

11. Measuring spectra of arid lands

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Introduction

Arid lands are the most amenable to spectral remote sensing for earth resources owing to the scarcity of vegetation and the consequently favorable exposures of surfaces. For this reason, most research into the use of multispectral measurements for geologic applications has been undertaken in arid or semi-arid regions. A large amount of multispectral data from laboratory, field, aircraft and satellite instruments now exist and significant progress has been made in the interpretation and use of these data.

Laboratory data have been used to establish both a physical and an empirical basis for remote sensing, allowing theory to be related to observable spectral features of pure and mixed substances, including minerals, rocks and soils. Field acquired spectral data bridge the gap between laboratory data and remote sensing aircraft and satellite scanners. This understanding of the spectral information in remotely sensed image data has led to image processing techniques designed to select and display that information required for a particular problem to be solved. These data have application to a wide variety of problems in geologic mapping and mineral exploration.

Landsat 1-3 data enable us to determine uniquely only the presence or absence of 'limonitic' rocks (iron oxides) and the presence or absence of vegetation. The presence of limonite is inferred from measurements of the Fe^{+3} charge transfer band, whose long wavelength is found between 0.4 and 0.6 μm and the Fe^{+2} - Fe^{+3} electronic transition, whose band lies between 0.8 and 1.0 μm in reflectance spectra. The presence of vegetation is inferred from the chlorophyll structure at 0.5 to 0.65 μm . These determinations are most easily accomplished using band ratioing techniques. While unique identification of other rock materials is not possible, considerable success can be achieved in discriminating among many rock units, and delineating boundaries between them. This allows large areas to be 'mapped' with only minimal field checking to identify the mapped units. These units do not necessarily correspond to traditional geologic units, being based on spectral, and hence compositional differences, rather than differences in geo-

logical age, origin, and lithology. To achieve maximum separation of units it is often desirable to apply one of several different image processing techniques, such as a principal component transformation or construction of color ratio composites.

By extending the wavelength range of scanners further into the infrared than the range measured by the present Landsat satellite scanners ($< 1.1 \mu\text{m}$), it is possible to identify additional surface materials. Using the Thematic Mapper Simulator aircraft scanners, with additional bands centered near 1.6 and 2.2 μm , it is possible to recognize the presence of hydrous minerals from the Al-O-H vibrational overtones of these minerals, located at wavelengths greater than 2.0 μm . Recognition of such hydrous phases sometimes allows mapping of hydrothermal alteration which is usually characterized by the presence of kaolinite, sericite, and possibly other clays. Use of very narrow wavelength bands in the region between 2.0 and 2.5 μm allows specific identification of some of these minerals.

Multispectral emission data in the middle infrared (8–14 μm) show great promise for determining the relative free silica content of rocks based upon the presence of Si-O vibrational absorption. A combination of reflectance and emittance spectral data from all wavelength regions can be expected to improve greatly the separability and identification of geologic materials.

Scanner image data can also be used to map structural features. Image processing techniques such as spatial filtering or edge enhancement may be used to increase feature recognition. These techniques for use of scanner data are covered in detail in other chapters of this volume.

In this chapter we concentrate on the principles of multispectral remote sensing for geologic applications, and discuss briefly some of the related instruments and techniques for data acquisition and data interpretation. This chapter is intended only as a brief introduction to the subject. The interested reader is encouraged to turn to the numerous excellent papers which discuss the various aspects of the subject in much greater depth.

Theory and laboratory data

Spectral remote sensing is based on the determination of the interaction of electromagnetic radiation with the atoms and molecules making up the surface of the object being sensed. In terms of quantum mechanics, atoms and molecules can exist only in certain allowed energy states. Their energy can change between these allowed energy levels by the absorption or emission of energy in the form of electromagnetic radiation, just equal in amount to the difference in energy between the allowed energy levels. These energy levels are dependant upon the electronic, rotational, vibrational and translational energy of the molecular spe-

cies, which, except for the translational energy, have only certain allowed values. Because materials have characteristic energy levels, measurement of the absorption or emission of electromagnetic radiation as a function of wavelength, upon interactions with the material, sometimes allows one to infer the type of material present. However, the energy levels of only the simplest of atoms and molecules in a gaseous state can be described exactly by quantum mechanics; the rest are too complicated and can only be approximated. When the atoms or molecules are in solid form, the energy levels are modified by effects of the crystal lattice or ligand field, so description of the energy levels in solids is even more approximate. Nevertheless, spectroscopists are usually able to assign experimentally-observed spectral features in materials to certain transitions between energy levels.

The spectrum of a rock is a composite of the spectra of its constituent minerals, and the spectrum of a soil is a composite of mineral spectra plus the spectra of organic materials and water. The spectral features of minerals, rocks and soils are produced by either electronic or vibrational processes; rotational features are found only in gases where the molecules are free to rotate. Electronic transitions require more energy than vibrational processes and most of these spectral features are located in the ultraviolet and visible range with only a few features, notably due to iron, extending into the infrared [1]. Electronic transitions produce spectral absorption features which are usually very broad. Fundamental vibrational processes give rise to much narrower spectral features in the middle and far infrared (MIR, FIR). None occur at wavelengths shorter than $2.5 \mu\text{m}$ [2]. The range between 1.0 and $2.5 \mu\text{m}$, referred to as the near or short wavelength infrared (SWIR), is the 'overtone' or 'combination tone' region. In this region there are abundant diagnostic spectral features due to the excitation of overtone and combination tone vibrations. Because, in remote sensing, the visible and SWIR are usually observed in the reflection mode and the MIR in the emission mode, we will discuss the two regions separately.

