Spectral and Microwave Remote Sensing: An Evolution From Small Scale Regional Studies to Mineral Mapping and Ore Deposit Targeting

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ABSTRACT

Spectral reflectance and microwave (radar) remote sensing are used routinely today for mineral exploration. Almost without exception this data is used in the preliminary or 'target generation' stage only, to assess terrain on a small scale regional level. However, mineral mapping and ore deposit targeting are also now possible.

Modern spectral remote sensing began in 1972 with the launch of ERTS-1 (later renamed Landsat 1) which carried on board the MSS (multispectral scanner). The MSS was designed for agricultural purposes, not geologic applications, but it did provide good structural information and a broad synoptic view of the ground.

The major limitations of the Landsat MSS for geologic studies are its coarse spectral resolution, and its limited spectral coverage, which does not extend into the region most useful for defining the spectral characteristics of minerals important to exploration, that is the SWIR (short wave infrared). This changed with the launch of Landsat 4 and 5 in the early 1980s, which carried the TM (thematic mapper) scanner. The TM system added coverage in the SWIR and MIR (mid infrared), providing explorationists with a tool for identifying alteration mineralogy on the earth's surface potentially indicative of economic ore deposits. The TM is now a routine exploration tool for many mineral exploration companies.

Unfortunately, the TM system's coarse spectral resolution can lead to the identification of 'false' alteration zones of no economic significance. The Japanese satellite JERS-1, launched in 1982, attempted to alleviate this problem, but its electro-optical sensors in the SWIR were short-lived and only a minor amount of useful information was obtained.

The near-term future of satellite spectral remote sensing for mineral exploration looks a little more encouraging. The ASTER satellite, to be launched by the Japanese in 1998, and LATI by the U.S. in 2004, will both offer higher spectral resolution and thus higher accuracy in determining surface mineralogy.

Aircraft spectral remote sensing offers both spatial and spectral resolutions that are several orders of magnitude better than any satellite system. The technology has advanced to the point where not only individual mineral species can be mapped, but chemical variations within the molecular structure of the crystal lattice of the mineral can also be detected. This capability will be available in a satellite with the launch of the LEWIS satellite in 1997.

We are currently at the beginning of an 'explosion' of spectral reflectance remote sensing data, as previously classified 'spy' satellite systems, and new high spatial and spectral resolution systems become available. However, most of these are of limited use to the explorationist, other than providing synoptic views of a region, structural information, and the ability to create DTMs (digital terrain models). Their primary application will be in GIS environments.

Microwave (radar) imaging remote sensing has only become widely accepted for exploration since the commercialization of satellite radar data from sensors such as ERS-1, JERS-1 and especially Canada's Radarsat satellite. Radar's big advantage over spectral reflectance systems is that data can always be acquired, since it is capable of penetrating cloud cover. This has proven invaluable in tropical regions where cloud cover is almost constant. Also, because radars are extremely sensitive to topographic change, they are excellent tools for mapping structure.

Spectral and radar sensing has evolved in the last 15 years, from something that was not much more than 'pretty pictures from space' to quantitative information quite capable of aiding in the discovery of an economic mineral deposit.

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 43–58

INTRODUCTION

The term *remote sensing* has historically included classical geophysics, such as magnetics, electromagnetics, and gravity. However, during the past two decades, it has come to imply spectral and microwave (radar) sensing and measuring of the earth's surface. The portion of the electromagnetic spectrum available for remote sensing extends from the ultraviolet at 400 nm to the microwave region at or about 50 cm.

Since the spectral properties of materials can be used for their identification, the use of spectra measuring devices in aircraft and satellites can indicate what is present on the earth's surface at a particular location without actually visiting that location; hence the true definition of the term *remote sensing*.

Virtually all disciplines and specialty industries in any way related to mapping, geographic, or spatial information have been quick to identify the usefulness of this technology and to utilize it for their own particular needs. Geologic mapping, and particularly, mineral exploration, have made extensive use of remote sensing techniques from the outset to help in locating economic mineral deposits.

Remote sensing can be an extremely effective tool but the user must be aware of its limitations. Early users soon learned (sometimes at substantial expense) that it was not a panacea. As a result, skepticism continues to linger.

Spectral reflectance, emittance, and microwave remote sensing are used routinely today for mineral exploration. Almost without exception this data is used in the preliminary or *target generation* stage of exploration to assess terrain on a small scale regional level. The following will illustrate the use of remote sensing for geologic mapping and mineral exploration, while discussing the limitations of currently available sensing systems and the features of new systems in development.

HISTORICAL PERSPECTIVE

Remote sensing began when the first aerial photograph was taken from a hot-air balloon in 1858. Aerial photography provided a synoptic view of the land and man soon realized the advantages of mapping the earth's surface from above. Photo interpretation reveals geologic structural information, bedding, and surface morphology, all based on photo tone, texture, pattern, shape, size and object association in a two dimensional regime. Figure 1 shows these six elements that humans intuitively use to interpret black and white images.

Colour photography adds another dimension to interpretation because the reflectance characteristics of materials are depicted as the human eye sees them, which increases the success of identification.

DEVELOPMENTS IN SPECTRAL REMOTE SENSING

Satellite spectral

Modern spectral remote sensing of the earth's surface began in 1972 with the launch of the ERTS-1 (later named Landsat 1) satellite, followed by Landsat 2 and Landsat 3 in 1975 and 1978. All were equipped with the MSS (multispectral scanner). The MSS collected data in a digital format in four spectral bands, covering the visible and near infrared (NIR) part of the spectrum and a single Landsat image covered an area of about 185 km across. The Landsat MSS program was not the first time the earth had been viewed from space. Photographs had been taken on the Mercury and Gemini flights in the early 1960s and by both U.S. and USSR spy and weather satellites. The Landsat program, however, provided an *open skies* policy of systematic data acquisition and sale to the general public. It also exposed the user community to the new concept of multispectral imaging and digital image processing.

The spectral resolution of the Landsat MSS was very coarse for geologic studies, and its limited spectral coverage did not extend into the short wave infrared (SWIR) region, from 2000 to 2500 nm, most useful for defining the spectral characteristics of minerals important to exploration. This changed when Landsat 4 and 5 were launched in 1982 and 1984, carrying the original MSS as well as a new scanner called the *Thematic Mapper* or *TM*.

The TM has two bands in the SWIR and one in the thermal emissive mid-infrared (MIR), as well as four bands in the visible and NIR part of the electromagnetic spectrum like MSS. The orbiting altitude of Landsat 4 and 5, however, is about 745 km, which is considerably lower than that of Landsat 1, 2, and 3. Because of this, a higher ground spatial resolution is possible, and hence was incorporated into the design of the TM, but not the MSS which remains at 80 m. The six reflective bands in the TM scanner have a spatial resolution of 30 m and the one MIR band is fixed at 120 m. Also, the swath coverage of Landsat 4 and 5 is virtually the same as Landsat 1, 2, and 3.

The TM system's SWIR sensing capabilities provides explorationists with a tool for identifying alteration mineralogy on the earth's surface potentially indicative of economic ore deposits. The routine use of TM as an exploration tool continues to this day in most mineral exploration companies. Unfortunately, its fairly coarse spectral resolution can lead to the identification of *false* alteration zones of no economic significance. The Japanese satellite JERS-1 (or Fuyo-1) launched in February 1992, attempted to alleviate this problem somewhat by having three spectral bands in the 2010 nm to 2400 nm SWIR region where Landsat TM had only one band (band 7) in the 2080 nm to 2350 nm SWIR region. However, the electro-optical sensors in the SWIR on board JERS-1 were fraught with problems shortly after launch and only a minor amount of useful information was obtained.

