm monitoring (D'Aguanno 1983), and monitoring of volcanic activity (Matson 1984).

One requirement common to all of these applications is frequent data acquisition, provided by the AVHRR. Although some locations within a daily swath may be at a large off-nadir viewing angle, the opportunity to view a scene, even at a high-scan angle, can be beneficial to those using the data. The AVHRR sensor system, although not designed for these applications, has demonstrated that high-temporal-frequency, low-spatial-resolution, satellite remotely sensed data can be used to analyze dynamic land-surface processes.

Research Needs

As emphasized earlier, the ability to accurately determine thermodynamic land-surface temperatures is essential to many potential applications in renewable-resource management. A major research challenge in attaining this ability lies in discovering techniques for removing atmospheric, surface-emissivity, and topographic effects from sensed data (Settle 1983; Price 1984).

Atmospheric Attenuation

In measuring sea-surface temperatures, brightness temperature measurements from spacecraft sensors are usually made in the wavelengths of an atmospheric window for which molecular absorption is small; generally between 10.5 and 12.5 μm, but also between 3.5 and 4.0 μm and 8.0 and 9.5 μm. However, atmospheric absorption and emission even in these windows are not negligible, and the problem is compounded when there are aerosols or thin clouds that attenuate the signal from the surface, but do not completely obscure it. An example of the effect of atmospheric moisture on remotely sensed temperature data is shown in Figure 24.

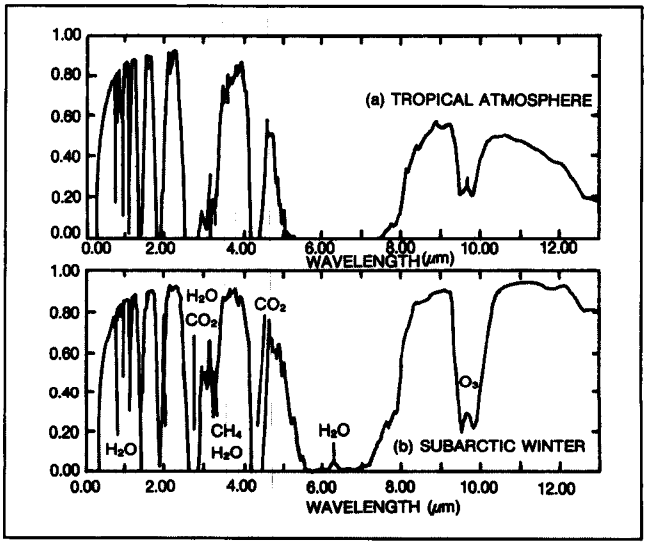


Figure 24. Comparative Transmission of Radiance through Moist and Dry Atmospheres. (Cocoa Beach Working Group, 1973.)

Even for clear-sky conditions, the brightness temperature error at 10.5 to 12.5 μm can be as large as 10K for topical atmospheres. Approximate calculations indicate that aerosols can cause temperature determination errors of 2K; sea-surface temperature measurements were in error by 2K after the 1982 El Chichon eruption (Jacobwitz 1973; Strong 1984; Walton 1985). For cloudy atmospheres, the use of the 4.3 and 15 μm atmospheric sounder frequencies (many narrow wavelength channels clustered in the two carbon dioxide absorption bands) to derive a temperature-humidity profile is hampered by the difficulty of constructing and operating such a sounder at appropriate spatial resolutions (Chahine 1977).

For clear atmospheres, a useful and generally successful method of correcting for atmospheric effects over the ocean surface consists of using multiband infrared measurements. In the 10.5 to 12.5 μm window, the principal absorbing agent is water vapor, whereas at 3.5 to 4.0 μm, water vapor absorption is smaller and absorption by nitrogen and other gases can be calculated because their mixing ratios vary little. Therefore, the difference between the measurements in the two windows can be used to correct for water vapor absorption (Anding 1970; Bernstein 1982; Deschamps 1980). The key factor enabling these corrections is that the spectral emissivities in these wavelength bands are known for the sea surface.

An effective implementation of this method consists of simulating brightness temperatures for a variety of atmospheric temperature and humidity profiles, using a radiative transfer model to correct for atmospheric absorption and emission, and then using these simulations to develop empirical temperature corrections. Thus far, the atmospheric models used do not account for clouds or other atmospheric aerosols, so only absorption and emission are considered (Wienreb 1980; Kneizys 1983). These methods are now in operational use by NOAA's sea-surface temperature mapping program.

Land Emissivity and Topography

A number of difficulties are encountered in attempting a straightforward extension of the methods used for sea-surface temperatures to the land surface, and the simple two-band method yields accurate temperatures under some conditions, but not under the wide variety of desired conditions (Price, 1984) encountered over land.

For example, although leaf canopies exhibit blackbody-like characteristics, most other land surface materials vary considerably in emissivity, and this causes brightness temperatures to differ from thermodynamic temperatures (Beuttner 1965; Griggs 1968; Hovis 1967). Emissivity may also vary with viewing angle, an effect that is usually more important over land than over water because the combination of surface slope and satellite scan angle routinely results in local viewing angles of over 50^0 (Dozier and Warren 1982). Also, the combination of variations in emissivity and heat capacity for different surface materials causes a wider range of land-surface temperatures than those over sea surfaces.

In addition to these effects, the instantaneous field of view of the sensor over land commonly contains radiance from surfaces of different temperatures and emissivities. The nonlinear response of the Planck function causes the brightness temperatures of such pixels to vary with wavelength even in the absence of atmospheric effects (Dozier 1981; Matson and Dozier 1981). Also, the variation in atmospheric profiles over land is increased by topographic changes, the boundary layer of the atmosphere is not as closely coupled to surface properties as is the case over the ocean, and aerosols are more prevalent over land.

A Possible Solution

Zhengming Wan (1985) investigated some of these problems in his Ph.D. thesis. For surfaces of known emissivity, he examined whether an approach similar to that used over the sea surface could be extended to estimation of land-surface temperatures. He examined a combination of atmospheric profiles used in the LOWTRAN6 code and a wide range of surface temperatures and used them in an azimuth-dependent radiative transfer code (Wiscombe 1976; Li in press) to generate spacecraft brightness temperatures for each case.

His empirical formulas, derived from statistical analysis of theoretical simulations over snow cover and sands, could potentially estimate land-surface brightness temperatures within viewing angles of 60° from nadir with a standard deviation of 0.2K and a maximum error of less than 1K under clear-sky conditions. For slightly adverse conditions (thin cirrus clouds, rural aerosols, or thin radiation fogs), the standard error rises to 3K with a maximum of 10K. From simulation data with a hypothetical four-band instrument (one in the 3.5 to 4.0 μm window and three in the 8.0 to 12.5 μm window), accuracy improves to a standard error of 2K with a maximum error of 6K. A further discussion of this approach is contained in Appendix A in the paper by Suits.

Recommended Instrument and System Performance

Instrument Parameters

The following instrument parameters in conjunction with Thematic Mapper bands 1, 3, 4, and 5 would accommodate the spectral, spatial, radiometric and temporal needs of the Evapotranspiration/-Botany Group:

3.50 - 3.95	60	0.3	0.5
8.10 - 9.50	60	0.3	0.5
10.30 - 11.30	60	0.3	0.5
11.50 - 12.40	60	0.3	0.5

As indicated, renewable-resource applications require a daily repeat coverage. As a result, the panel recommends a low-resolution instrument, to be flown in conjunction with the one defined above. The spectral characteristics would be identical to the high-resolution instrument, but the spatial resolution would be 1 km, with a minimum swath width of 2750 km and a NEΔT of 0.5K in the thermal bands.

These instruments would provide high- and low-resolution coverage simultaneously, daily low-resolution coverage, and the potential of calibrating the off-nadir measurements for atmospheric constituents. The high-resolution instrument could also be used to calibrate the other instrument. This procedure of combining the fine and coarse scales is untested, but could provide an opportunity to evaluate visible, near-infrared, and thermal data and their derived indices. The result would be an exciting tool, enabling the incorporation of remotely sensed data from one platform into many commercial and operational renewable-resource applications.

System Parameters

Overpass Time

Under clear skies, surface temperature reaches a maximum at about 1300 hours local sun time (LST). Between about 1100 and 1400 LST, the change in temperature is relatively small; however, after 1400 and before 1100 LST, the temperature changes rapidly. The most rapid changes occur just after sunrise and just before sunset. Following sunset, the rate of temperature decrease diminishes gradually with time, and, from 2300 LST until dawn, the rate of temperature decrease is relatively slow compared to that near sunset.

Therefore, it follows that the maximum thermal response is at about 1300 LST.* At this time, the amount of signal is largest by comparison to the noise inherent in measuring and interpreting surface temperatures. For example, at 0900 and 2100 LST there is very little difference between day and night temperatures, and the spatial variation of surface temperatures are in transition from day to night or night to day regimes. Consequently, the pattern of surface temperatures near dawn or dusk or within the regime of rapidly changing surface temperatures is seriously degraded to the point where the bulk of agricultural, meteorological, and hydrological applications are no longer viable.

Although the optimal times for satellite sensing of thermal-infrared temperatures would be in a 1400 to 0200 LST cycle, the importance of diurnal cloud cover must also be taken into consideration. Diurnally forced cumulus convection occurs because the heating of the surface causes the atmosphere to undergo turbulent exchanges within the boundary layer. These exchanges produce thermals that manifest themselves in cumulus clouds. Sometimes the vertical mixing is sufficient to produce a cover of stratus or stratocumulus cloud that largely obscures the satellite's view of the surface. Consequently, diurnally forced cloud cover tends to be at a minimum at dawn, rising to a maximum near or shortly after noon LST, and decreasing rapidly at sunset. Accordingly, we recommend that the satellite orbit be fixed so as to provide measurements at 1100 and 2300 LST, since we feel that these times will result in an adequate signal while reducing the probability of cloud interference.

*Maximum thermal response is defined as the maximum temperature discrimination between surface elements and also as the greatest difference between day and night temperatures.

Sensor Calibration

In order to acquire repetitive measurements with the precision needed for monitoring terrestrial productivity and the hydrologic cycle, it will be necessary to attain a level of sensor calibration not currently realized. Intensive analysis of Coastal Zone Color Scanner data over a period of several years has shown that the largest single source of sensor system degradation occurred, not in the detectors, but in the receiving telescope optics. Since derivation of biophysical parameters requires a knowledge of the radiometric performance of the entire instrument, a periodic assessment of the entire instrument's radiometric accuracy is a fundamental requirement for effective application of these observations in renewable-resource analyses.

Summary

In the discussions of this panel, primary consideration was given to defining a satellite remote-sensing system that would provide information on the primary productivity of the land surface, evapotranspiration, and crop stress.

Recent research has shown that accurate land-surface temperature measurements derived from sensor brightness temperatures could be used to develop stress indices related to crop yield, crop biomass production, and evapotranspiration. The accurate assessment of land-surface temperatures may also be of value in other biophysical sciences and renewable-resource applications. These include utilization in climatology and meteorology, soil moisture estimation, forest-fire mapping, determination of surface wind fields, and estimation of a snow-surface energy balance.

A major factor that may limit the value of thermal-infrared observations to renewable-resource workers is the alteration of sensed emissions by atmospheric variables. For instance, it is recognized that the thermal signal from the earth's surface is degraded by the atmosphere's water-vapor content, and there has been much research on how to correct space-measured brightness temperatures for this and other atmospheric interferences, including cloud cover over oceans. By comparison to research related to deriving accurate sea-surface temperatures, the derivation of land-surface temperatures is primitive, despite its many possible applications. The availability of four-or five-band, multispectral, thermal-infrared observations may provide the means of correcting data for atmospheric interference over land, thus enabling an accurate assessment of surface temperatures to be made.

A second major factor identified by the panel that will ultimately determine the commercial and scientific value of multiband thermal-infrared data to the renewable-resource community is the timeliness of data acquisition. The 16-day repeat cycle of the current Landsat orbit is much too infrequent to permit monitoring of the temporal progression of land conditions of interest. An approach to overcoming this obstacle suggested by panel members is to fly a wide-scan imaging sensor along with the Thematic Mapper sensor on the Landsat platform. This sensor, configured spectrally to replicate the Thematic Mapper sensor (augmented with several bands in the thermal infrared), would enable near-daily low-spatial-resolution measurements to be made that would permit temporal monitoring of regional surface conditions. The data from these two sensors would significantly enhance the value of Landsat data in renewable-resource analyses.

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INSTRUMENT PANEL REPORT

Panel Chairman: Dan LaPorte

Contributors:

John Barker, William Barnes, Jack Engel, William Malila, Marvin Maxwell, Gerry Meeks, Aram Mika, Frank Palluconi

In the absence of instrument-feasibility constraints, requirements-definition exercises often lead to unrealizable performance specifications. While such exercises are useful for establishing long-term technical goals, they tend to be unfruitful in a practical sense because the objectives cannot be achieved within current technical and/or economic constraints. The inherent conflict between science desires and technical constraints was recognized at the outset of the Thermal Infrared Working Group conference, so the Instrument Panel was established to provide engineering support to the two science panels. This support role encompassed the following tasks:

- *Provide parametric information regarding performance tradeoffs in the thermal-infrared regime. Specifically, establish the feasibility envelope showing the achievable combinations of spatial resolution (ground sampling distance or IFOV), spectral resolution (bandwidth), spectral coverage (wavelength limits), and radiometric resolution (NEΔT).*
- *Examine the technical feasibility of realizing the science panels' recommended set of instrument specifications.*
- *Address other remote-sensing instrumentation needs, as defined by the science panels.*

Design Tradeoffs

Physical constraints lead to a direct tradeoff between spatial, spectral, and radiometric resolution; i.e., any one performance parameter can be improved only at the expense of the other two. Moreover, the need for frequent repeat coverage, which manifests itself as a requirement for a wide field of view, also competes directly with spatial, spectral, and radiometric performance.

Economic and schedule factors comprise another overlay on the design tradeoffs. For the purposes of this working group, Landsat 7 (to be launched in early 1991) was selected as the initial spacecraft to include a multispectral thermal-infrared capability; there is insufficient time to incorporate

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this feature on Landsat 6 (early 1989 launch). Furthermore, obtaining funds for a full-scale development program for an entirely new instrument and associated ground processing system is highly unlikely in view of current budget limitations. Such a new start would cost on the order of $50M, and this amount is not easily accommodated in either NASA or NOAA budgets. The prospect for full commercial funding of a new multispectral thermal-infrared instrument is also remote because the market projections for the sale of this data are too small and speculative to attract investment capital.

In light of the foregoing, the most attractive route for providing a multispectral thermal-infrared capability is via design modifications to the Thematic Mapper instrument. Fortunately, the basic design parameters of the Thematic Mapper, such as aperture size, focal length, and scan rate, still permit us to entertain levels of performance that are fruitful for the application scientists. By using this approach, this capability can be obtained for the incremental cost of upgrading the instrument and associated equipments, and the cost will be markedly lower than a new start.