When electromagnetic radiation impinges on a material, energy will be selectively absorbed at those wavelengths corresponding to the energy required to raise the energy state of the constituent particles from one energy level to another. If a continuous spectrum of electromagnetic radiation is reflected from a surface, a depletion of radiation will be observed at these wavelengths. The position and relative strength of these absorption features are the key to material identification.

The most widely used spectral remote sensing technique uses the sun as a source of radiation. The sunlight illuminates the surface, interacts with it, and is reflected into the detector, which measures the intensity as a function of wavelength, so we refer to this as reflectance spectroscopy. In reality the radiation arriving at the surface is scattered by the material in all directions; some penetrates the material where it is preferentially absorbed at wavelengths charac-

teristic of the material, and then is scattered in the direction of the detector. It is this absorption which produces the spectral signature of the material.

The visible and near infrared spectra of rocks and minerals have been discussed by numerous authors. One of the largest collections of such spectra is given in a series of papers by Hunt and Salisbury [1, 3, 4, 5] and by Hunt et al. [6-12] which contain the spectra of over 200 minerals and 150 rock samples. Most of the laboratory spectra illustrated here are originally from that important collection.

The most common components of minerals and rocks, namely silicon, aluminum, and oxygen do not possess energy levels such that transitions between them can yield spectral features in the visible and near infrared range. Consequently, no direct information concerning the bulk composition of geological materials is available in this range. However, considerable indirect information is available because the crystal structure imposes its effect upon the energy levels, and therefore upon the spectra of specific ions present in the structure [13-15].

The electronic energy levels of an isolated ion are usually split and displaced when located in a solid. This is particularly true for the transition metal ions, iron, copper, nickel, cobalt, manganese, chromium, vanadium, titanium, and scandium. These new energy values are primarily determined by the valence state of the ion (for example, Fe^{2+} or Fe^{3+}), and by its coordination number and site symmetry. The spectrum is also affected by the type of ligand formed (for example, metal-oxygen), the extent of distortion of the metal ion site from perfect, and the value of the metal-ligand interatomic distances. Although all the electronic features in the spectra are derived from the transition metal ion, the indirect information provided is about the type of crystal field in which it is located, and it is the type of indirect evidence that provides information concerning the bulk structure of minerals and rocks from crystal field effects [15].

In naturally occurring geological materials most spectral information in the visible and near infrared reflectance spectrum is dominated by the very common presence of iron. Examples of the spectra of some iron-bearing minerals are shown in Figure 1 (after [16]). The rapid fall off in reflected intensity toward the ultraviolet is due to the very strong intervalence charge transfer transition between the ferric and oxygen ions. The features marked with arrows are crystal field transitions.

In the short wavelength infrared, features are observed due to the overtones and combinations involving materials that have very high fundamental frequencies. The most common of these near infrared bands involve the OH stretching mode, and water. In the laboratory spectra of minerals and rocks, whenever water is present two bands appear at $1.4 \mu\text{m}$ and at $1.9 \mu\text{m}$. Other bands will also appear depending upon the form of the water in the mineral. There is only one OH fundamental stretching, which occurs near $2.77 \mu\text{m}$. This fundamental OH stretching mode may form combination tones with other

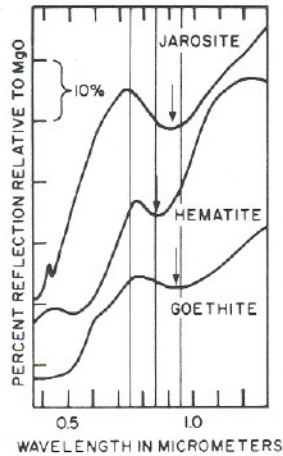


Fig. 1. Visible and near infrared spectra of some iron bearing minerals [16].

fundamentals, including lattice and vibrational modes. In particular, such combinations with fundamental Al-OH or Mg-OH bending modes produce features near 2.2 or 2.3 μm , respectively. Figure 2 [15] displays typical spectra of minerals that contain hydroxyl groups (muscovite, kaolinite) or water (montmorillonite, gypsum, and quartz). The vertical lines mark the centers of the various spectral features.

In addition to the water and OH features, the carbonate minerals display somewhat similar features between 1.6 and 2.5 μm , which are due to combinations and overtones of the four fundamental internal vibrations of the planar CO_3^{2-} ion. These fundamental vibrations produce five features in the near infrared near 1.9 μm ; 2.0 μm ; 2.16 μm ; 2.35 μm ; and 2.55 μm [15]. Figure 3, after Hunt and Salisbury [3], shows the spectra of some carbonates. In addition to the carbonate bands apparent in all four spectra, the magnesite and rhodochrosite have a broad ferrous ion band centered near 1.1 μm .

In the middle infrared (MIR) (5–40 μm) region of the spectrum, the emission spectrum of the surface material can be measured. Electromagnetic black-body radiation being emitted as a continuous spectrum will be differentially absorbed before exiting the material.

Laboratory measurements of middle infrared spectra of rocks and minerals show many diagnostic features. The region between 8 and 14 μm holds the most promise for remote sensing because this is an excellent spectral window in the Earth's atmosphere and is also the region of maximum thermal emission at terrestrial surface temperatures [17]. Within this spectral range, the most prominent spectral features are due to silicon-oxygen stretching vibrations. These features change wavelength and intensity with varying composition and struc-