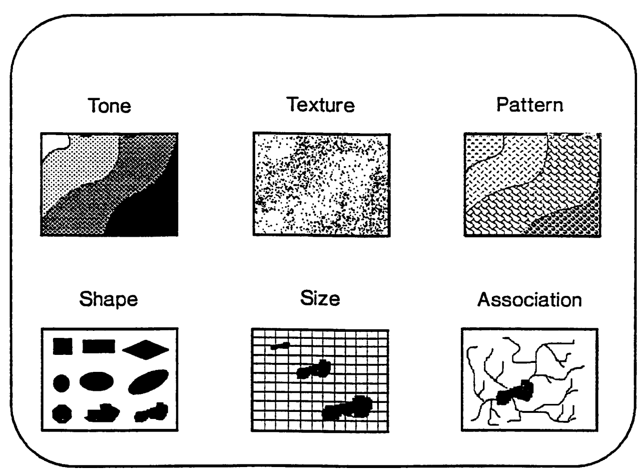

Figure 1: *Elements of interpretation.*

Table 1: ***Major electro-optical and photographic remote sensing satellite systems (active and inactive).***

System	Data acquisition mode	Data distribution format	Sensor types[1]	Spatial resolution (Metres)	Swath (Kms)	2.0 -2.5 μm Sensing (Y/N)
LANDSAT TM	Digital	Digital	M	30	185	Y
LANDSAT MSS	Digital	Digital	M	80	185	N
SPOT 1, 2, 3	Digital	Digital	M, P	20 (m), 10 (P)	60	N
IRS-1A, 1B, P2	Digital	Digital	M	73, 36	148	N
IRS-1C	Digital	Digital	M, P	23 (m), 6 (P)	141 (m), 70 (P)	N
IRS-P3	Digital	Digital	M	> 600	248	N
MOMS 1,2	Digital	Digital	M, P	18 (m), 6 (P)	80, 40	N
JERS-1	Digital	Digital	M	18	75	Y (limited)
AVHRR	Digital	Digital	M	> 1000	3000	N
CBERS-1 CCD	Digital	Digital	M	20	120	N
OFEQ-1, 2, 3	Digital	Digital	M, P	5 (m), 1 (P)	40	N
SPIN-2	Photo	Scanned to Digital	M, P	2	40, 300	N
CORONA, ARGON, LANYARD	Photo	Scanned to Digital	M, P	2 to 8	50 to 200	N

1. M = Multispectral P = Panchromatic

The AVHRR (Advanced Very High Resolution Radiometer) sensor aboard the NOAA weather satellites provide a huge synoptic view of the earth, with a swath of about 3000 km. Entire structural provinces can be examined on one image, but ground spatial resolution is about 1 km. The AVHRR-2 sensor has three thermal emissive infrared bands, which can provide some very coarse regional discrimination between rocks and soils based on silica content. For more information on AVHRR refer to Hastings and Emery (1992).

In 1978 the experimental thermal satellite HCMM (Heat Capacity Mapping Mission) was launched, and thermal data appropriate for reconnaissance geologic exploration were acquired. Because the data were collected in real time by six tracking stations, coverage was restricted to the continental US, parts of Canada, Australia, Europe, and North Africa, and the mission lasted only 28 months. The satellite took surface measurements over the same spot on the earth every 12 hours, measuring reflective and emissive radiance during the day and only emissive radiance at night. The difference between the two measurements defined a property known as *thermal inertia*. It is dependent upon the density, water content (and its state), and composition of geologic materials, and can be sensed below the surface of coatings or thin debris cover that control reflective or radiance measurements.

The thermal property measurements from HCMM can be used to discriminate certain lithologic types, to map alteration associated with silification or dolomitization, to differentiate soils with varying moisture contents and porosities and to distinguish geologic units that are obscured by the presence of thin surface covers (Watson *et al.*, 1971). For further information the reader is directed to the references cited.

A plethora of new satellite spectral remote sensing sensors and previously classified information, both photographic and electro-optical has entered the public domain since the launch of Landsat 1 and especially within the last decade. A list of the major systems is presented in Table 1.

As none except Landsat TM and the short lived JERS-1 SWIR scanner sense the portion of the electromagnetic spectrum (2000 nm to 2500 nm) useful to mineral exploration, these will not be discussed further.

They can provide greater ground spatial resolution, synoptic view, and stereo imaging capability from which three dimensional Digital Terrain Models (DTMs) can be created. Some have channels covering the visible and near infrared capable of discerning ferric oxides, but not able to distinguish between iron oxides produced from the weathering of iron sulphides.

Airborne spectral

The real power of spectral remote sensing is the direct detection of most surface materials from space based solely on their spectral properties. The technology exists for this now. Laboratory reflectance spectra for the most common rock-forming silicate, oxide, carbonate, and sulphate minerals were determined by Hunt and Salisbury (1970, 1971) for the visible to SWIR. Also, Hunt and Ashley (1979) determined visible to SWIR spectra for a suite of hydrothermally altered rocks representing potassic, argillic, phyllic and propyllitic alteration. The spectral reflectance plots of some minerals and typically associated with hydrothermal alteration are shown in Figure 2. Also included are the reflective spectral band channels for Landsat 4 and 5 TM. The data gaps in the spectral curves in the vicinity of 1400 and 1900 nm are atmospheric absorption features due to water vapour and CO_2 in the atmosphere. These spectral curves are representative of data acquired in non-laboratory, or field conditions.

Each of these indicator minerals has its own distinctive *spectral curve* especially in the 2000 to 2500 nm region. The troughs in the curves are known as *absorption features* and their width, depth, and location are diagnostic of that mineral. If the sampling system measuring these curves has a narrow enough bandwidth, and the sampling is done in the correct location, the minerals can be uniquely identified.

An airborne system exploiting these spectral characteristics of the SWIR region for minerals was developed in 1980 by Collins (Collins *et al.*, 1981) with Geophysical Environmental Research Corp. (GER) using two parallel input spectroradiometers, one sampling between 350 and 1100 nm using 512 channels with 1.4 nm bandwidths, and the second sampling between 2000 and 2500 nm using 64 channels with either 8 or 16 nm bandwidths. In 1981, Goetz *et al.* (1982) acquired data from the space shuttle with the *SMIRR* radiometer covering the 500 to 2350 nm wavelength region with 10 channels, 3 of which were 20 nm wide in the SWIR region. However, both the Collins and the SMIRR systems were *profiling* systems, not *imaging* systems like Landsat. Spectral profiles from airborne surveys were draped over orthophotos to accurately locate mineral species on the ground.

The next evolution in data acquisition was *imaging spectroscopy,* and just such an instrument, known as the AIS (Airborne Imaging Spectrometer) was built and flown by the Jet Propulsion Laboratory from 1982 to 1987. This instrument, with 128 spectral bands, produced a raster image comprised of picture elements (or *pixels*) each with a reflective spectrum covering the region from 800 to 2500 nm. Spectroscopists (and geologists!) now had a tool that could directly identify mineral species on the earth's surface from a remote survey platform in a spatial capacity, i.e., remote sensing *mineral mapping*.