Recommendations

Within these guidelines, parametric performance curves were generated for the science panels. The key curves show the tradeoff between NEΔT and IFOV, with spectral bandwidth and band-center wavelength as parameters. Two examples are illustrated in Figure 25. In this fashion, the instrument panel established

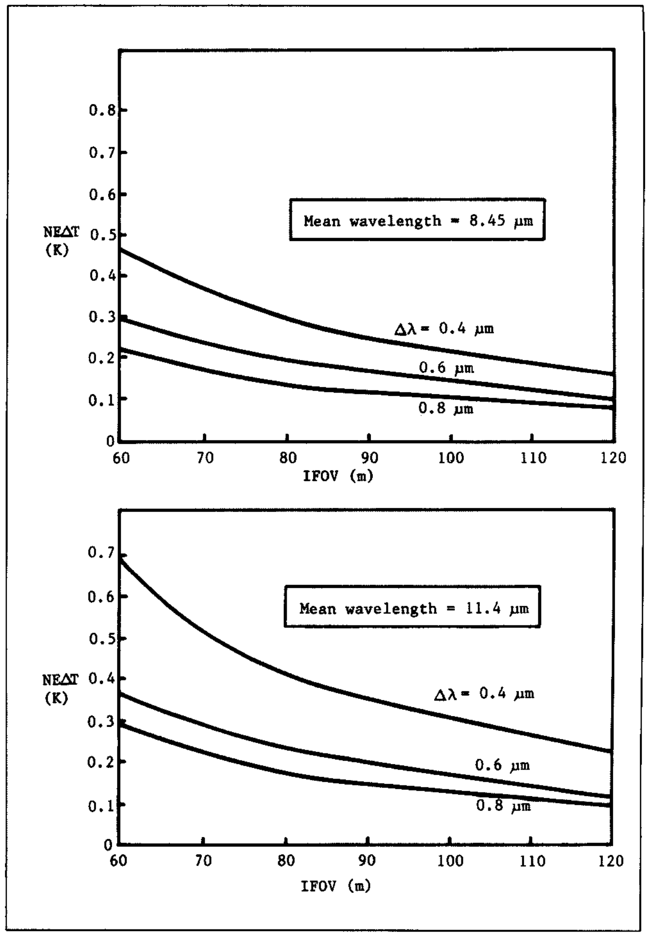

Figure 25. Tradeoffs Between NEΔT and IFOV, with Spectral Bandwidth and Band-Center Wavelength as Parameters.

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the tradeoff boundaries, and the application scientists selected the operating points within those boundaries. This process led to a set of prioritized spectral band recommendations shown in Table 1. These choices reflect the merged preferences of both the Geology and Evapotranspiration/Botany Panels.

Table 1. Spectral Band Recommendations

PRIORITY	λ_{min} (μm)	λ_{max} (μm)	IFOV (m)
1	3.53	3.93	120
	8.2	8.75	60
	8.75	9.3	60
	10.2	11.0	60
	11.0	11.8	60
2	3.53	3.93	120
	8.2	8.75	60
	8.75	9.3	60
	10.2	11.0	60
	11.5	12.4	60
3	3.53	3.93	120
	8.2	8.75	60
	8.75	9.3	60
	10.2	11.0	60
4	8.2	8.75	60
	8.75	9.3	60
	10.2	11.0	60
	11.0	11.8	60
	11.5	12.4	60
5	8.2	8.75	60
	8.75	9.3	60
	10.2	11.0	60
	11.0	11.8	60
6	8.2	8.75	60
	8.75	9.3	60
	10.2	11.0	60
	11.5	12.4	60

In addition to spectral band selection, the working group discussions encompassed a number of other topics germane to thermal-infrared remote sensing. These discussions were distilled into the following set of recommendations, which were then presented to the instrument panel:

1. *Adopt the highest priority band selection shown in Table 1, according to feasibility of implementation. The recommended NEΔT is 0.33 to 0.5K (corresponding to an NE$\Delta\epsilon$ of 0.01) at a 300K surface temperature, and the recommended nodal crossing time is 10:00 to 11:00 local sun time (LST).*
2. *Improve the ground-processing algorithms currently utilized for band 6 of the Thematic Mapper to provide data that is truly useful in operational applications. Preliminary analyses indicate that the inherent NEΔT of the instrument is being degraded by a factor of three or four by the ground-processing approach. Prelaunch test data on the Thematic Mapper instruments indicated NEΔT performance in the range of 0.12 to 0.13K, while the apparent NEΔT of processed band 6 scenes from the spacecraft is, at best, on the order of 0.5K.*
3. *"Digitize the noise" in all future thermal-infrared sensors; i.e., select a quantization scheme that fully captures the inherent sensitivity of the instrument.*
4. *Develop and operate a wide-field sensor to complement the Enhanced Thematic Mapper (ETM) on Landsat 7. The sensor's spectral coverage should duplicate ETM bands 1, 3, 4, 5, and the proposed thermal bands; spatial resolution should be 1 km over a 2750 km swath width, providing one-day revisit time from the 705 km Landsat orbit.*
5. *Develop and operate a thermal-infrared profiling spectrometer for geologic research on Landsat 7. The panel recommends 20 bands in the 3 to 5 μm region, 40 to 50 bands in the 8 to 12 μm region, with an NEΔT of 0.1 to 0.3K. The spatial footprint of this instrument should comprise a narrow swath (one or several 120m pixels) that can be pointed to any position within the ETM field of view. Moreover, the profiling spectrometer pixel(s) must be coregisterable with the ETM images, so that the detailed spectral information provided by the profiling spectrometer can be used as a complement to the high spatial resolution imagery of the ETM.*

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Results

The above recommendations, generated during the 5-7 February workshop, were subsequently studied by a group of instrument experts. The results of this work were presented to the panel chairmen and other representatives (see Appendix B) on 25 March 1986 and are summarized as follows:

1. *Implementation of the Priority 1 band selection appears feasible via modification to the ETM instrument being developed for Landsat 7. (The modifications are described in some detail later in this section.)*
   - *The desired spectral and spatial performance can be attained; however, NEΔT may be somewhat higher than desired. Wider spectral intervals may be required if NEΔT is deemed to be the more important performance parameter.*
   - *The addition of the MWIR band (3.7 μm), referred to as band M, can be accommodated. Inclusion of this band will not affect data formats, since band M will occupy the former band 6 data slot.*
2. *A preliminary review of the ground-processing algorithms for Thematic Mapper band 6 data indicates that the apparent NEΔT in the delivered images and computer-compatible tapes can, indeed, be improved. These improvements will be implemented as soon as practicable.*
3. *NEΔT will not be limited by quantization noise on the Landsat 6/7 ETM instruments (although the quantization noise is not negligible). The digitization approach has been improved for these sensors; nine-bit analog-to-digital converters will be utilized along with ground-commandable gain selection.*
4. *A wide-field-sensor design concept was developed and presented to the working group. The performance requirements established for this instrument can be readily achieved with a straightforward design employing a cross-track scan mirror and refractive optics. The principal challenge in fielding such a sensor is economic rather than technical, i.e., it is not yet clear if future revenues generated by this instrument will be sufficient to recover the development and operating costs of the sensor and associated equipments.*
5. *A profiling spectrometer meeting the performance objectives established by the Geology Panel is technically feasible. A preliminary design concept was presented to the working group on 25 March, and this concept has since been refined. Based on the Thermal Emission Spectrometer (TES) design for the Mars Observer program, the profiling spectrometer proposed for Landsat features NEΔTs ranging from 0.08 to 0.3K with a spectral resolution of 10 cm^{-1} in the 8 to 14 μm band and 67 cm^{-1} in the 3 to 5 μm band.*

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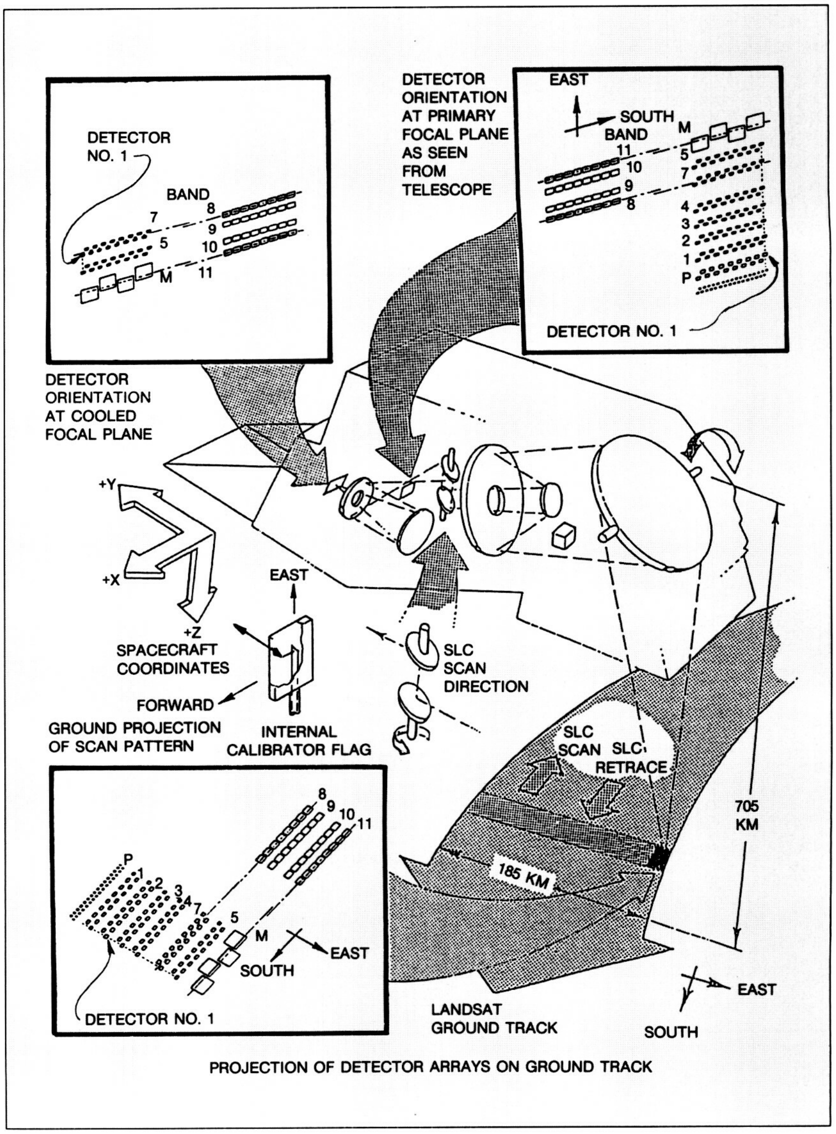
Thematic Mapper Design Modifications for Multispectral Thermal Infrared

The principal design changes required to accommodate the five thermal-infrared bands are in the instrument's focal plane and associated electronics. The focal plane configuration is envisioned as shown in Figure 26, and its projection on the ground track is illustrated in Figure 27. As indicated, band M will reside in the general location that was previously occupied by band 6. Bands 8 through 11 will be offset in the track direction by exactly one array length from bands 5, 7, and M. Bands 5, 7, and M will be fabricated as a monolithic assembly of indium antimonide detectors, while bands 8 through 11 will be fabricated in two, two-band chips, using photoconductive mercury cadmium telluride material. Band M will be

Figure 26. Orientation of Focal Planes and Their Projection on the Ground Track.



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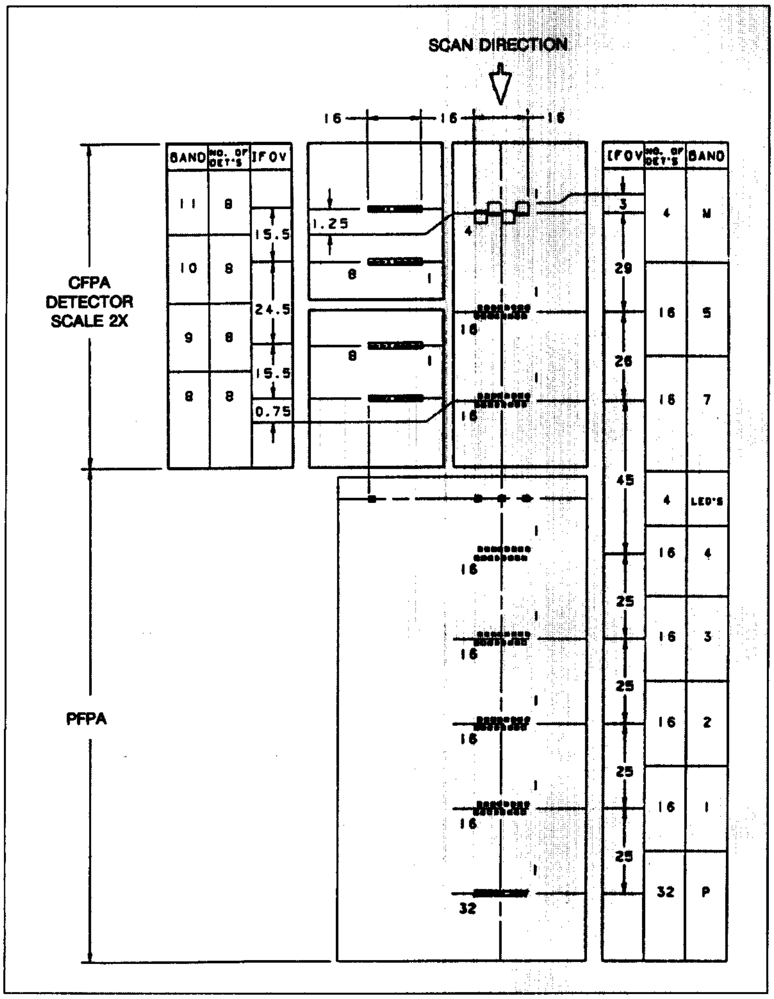

Figure 27. Detailed Focal-Plane Projection on Ground Track.

configured as an offset linear array to minimize the field angle in the scan direction while accommodating the multiplexer's prior method of sampling band 6. This implies 0.005 inch gaps and a 112.5 by 120m footprint. Bands 8 through 11 will be configured as linear arrays with 0.0005 inch gaps, resulting in a 52.5 by 60m footprint.

In addition to these major changes in the cooled focal plane assembly, many detailed changes to other Thematic Mapper components will have to be made. For example, the optical baffles, internal calibrator, multiplexer, and cooler will require modifications to accommodate the new bands. Detector cooling was a key concern because of the incremental thermal load associated with the additional detector. This issue was reviewed, and it appears that the Thematic Mapper cooler has sufficient performance margin to operate the new focal plane at a temperature of 85K.

Performance

Extensive analyses were conducted to predict NEΔT/NEΔε performance for the modified instrument. As summarized in Table 2, NEΔT may be greater than desired for the Option A (Priority 10) band selection. Widening the bands improves the NEΔT, as shown by Option B.