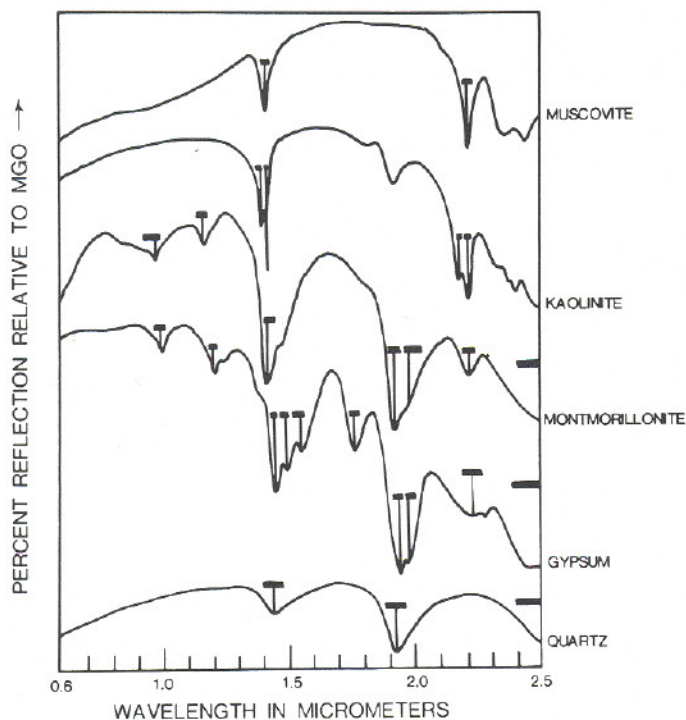


Fig. 2. Visible and near infrared spectra of some hydroxyl and water bearing minerals [15].

ture [18–20, 2, 21]. Lyon and Patterson [22] indicated that these features (known as ‘Reststrahlen’ bands in reflectance spectra of polished samples) shift to shorter wavelengths as silica content increases.

The most complete set of laboratory spectra of rocks available for the MIR are the transmission and reflection spectra of Hunt and Salisbury [20, 2, 19]. It is important to note that the transmission spectra were obtained using two different sample preparation techniques, the conventional method of the powdered specimens being compressed in KBr pellets, and by deposition of thin layers of fine particles onto a mirror. The principal Christiansen peaks [23] appear in the spectra of the deposited particles (with the particles on the mirror in air), but not in the spectra obtained from the samples in the KBr pellets. This is because the Christiansen peaks, which are located at or near the wavelength at which the refractive index of the material matches that of the medium in which it exists, are minimized in the KBr pellets where the refractive index is closer to the rock samples than is the refractive index of air. However, apart from this difference, most of the absorption features are similar. The reflection spectra measured using polished rock surfaces display more significant differences. Emission

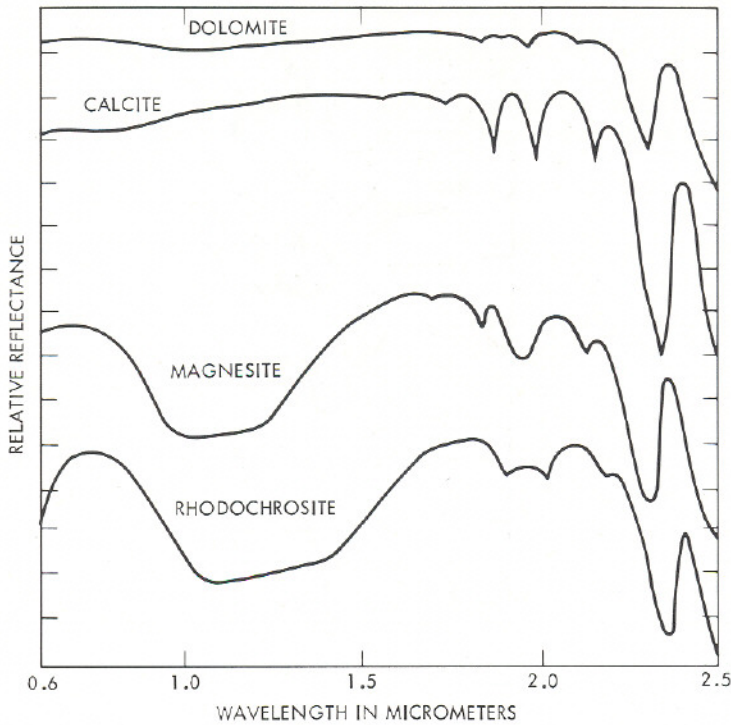


Fig. 3. Visible and near infrared spectra of some carbonate minerals [3].

spectra, which would be the most applicable to remote sensing of emitted radiance are more difficult to measure and interpret. Most of the differences between the spectra obtained in the various modes have been shown both theoretically and experimentally [23, 24, 25] to be dependant upon such variables as particle size, surface roughness, packing density, and near-surface temperature gradients. These parameters affect both the intensity and location of spectral features. Nevertheless, we use the laboratory spectra as a key to interpreting the spectra of natural surfaces. In many cases there are a sufficient number of identifiable spectral features for mineral recognition. In Figure 4 we show a few of the laboratory spectra of Hunt and Salisbury [19, 20, 2] illustrating the features likely to be detected by remote sensing. In the silicate rocks (quartzite, quartz monzonite, monzonite, latite, olivine basalt), the broad, deep decrease in transmission between 8 and 11 μm has been identified by Hunt and Salisbury as being due to Si-O stretching vibrations. The depth and position of the band have been shown to be related to the structure of the constituent minerals and are especially sensitive to the quartz content of the rocks. In the carbonate rocks (limestone, dolomite), the most prominent feature is the C-O