Advances in airborne imaging spectroscopy have been happening rapidly since the early 1980s and continue to this day. NASA's well-known Advanced Visual and Infrared Imaging Spectrometer (AVIRIS) commenced flying in 1987. AVIRIS acquires data in the spectral range from 400 to 2450 nm in 224 spectral channels each having a resolution of about 10 nm. The instantaneous field of view (IFOV) is 1.0 mrad, which at the flight altitude of 20 km provides a ground spatial resolution of 20 m, and with a full field of view of 30° provides a swath width of about 11 km. Initially, the AVIRIS had poor signal to noise (S/N) performance from 1987 through to 1989; however, with system upgrades and improvements being done on an annual basis, the instrument now produces superb S/N data, somewhere in the range of about 400:1 at the time of this writing. The AVIRIS can be contracted out to private industry.

Since the 1980s 30 to 40 different airborne imaging spectrometers have been built and flown by government and industry. They differ in the number of channels used (and their bandwidths), the portions of the electromagnetic spectrum sampled within the visible, near infrared, shortwave infrared, and middle (or thermal) infrared, and their field of view. In addition to the AVIRIS, the user community currently has several contractors to choose from for airborne imaging spectrometry surveys, and some exploration companies have purchased their own systems for the potential strategic edge that today's imaging spectrometers can give to exploration.

Sensing systems such as AVIRIS are commonly referred to as *hyperspectral*, rather than multispectral. The term is becoming accepted as referring to a sensing system with somewhat more than 100 channels and typically with contiguous bandwidths.

The visible, NIR, and SWIR do not provide much spectral discrimination of silicate rocks. However, the 8–14 micron region within the mid-infrared, or the thermal region of the electromagnetic spectrum (3–15 microns) not only allows for differentiation between most silicate and non-silicate rocks but also discriminates among different silicate rocks.

Work by Kahle and Rowan (1980) showed that silicate rocks in the East Tintic mining district of Utah were spectrally separable on a digital image acquired by a multispectral thermal infrared scanner on board an aircraft. In 1982 a more sensitive 6-channel aircraft-mounted system known as *TIMS* (Thermal Infrared Multispectral Scanner) was constructed.

Today, numerous aircraft imaging scanners have the ability to sense in the thermal part of the spectrum, and many of these are commercially available.

All of the existing thermal sensors mentioned so far are passive systems that measure the radiation emitted from the surface of the earth. Variations in the intensity of the emitted radiation is heavily influenced by surface temperature. Research and development is currently being done in laser reflectance spectrometry to alleviate this problem. Lasers are active systems which transmit their own electromagnetic radiation. They can be tuned to the very narrow bandwidths in the thermal infrared required to accurately determine silicate mineralogy, without interference from surface temperatures.

Field spectrometry

The interpretation of the digital image processing of remotely sensed spectral data must include verification of the results on the ground. If an indicated mineral species is not present, the error in analysis must be corrected, and if necessary, the airborne sensors recalibrated accordingly.

Visually determining the predominant component of some surface material (i.e., grass, asphalt, painted surfaces) is usually fairly mundane and does not required the use of sophisticated instruments. However, visually determining the predominant mineral(s) in an outcrop or hand specimen can be extremely difficult, particularly if the rock is fine grained, amorphous, and/or weathered. Accurate determination of mineralogy using a portable field instrument to measure mineral spectra can save great expense in mineral exploration particularly if the mineral mapping is being done from an aircraft.

The first field spectrometer was developed by GER Corp. in 1978 and several types are now commercially available. They basically fall into two categories: those that have their own light source for illumination of the specimen, and those that utilize the sun for illumination. Both systems have very high spectral resolution with bandwidths as narrow as 1–2 nm and extending from 400 to 2500 nm. Hence, they can be extremely accurate in determining both mineral species and chemical variations within the molecular structure of the crystal lattice of the mineral. None of the commercially available field spectrometers have sensing capabilities in the mid-infrared.

DEVELOPMENTS IN MICROWAVE (RADAR) REMOTE SENSING

Microwave systems differ from spectral sensors in that they can be *active* systems, meaning they provide their own source of energy for illuminating a target. Spectral sensors by contrast are *passive* systems since they rely on the reflected energy from the sun for stimulation.

Active microwave sensors provide their own illumination of a target and are known as *radars*. (Passive microwave sensors, called *radiometers,* measure low levels of radiation originating from somewhere other than the radiometer, and have no application in geology or mineral exploration).

Active microwave sensors are further divided into *non-imaging radars* and *imaging radars*. Non-imaging radars include altimeters and scatterometers and will be discussed no further. Imaging radars, however, have proven very useful for geological mapping and mineral exploration.

In 1886 Heinrich Hertz used resonators at a frequency of about 200 MHz for transmitting electromagnetic energy, and subsequently receiving a return reflected signal. Although, as Table 2 illustrates, this frequency was not within the microwave range, it was the beginning of the extensive use of microwave imaging sensors for remote sensing.

Major advances in the development of active microwave systems were made during World War II when the first airborne radars were deployed to detect other aircraft and ships at sea. By the end of the war, radars producing images of the ground were common place.

Table 2: ***Band designations of the microwave spectrum most commonly used by imaging radars.***

Band designation	Wavelength (cm)	Frequency (GHz)
X	2.4 – 3.8	12.5 – 8.0
C	3.8 – 7.5	8.0 – 4.0
S	7.5 – 15.0	4.0 – 2.0
L	15.0 – 30.0	2.0 – 1.0

The imaging radars developed during World War II used a system known as *B-scan* which produced severe distortion effects of objects on the ground. This problem was rectified with the invention of the *plan-position indicator* (PPI) radar which produced a reasonably accurate image of the ground. During the 1950s a new type of radar, known as *side-looking airborne radar* (SLAR) was developed. Because of advances in antennae design and components, high resolution imaging became possible, with data recorded on a continuous strip of film. In 1952, radar imaging using a new radar antennae and different signal processing, known as *Doppler beam sharpening*, was developed and soon became known as *synthetic aperture radar* (SAR). Two types of imaging radars are in use today, the SAR and the *real aperture radar* (RAR). It is important to note that either type can be used in a SLAR configuration, but RAR can only be used on an airborne platform, as opposed to a space platform. In RAR, the along-track ground resolution is determined by the actual length of the antenna aperture, whereas in SAR signal processing produces the equivalent of a longer or *synthetic aperture* antenna. Its along-track resolution is independent of distance from the radar transmitter. This provided improved resolution for airborne radars but also allowed for satellite based imaging radars with fine resolution.

The first major radar mapping project was conducted by the U.S. Army and government of Panama in 1967, using a RAR Westinghouse AN/APQ-97. In 1969 the system became commercialized and was used extensively throughout the world for geologic mapping. By the early 1970s the SAR GEMS (Goodyear Electronic Mapping System) and Motorola's RAR were being used to map large portions of the earth's surface, usually for mineral or petroleum exploration. Airborne radar surveys of the earth continue to this day, often with ground resolutions of just a few metres. Advances in digital image processing and Global Positioning System (GPS) have allowed the production of fully georectified radar maps and digital elevation models (DEMS).

The most significant recent advance in airborne radar is the 1995 development of Interferometric Synthetic Aperture Radar (IFSAR) by the Environmental Research Institute of Michigan (ERIM). Two SAR antennas are fixed on the same aircraft separated in the *y* direction. By measuring the phase difference in wavelength of the radar return signal from the same point on the ground to the two antennas, high resolution and highly accurate elevations can be derived, usually within a few centimeters. This technology is also available on a commercial basis.

The first SAR to fly in space was aboard NASA's SEASAT satellite, launched in 1978. This provided the first synoptic high-resolution radar images of the earth's surface. SEASAT acquired data with a swath width of 100 km and a ground resolution of 25 m, using a wavelength of 23.5 cm (L-band). Data were transmitted only when within range of a receiving station, which limited ground coverage to North America, Central America, and Western Europe. Unfortunately, data acquisition was terminated after only 105 days.