Although the desired radiometric performance is shown to be attainable with broadened spectral bands, the increase in bandwidth was judged to be unacceptable, and Option A (the first priority bandset) was deemed preferable.

Table 2. Performance Tradeoff Between NEΔT and Spectral Bandwidth

Band No.	IFOV (m)	Option A (Priority 1 Bands)			Option B (Wider Bands)			MTF
		Δλ (μm)	NEΔT (K) (at 300K)	NEΔε	Δλ (μm)	NEΔT (K) (at 300 K)	NEΔε	
M	120	3.53–3.93	0.29	0.012	3.53–3.93	0.29	0.012	0.44
8	60	8.2–8.75	0.48	0.009	8.1–8.8	0.37	0.007	0.32
9	60	8.75–9.3	0.47	0.008	8.7–9.4	0.35	0.006	0.31
10	60	10.2–11.0	0.54	0.008	9.9–11.3	0.33	0.005	0.29
11	60	11.0–11.8	0.57	0.008	10.4 –11.9	0.33	0.005	0.28

Santa Barbara Research Center identified several areas where minor design changes could be made that would result in an improvement of about 25 percent in NEΔT. These changes include using thinned detection material, optimized for each spectral band, with back-side reflectors. If these changes are implemented and yield the expected results, the performance will be as shown in Table 3.

Table 3. Potential Improved Performance

Band No.	IFOV (m)	Option A' (Priority 1 Bands)		
		Δλ (μm)	NEΔT (K) (at 300K)	NEΔε
M	120	3.53–3.93	0.29	0.012
8	60	8.2–8.75	0.38	0.007
9	60	8.75–9.3	0.38	0.006
10	60	10.2–11.0	0.43	0.006
11	60	11.0–11.8	0.46	0.006

Regarding the data formats for Landsat-6 and 7, the schemes in Table 4 were presented:

Table 4. Data Formats Including Multispectral Thermal Infrared

Data Formats			Spectral Bands											
			P	1	2	3	4	5	6/M	7	8	9	10	11
Landsat 7	Landsat 6	1		✓	✓	✓	✓	✓	✓*	✓				
		2	✓				✓		✓*	✓				
		3	✓				✓	✓	✓*					
		4		✓		✓	✓		*	✓	✓	✓	✓	✓
		5		✓		✓	✓	✓	*		✓	✓	✓	✓
		6	✓						*		✓	✓	✓	✓

*Landsat-7, Band M

As shown, there would be three formats available for Landsat-6 and six for Landsat-7. The use of two multiplexers would permit two formats to be selected simultaneously, thereby transmitting all of the available data.

Figure 28 shows the spacecraft proposed for Landsat-6 and 7. As conceived, the modularized spacecraft could be carried to an initial orbit by the Space Transportation System (STS). The spacecraft would then be boosted into its operational orbit at 705 km. Alternatively, it could be launched by an expendable booster. As shown, the modular design will enable periodic on-orbit replacement of modules and other servicing, extending the potential useful life of the system.

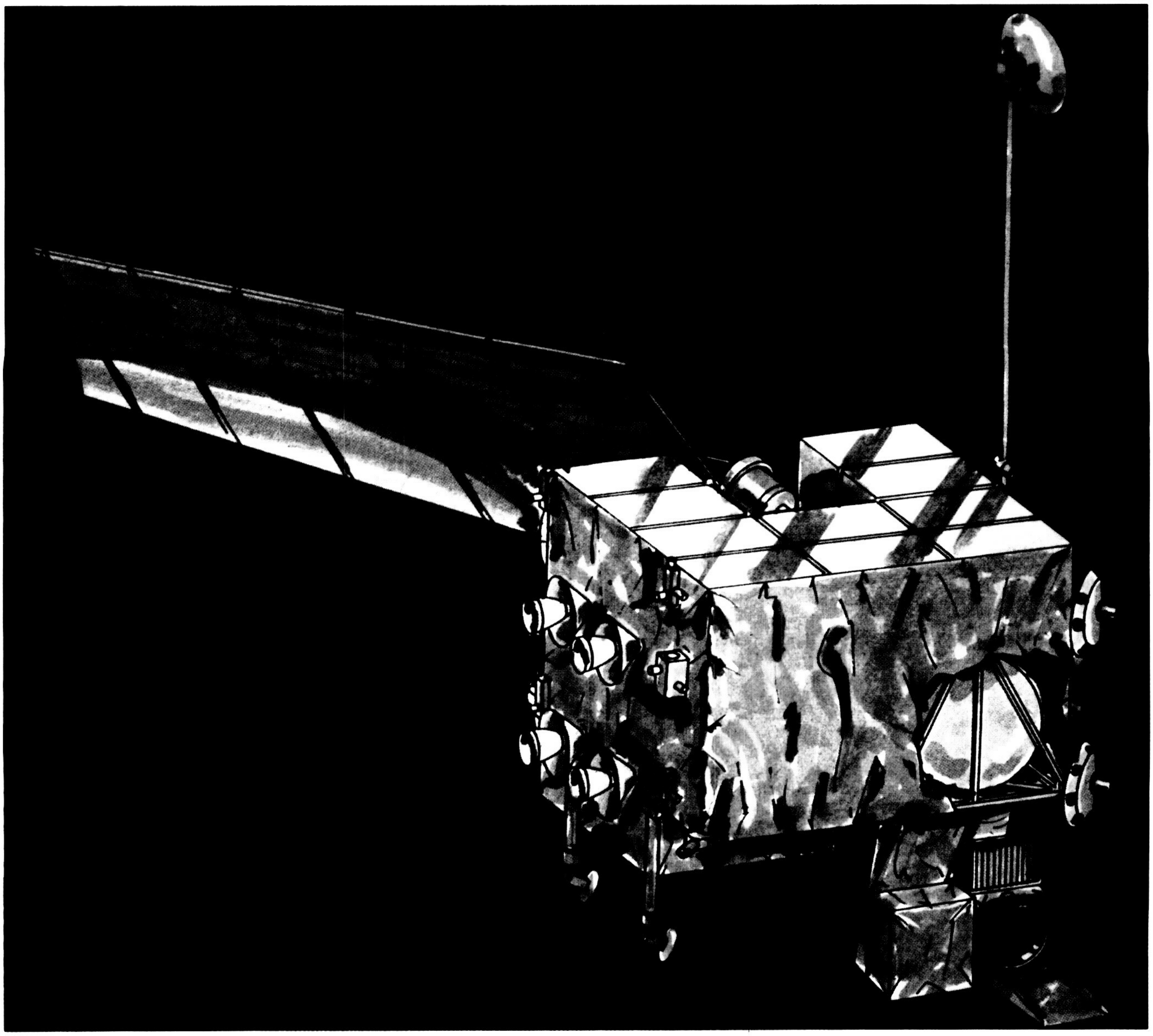

 Figure 28. Omnistar Spacecraft Proposed for Landsats 6 and 7.

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Appendix A KEY ARTICLES

The following previously unpublished articles are published in this appendix since they contain information especially relevant to the interests of the Thermal Infrared Working Group:

Christensen, P.R. A Study of Filter Selection for the Thematic Mapper Thermal-Infrared Enhancement.

Christensen, P.R.; Malin, M.L.; Anderson, D.L.; and Jaramillo, L.L. Thermal Imaging Spectroscopy in the Kelso-Baker Region, California.

Christensen, P.R.; Kieffer, H.H.; Chase, S.C.; and LaPorte, D.D. A Thermal Emission Spectrometer for Identification of Surface Composition from Earth Orbit.

Malila, W.A., and Suits, G.H. Considerations in Multiband Thermal Sensor Definition.

Suites, G.H. Summary of Thermal Band Selection Strategy.

A STUDY OF FILTER SELECTION FOR THE THEMATIC MAPPER THERMAL-INFRARED ENHANCEMENT

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The purpose of this report is to describe a study of band location for the multichannel thermal-infrared scanner proposed for the Thematic Mapper. The intent of this work was to provide a preliminary investigation of the effects of atmospheric attenuation and spectral averaging on the ability to discriminate major rock types using infrared data. No attempt was made to assess the full range of possible atmospheric conditions, nor to investigate a complete suite of rock compositions. The results do, however, provide some insight into the choice of bandpasses and indicate that this spectral region will be very useful for rock discrimination.

The rock spectra used were all diffuse reflectance spectra taken from Lyon (1964). The data were acquired with a spectral resolution (~5 cm^{-1}) and a radiometric accuracy that is adequate for this study. The major igneous rock compositions studied were ultrabasic (dunite), basic (basalt, gabbro), intermediate (andesite, monzonite), and silicic (granite, rhyolite). Also included were limestone and a clay mineral, kaolinite. The atmospheric absorption properties were taken from the Infrared Handbook (1978, p. 5-92), and were arbitrarily scaled to 40% transmission at the center of the 9.7 μm ozone band. The effect of this scaling is to adjust the magnitude of the atmospheric absorption bands relative to the rock absorption bands. The correct scaling depends on the absolute magnitude of the rock emissivity, which has not been well documented for naturally occurring surfaces. The scaling chosen here was determined largely by scaling the simulated spectra to Nimbus 4 spectral observations of the earth's surface (Prabhakara and Dalu, 1976).

Four choices were made for potential band locations. These include: two sets with four bands spaced over the 8 to 12 μm region, with two bands on either side of the 9.7 μm ozone absorption band; one set with two bands on the short wavelength side and one band on the long wavelength side of the ozone band; and one set with one band shortward and two longward of the ozone band. For comparison, the six

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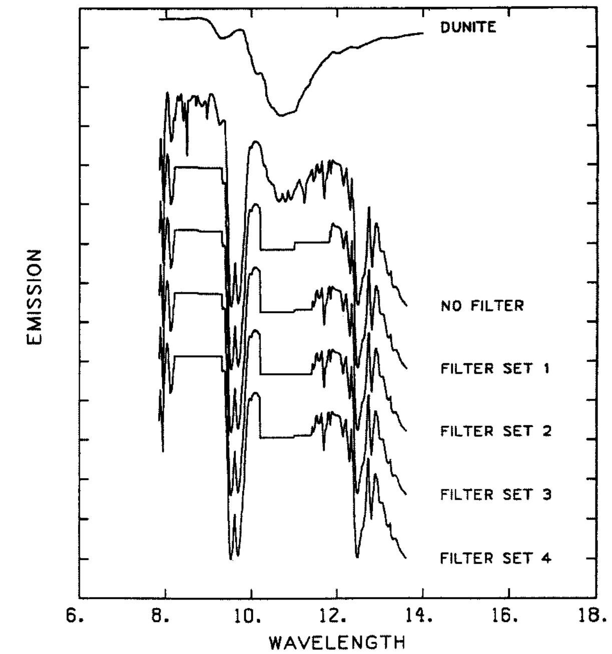
TIMS bands were also modeled. The actual band-passes used are (μm):

Filter Set 1	Filter Set 2	Filter Set 3	Filter Set 4
8.2–8.75	8.2–8.75	8.2–8.75	8.2–9.3
8.75–9.3	8.75–9.3	8.75–9.3	10.2–11.0
10.2–11.0	10.2–11.0	10.2–11.4	11.0–11.4
11.0–11.8	11.0–11.4		

In all cases, the filters were assumed to have a square-wave response. The results of this modeling are shown in Figures 1(a) through (i), giving the input rock spectrum, the rock spectrum convolved with the atmospheric transmission, and the resultant spectra for each of the four filter sets. Figure 2 shows the summary of rock spectra for each filter set and for TIMS.

Figure 1. Modeling Results.



1(a). Dunite.

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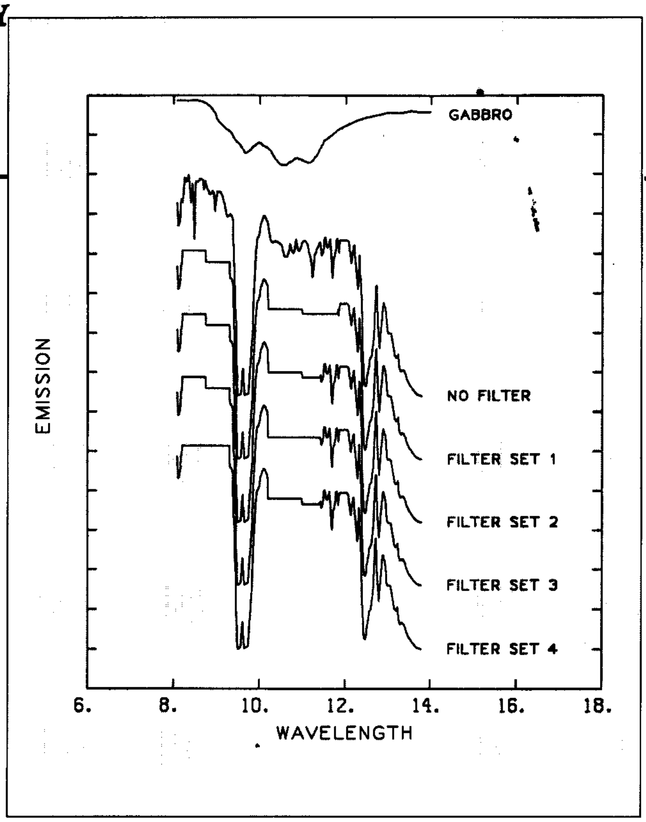
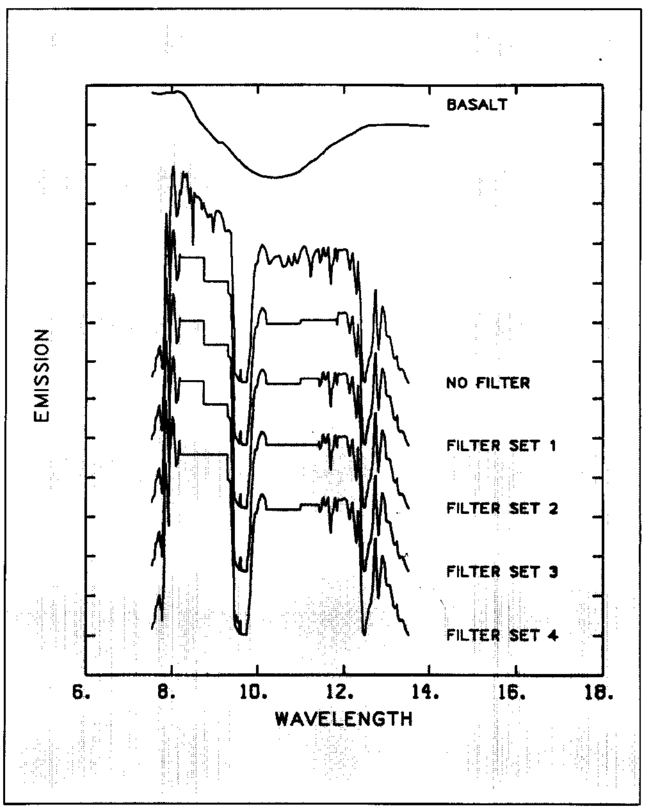
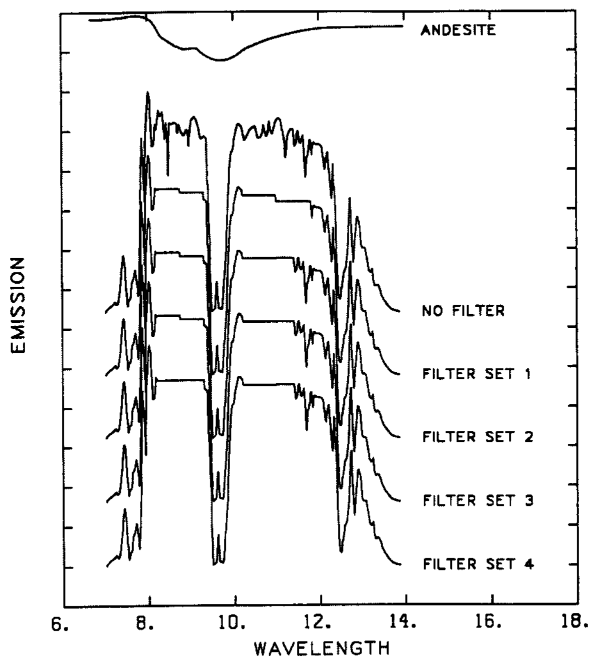