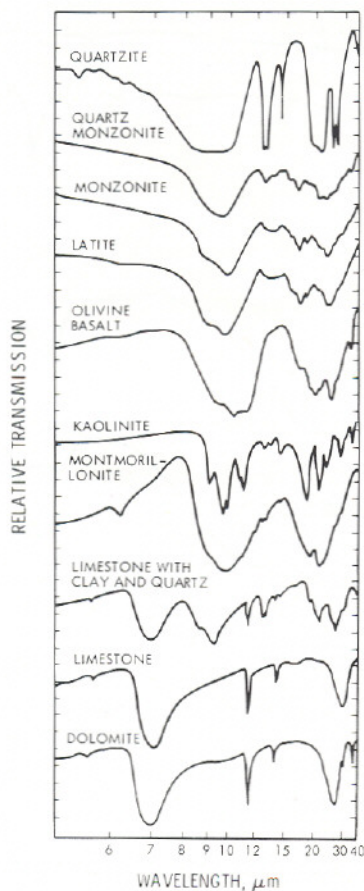


Fig. 4. Middle infrared spectra of some rocks and minerals [19, 20, 2].

asymmetric stretch which, near $7 \mu\text{m}$, lies outside the 8 to $14 \mu\text{m}$ atmospheric window. Throughout the 8– $14 \mu\text{m}$ region, the carbonate spectra are almost flat or show a gradual rise except for the narrow, out-of-plane bending feature near $11.5 \mu\text{m}$. Spectral features between 8 and $14 \mu\text{m}$ in the clays (kaolinite and montmorillonite) are ascribed by Hunt and Salisbury to various Si-O-Si and Si-O stretching vibrations and an Al-O-H bending mode. The montmorillonite features are less distinct than those in the kaolinite, because the numerous exchangeable cations and water molecules in the montmorillonite structure allow many different vibrations.

Field data

Acquisition of spectra of undisturbed surfaces in the field is an important step between the understanding of laboratory spectra of carefully prepared small samples and the interpretation of airborne or satellite spectrometer or multi-spectral scanner data of large areas of the natural surface materials. Several field portable instruments are now commercially available, with a variety of different wavelength ranges, spectral resolutions, fields of view, sensitivity, and data recording systems. The data from three experimental systems developed at the Jet Propulsion Laboratory will be described here, the Portable Field Reflectance Spectrometer (PFRS), the Hand-Held Ratioing Radiometer (HHR), and the Portable Field Emission Spectrometer (PFES).

The PFRS [26], see Figure 5, is a self-contained portable field instrument which measures surface reflectance in the wavelength region from 0.442 to 2.53 μm with moderate resolution ($\Delta\lambda/\lambda = 0.04$ from 0.44 to 0.7 μm and 0.015 from 0.7 to 2.53 μm). The instrument utilizes a circular variable filter and a cooled lead-sulfide detector. With the tripod-mounted optical head approximately 1.3 m above the surface, the field of view is rectangular and covers 200 cm^2 . The reflectance spectrum of a natural surface illuminated by the sun is taken, followed immediately by the taking of a spectrum of a standard (fiberfrax, a ceramic wool) placed over the surface in the same orientation. Each scan takes thirty seconds and the data are recorded on a digital cassette in a backpack containing the recorder, instrument electronics and power supply. By taking a point-by-point ratio of the spectra of the surface and the standard, a bidirectional reflectance spectrum, independent to the first order of source and atmospheric conditions and surface attitude, is obtained.

Some typical spectra taken using the PFRS are shown in Figure 6. These illustrate most of the features discussed in the previous section. The gaps at 1.4 and 1.9 μm are imposed because strong atmospheric water absorption bands reduce the incident solar radiation below a useable level. Curve 1 is the spectrum of unaltered tuff fragments and soil and can be seen to be spectrally quite flat. Curves 2 and 3 are argillized andesite and silicified dacite. Both spectra have iron absorption features around 0.9 μm and strong OH absorption near 2.2 μm . The spectrum of an opaline tuff, curve 4, shows a much weaker iron absorption with a still fairly strong OH feature. A typical carbonate – a tan marble is shown in curve 5, with a strong carbonate band near 2.35 μm . Finally, curve 6, the spectrum of ponderosa pine, illustrates the chlorophyll absorption features in the visible and near IR, with the sharp rise in reflectance around 0.7 μm typical of most vegetation. Thousands of field spectra of surface materials have now been obtained [27]. Use of these data has demonstrated that the spectral features noted in the laboratory are indeed present in naturally occurring materials in situ in sufficient strength to be used for remote sensing for geologic applications [28–30].



Fig. 5. The Portable Field Reflectance Spectrometer.

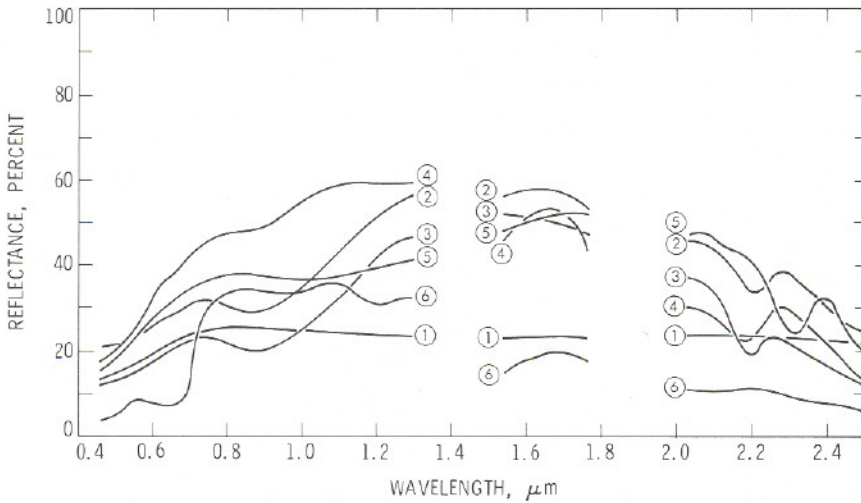


Fig. 6. Field-acquired reflectance spectra of (1) unaltered tuff fragments and soil; (2) argillized andesite fragments; (3) silicified dacite; (4) opaline tuff; (5) tan marble; and (6) ponderosa pine [35].