On November 12, 1981, NASA launched the Space Shuttle Columbia, carrying a SAR radar known as Shuttle Imaging Radar-A (SIR-A), to acquire radar images of a wide variety of different geologic regions around the Earth. A total of about 10 million km2 of the earth's surface were recorded, which corresponded to about 480 minutes of sensor time. The SIR-A acquired data with a swath width of 50 km and a ground resolution of 40 m, using a wavelength of 23.5 cm (L-band). Unlike the SEASAT mission, the radar data were recorded optically on-board the shuttle.

NASA's second space shuttle radar mission (SIR-B) was launched on October 5, 1984. SIR-B acquired data in a digital format and had the ability to change the incidence angle of the radar signal with the earth. Approximately 6.5 million km^2 of the earth's surface was acquired by SIR-B using a 23.5 cm wavelength L-band. The swath width varied from 20 to 50 km, depending on the incidence angle, and, similarly, the ground resolution varied from 25 m (azimuth) by 17 to 58 m (range).

In 1987 the Soviet Union launched COSMOS-1870, which was a precursor to its Almaz-1 SAR launched on March 31, 1991. Almaz-1 lasted approximately a year and a half and provided imagery with a swath of 40 km and a 15 m ground resolution. Germany included a SAR as part of the payload of a space shuttle mission in 1983, known as the Microwave Remote Sensing Experiment (MRSE). The European Space Agency (ESA) launched ERS-1 in July, 1991. It carries on-board an imaging SAR that operates with a 5.6 cm wavelength (C-band) and provides a ground resolution of approximately 28 m and a swath of 100 km. ERS-1 is the first public domain SAR satellite to provide near full global coverage on a routine basis. The ESA launched ERS-2 in April 1995, an identical twin of ERS-1, relegating ERS-1 to a *backup* system to ERS-2 and occasionally for interferometry measurements. The Japanese satellite JERS-1, launched in February, 1992 carries an imaging SAR which transmits a L-band signal and produces a ground spatial resolution of 18 m; swath width is 75 km. Like ERS-1, and ERS-2, JERS-1 provides near full global coverage on a routine basis.

NASA, the German Space Agency (DARA) and the Italian Space Agency (ASI) collaborated on two shuttle-based radar programs in 1994. They used the SIR-C/X-SAR, consisting of the SIR-C which transmitted a dual frequency radar L-band (23 cm wavelength) and C-band (6 cm wavelength) with four polarizations, and the X-SAR which transmitted a X-band radar (3 cm wavelength). A total of about 50 hours of data corresponding to roughly 50 million square kilometers of ground coverage, was collected during each mission. The ground swath varied from 15 to 90 km depending on the imaging mode and incidence angles of the radar.

Finally, on November 4, 1995, Canada launched the Radarsat satellite, certainly the most versatile of the four global orbiting/acquisition public domain satellites, which include ERS-1, ERS-2, and JERS-1. Radarsat operates a single frequency C-band SAR (5.6 cm wavelength) with seven different beam modes, a range of incidence angles, swath coverage of 50 to 500 km, and ground spatial resolution up to 10 m.

PRINCIPLES OF REMOTE SENSING

Spectral remote sensing

Spectral reflectance plots of various minerals are shown in Figure 2. The slopes of these curves as well as the position, width, and depth of the absorption features are diagnostic of each mineral. The spectral reflectance of minerals in the visible and near infrared part of the spectrum (less than 1000 nm) is determined by the presence or absence of transition metals.

Phyllosilicates of A1-OH and Mg-OH have narrow spectral absorption features within the 2100 to 2400 nm region. Clay minerals such as kaolinite, montmorillonite, muscovite, pyrophyllite, illite, and dickite are found in hydrothermally altered aureoles around ore bodies such as porphyry copper and epithermal gold deposits. These aluminum-rich clays tend to produce strong absorption features in the vicinity of the 2200 nm region, however, variations in crystallography produce the different shapes in the spectral curves. When the octahedral sites in the phyllosilicates are occupied by magnesium instead of aluminum, the combination OH stretch and Mg-OH bending produces strong absorption features in the vicinity of 2300 to 2350 nm. Unfortunately, the main absorption feature for the magnesium-rich clays occurs at approximately the same position as the main carbonate feature, at 2330 nm which can lead to ambiguities in spectral differentiation.

Alunite is another important mineral typically associated with high sulphidation alteration in and around porphyry and epithermal deposits. Although it is classified as a sulphate the spectral features of alunite are produced entirely from the combinations and overtones of the OH stretch and the Al-OH band within the crystal lattice (Hunt *et al.* 1971).

As shown in Figure 2, Landsat TM band 7, which covers the range from 2080 to 2350 nm, is too wide to differentiate minerals in this part of the spectrum, although it can detect broad families of minerals, such as clays, carbonates, and sulphates. The JERS-1 satellite provided three bands in the spectral region of TM band 7, potentially allowing for discrimination between at least the Al-clays and carbonates, however the electro-optical sensors on-board JERS-1 had problems and only a minor amount of useful information was acquired. At this time, the only commercially available survey-type sensor with SWIR capabilities is

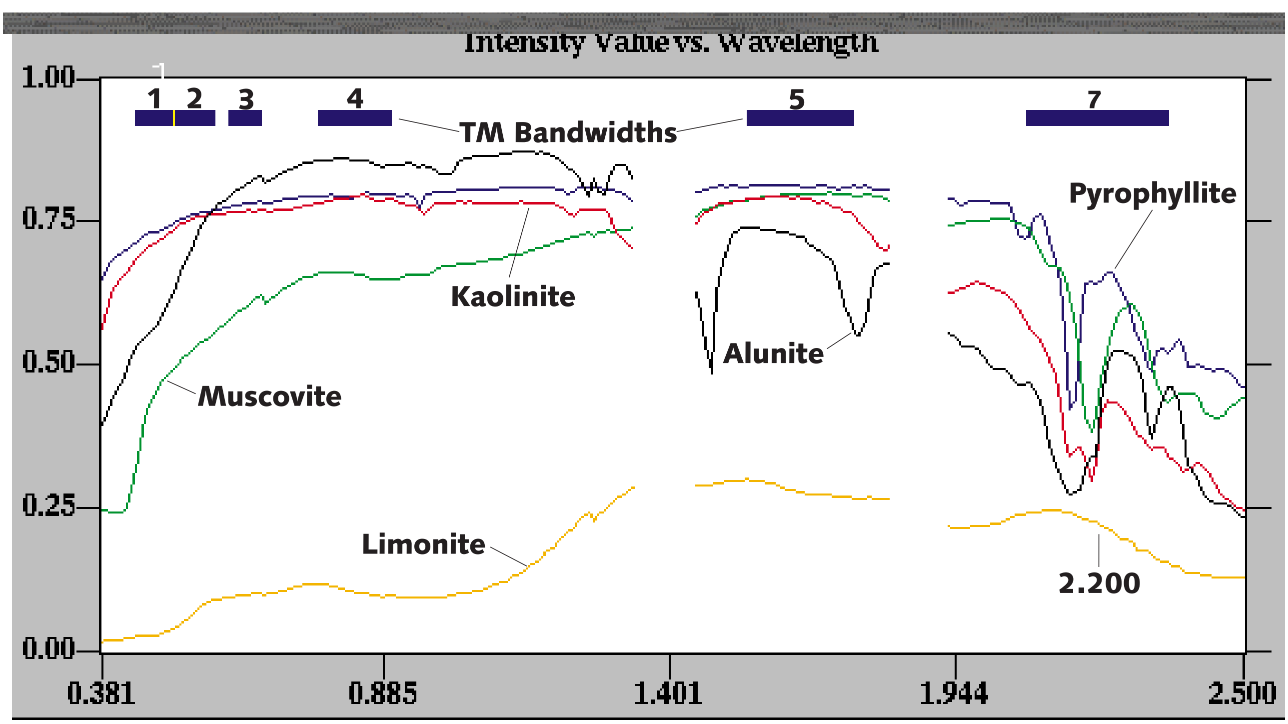

Figure 2: *Mineral spectral reflectance curves and Landsat TM bandwidths.*

still the Landsat TM. The data acquired by Landsat TM will therefore be the focus of the remainder of this section.