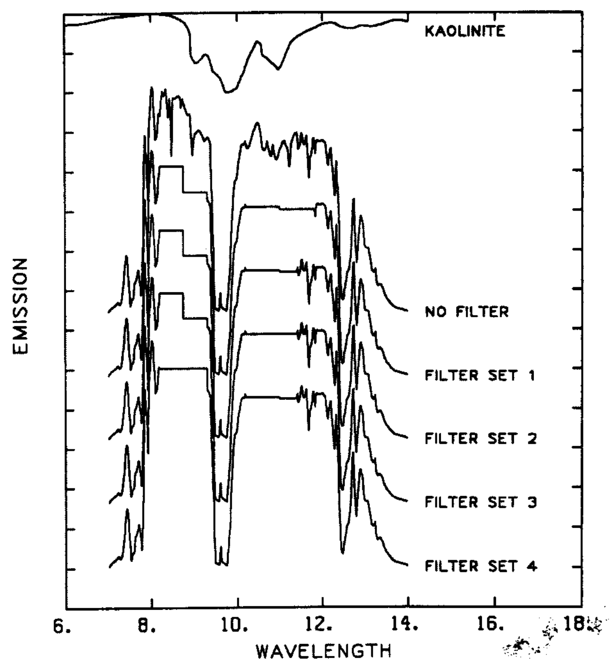
1(b). Gabbro.



1(c). Basalt.



1(d). Andesite.



1(e). Kaolinite.

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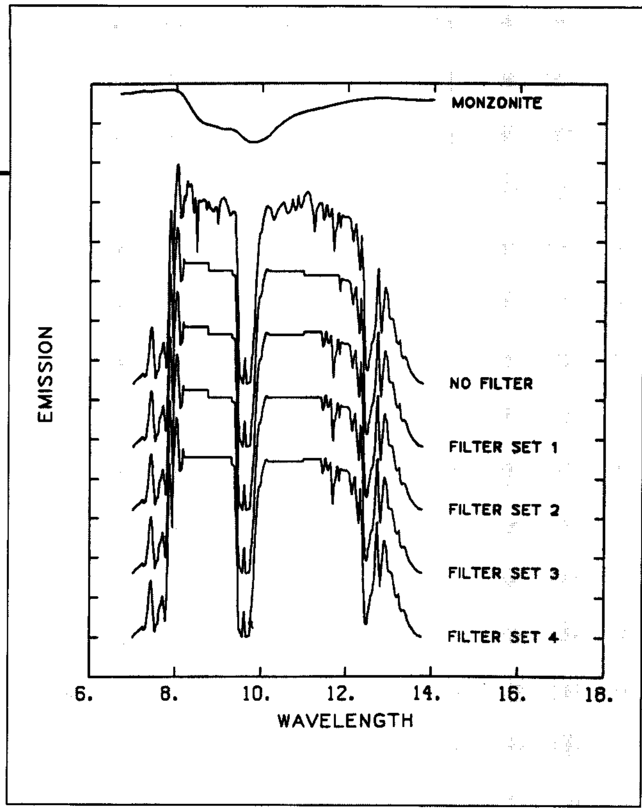
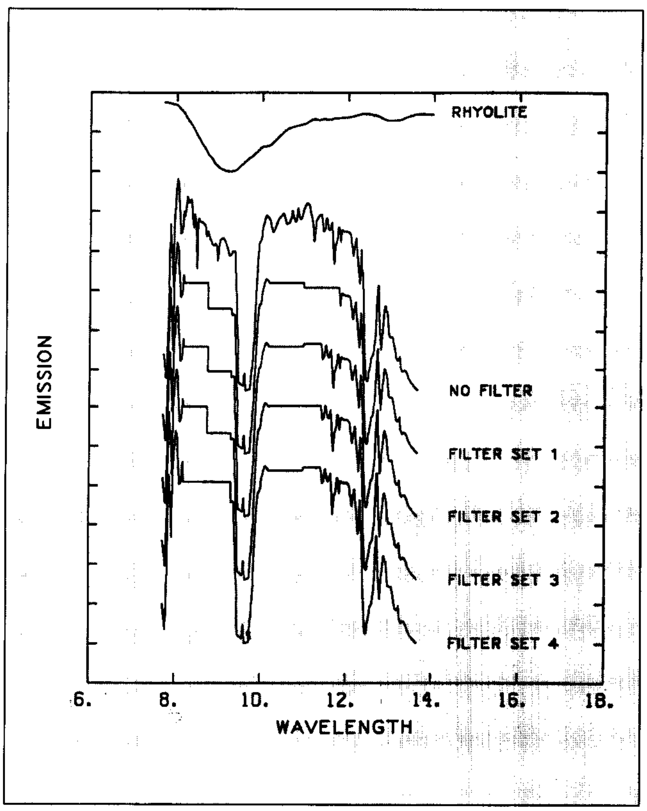
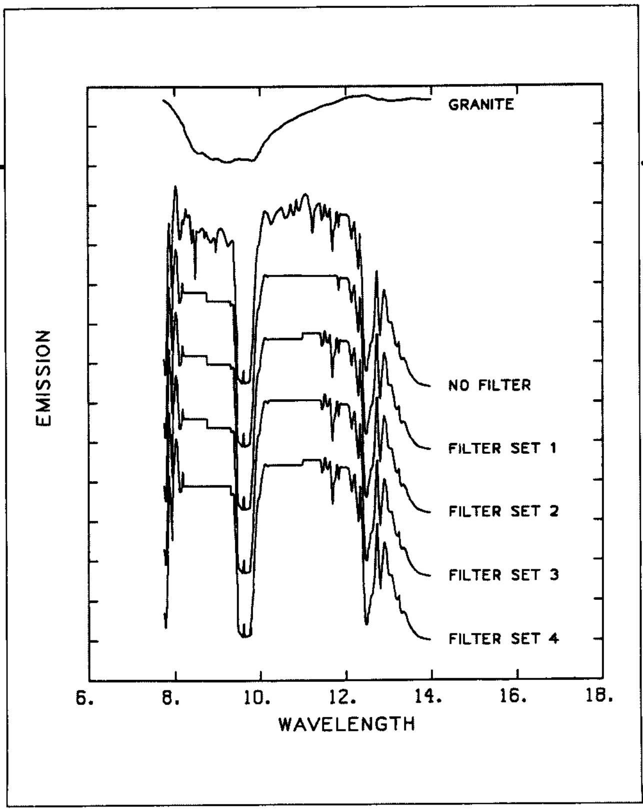


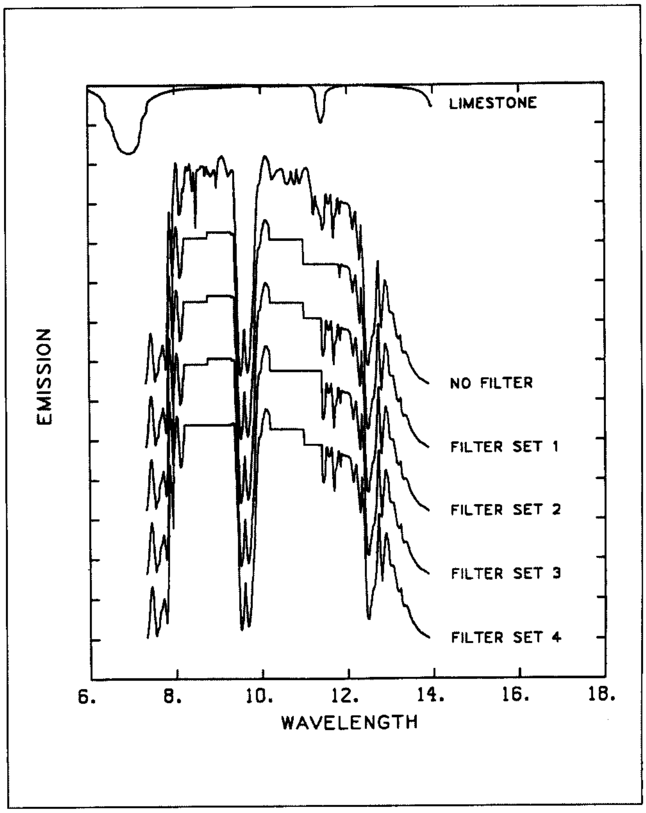
1(f). Monzonite.



1(g). Rhyolite.



1(h). Granite.



1(i). Limestone.

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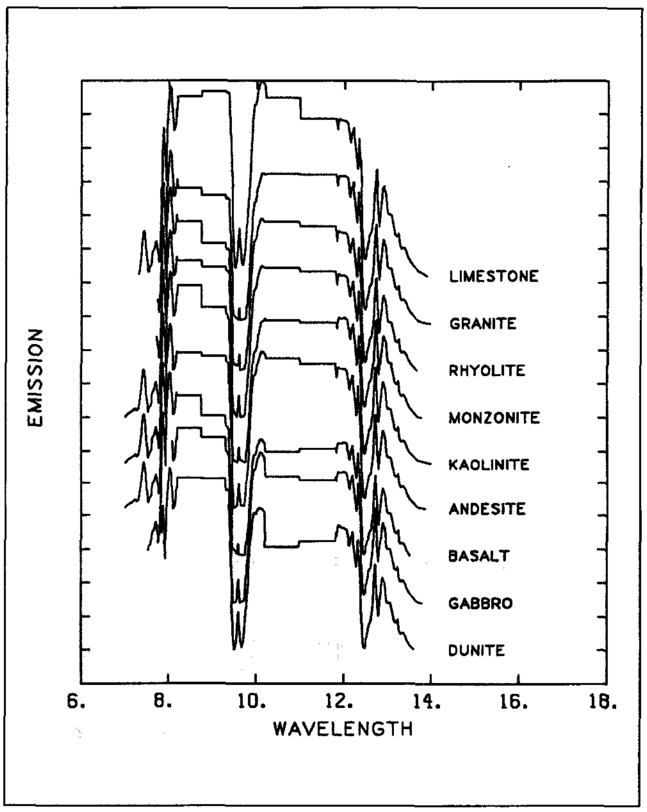
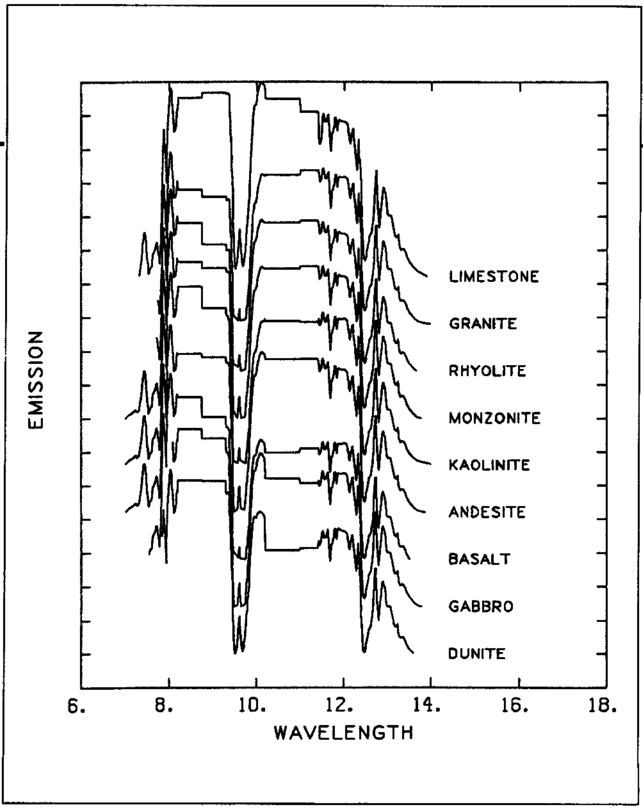
As shown in Figure 2, it appears that for the limited number of rock types considered, the use of two bands longward of the ozone band instead of only one improves the capability for distinguishing ultrabasic (dunite) from basic rocks (basalt, gabbro), and for identifying limestones. Ultrabasic rocks have important geologic significance, although they are of limited occurrence in continental environments. Limestones are widespread and are an important rock type to be identified. This study suggests that a narrow band from 11.0 to 11.4 μm (Set 2) does not provide a significant improvement in the discrimination of limestones compared to the use of a wider band from 11.0 to 11.8 μm (Set 1). The discrimination of ultrabasic rocks is improved using the wider bandpass. Thus, given additional radiometric sensitivity requirements, it appears that a band from 11.0 to 11.8 μm may be preferable. In either case, two bands in the 10.3 to 11.8 μm region are desirable.

The study performed here also indicates that there is a significant improvement in the characterization of rock spectra using two bands in the 8.2 to 9.3 μm region instead of only a single band (Figure 2). This is particularly true for distinguishing limestone from silicic igneous rocks. Basic and ultrabasic rocks are also clearly separated using two bands, as are silicic igneous rocks and clay.