The Hand-Held Ratioing Radiometer (HHRR) has been developed for use in identifying rocks and minerals in the field (see Fig. 7). This small field instrument is an outgrowth of analysis of laboratory spectra and field spectra from the PFRS. The HHRR is a self-contained, dual-beam, ratioing radiometer with digital readout. It contains two optical trains, each containing two repeater lenses and a cooled lead-sulfide detector. One of the trains is adjustable so that measurements can be made from distances of 1 meter to infinity. The optical trains are intersected by a set of two, coaxially-mounted filter wheels each containing five interference filters. Filters with band passes as narrow as $0.01 \mu\text{m}$ can be used in the region 0.4 to $2.4 \mu\text{m}$. The instrument measures the surface radiance in the two channels and simultaneously displays the ratio.

There is a need for geologists to identify and rapidly map the composition of surface materials. In particular, clay minerals and other OH^- bearing silicates can be difficult to identify in the field. The normal procedure is to return the samples to the laboratory for X-ray analysis. As shown in the previous section, clays and carbonates have unique spectral properties in the 2 – $2.5 \mu\text{m}$ region. The HHRR provides a means to identify a number of mineral and rock types. By using properly chosen spectral filters, and ratioing the signals to remove the effect of topography (i.e. directional effects) on the brightness measured, a number of materials can be identified uniquely. Table 1 lists one choice of filters used in HHRR (and also in the Shuttle Multispectral Infrared Radiometer (SMIRR) discussed in the last section of this chapter). Ratio values are shown in Table 2 for several minerals, using these filters. It can be seen, for instance that



Fig. 7. The Hand-Held Ratioing Radiometer.

Table 1. Spectral bands for HHRR and SMIRR.

Channel	Center (μm)	Half-power Bandwidth (μm)
1	$0.5 \pm .02$	0.1
2	$0.6 \pm .02$	0.1
3	$1.05 \pm .02$	0.1
4	$1.2 \pm .02$	0.1
5	$1.6 \pm .02$	0.1
6	$2.1 \pm .02$	0.1
7	$2.17 \pm .005$	0.02
8	$2.20 \pm .005$	0.02
9	$2.22 \pm .005$	0.02
10	2.35 ± 0.15	0.06

Table 2. Normalized band-ratios of calculated responses to laboratory reflectance data for HHRR filter bandpasses.

Band-ratio	Alunite	Kaolinite	Montmorillonite	Calcite
2.10/2.20	1.11	1.35	1.26	1.00
2.10/2.22	0.93	1.25	1.53	1.01
2.17/2.20	0.86	1.07	1.32	1.01
2.17/2.22	0.72	0.98	1.59	1.01
2.17/2.35	0.72	1.02	2.02	1.11

montmorillonite and kaolinite yield very different ratio values for filters centered at 2.10 and 2.17 μm . For a number of materials, HHRR can thus be used as an analytical tool in the field. The instrument can be used on the ground or from a moving vehicle or aircraft.*

The Portable Field Emission Spectrometer (PFES) used the same electronics and digital recording backpack as the PFRS, with a new filter wheel and detector system allowing emission spectra to be measured in the 3–5 μm and 8–14 μm ranges. Three PFES spectra of monzonite, quartz monzonite, and quartz are shown in Figure 8. Here we see the Si-O absorption feature becoming progressively deeper with increased quartz content of the rock. The instrument will continue to be used to test the feasibility of using measurements of emission spectra of naturally occurring materials as a remote sensing technique.

* HHRR is now being manufactured by Barringer Research, Inc., Golden, Colorado, U.S.A.

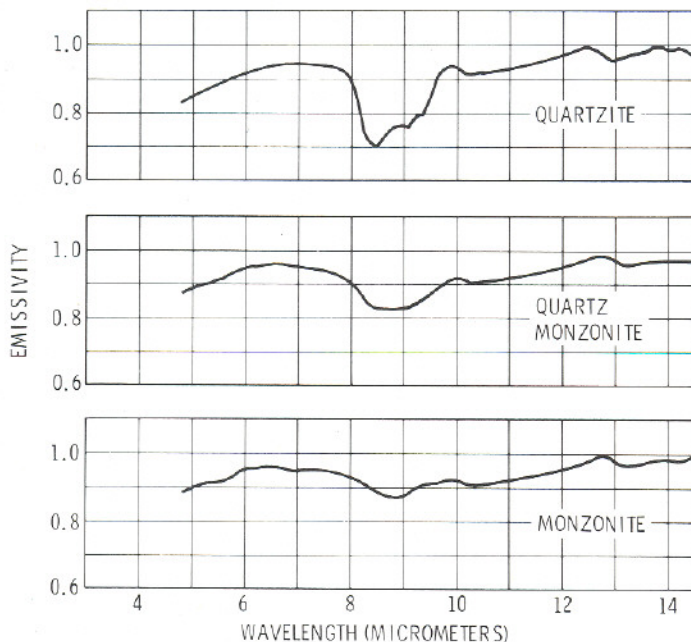


Fig. 8. Field-acquired emission spectra.

Aircraft and satellite spectral measurements

Aircraft and satellite instruments observing the Earth in the visible and infrared wavelengths, exist both as profilers, taking measurements in a series of points lying on a line along the track of the aircraft or spacecraft, or as scanners, building up an image of a scene by scanning back and forth across the tract while allowing the motion of the craft to create the second dimension of the image. Radiometers measure the radiance from one, or possibly more discrete broad band portions of the spectrum, while spectrometers measure data from a few medium width wavelength bands or up to hundreds of narrow wavelength bands or channels.