Sensors that can acquire data in the visible and NIR, such as Landsat MSS, are capable of detecting limonite, typically a product of both hydrothermal alternation and the oxidation of ferromagnesian minerals. Obviously, it would expedite regional prospecting if those limonite sources could be differentiated. Using Landsat TM band 7, and Landsat TM band 5, OH-bearing minerals, a characteristic of many hydrothermally altered rocks can be detected. Thus, the exploration geologist now has a cheap and reasonably effective tool for prioritizing regions of the earth's surface from space for ground follow-up work.

Mineral exploration and target definition with spectral remote sensing

Spectral remote sensing is one tool the explorationist has to aid in targeting a mineral deposit. The information is usually integrated with all other available data such as geological, geophysical, geochemical, radar, and interpreted within the context of a geologic model.

Remote sensing instruments detect electromagnetic radiance from the first few microns of any surface. Therefore a target material must be exposed to sunlight. Anything covering the target, no matter how minor will affect the spectral signal of the target. A good example would be lichen covering an exposed outcrop. Although a field geologist may consider the outcrop *barren* of any cover, to the spectrometer the spectral signature says *lichen* (or more specifically *chlorophyll*).

Two important concepts must be kept in mind when analyzing remote sensing data or when considering purchasing spectral data for targeting; these are spectral and spatial resolution. The importance of bandwidth to spectral resolution has already been discussed (Landsat TM band 7). Also, if an explorationist is interested in targeting rocks and minerals that have diagnostic absorption features in the SWIR region, then quite obviously a sensor that has SWIR detection capabilities must be used. For this reason Landsat MSS or SPOT is useless for looking for hydrothermal alteration. Spatial resolution is the smallest sample cell of the earth's surface that is measurable based on the design of the sensor detectors. For example, Landsat TM has a spatial resolution of 30 m for its six reflective bands and 120 m for its one thermal band. The implications of spatial resolution and targeting are important. If the target is not large enough to fill at least most of the ground sample cell it simply will not be seen by the detector. Spectral remote sensing imaging systems such as Landsat, SPOT, etc., acquire data in a digital format which is produced as a raster grid of ground cells or pixels for use in computer-based image analysis systems. For Landsat TM, the target would actually have to be much larger than 30 m per side to ensure that at least one pixel on the raster grid covered the target to guarantee detection. Table 3 lists the bands and spectral bandwidths of the seven channels on the Landsat TM sensor.

Each of the seven raster grids of data produced represents the slice of electromagnetic spectrum described for that band as listed in Table 3. Because each band of raster information is registered with the others, a seven channel spectral profile can be produced for each ground pixel. Dozens of software algorithms have been written by image analysts to extract meaningful information from this data. For Landsat TM, typically only the six reflective bands, i.e., bands 1, 2, 3, 4, 5, 7 are evaluated together. Band 6, the thermal band, provides useful information but is treated separately.

Table 3: *Landsat TM band designations and bandwidths.*

Band number	Bandwidths (micrometers)	
1	0.45 – 0.52	Visible
2	0.52 – 0.60	Visible
3	0.63 – 0.69	Visible
4	0.76 – 0.90	Near Infrared
5	1.55 – 1.75	SWIR
7	2.08 – 2.35	SWIR
6	10.40 – 12.40	(Thermal)

A hyperspectral data set, such as that acquired by AVIRIS, would have 224 bands of information for each ground pixel. Spectral profiles, similar to those in Figure 2, could be produced and thus mineral mapping through wave form analysis could be performed.

Many image analysis and processing techniques can be used to interpret the spectral data. Each band of Landsat TM data would produce a gray-scale image of the earth's surface. If the imaging system is designed with three color *guns*, i.e., red (R), green (G), and blue (B), then three bands of Landsat TM data could be assigned to each gun (or color) and a color image would result. Any three sets of digital information could be assigned for each color to produce an RGB image.

Many image analysis and processing techniques are used to extract information from remote sensing spectral data. Several of the more commonly used ones are described here.

Simple three band color composites such as R,G,B images can provide excellent lithologic discrimination in arid and semi-arid environments, particularly if each band is contrast enhanced. For Landsat TM, combinations of bands 7, 4, 1 or 7, 4, 2 or 5, 4, 2 as R,G,B are preferred, as each includes representation from the SWIR, NIR, and visible parts of the spectrum, to maximize discrimination. TM band 2 is commonly used in place of TM band 1 because its longer wavelength is not as affected by atmospheric scattering.

Mineral explorationists often use band ratios of Landsat TM data to enhance rock alteration. Ratios exaggerate subtle differences in spectral response between bands. However, they also subdue the effects of topography by minimizing differences in albedo (brightness). A ratio of Landsat TM bands 5/7 will enhance rocks which are rich in Al-OH, such as those clay and sulphate minerals produced from hydrothermal fluids and associated with porphyry copper deposits. However, this ratio can also indicate non-economic carbonate mineralization. A ratio of Landsat TM bands 3/1 will enhance rocks which are rich in ferric iron oxide (limonite), either from hydrothermal alteration or the oxidation of Fe-Mg silicates. Together these two ratios are capable of identifying areas of high prospectivity. These two ratios are often combined with a TM 4/5 ratio which shows little spectral contrast in rocks with either ferric iron or Al-OH minerals. In a three color composite of TM 5/7 as red, TM 3/1 as green, and TM 4/5 as blue, ferric oxide rich areas will be portrayed as green, clay-rich areas will be red, and where both are present will be orange to yellow. Vegetation also has a high TM 5/7 ratio product and therefore may be confused with clay, but it also has a high TM 4/3 product, and processing algorithms using both ratios can successfully filter out the effects of vegetation.

The topographic detail lost through band ratioing can be processed back to provide a more intuitive look at the image data.