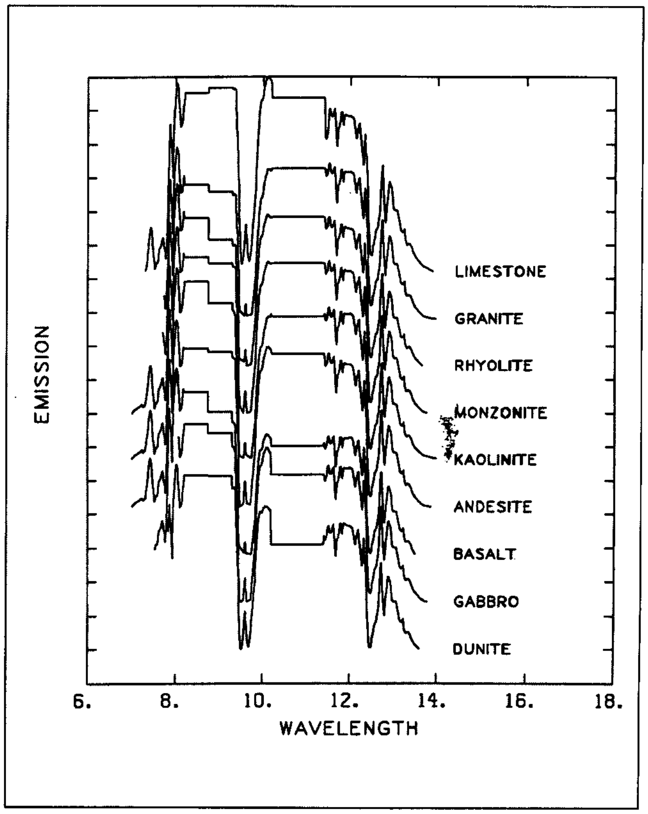
Figure 2. Summary of Rock Spectra for Each Filter Set.



2(a). Filter Set 1.



2(b). Filter Set 2.



2(c). Filter Set 3.

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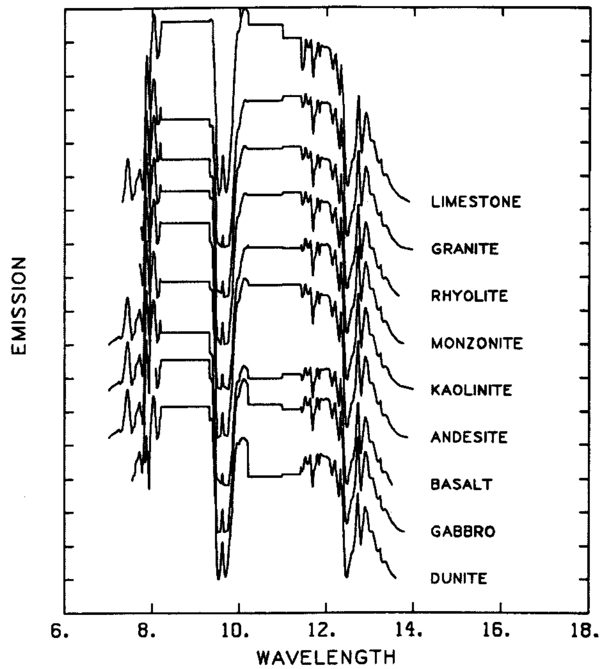
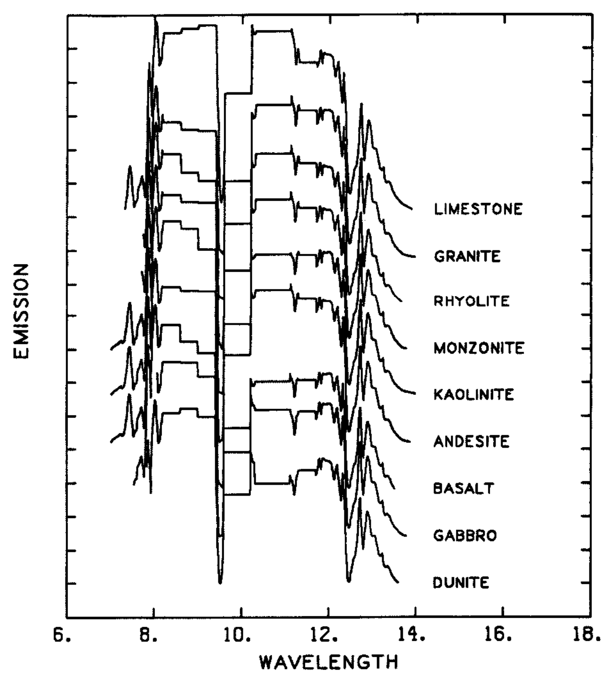


2(d). Filter Set 4.



2(e). TIMS Filters.

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In summary, it appears that either four, or less preferably three, bands in the 8 to 12 μm region would provide an excellent capability to distinguish a wide variety of rock types. A fourth band with a long wavelength cutoff at 11.8 μm, rather than 11.4 μm, provides somewhat better discriminability of basic rocks and does not appear to seriously compromise the ability to identify limestones. Given a choice of only three bands in the 8 to 12 μm region, two bands on the short wavelength side of the ozone band are preferred, with some loss in the ability to discriminate basic and ultrabasic rocks. These results must be viewed as preliminary, however, given the very limited suite of rock spectra and atmospheric properties considered. A more complete investigation would be desirable before the final selection of filter bandpasses for the enhanced Thematic Mapper.

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THERMAL IMAGING SPECTROSCOPY IN THE KELSO-BAKER REGION, CALIFORNIA

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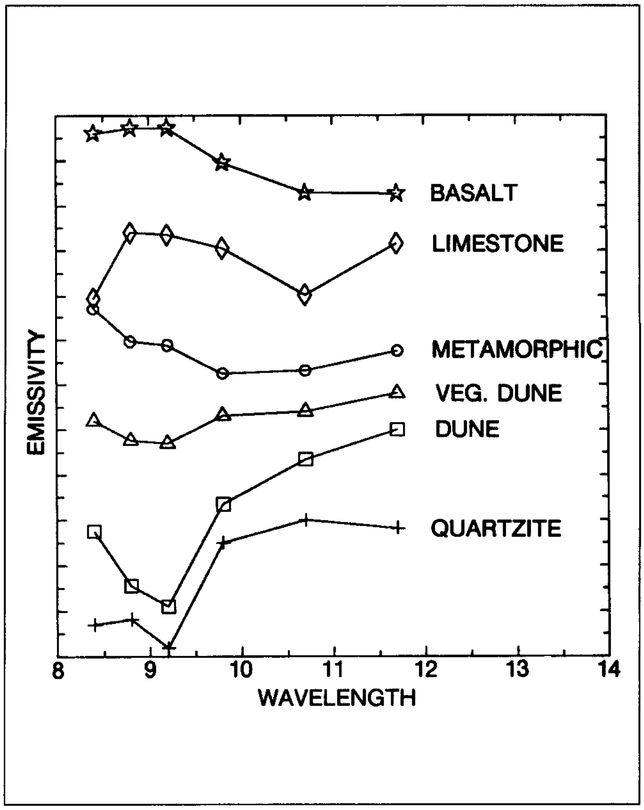
The primary objective of our study was to assess the ability of TIMS data to uniquely identify rock composition using thermal-infrared spectroscopy. For this study, we selected a region with a wide range of rock and soil types in an arid environment and compared the spectra acquired by TIMS to laboratory spectra of collected samples. A second objective was to use the TIMS data to study the potential for compositional mapping of Mars, the Moon, and other solar system bodies, in addition to the Earth.

To address these goals, a TIMS image was acquired of the Kelso-Baker region in the Mojave Desert of California at a surface resolution of approximately 7m. The image covers a range of mapped rock compositions, including the Cima volcanic complex, composed of basalt/andesite flows, the quartz-rich Kelso sand dunes, and a suite of carbonates, quartzites, and metamorphosed sedimentary rocks in the Kelso mountains, as well as a range of alluvial materials. Each of these components can be readily distinguished based on variations in their spectral properties over the six TIMS bands. We generated a principal component image of the region using bands 1, 3, and 5, and applied the technique described by Kahle and Rowan (1980) and Kahle and Goetz (1983). This image was then used to map the areal extent of each geologic component. These units were compared to existing geologic maps of the area to determine the ability of TIMS to reproduce and improve the mapping capabilities obtained by direct field investigation. This study revealed subtle compositional distinctions not previously mapped and, as has been reported previously (Kahle and Goetz, 1983; Gillespie et al., 1984), the TIMS data in many cases greatly improved the location of geologic contacts and identified small outcrops not previously mapped. Using the unit map derived from the TIMS daqta, a field reconnaissance was conducted in May 1985 to investigate the cause of the variations in spectral properties and to collect samples for laboratory analysis.

TIMS Spectral Analysis

Using data from each of the six TIMS bands, spectra of the major units were made. These spectra were generated from data calibrated for instrument response. Each spectral point was determined by averaging over areas three pixels by three pixels in size. Examples of these spectra are shown in Figure 1. Figure 1(a) gives the data offset in emissivity for clarity; Figure 1(b) shows the same data plotted with no offset. The emissivity scale is approximate, based on preliminary estimates of surface kinetic temperature.

Figure 1.
Six-Point Spectra Extracted from TIMS Image of Rock Units in the Kelso-Baker Region, California.
Spectra are offset in emissivity for clarity.



1(a).

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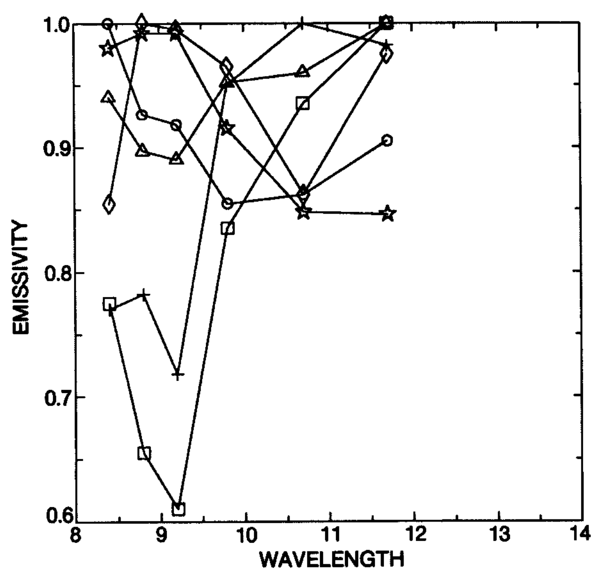

1(b). Same Data Shown in Figure 1(a), But with No Offset in Emissivity.

Field Studies

A variety of surfaces were examined to determine the composition of the rocks present and to study the origin of the units characterized by the TIMS data. The region can be roughly divided into three geologic provinces using the TIMS data alone. These consist of the basalt flows at the north end of the region, the high-silica sand dunes to the south, and the sediments and meta-sediments in the center portion of the study area.

The sand dunes have a very high silica content, as can be seen from the six-point spectra extracted from the original TIMS images (Figure 1). The spectral character of the dunes varies across the field. However, this variation is due to changes in the depth of the absorption band centered at 9.2 μm, rather than in the position of the band center (Figure 1). Field investigation revealed that these changes are produced by variations in the abundance of vegetation, which appears to be essentially blackbody in nature. Therefore, the vegetation reduces the spectral contrast, but does not introduce a second spectral component. Using the TIMS data alone, the active, vegetation-free regions of the dunes can be readily distinguished from the inactive regions stabilized by plant cover. Because of the strong differences in the spectral properties of quartz sand and vegetation, TIMS provides a useful tool for remotely distinguising regions of unvegetated, active sand from regions with low (~10%) plant cover.

The Cima basalt flows in the northern portion of the area appear very uniform in both the TIMS image and the six-point spectra (Figure 1). Even when this area was isolated, a principal component stretch performed on this region alone did not reveal significant variations. The composition of these flows does not appear to vary significantly throughout the field, consistent with the uniform spectral signature observed by the TIMS data. However, field investigation showed that a wide range of surface textures and particle sizes does occur on these flows. The surfaces observed include fresh, relatively unweathered lavas, with up to 1.5m of surface roughness, as well as smooth, desert pavements composed of basalt fragments that cover up to 90% of the surface, and smooth deposits of 1 to 10 mm cinders. These observations indicate that surface texture does not play an important role in controlling the thermal emission characteristics in this area. This finding has important implications for extrapolation of thermal-infrared spectral measurements to other regions and to other planetary surfaces. For this region, composition, rather than texture, controls the observed thermal-infrared spectral properties.

The greatest compositional variability occurs in the combined suite of sediments, meta-sediments, and igneous intrusives of the Kelso mountains. Several units are easily distinguished spectrally (Figure 1), including carbonates and quartzites. Of particular interest is a suite of rocks that have been mapped together as pre-Cambrian metamorphic rocks. This suite is readily separated into different units using the TIMS data. Field investigation of these units revealed them to be a range of silica-rich igneous and metamorphic rocks that had subtle differences in the composition and abundance of mafic and feldspar components. These subtle differences can be identified in hand specimens of the different units, but the distinctions are not simple, nor readily apparent. The increased abundance of mafic minerals in the metamorphic rocks can be seen in the spectra (Figure 1) as an absorption band near 9.8 μm. The quartz minerals also produce an observable absorption band between 8.8 and 9.2 μm, as can be seen by comparing the spectra of this material to that of the quartz sand dunes. Therefore, it is possible to infer the general composition of these rocks as containing both abundant silica-rich and mafic minerals from the TIMS spectra alone, although at present no attempt has been made to estimate the abundance of these components.

In summary, the TIMS data provide an excellent means for discriminating and mapping rocks of very similar mineralogy. The spectra obtained from the TIMS data demonstrates the differences in absorption band location and strength between different rock types, and confirm that there are systematic differences. Qualitatively, the spectral character can be used to predict the dominant mineralogy of these rocks. These predictions are confirmed by hand specimen and laboratory spectral analysis. For the rocks in this study area, it is composition, rather than particle size or surface texture, that controls the thermal-emission characteristics. These finds suggest that thermal-infrared spectroscopy can provide a powerful tool for identifying and mapping rock composition on the Earth and other terrestrial planets.

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A THERMAL EMISSION SPECTROMETER FOR IDENTIFICATION OF SURFACE COMPOSITION FROM EARTH ORBIT

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Measurement Objectives

The primary measurement objectives for an Earth-orbiting Thermal Emission Spectrometer (E-TES) are:

1. To obtain thermal-infrared spectra of sufficient radiometric, spectral, and spatial resolution to permit compositional units and mixtures to be identified and mapped; and

2. To characterize the atmospheric transmission in the 3 to 5 and 7 to 14 μm regions with sufficient accuracy to allow the spectral properties of H_2O, O_3, CO_2, and other atmospheric constituents to be separated from surface emission properties.

Measurement Requirements

The measurement requirements for the E-TES are predicated on the desire to obtain spectra of sufficient quality to uniquely identify surface materials. The noise equivalent emissivity, temperature, and reflectance requirements are summarized below.