Aircraft data can be used as an intermediate step between field acquired data and data acquired from orbiting satellite systems. These data can be used both to prove that a remote sensing technique will work prior to the construction and deployment of expensive orbiting systems, and to examine in more detail areas which appear, on satellite data, to be of interest but where better spatial detail is required. Satellite data have the advantages of covering large portions of the Earth, often many times, under nearly uniform viewing conditions.

Data from the Landsat satellite system and from three of NASA's experi-

mental multispectral aircraft scanners will be discussed here, to illustrate some of the geologic information that can be obtained in arid regions from such instruments. Interpretation of the image data is based on an understanding of the spectral characteristics of the surface materials as discussed in the previous sections.

By far the best known and most widely used multispectral satellite data of the Earth are from the Landsat satellites. These are a series of satellites (four to date, with more planned) launched at intervals so as to provide continuous coverage from 1972 onward. The instrument on the first four satellites of interest here is the Multispectral Scanner (MSS) which has four channels in the spectral region 0.5 to 0.6 μm (channel 4), 0.6 to 0.7 μm (channel 5), 0.7 to 0.8 μm (channel 6) and 0.8 to 1.1 μm (channel 7). The data are acquired over a swath width of 185 km, from a sun-synchronous orbit, with repeating coverage of the Earth every 18 days. The instantaneous field of view (or picture element, pixel, size) is approximately 60 m \times 80 m. The data are available in either digital or image format from the EROS Data Center in Sioux Falls, South Dakota. In addition, on Landsat 4, the new Thematic Mapper was also flown with wavelength channels as shown in Table 3.

The use of Landsat data to study landforms of arid regions is described in other chapters. The discussion here is concerned with the geologic information that can be derived from spectral MSS data. Photographic Landsat data products have some use in lithologic discrimination. A black and white image from a single MSS channel will allow some separation of rock units based on their brightness and textural differences. Color composites of three bands will allow better separation, based on spectral (color) differences between units. However, the best success is achieved if the Landsat data are digitally processed to enhance the particular features of interest. Color ratio composites have proven to be very useful in emphasizing spectral differences between units while subduing the unwanted brightness differences related to topographic effects [31, 26, 32]. Because the MSS bands are situated in the visible and near infrared regions of the spectrum between 0.5 to 1.1 μm , these color ratio composites are well suited for identifying the presence of iron oxides, as discussed in the previous sections. The 'limonitic' rocks are often associated with hydrothermal alteration which may be related to economically important mineralization. However such color composites will also indiscriminately indicate areas where iron oxides have no relationship to hydrothermal alteration such as iron-oxide rich volcanic or sedimentary rocks or some areas of weathered alluvium. Additionally, areas of economically important hydrothermal alteration may not happen to contain significant limonitic material so they will fail to be identified by the MSS. Possible solutions to resolving some of these ambiguities can be found by looking at either narrower wavelength band data to help identify particular iron oxides, or by examining data from longer wavelengths in the SWIR as provided