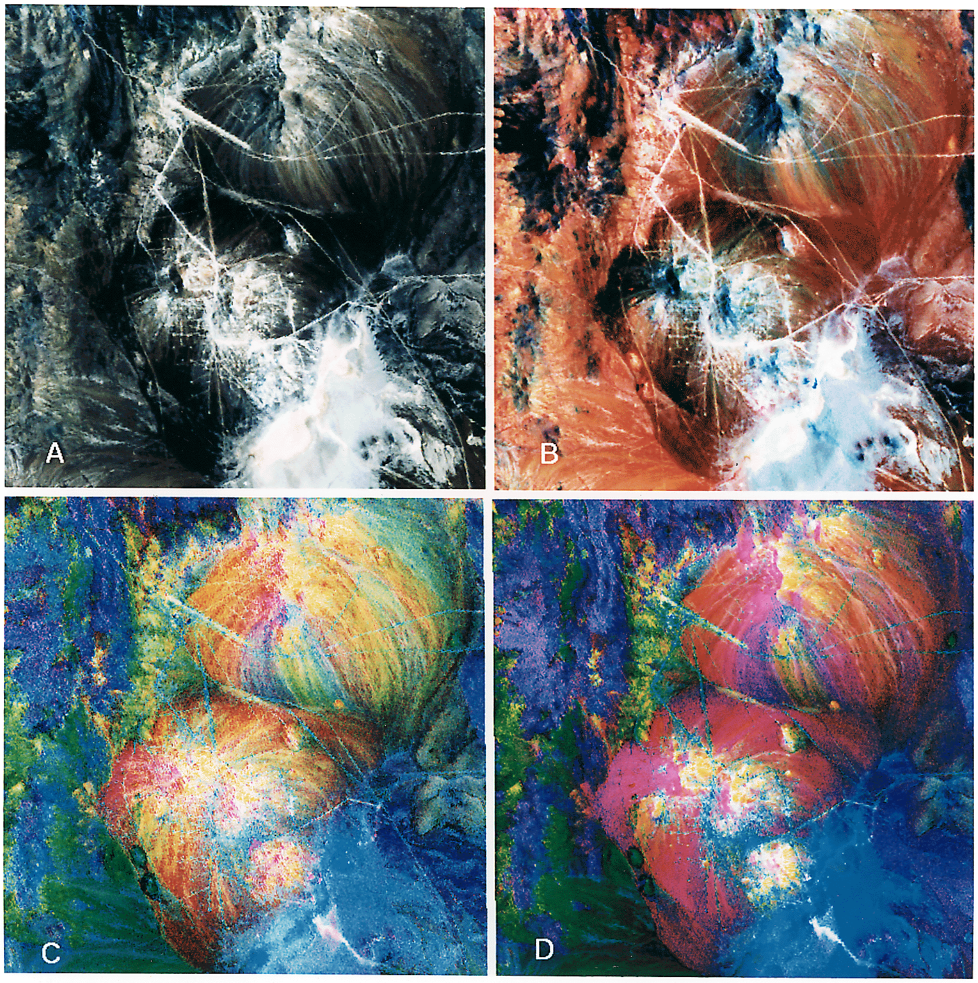

Figure 3: *Landsat 5 TM subscene acquired over the Escondida mine, Chile, pre-production, October 27, 1986. (**a**) TM bands 3, 2, 1 (R,G,B) colour composite; (**b**) TM bands 7,4,1 (R,G,B) colour composite; (**c**) colour ratio composite; (**d**) principal component PC 3,1,2 (R,G,B) composite.*

Principal components analysis is also extremely successful at discriminating surficial materials. It is a factor analysis technique based on variance and co-variance statistics and the generation of eigen vectors and values. The method reduces the dimensionality of the data by removing spectral data redundancy and producing new variables. A color composite image can be produced by selecting any three of the principal components and arbitrarily assigning R,G,B to the individual components. The resultant principal component images can be used for distinguishing between rather than identifying surface materials or lithologies. However, identification information can be extracted from principal components imagery if some *a priori* information is available, such as a geologic map.

One variation of principal components is *directed* principal components whereby one or more data bands are removed from the calculations to eliminate information about unwanted material, such as vegetation. Another corollary of principal components analysis is the *decorrelation-stretch* technique, which can suppress the spectral noise which is common in standard higher components. Components are then transformed back into their original orthogonal space so that the images are more intuitively interpreted.

Figure 3 shows a Landsat TM data set over what is currently the Escondida mine in Chile. The image was acquired by the Landsat 5 TM sensor on October 27, 1986, several years before mining operations began there. Figure 3a illustrates a TM band 3, 2, 1 (R,G,B) color composite, which has low spectral contrast and poor surface discrimination compared to Figure 3b, which shows a TM 7, 4, 1 (R,G,B) color composite. Figure 3c is a color ratio composite image of TM bands 5/7 (R), TM bands 3/1 (G) and TM bands 4/5 (B). Areas showing both high concentrations of ferric oxide as well as probable hydrothermal clays are displayed as yellow to orange. Figure 3d is a principal component image of principal components PC 3 (R), PC 1 (G), and PC 2 (B). Note that the regions of high priority defined by Figure 3c are displayed as yellow.

Image analysts and interpreters need to quantify the digital information that is obtained from either raw data or as a result of image processing algorithms. Classification algorithms, either *supervised* or *unsupervised*, find common spectral properties among pixels and identify these as per user defined parameters. Supervised classifiers use the multiband pixel values characteristic of the selected training site(s) to classify the entire image into these specific training site categories. Thus, a particular rock unit could be used as a training site to locate other sites of this type throughout the image scene. Unsupervised classifiers use algorithms to assign or subdivide all pixels within the image data set into classes or groups based on spectral values alone, assuming that similar cover types will have similar spectral values. Both supervised and unsupervised classifiers produce results with widely varying degrees of accuracy.

The middle infrared (MIR) (or thermal infrared), particularly in the region from 8 to 14 microns, can differentiate between most silicate and non-silicate rocks and discriminate among different silicate rocks, including hydrothermal silification. Figure 4 shows the transmission spectra of some common silicates. Only airborne systems currently carry sensors that have the ability to detect multichannel MIR emittance.

Some researchers have found that areas of intense silification can be determined indirectly from sensors without MIR capabilities, such as Landsat TM. The technique, based on high albedo contrast between silica rich bodies and surrounding host rocks, has proven successful in many instances; but this is not a direct detection method.

In contrast to arid and semi-arid environments, deriving lithologic information from regions where rock and soils are completely covered by vegetation presents a formidable problem. Lichen, grasses, shrubs, or mature trees, all will produce a chlorophyll signature. Geobotanical studies of the relationship between lithologic composition and geographic plant distribution, particularly for plant species that favor specific rock/soil geochemistry, can be combined with identifying these plants based on their spectral characteristics, to establish correlation between plant spectra, plant species, and underlying geology.

Geologic structure, i.e., faults, fractures, folds, etc., are the most obvious features on remote sensing imagery and are especially important to the exploration geologist since it has long been known that faults and folds can affect and control the location of mineral deposits. Satellite based sensors offer a broad synoptic view of the earth and hence are particularly well suited for regional or even continent-wide structural studies. However, satellite systems with higher spatial resolution are also capable of detecting structure on a local scale. The interpretation of geologic structure based on remotely sensed spectral information is best evaluated in conjunction with other data sets, particularly geophysics. Digital processing of remote sensing data does provide a powerful method of enhancing structural elements. Techniques such as *edge enhancement* and *directional filtering* can be used to enhance faults, folds, and structural fabric. Also, digital processing of data from thermal sensors can map fault and fracture zones that are *cooler* than surrounding rock and soil because of contained water, particularly in arid and semi-arid environments.

Digital image processing and analysis of *hyperspectral* remote sensing data typically seeks to define unique mineral (or plant, or manmade) spectral *end members* and from that produce mineral abundance maps. To produce laboratory-like curves, similar to those in Figure 2, the effects of the atmosphere have to be removed, and the data must be converted from radiance to reflectance values. Figure 5 is an example of a digitally processed AVIRIS airborne hyperspectral data set covering the Cuprite Mining district of Nevada. Cuprite contains mineralization of two different types and ages. The younger event, dated at about 7 million years is characterized by acid sulphate alteration that has converted Cambrian siltstones and tertiary tuffs, flows, and volcanic sedimentary rocks to silicified, opalized, and argillized rocks. Uneconomic concentrations of gold occur throughout. The older mineralization is Mesozoic in age and consists mainly of copper-lead veining with minor silver in unaltered Cambrian siltstones. The image shows the location of clay and sulphate minerals that were derived from the analysis of the AVIRIS data.