Spectral range:	3 to 5 μm 7 to 14 μm (1430 to 715 cm^{-1})
Spectral resolution:	
3 to 5 μm band	0.1 μm
7 to 14 μm band	10 cm^{-1}
NE$\Delta\epsilon$ in spectrometer channels:	0.2% at 300K and 10 μm
NEΔT in spectrometer channels:	0.05K at 300K and 10 μm
NE$\Delta\rho$ in solar reflectance channel:	0.1% of solar flux
NEΔT in thermal bolometric channel:	0.1 K at 300K
Spatial resolution:	120m

Approach

Introduction

The potential for compositional mapping of planetary surfaces by remote thermal infrared sensing has long been recognized (e.g., Lyon, 1962; Logan et al., 1975; Kahle and Goetz, 1983). This technique has been applied successfully to the study of several solar system objects: silicate reststrahlen features observed by the IRIS experiment on Nimbus 4 have been used to study the composition of deserts on Earth (Prabhakara and Dalu, 1976); Mariner 9 IRIS spectral and the Viking IRTM broadband infrared observations of Mars revealed the presence of distinctive surface emissivity features (Christensen, 1982; Christensen et al., 1985); thermal-infrared spectral features have been observed in the lunar surface (Potter and Morgan, 1981); and strong spectral features are present in the 15 to 30 μm spectrum of Io (Pearl, 1983). However, detailed mapping of small-scale compositional units has previously been precluded by the averaging effect of the large field of view and the lack of sufficient radiometric sensitivity in the instruments available.

Recently, however, multispectral thermal-infrared scanners, with much improved sensitivity and spacial resolution, have provided striking examples of the ability to discriminate and identify the composition of geologic materials using the thermal-infrared spectral region (Kahle and Goetz, 1983; Gillespie et al., 1984). Based on these recent developments, a study was undertaken through the NASA Planetary Instrument Definition and Development Program (PIDDP) and the Santa Barbara Research Center to develop an instrument concept for a thermal-infrared spectrometer to map surface composition. That study led to the design of a Thermal Emission Spectrometer (TES) proposed for the Mars Observer Mission and a Thermal Emission Spectrometer/Radiometer (TESR) proposed for the Comet Rendezvous/Asteroid Flyby Mission. These instrument concepts in turn form the basis for the E-TES instrument to be operated in Earth orbit.

Thermal Infrared Spectroscopy

Theory

The fields of visible and infrared spectroscopy are based on the principle that atoms and molecules within a solid produce absorption bands whose wavelengths and strengths are characteristic of the composition and struction of the material observed. Visible and near-infrared reflectance spectra have been used to discriminate some geologic materials, in particular Fe, CO_3, H_2O, and OH-bearing clays and other weathering products (McCord et al, 1982a,b; Singer, 1982; Singer et al., 1984; Goetz et al., 1982). However, many geologically important elements, including Si, Al, O, and Ca, do not produce absorption bands in the visible or near-infrared. Therefore, the presence of these elements can only be inferred indirectly from the changes they produce in observed absorption bands (Hunt and Salisbury, 1970), and their abundances cannot be determined.

In contrast, nearly all silicates, carbonates, sulfates, phosphates, oxides, and hydroxides have mid-infrared spectral features associated with the fundamental vibrational motions of the major elements (Figure 1; e.g., Lyon, 1962; Hunt and Salisbury, 1974, 1975, 1976; Farmer, 1974). The vibrational energy, and therefore the wavelength, of these bands is diagnostic of both the anion composition and the crystal lattice structure. Thus, the mid-infrared spectra provide a direct means for identifying the composition of many silicates and other common materials and for interpreting the crystal structure, and therefore the mineralogy, of these materials. Used together, the mid- and near-infrared spectral observations provide unique and complementary mineral identification and improved determinations of rock compositions.

A strong theoretical framework exists for interpreting observed spectral features on the basis of ion mass, bond strength, and crystal structure (e.g., Lazarev, 1972; Farmer, 1974; Karr, 1975). Laboratory studies document the mid-infrared spectral bands of many minerals and rocks (Lyon, 1962, 1964; Hovis and

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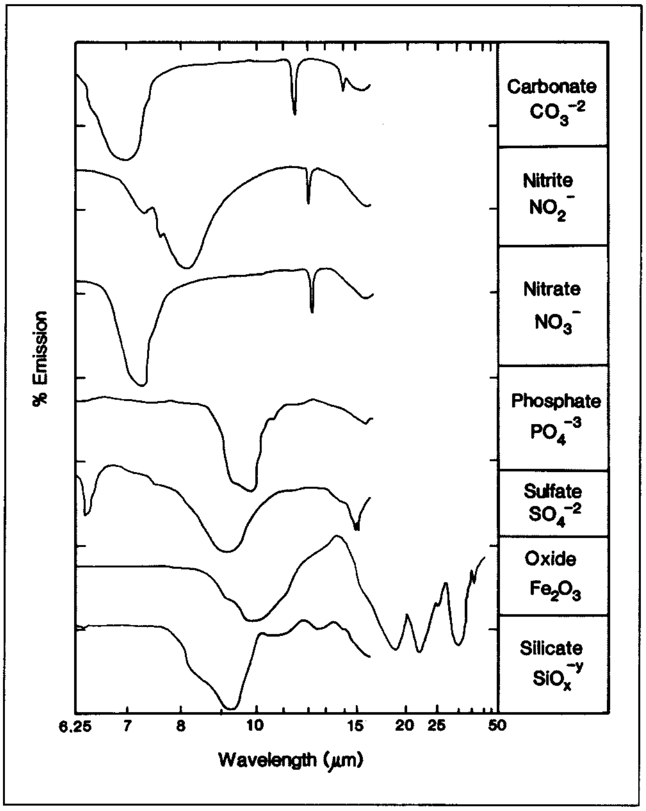
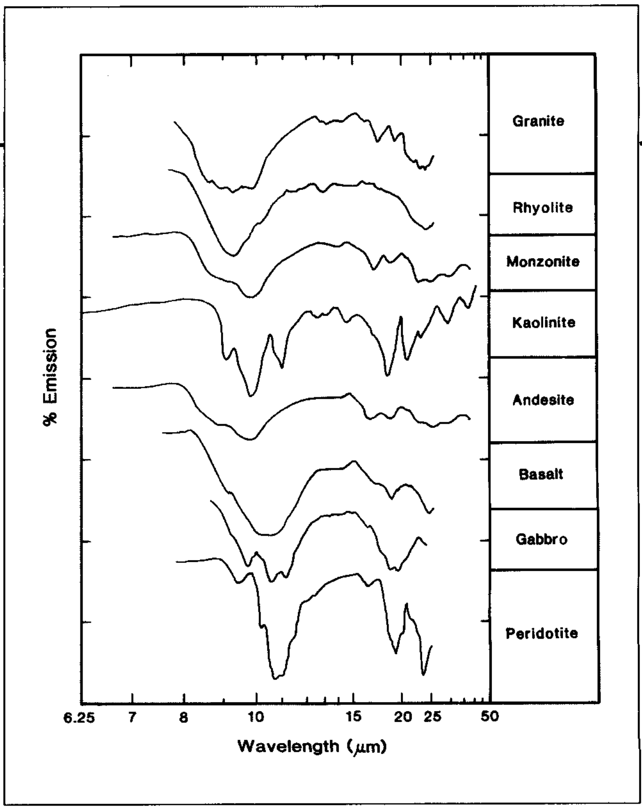


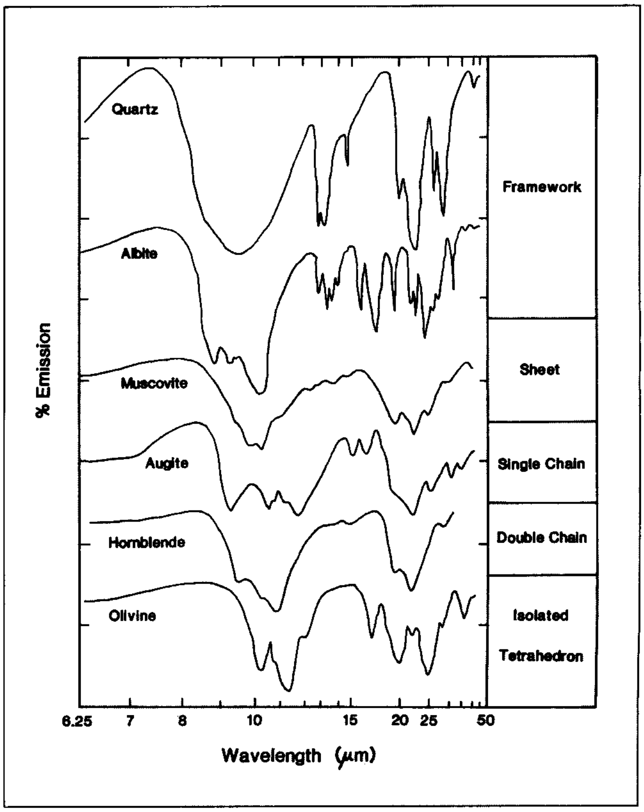
Figure 1.
Thermal-Infrared Spectra of the Major Mineral Groups.
Data in all figures are reflectance spectra converted to emission spectra using Kirchhoff's law, unless otherwise noted. The vertical axis divisions are spaced 0.1 in emissivity.

Callahan, 1966; Goetz, 1967; Hunt and Salisbury, 1974, 1975; Vincent et al., 1975; Farmer, 1974; and others), and show that the location, strength, and form of these spectral features vary systematically with composition and crystal structure (Figure 2). Vibrational motions associated with Si-O stretching modes occur between 8 and 12 μm, depending upon the mineral structure. Typically, the absorption wavelength shifts to higher frequency as the bond strength within the lattice increases (Figure 2; Vincent and Thomson, 1972; Hunt and Salisbury, 1975). Thus, in silica-bearing (SiO_2) minerals, the wavelength of the Si-O absorption band decreases from 11 to 9 μm in a uniform succession for minerals with chain, sheet, and framework structure (cyclo-, phyllo-, and tectosilicates) (Figure 2; Hunt and Salisbury, 1974; Hunt, 1980), and thus provides a direct means for discriminating minerals with these structures. Additional bands occur in silicates through the 12 to 40 μm range associated with a variety of Si, O, and Al stretching and bending motions (Figures 1 and 2). Carbonates have strong absorption features associated with CO_3 internal vibrations in the 6 to 8 μm region which are easily distinguished from the silicate bands (Figure 1; Adler and Kerr, 1963; Hunt and Salisbury, 1975). Hydroxide-bearing minerals (clays) also have characteristic mid-infrared spectra (van der Marel and Beutelspacher, 1976), with spectral features due to fundamental bending modes of OH attached to various metal ions, such as an OH-Al bending mode near 11 μm in kaolinite (Figure 2; Hunt, 1980). Phosphates and sulfates also have diagnostic absorption bands (Figure 1) associated with PO_4 and SO_4 groups, as do oxides, nitrites, nitrates, sulfides, and Cl- and F-bearing salts (Figure 1; Hunt and Salisbury, 1975), which allow these minerals to be identified if they are present.

Figure 2.
Thermal-Infrared Spectra of Minerals and Rocks.



2(a). Candidate rocks varying from high SiO_2 (granite) to low SiO_2 (peridotite). Note the shift in the 9 μm band with varying SiO_2 content.



2(b). Silicate minerals, showing the correlation between band location (vibrational energy) and mineral structure.

For natural, particulate surfaces, the spectral character of the emitted energy is modified by scattering of the outgoing energy within the surface. Thus, the physical properties, such as particle size and packing, can produce changes in emission spectra (Logan et al., 1975; Salisbury, 1985). Variations in physical properties, however, only affect the relative depth and not the position of the absorption features, and only become important as the particle size approaches the wavelength being observed (Lyon, 1964; Hunt and Vincent, 1968; Hunt and logan, 1972). Solid, smooth surfaces have the greatest spectral contrast, with emissivity differences as large as 0.6 measured in emission (Lyon, 1964). This contrast is reduced to 0.3 for roughened surfaces, and is further reduced to 0.1 and 0.05 for surfaces composed of 10 to 20 and 20 to 45 μm particles, respectively (Lyon, 1964). The radiometric requirements for the E-TES have been explicitly chosen to permit spectral contrasts such as these to be measured, something that previously has been difficult due to limitations in detector sensitivity.

The effects of scattering have been modeled using Lorentz-Lorenz theory and Rayleigh scattering (Emslie and Aronson, 1973; Aronson and Emslie, 1973), Kubelka-Munk diffuse reflection theory (Wendlandt and Hecht, 1966; Vincent and Hunt, 1968), Mie scattering theory (Conel, 1969), and Chandrasakhar scattering theory (Hapke, 1981), incorporating the particle size and the real and imaginary indices of refraction of mineral powders. Using these theories, the spectral properties of materials in emission, reflection, and transmission have been successfully reproduced.

In very fine powders (<75 μm), another diagnostic spectral feature is observed in addition to the reststrahlen band. An emission maximum occurs on the short wavelength side of an absorption band, where the real index of refraction of the powder material is equal to that of the atmosphere. The location of this maximum, referred to as the Christiansen frequency, varies with silica content in minerals, and consistently decreases in frequency with increasing silica abundance and bond strength (Conel, 1969; Logan and Hunt, 1970; Logan et al., 1973). This provides a second tool for using mid-infrared spectra to differentiate geologic materials remotely that is especially useful for fine particulate surfaces. Using the results from such studies, a quaqntitative basis can be developed for interpreting observed spectral characteristics and for remotely determining rock composition (Lyon, 1972; Vincent and Thomson, 1972; Vincent et al., 1972; Vincent, 1973; Kahle and Goetz, 1983).

Laboratory Measurements

Laboratory measurements of rocks and minerals have been made using transmission, specular and diffuse reflection, and emission techniques. Of these, transmission provides the greatest spectral contrast and permits detailed assignment of individual bands to specific ions and vibrational modes (Lazarev, 1972; Farmer, 1974). While the band locations in emission are unchanged from those measured in transmission, the relative spectral contrasts can be altered, thus making difficult direct comparison of transmission spectra and spacecraft emission measurements. Specular and diffuse reflectance techniques are also widely used (e.g., Hunt and Salisbury, 1974, 1975, 1976; Vincent et al., 1975; Logan et al., 1975; Salisbury and Eastes, 1985), primarily because of the ease with which they can be made relative to emission measurements. The greatest contrast in specular reflectance observations from polished surfaces occurs in the strongest absorption features; the contrast of diffuse reflectance measurements from powders is somewhat reduced due to the effects of scattering. However, such scattering increases the depth of weak bands relative to strong bands (Clark and Roush, 1984; Clark and Lucey, 1984), and can add diagnostic information for mineral identification and abundance determinations. The diffuse reflection can be related to emission from natural surfaces through Kirchhoff's law, which, though only strictly valid for total hemispherical reflection, has been demonstrated to hold for directional reflection and emission from mat surfaces (Hunt and Vincent, 1968). Thus, the fraction of emitted (ϵ) and reflected (R) energy are related by:

$$\epsilon = 1 - R$$

Finally, a number of direct emission measurements have been reported in the literature (e.g., Lyon, 1964; Conel, 1969; Logan and Hunt, 1970; Hunt, 1976); additional emission spectra have been acquired using the TES brassboard instrument.