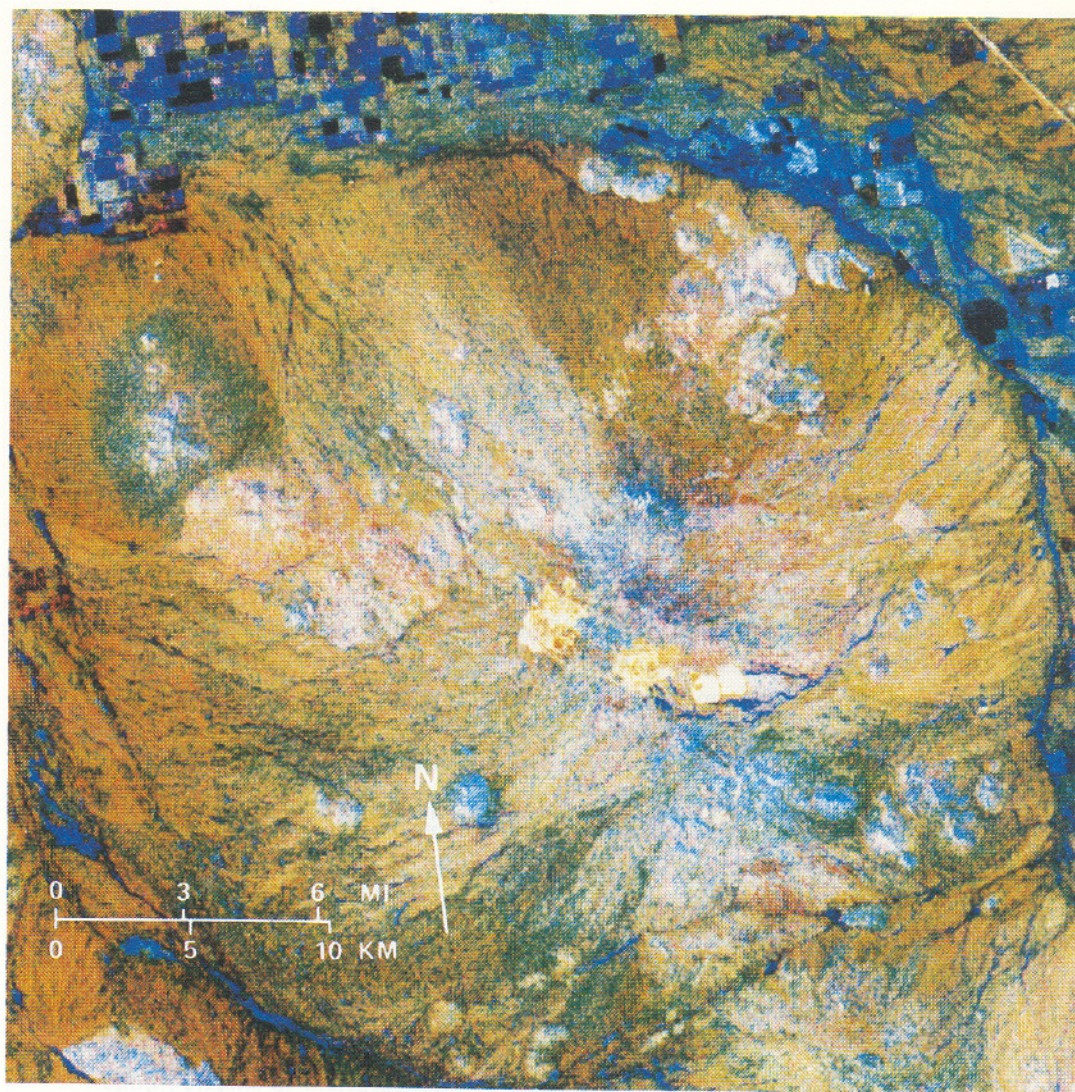


Fig. 9. Landsat color ratio composite of Silver Bell Mining District, Arizona [36].

by the Thematic Mapper, to look for evidence of the OH bands of the layered silicate minerals, which are also often associated with hydrothermal alteration [28, 33–35].

An example of an Landsat MSS color ratio composite is shown in Figure 9 [36]. This is an image of the Silver Bell mining district, near Tucson, Arizona in the Southwestern desert region of the USA. Band ratios $4/5$, $5/6$ and $6/7$ are

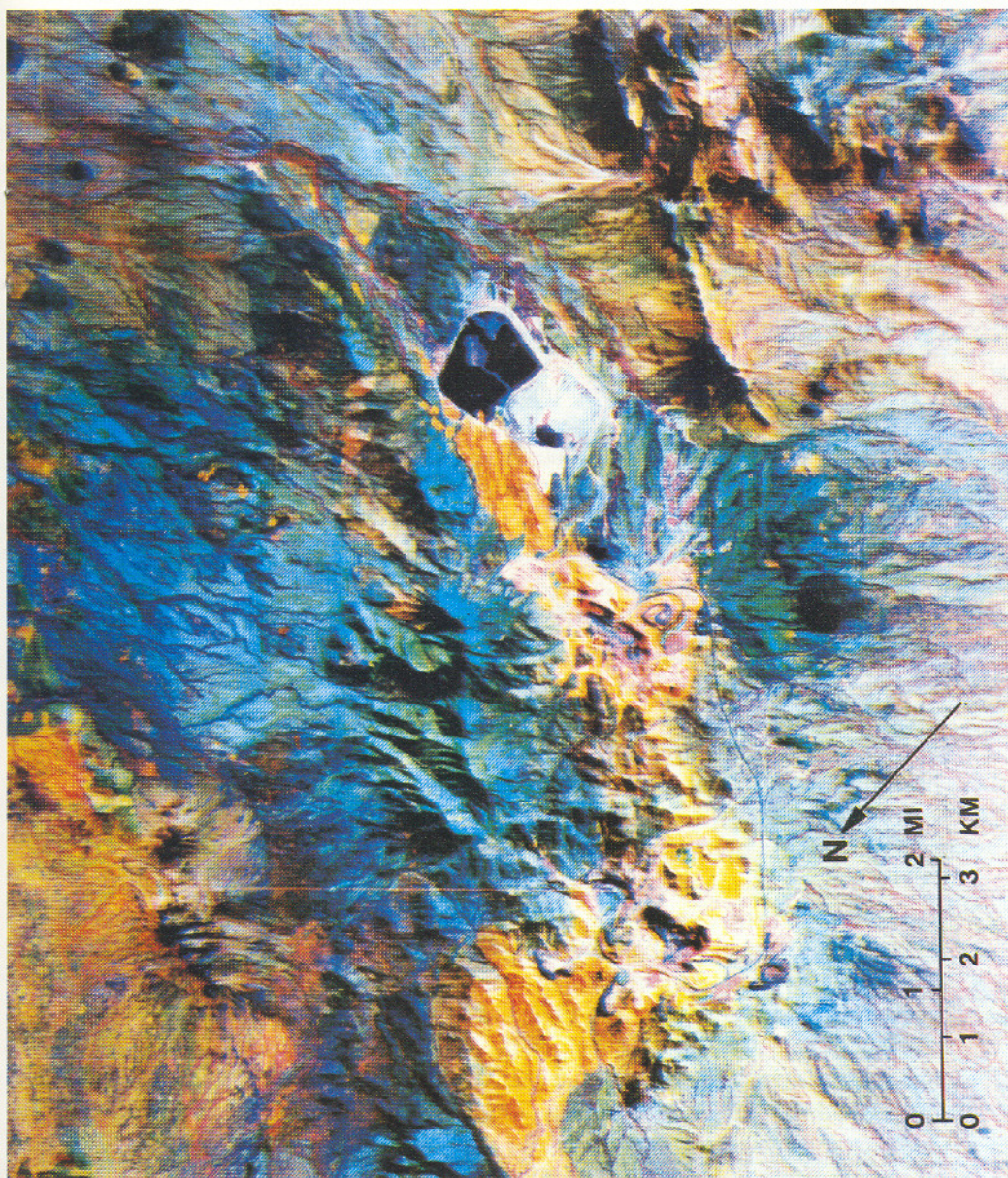


Fig. 10. Thematic Mapper Simulator color ratio composite of Silver Bell Mining District, Arizona [36].

displayed in blue, green, and red respectively. The two irregular shaped yellow areas near the center are two open pit porphyry copper mines. The nearby yellow squares are leaching pits. The orange areas north of the leach pits, around the pits, south of the right pit and in the right corner all contain iron-oxide bearing materials. Some of these rocks are hydrothermally altered but some are unaltered sedimentary red beds.