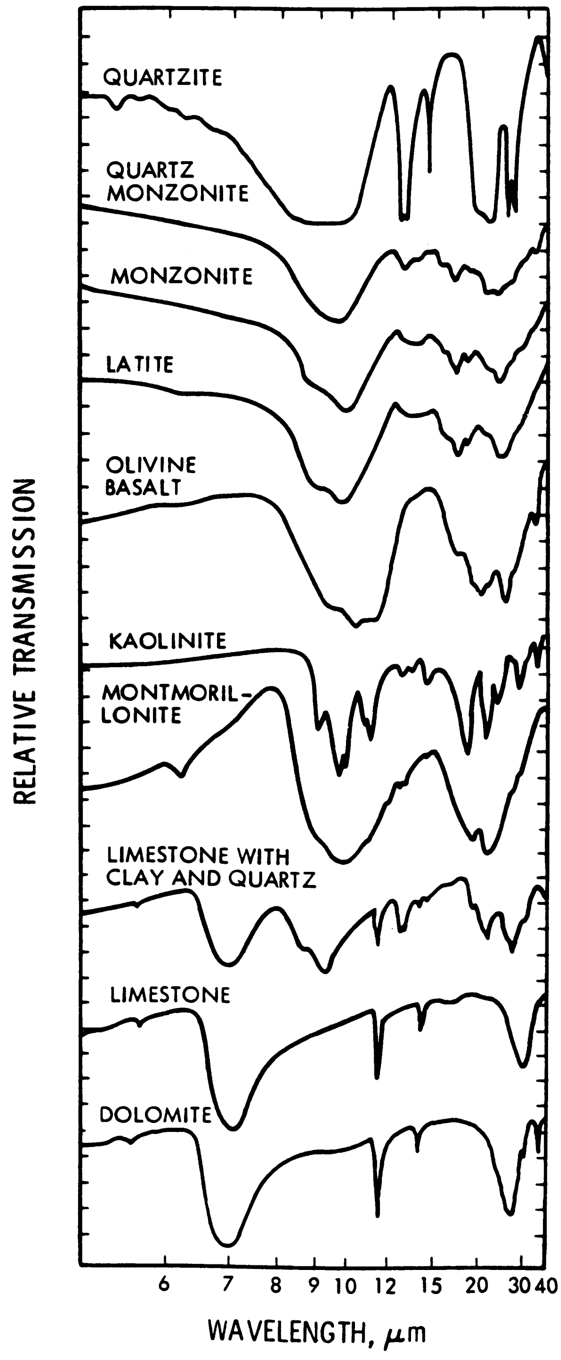

Figure 4: *Transmission spectra of some common silicates (from Hunt and Salisbury, 1975).*

It is important to note that very subtle spectral differences can be mapped, such as kaolinite crystallinity variations, and Na-rich versus Ca-rich montmorillonite.

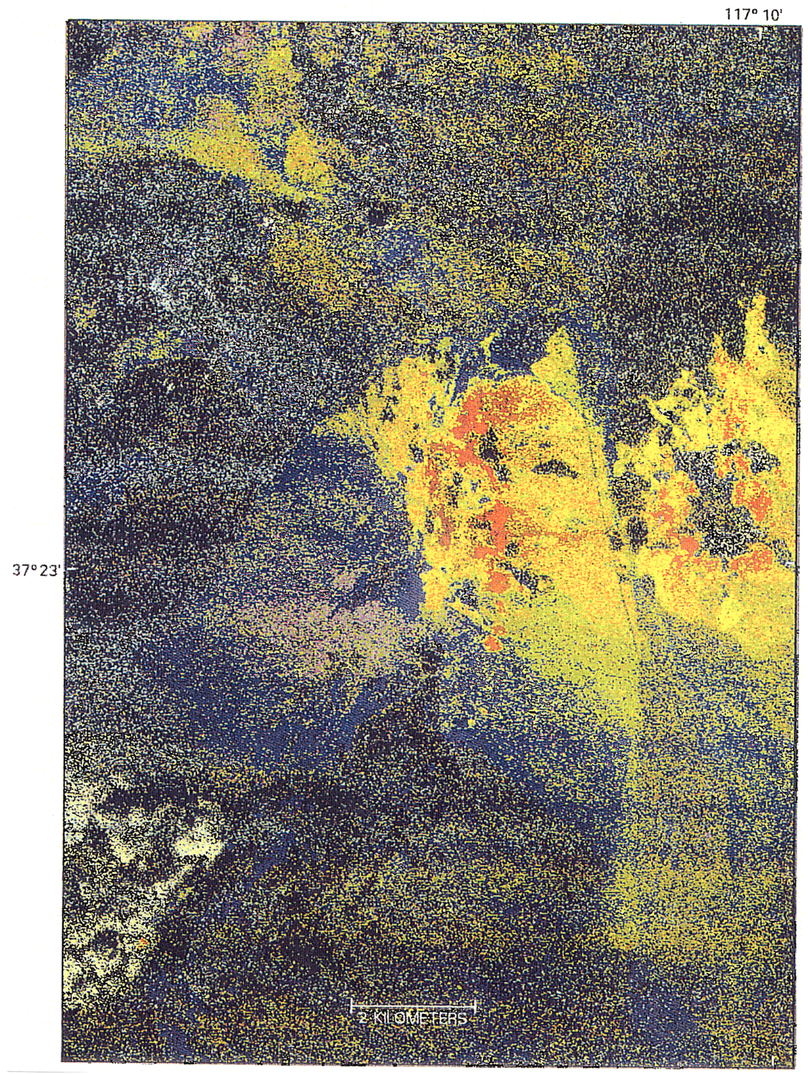

Figure 5: *A colour mineral map of clays and sulfates for Cuprite, Nevada. Alunite is red and occurs in opalized and argillic zones on both sides of the highway. Dickite is orange and is closely associated with kaolinite in the altered zones. Kaolinite (well-crystallized) is yellow. Kaolinite (medium crystallized) is yellow green. Kaolinite (poorly crystallized) is green. (Halloysite and poorly crystallized kaolinite are spectrally indistinguishable at 2.2 µm). Ca-montmorillonite is light blue and occurs in the northeastern portion of the scene. Na-montmorillonite is blue and occurs in rock units and as loess accumulations on alluvial fans and in playas. Some muscovites have a similar spectral signature and are also mapped as montmorillonite (with further research, these minerals may be separated). Buddingtonite is purple and is located only in a few pixels east of the highway. Paragonite is magenta and occurs mostly in the lower left center of the image. Chlorite occurs as an intimate mixture with the paragonite. Opalized tuff is white and occurs in the lower left corner as well as in the central region of the Cuprite alteration zone. (from Clark et al., 1995).*

Microwave (radar) remote sensing

Considering the incredible amount of ground surface information achievable with spectral imaging scanners such as Landsat, SPOT, etc., the obvious question is, "What can imaging radars add?" There are several answers:

1. Radars penetrate cloud cover (and to a high degree rain). This is certainly the most important reason. Most tropical environments on earth have cloud cover which may be permanent for most of the year. Thus, acquiring a spectral image is virtually impossible.
2. Radars are active sensors. Since they have their own source of illumination they can operate in the night. This can be advantageous in polar regions that may be dark for several months.
3. Radars have greater penetration through vegetation than optical wavelengths.