Figure 3 shows a comparison of spectra acquired using diffuse reflectance and emission methods, and confirms that emission and diffuse reflectance are directly related. This comparison demonstrates that the significant spectral features are retained in reflectance and emission spectra and that sufficient spectral contrast exists to permit materials to be distinguished. The use of existing diffuse reflectance libraries to predict the presence of absorption features and to interpret spacecraft observations is thus justified.

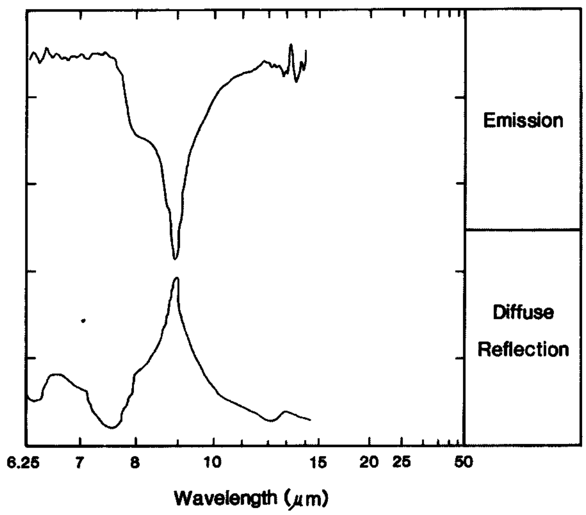


Figure 3.
Comparison of Emission and Diffuse Reflectance Spectra of Quartz.
Emission measurements were on 350 to 590 μm particles at room temperature using a cold background and a carefully controlled temperature within the sample to eliminate temperature gradients (from Brown and Young, 1975). Reflectance measurements were made on 100 to 250 μm particles, measured in total hemispheric reflection (from Hovis and Callahan, 1966).

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Natural surfaces consist of mixtures of materials produced by a complex series of surface processes. Crucial to the success of any remote sensing experiment is the ability to identify the different compositional components within the surface and to provide an estimate of their relative abundance. Figure 4 shows the spectra of three common minerals, olivine, augite (pyroxene), and labradorite (feldspar), along with the measured spectra of a mixture composed of ⅓ of each of these components. The spectral character of the feldspar and pryoxene is easily identified in the mix, and subtle changes to the spectrum produced by the olivine can also be detected. Figure 4 also shows a synthetic spectrum produced by numerically adding the spectra of each component. The spectral properties of intimate mixtures are usually complex, nonlinear combinations of the end-member optical properties (i.e., Hapke, 1981; Clark, 1983; Clark and Roush, 1984; and references therein). For dark grains with low single scattering albedo, the number of scatterings per grain decreases toward unity and the spectrum of initimate mixtures approaches the linear addition of cross-sectional areas as illustrated in Figure 4. Thus, accurate abundance estimates can be made with mid-infrared data using simple, linear combinations of spectra. Using the optical constants of the materials comprising the mixture, further refinements in the abundances, along with grain size estimates, can be made using scattering theroy (Omori, 1967).

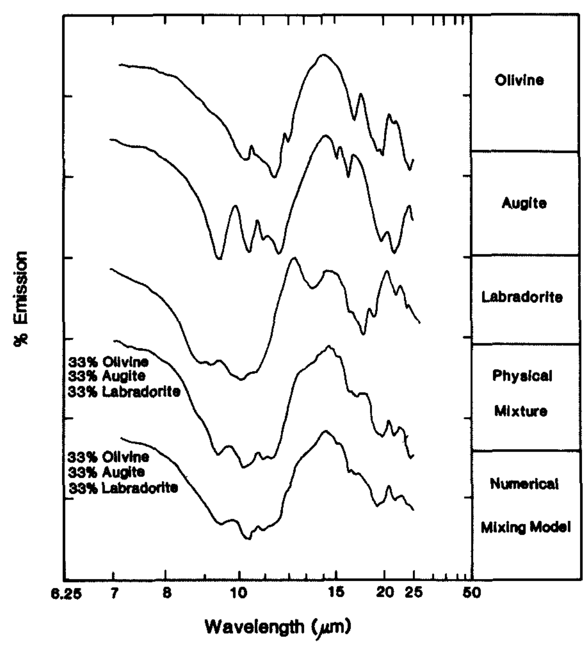
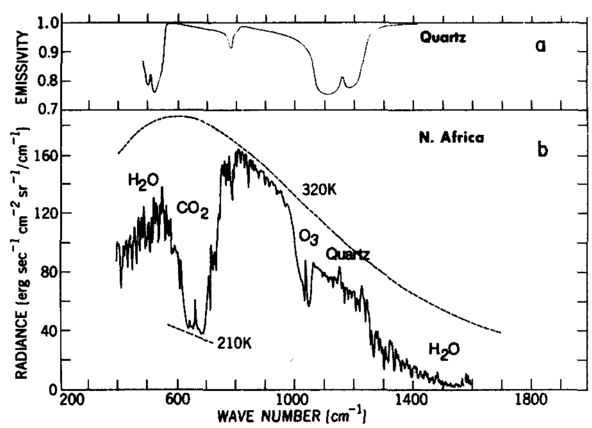


Figure 4.
Spectra of Mineral Mixtures.
Comparison of spectra of three components, together with measured and modeled spectra of a mixture of these components. Distinctive spectral features due to each component can be identified in the mixture. Note the close agreement between observed and modeled spectra of the mix. Data from Lyon (1962).

Aircraft/Field Observations

Mid-infrared spectral observations have been successfully used as a tool to determine rock compositons on the Earth (Lyon, 1972; Vincent and Thomson, 1972; Prabhakara and Dalu, 1976; Kahle and Rowan, 1980; Kahle and Goetz, 1983; Abrams et al., 1984; Gillespie et al., 1984; and others). From spaceborne thermal-infrared spectrometers, spectral features related to silicate emission bands have been observed on the Earth (Figure 5), demonstrating the potential for using these measurements to determine surface composition. However, because of the strong absorption of energy emitted from the Earth's surface by the atmosphere at wavelengths beyond 14 μm (Figure 5), most terrestrial applications have emphasized the 8 to 14 μm region and have used primarily variations in the wavelength of the 9 μm Si-O band to determine silica abundance and coordination state.

Figure 5.
Identification of Quartz Sand by Thermal-Infrared Remote Sensing.
Nimbus-4 thermal emission spectrum of the Sahara showing the spectral features of quartz between 1050 and 1200 cm^{-1} and at 800 cm. H_2O, CO_2, and O_3 features are also visible. Adapted from Hanel (1981).



The development of the six-channel Thermal-Infrared Mapping Spectrometer (TIMS) instrument has greatly improved the capability for compositional mapping using mid-infrared spectral observations and serves to directly demonstrate the usefulness of this spectral region in geologic applications (Kahle and Goetz, 1983). Fundamental to the success of this instrument is its high radiometric precision, having a noise equivalent temperature (NEΔT) of 0.1 K (Palluconi and Meeks, 1985). The TIMS instrument can define and map subtle variations in spectral characteristics and surface composition, distinguishing between silica-rich, clay-rich, volcanic, and carbonate rocks (Kahle and Goetz, 1983; Gillespie et al., 1984). In conjunction with acquisition of aircraft scanner data, field emission spectra also have been obtained which correspond well with the remotely obtained spectra, and with laboratory spectra of returned samples (Kahle, 1984). In addition, active infrared laser spectroscopy has been performed, and the ratio of reflectance at two wavelengths agrees very well with the ratio of equivalent TIMS emission measurements (Kahle et al., 1984), again confirming the correspondence between emission and reflectance observations.

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A TIMS image was acquired of the Kelso dunes and the Kel-Baker (Cima) lava field in the Mojave Desert, California, to study the identification of rocks and minerals using this image. An image was generated using a principal components stretch of TIMS bands 1, 3, and 5 (8.2 to 8.6 μm, 9.0 to 9.4 μm, and 10.2 to 11.2 μm), with the different colors observed in this image representing differences in rock and soil lithologies, as confirmed by field investigation (Christensen et al., 1985b). Silica-rich materials, such as quartz sand dunes and the quartzite unit, are easily istinguished from silica-poor rocks such as basalt/andesite flows. These differences are due to the shift in the Si-O spectral feature from 8.5 μm in the quartz-rich rocks to 9.5 μm in the basalt. Additional rock units that can be discriminated in this image include a dolomite (carbonate) and clay-rich sediments. The spectral properties of the different rock types are readily apparent in six-point spectra generated using all six TIMS bands, shown in Figure 6. In addition, these spectra show more subtle differences in spectral properties than can be represented in a color image.

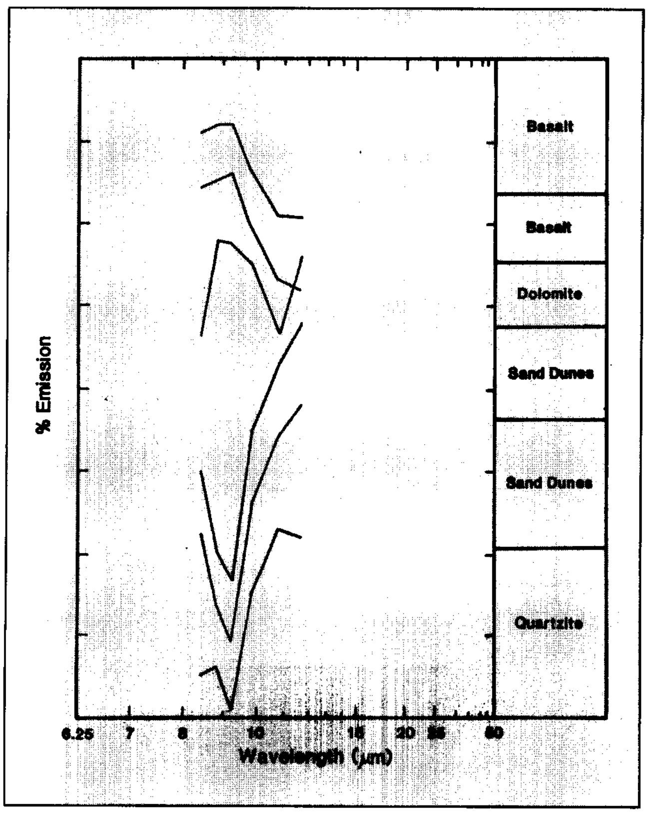
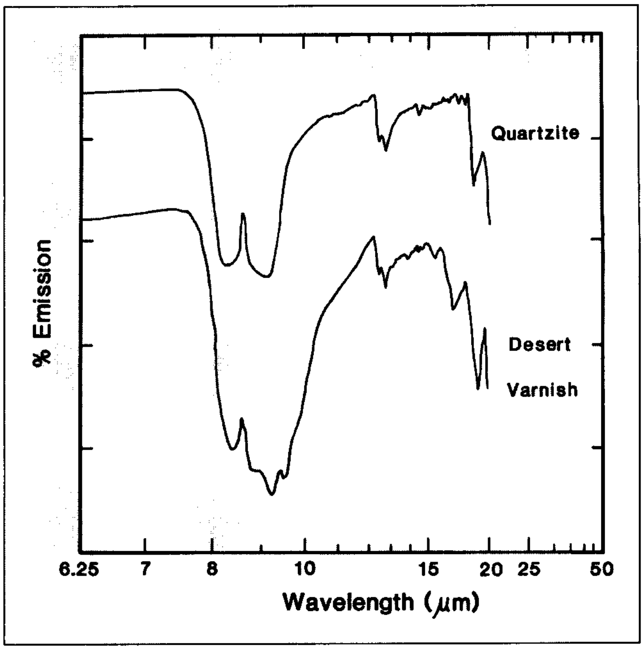


Figure 6.
Six-Point TIMS Thermal-Infrared Emission Spectra.
Spectra were extracted from the TIMS images averaged over 16 pixels. These rock groups, representing a range of Mars analog materials, are easily distinguished.

In conjunction with the TIMS observations, samples were collected and analyzed using both a commercial spectrometer (M.J. Bartholomew, personal communication) and the TES brassboard instrument. The close agreement between the TIMS spectra and the laboratory spectra demonstrates the ability to measure emission spectra remotely. Of particular interest for application to many naturally occurring surfaces are spectra of heavily coated and varnished surfaces. Figure 7 gives the laboratory spectrum of the varnished rock surface collected from an alluvial fan surface. The TIMS spectrum of this material is very similar to that of quartz-rich rocks, yet it cannot be identified as such visually, due to a coating approximately 50 μm thick that obscures the underlying rock at visible and near-infrared wavelengths. Its thermal-infrared spectrum, however, clearly shows the presence of quartz spectral features (Figure 7). When broken, this rock can be seen to be quartz-rich. These observations demonstrate the capability of thermal-infrared observations to penetrate layers that are optically thick in the visible and identify the composition of the underlying rock. This represents a significant improvement in compositional determination by thermal-infrared observations over visible and near-infrared for coated or varnished rocks.

Figure 7.
Thermal-Infrared Spectrum of Varnished Surfaces.
Laboratory spectrum of varnished surfaces, with quartzite spectrum for comparison. Quartz spectral features at 8.5 and 12 μm are easily distinguished.



The TIMS results thus illustrate that: (1) the thermal-infrared spectral region contains very diagnostic information that has been demonstrated to provide rock type identification in actual practice. Substantial differences in infrared absorption bands do exist in natural surfaces at levels that can be readily detected, provided that sufficiently high radiometric performance is achieved; and (2) the broadband spectra compare well with the more detailed laboratory spectra, indicating that spectra with the same resolution as the E-TES experiment are sufficient to uniquely determine rock composition.

Summary

There is sufficient laboratory and aircraft experience using thermal-infrared data to demonstrate the excellent potential for using these observations to provide diagnostic information for rock and mineral identification. The present and planned possibilities for thermal infrared remote sensing observations have focused on the use of multichannel imagery, rather than full spectral information, to exploit this potential. Because of their lack of spectral resolution, however, these observations do not provide a means for uniquely identifying surface materials, nor for determining the abundance of mixed surface components. The proposed Thermal Emission Spectrometer is designed to provide the spectral resolution necessary to make such determinations possible. This instrument would retain adequate spatial resolution (~120m) to discriminate individual surface units, but is not intended to provide a full imaging capability in its initial configuration. It is envisioned that the E-TES observations would be put into a spatial context by combined use with thermal-infrared Thematic Mapper (TM) images. The TM data would be used for mapping and discriminating different surface units spatially, and the E-TES data would provide the means for remotely determining the composition of the various units, using selected observations of a limited number of targets within a TM image. Used together, these two instruments would provide a very powerful tool for compositional mapping of the Earth's surface.