Aircraft flights were made in this area with two of NASA's multispectral scanners. One, the M²S 11-channel scanner has 10 channels between 0.4 and 1.1 μm and one middle IR channel, and the other scanner, the Thematic Mapper Simulator has the 8 channels shown in Table 3. (The Thematic Mapper Simulator is an aircraft equivalent (simulator) of the Thematic Mapper, the new scanner on Landsat 4.)

Analysis of color ratio composite images from the M²S 11-channel scanner at other nearby mining districts suggests that hematitic areas could be separated from limonitic/goethitic areas because of the narrowness of the bands on this particular scanner. It is possible that the shift of the Fe^{+3} absorption band from 0.85 to 0.95 due to the change from hematite to limonite/goethite was being detected, but this still needs to be verified in the field [36].

This same scanner, though, showed essentially no new information at Silver Bell other than improved spatial resolution. A great improvement was realized at Silver Bell, however, with data from the Thematic Mapper Simulator. These data are shown in Figure 10 with the ratios 0.83/1.15, 0.66/0.56, and 1.65/2.22 displayed in blue, green and red. These ratios were chosen so that iron-oxide minerals would appear green and hydrous minerals red. Materials with both of these substances present should then appear yellow. The yellow areas do indeed correspond to the field mapped areas of hydrothermal alteration. The sedimentary red beds south of the pits, which were indistinguishable from the altered rocks on the Landsat MSS image, now appear green and hence are clearly distinguishable [36].

As previously mentioned, the other limitation on the ability of Landsat MSS data to identify areas of hydrothermal alteration, i.e., areas with hydrous minerals but no iron oxides, has also been shown to be identifiable if the correct wavelength channels are available. NASA's 24-channel aircraft scanner was flown over Cuprite, Nevada, also in the American Southwestern Desert. This scanner had channels in the visible and near IR very similar in wavelength to those on the Thematic Mapper Simulator, including those centered near 1.6 and 2.2 μm . Here, despite the lack of significant iron oxides, color ratio composites clearly delineated areas which were bleached and highly altered, even separating into various grades of alteration [37].

The use of spectral emittance data in the middle infrared (MIR) for mineral identification has also been demonstrated with NASA's 24-channel scanner data [38, 39] following earlier demonstrations with 2-channel data [40-42]. The 24-

Table 3. Thematic Mapper (TM) and Thematic Mapper Simulator (TMS) channels.

TMS Channel	TM	Wavelength (μm)	TMS Channel	TM	Wavelength (μm)
1	1	0.45–0.52	5	–	1.00–1.30
2	2	0.52–0.60	6	5	1.55–1.75
3	3	0.63–0.69	7		2.08–2.35
4	4	0.76–0.90	8		10.4–12.5

channel scanner had 6 channels between 8 and 13 μm . A principal component color composite image using three bands is shown in Figure 11, from data acquired over Tintic, Utah, a semi-arid geologically complex area of high relief and moderate vegetation. In general, the red colors represent rocks in which quartz is a major constituent, while green indicates non-silicate rocks (carbonates) and vegetation. The more intense the red, the higher the quartz content of a unit, illustrating the dominant effect of the Si-O spectral features in this wavelength region. It is significant, for instance, that quartz monzonite and quartz latite appear pinkish in the image while monzonite and latite appear blue. This image helps demonstrate the promise this spectral region holds for geologic applications.

Ongoing Research and Future Systems

Based on the encouraging results to date of multispectral remote sensing for geologic applications, several new experimental systems are in operation, and others are planned.

As mentioned earlier, the Thematic Mapper with bands similar to those on the current MSS, and with the addition of the important bands centered near 1.6 and 2.2 μm has been flown on Landsat 4. In addition to the new spectral channels, the instrument has improved spatial resolution, 30 m rather than the 80 m of the MSS. First results are promising.

An experimental narrow band profiling instrument, the Shuttle Multispectral Infrared Radiometer (SMIRR), was flown on the second Space Shuttle flight [44]. This instrument had 10 medium and narrow band filters (see Table 1), similar to the field instrument HHRR described earlier, and was designed to test and successfully demonstrated the feasibility of using narrow band spectrometry for mineral identification from space. An Airborne Imaging Spectrometer (AIS) has been developed that is capable of acquiring images in 128 spectral bands simultaneously in the region 1.2–2.4 μm . Future imaging spectrometer systems are being developed for high altitude aircraft (Airborne Visible Infrared Imaging



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 Fig. 11. Color composite image of the East Tintic Mountains, Utah, based on principal component transformations of middle infrared multispectral data, with (A) quartz rich rocks; (B) inter-layered quartz-rich and carbonate rocks; (C) silicified rocks; (D) quartz latite and quartz monzonite; (E) latite and monzonite; and (F) areas that exceeded the thermal response range of the scanner [38].

Spectrometer (AVIRIS)) and shuttle (Shuttle Imaging Spectrometer Experiment (SISEX)). The imaging spectrometer systems have the advantage that for each pixel in the image it is possible to derive a complete reflectance spectrum. SMIRR is a precursor to narrow band imaging systems.

A new aircraft scanner, the Thermal Infrared Multispectral Scanner (TIMS), has been completed with six bands in the 8 to 13 μm range, comparable to the (no longer operational) 24-channel scanner. The first data from this instrument [45] have proven to be as useful geologically as anticipated from the 24-channel data results, and it is considered as a precursor to an orbiting system.

As the number of wavelength channels identified to be important becomes larger, with more and narrower channels, and as increased spatial resolution is demanded, new scanner and data processing technology must be developed.

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