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CONSIDERATIONS IN MULTIBAND THERMAL SENSOR DEFINITION

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Multiband thermal sensors have been developed because there are useful variations in the spectral radiances observable through the atmosphere from common scene materials. These variations result from differences in the temperatures of the materials, differences in their emittance spectra, and spectral variations in atmospheric transmittance and path radiance. Some meteorological satellite users have successfully used multiple thermal band data, and the EOSAT decision to consider the inclusion of multiple thermal bands on the Landsat-7 Thematic Mapper represents an excellent opportunity for Landsat users to further exploit those spectral differences.

Key issues that should be addressed include: (1) number, placement, and width of spectral bands, (2) sensor spatial resolution and swath width, (3) radiometric performance specifications (accuracy, precision, dynamic range, signal response characteristics, and quantization detail), (4) provisions for performance monitoring and quality assurance, and (5) relationships to other Thematic Mapper bands and complementary sensors.

Spectral Band Specification

The required number and placement of spectral bands can be application-specific. When special knowledge permits one to invoke certain assumptions, fewer bands may be required. Anding and Kauth (1970) were among the first to identify the utility of two long-wavelength infrared (LWIR) thermal bands (8.85 to 9.35 μm and 10.5 to 11.5 μm) to correct for atmospheric effects in sea-surface temperature determinations, taking advantage of the near-blackbody spectral emittance of sea water. For detection of semitransparent clouds, they recommended a third band in the mid-wavelength infrared (MWIF) region (4.65 to 5.15 μm). (These and later-discussed spectral band combinations are summarized in Table 1.) Subsequently, Advanced High Resolution Radiometer (AVHRR) sensors in NOAA satellites have been implemented with two and three thermal bands (3.55 to 3.93 μm, 10.5 to 11,5 μm, and 11.5 to 12.5 μm) for operational sea-surface temperature measurements (McClain, 1981; McMillin and Crosby, 1984) with rms errors of approximately 1K.

Table 1. Summary of Spectral Band Combinations Discussed in the Text

Investigators	Band Limits (μm)	Purpose
Anding and Kauth (1970)	10.50 to 11.50 8.85 to 9.35 4.65 to 5.15	Sea-surface temperature with atmospheric compensation Detection of thin clouds.
AVHRR	11.50 to 12.50 10.50 to 11.50 3.55 to 3.93	Sea-surface temperature with atmospheric compensation. Nighttime cloud detection and temperature estimation.
Vincent, Thomson, and Watson (1972)	9.40 to 12.10 8.20 to 10.90	Thermal ratios for silicate mineral mapping.
Holmes, Neusch, and Vincent (1980)	11.00 to 12.00 9.50 to 10.50 8.10 to 9.10	Differentiation between acidic rock types.
Dozier (1981)	11.50 to 12.50 3.55 to 3.93	Subpixel hot-spot temperature and area estimation. (AVHRR)
Suits (1985)	11.00 to 12.00 10.00 to 11.00 8.00 to 9.10	Temperature and emissivity mapping, 1.0 μm bandwidth.
	11.00 to 11.50 10.50 to 11.00 8.00 to 8.50	Temperature and emissivity mapping, 0.5 μm bandwidth
	12.00 to 13.00 10.00 to 11.00 8.00 to 9.00	Temperature estimation only

Lyon and Patterson (1969) utilized an airborne spectrometer for identifying geological materials. Vincent (1973) and Vincent, Thomson and Watson (1972) demonstrated the use of ratios of two thermal bands (8.2 to 10.9 and 9.4 and 12.1 μm) in an airborne scanner to map silicate minerals, taking advantage of spectral emittance variations called the "reststrahlen effect." Holmes, Neusch, and Vincent (1980) recommended that three thermal bands (8.1 to 9.1, 9.5 to 10.5, and 11 to 12 μm) be utilized for better differentiation between various acidic and basic rock types, defining a geologic rock parameter. They also noted the utility of three channels in correcting for the temperature of the material and for discriminating between graybodies and selective radiators. The recent development of the airborne Thermal Infrared Multispectral Scanner (TIMS) has provided investigators with data in six LWIR thermal bands. Commonly, two or three band ratios or transformed variables are formed (e.g., Kahle and Goetz, 1983). Geologic remote sensing applications exploiting thermal inertia differences have resulted from the High Capacity Mapping Mission (HCMM) satellite program (e.g., Price, 1982).

Agriculturalists, botanists, and hydrologists are interested in temperature measurements for detecting and assessing plant stress, estimating evapotranspiration, and measuring water, snow, and ice temperatures, among other applications. Water, snow, and ice have flat spectral emittances. Vegetation is generally considered to be a good graybody radiator when ground cover percentage is high. However, when substantial amounts of soil are visible, those soils containing silicates can cause temperature errors due to their spectral emissivity features. Band selection here should be aimed at temperature accuracy in the face of expected emissivity variations and atmospheric effects. Multispectral thermal imaging also should be useful for soil mapping and agricultural monitoring, applications which, to date, have received much less attention than others. Bands useful for geologic mapping would also be appropriate here. Land-surface temperature estimates would be expected to be less accurate than sea-surface estimates, due to their more variable spectral emittances.

Urban remote sensing in thermal regions generally has received less attention than that associated with natural scenes (Goward, 1981). Thermal mapping has confirmed the existence of heat islands containing cities. Dozier (1981) described the use of one LWIR band (11.5 to 12.5 μm) and the MWIR band (3.55 to 3.93 μm) on AVHRR to estimate temperatures and sizes of industrial targets smaller than the instantaneous field of view.

In 1985, G. Suits conducted an internal, ERIM study (summarized in the following article) that explored thermal band selection for general applications. He included spectra from a variety of scene materials (rocks, soils, vegetation, water, and man-made materials) in a simulation study aimed at selecting three LWIR thermal bands. All combinations of three non-overlapping 1.0 μm bandwidths at 0.2 μm steps over the region 8.0 to 13.0 μm were examined. With accuracy of temperature estimation as the only criterion, the selected bands were 8 to 9, 10 to 11, and 12 to 13 μm. When the criterion of maximizing the capabillity to map emissivity variations was added, the choice became 8 to 9, 10, to 11, and 11 to 12 μm, with only a slight sacrifice of temperature accuracy. When 0.5 μm bandwidths were considered, the choice was 8.0 to 8.5, 10.5 to 11.0, and 11.0 to 11.5 μm. Band selection was controlled by sample emissivity variation more than by detector response and atmospheric effects. Four-band LWIR systems were not considered in that study; however, the conjecture was made that more general information on material characteristics might result from the addition of a fourth band in the MWIR region (3.5 to 5.5 μm) rather than in the LWIR region.

Suits also examined the application of Dozier's method of subpixel estimation of spatially unresolved hot targets. Using thermal band data alone, he concluded that (1) if target and background emittance are the same within each band (may be different between bands), the method permits use of MWIR and LWIR bands to accurately compute hot-target temperature and fraction of pixel fill; however (2), if not, the estimation errors can be large, e.g., ~30K in "benign" cases studied and much larger for some man-made materials.

In the 3.5 to 5.5 μm region, one finds two conflicting arguments for band location. The 3.5 to 4.0 μm band is in a "clean" atmospheric window and has been used in the AVHRR. However, it is much more susceptible to reflected solar radiation, reducing its utility for daytime applications below that afforded by a band in the region from 4.5 to 5.5 μm where, on the other hand, water vapor has an increasing effect on transmission as the wavelength lengthens. In general, there is a lack of good spectral emittance data in the 3 to 6 μm region, especially data linked directly to 8 to 14 μm measurements. Again, the potential utility of the longer MWIR wavelengths for detection of thin clouds is noted.

Radiometric Performance

Two major measures of radiometric performance are precision and accuracy. Noise-equivalent temperature difference (NEΔT) or radiance difference (NEΔL) are measures of precision. Experience with thermal scanners indicates that those with a NEΔT on the order of 0.1K produce imagery that is of good quality and pleasing to analysts. With 0.5K, images tend to be considered to have poor contrast and are less acceptable to analysts, qualitatively speaking. Images with NEΔTs of 0.25 to 0.35K ought to be acceptable for most purposes.

Accuracy relates to a sensor's capability to measure absolute temperatures. A need for this capability is not always recognized until refined remote sensing applications are developed. For instance, the Thematic Mappers on Landsats 4 and 5 do not have the capability for full-aperture temperature calibration like, for example, the capability built into the GOES/VISSR where temperatures of eight different optical components are monitored and used in temperature calibration (Menzel et al., 1981).

Temperature accuracy can be important for plant stress assessments and hydrological applications, as well as for applications like monitoring the environmental images of thermal discharges from power plants.

Thermal band ratios have been found to be useful for mapping emissivity variations and provide an excellent tool for geologists, especially when combined with ground observations. However, we believe that absolute temperature accuracy can be important in accurately assessing the actual emittances of materials (i.e., remote material identification) and in correcting for atmospheric effects. Also, temperature accuracy is important for thermal inertia calculations.

Precise temperature measurements at the sensor will be of less value if they are not transmitted to the ground with fidelity. Therefore, the temperature (radiance) range spanned and the number of quantization levels employed should be commensurate with the needs and the sensor capability. For example, the 256 levels in TMs on Landsats 4 and 5 (approximately linearly) span a temperature range of 200 to 340K or about 0.55K per video quantum level. Use of more bits or a nonlinear response characteristic should be considered in future systems.

Performance Monitoring and Quality Assurance

Performance monitoring begins with good prelaunch calibration of the system and full characterization of its relevant characteristics and their dependence on temperature and other environmental conditions. For example, spectral responses of each individual detector channel should be provided, as well as their relative and absolute response. We noted earlier the desirability for increased monitoring of onboard temperatures for use in thermal-band calibration. We applaud the announced EOSAT intent to include a capability to image the moon monthly during the lifetime of the satellite. This will provide an invaluable data base for performance assessment and monitoring; hopefully, funds will be made available to extract and analyze these data on an ongoing basis and to provide them to Landsat data users.

Relationships to Other TM Bands and Complementary Sensors

The thermal bands respond to temperature and will saturate on hot targets such as forest fires; observations of saturation in TM Bands 5 and 7 also were reported at the workshop. M. Trichel* has nnoted that short-wave-infrared (SWIR) bands on Skylab S-192, which are comparable to TM Bands 5 and 7, also saturated when viewing fires and hot targets. He suggests that TM5 and TM7 incorporate nonlinear responses at the high end to preclude saturation and provide quantitative information on such targets.

The high-resolution panchromatic band being planned for Landsats 6 and 7 is another welcome addition. Its spectral response limits should be reviewed, taking into account expected spectral contrasts and system noise performance.

The suggestion for a complementary low-resolution wide-swath sensor to provide vegetation and other monitoring capability on a one- or two-day cycle is very promising as well. The automatic spatial registration of those data with the higher resolution TM data would be of great bennefit to users.

The proposed thermal-infrared spectrometer would be a useful research instrument and would permit detailed spectral analysis of selected areas along the flight path, in conjunction with the thermal bands of TM.

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SUMMARY OF THERMAL BAND SELECTION STRATEGY

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The thermally emitted spectrum from any material surface depends upon two separate factors: the surface temperature, which is the measure of heat energy concentration available for emission, and the spectral emissivity of the surface, which is the inherent efficiency of the surface in converting and launching heat energy into radiant energy outside the surface. If we neglect atmospheric interference with remotely sensed thermal radiation, we express the relationship between emitted radiation and remotely received signals, S, in any selected narrow band with band center, λ, as:

$$S = [R_L(\lambda)][\epsilon(\lambda)][L_\lambda(\lambda,T)][\lambda\Delta],$$

where: $R_L(\lambda)$ is the calibrated radiometer response,

$L_\lambda(\lambda,T)$ = Planck's blackbody spectral radiance formula,

T = absolute surface temperature,

$\epsilon(\lambda)$ = surface spectral emissivity, and

$\Delta\lambda$ = spectral bandwidth of the radiometer.

We will know only the band center, the radiometer response, and the bandwidth of our radiometer. Therefore, when a signal, is received, we will have a relationship with two unknowns, $\epsilon(\lambda)$ and T.

Given a received signal, if one of these unknowns can be determined from ancillary information, the other can be obtained. In the case of a sea-surface temperature measurement, the surface would always be water with a known emissivity of 0.98 over the entire thermal band, so that any one band would be sufficient. Consequently, the number and spectral positions of thermal bands are chosen in this application solely for the purpose of accounting for atmospheric transmittance and path radiance variations from atmosphere to atmosphere. Anding and Kauth (1970) found that a certain pair of bands would be sufficient to nullify the atmospheric influence in cloud-free conditions.

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In the case of terrain-surface mapping, the problem is made difficult because neither the temperature nor the spectral emissivity is known from pixel to pixel. If we increase the number of bands to N bands with N different band centers, we have N signals providing N relationships but with $N+1$ unknown quantities; the $(N+1)$th unknown being the temperature. Some assertion from ancillary information is required no matter how many bands are used in order to make the solution to these relationships determinant.

When the problem of choosing band centers, bandwidths, and the number of bands is seen in this light, then one can see that arguments for placing bands next to or away from various favorite spectral regions, or for choosing narrow spectral bands in order to resolve the spectrum, or increasing bandwidths to improve signal-to-noise ratio do not address the heart of the problem of finding the needed extra relationship to achieve a determinant solution.

If we could find some functional relationship between spectral emissitivities and temperature in whatever bands we wish, i.e.,

$$f[\epsilon(\lambda_1),\epsilon(\lambda_2),\ldots,\epsilon(\lambda_N),T] \equiv \text{constant},$$

where the relationship holds even just approximately for all material samples we may encounter in the terrestrial scene, then we would have located the extra relationship and a viable band set for further refinement.

For the band choice study we performed, we chose the extra relationships to be the simple linear relation for a three-band system,

$$T = C_1\Delta S(\lambda_1) + C_2\Delta S(\lambda_2) + C_3\Delta S(\lambda_3) + C_4,$$

where: $\Delta S(\lambda)$ = difference between received signal and the signal obtained from a local reference blackbody source.

The rationale is that, given any sample material in view at low temperature, the signals received from that sample must all increase approximately linearly as the surface temperature increases. Of course, as long as the spectral emissivities are the same from pixel to pixel, this relationship must be valid over an entire image. The question remains as to how reliable this relationship is when confronted with 185 different kinds of surface materials, with each material existing at eight different temperatures spanning the expected terrestrial range, and where the received signals, combined with detector noise, were received through some type of atmosphere. Computer modeling of received signals were used to answer the question.

A modeling procedure for the selection of three spectral bands for an LWIR sensor was developed and run for optimum temperature accuracy and emissivity mapping. Over an hypothetical sample population of 185 different kinds of materials, a temperature range of 35°C, and different clear-atmospheric conditions, the optimum band choices were 8 to 9 μm (most sensitive), 10 to 11 μm, and 11 to 12 μm.

The linear relationship with temperature was a valid temperature estimator with a standard deviation of 3.66°C. The errors in temperature estimation were not normally distributed. Using the estimated temperature, one may proceed to estimate the emissivities for each pixel.

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