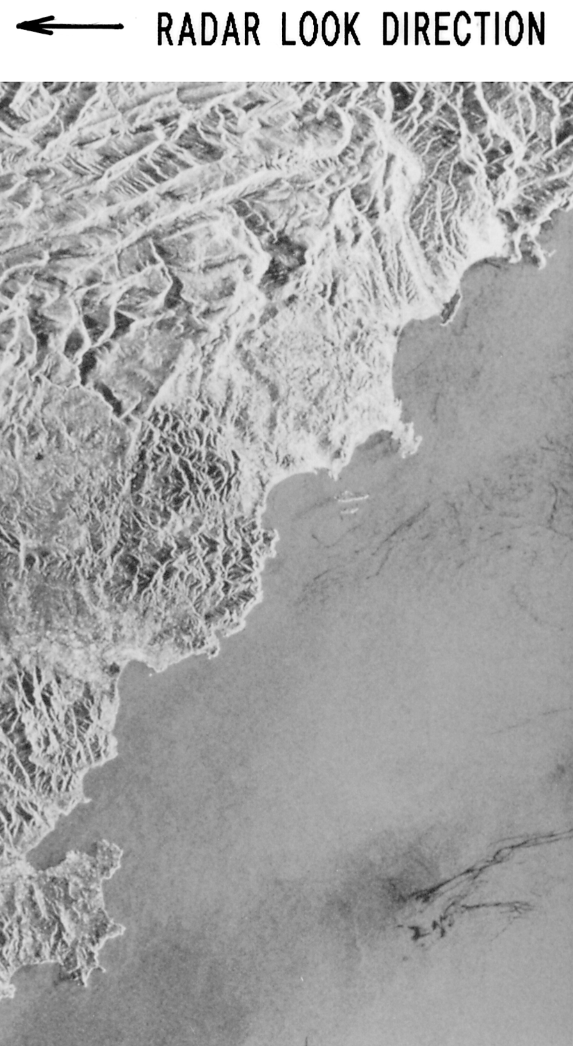

Figure 6: *ERS-1 image showing radar shadow, foreshortening, and layover effects in a region of mountainous terrain.*

4. Radars provide information about the surface that is different from that acquired by the visible, NIR, and SWIR region of the spectrum. Therefore, if conditions permit, it is advantageous for interpretive studies to have both optical and radar data.

Since radars are single channel they produce gray-scale (or black and white) images which are representations of the interaction between the radar pulse beam and the earth's surface. Radars provide information about surface topography, roughness, and moisture content.

The amount of return energy echo back to the radar is known as *backscatter.* The brightness of the radar image represents the amount of backscatter energy returned to the receiver, with darker areas indicating weaker signals.

Backscatter is a function of system parameters of the radar as well as terrain parameters; each are discussed below.

Radar system parameters

- **Wavelength:** Table 2 lists the wavelength and frequency designations of the radar bands. The most popular for imaging radars are X, C, S, and L bands. Spaceborne systems such as ERS-1, -2 and Radarsat use C-band radar with a wavelength of about 5.6 cm. JERS-1, SEASAT, and SIR-A, -B, -C used L-band radar with a wavelength of about 23 cm. The longer the wavelength the greater the degree of penetration through vegetation cover, and to some degree, soil, although, this is also a function of the density of the vegetation and its moisture content. C-band radars generally do not penetrate canopy cover, however L-band radars do.
- **Polarization:** Polarization refers to the orientation of the electric and magnetic fields of the transmitted and received waves. Radars can be configured to transmit and receive either horizontal or vertical polarized waves. Energy transmitted and received in the same

direction would be referred to as *like-polarized* and designated as HH for *horizontal transmission–horizontal reception* or VV for *vertical transmission–vertical reception*. Likewise, when transmitted and received energy is polarized in opposite directions it is referred to as *cross-polarized* and is designated accordingly as HV or VH. Ground surface information will vary based on the transmitted and received polarity of the radar waves.

- **Incidence angle:** The incident angle is a measure of the angle between the radar pulse wave and the ground surface. Rarely is ground terrain flat within a given radar image, therefore the effective incidence angle will vary with terrain slope. Incidence angle, along with surface roughness, is one of the dominant controls of the strength of the backscatter signal. The closer to perpendicular the terrain slope is with the transmitted signal the stronger the backscatter response.
- **System noise:** System noise refers to the inherent electrical noise within the radar system which manifests itself as *speckle* on radar imagery. Speckle is typically more pronounced in satellite radar than airborne radar.

Radar terrain parameters

- **Surface roughness:** Surface roughness is a relative term as it is a function of wavelength. Generally a surface is considered smooth if the local height variations are smaller than the radar wavelength. It follows that what would be a smooth surface in one wavelength would be a rough surface in another wavelength. Surface roughness, along with incidence angle, is a dominant control in the strength of the backscatter signal. The rougher the surface the stronger the backscatter response. However, with incidence angles greater than 70°, incidence angle is the dominant influence on the strength of the return signal and smooth surfaces will actually produce a stronger return signal than rough surfaces.
- **Dielectric properties:** The reflection of a radar signal from a surface is dependent on its electric properties. The presence of moisture increases a material's dielectric constant, and as the dielectric constant increases the backscatter return signal increases (assuming wavelength, incidence angle, polarity, and surface roughness are constant). This is particularly evident for vegetation, where the radar return signal is stronger in vegetation containing more moisture. However, variations in the dielectric constants of rocks are too small to have much effect on the return radar signal and hence composition cannot be directly determined.

Penetration of soil by radar waves is a function of moisture content of the soil as well as wavelength. The longer the wavelength the greater the depth of penetration and the dryer the soil the greater the depth of penetration. However, it takes very little moisture to attenuate penetration. Even using L-band radar in hyper-arid environments penetration might be, at best, a few metres.

Radars transmit energy in a wave front projected to the side of either an aircraft or a spacecraft. Because of both the physics and geometry of this configuration, three geometric distortion effects can occur when processing this data to a two dimensional image. These are: *shadow*, *foreshortening*, and *layover*.

- **Radar shadow:** Radar shadow is a function of the angle the transmitted radar signal makes with the terrain. For example, a ridge may have backslopes that are too steep with respect to the radar incidence angle to be illuminated. Hence there is no return signal from these backslopes because they occur in the radar shadow and the resultant image has a black region indicated. However, radar shadow is a necessary feature for enhancing structure for geologic interpretation.
- **Radar foreshortening:** Foreshortening in radar is analogous to foreshortening in aerial photography, i.e., objects that are directly below the aircraft's camera have no appearance of height because the base and top of the object are superimposed in the film product. Foreshortening in radar refers to the appearance of shortening of an object because it has been displaced towards the radar through processing to a two-dimensional image. It will be at a maximum when the incidence angle of the radar is perpendicular to the terrain slope, so that the base, slope, and top of the ridge would be imaged simultaneously and therefore superimposed on the image. Foreshortening effects can be reduced by a shallow incidence angle with the earth, but then shadowing effects increase. The opposite effect of increasing the incidence angle, or the terrain slope, leads to radar layover.
- **Radar layover:** Radar layover typically occurs in areas of extreme relief. If the angle of the slope facing the radar is greater than the angle of incidence of the radar wave then the top of the mountain will be illuminated before the middle and lower parts are illuminated. Therefore the return signal from the top of the mountain will reach the radar before the lower parts, so that in the two dimensional image the top of the mountain is *laid over* relative to its base. Mountains appear to *lean* towards the radar in the image product.

Figure 6 is an ERS-1 image illustrating radar shadow, foreshortening, and layover effects in a region of mountainous terrain.

Radar image interpretation and its application to geology and exploration

Imaging radars are an excellent tool for identifying geologic structures for mineral exploration because they are extremely sensitive to variations in topographic relief. Mapping lithologic units in desert environments is possible with radars, but, in heavily vegetated regions this becomes extremely difficult. Shorter wavelength radars such as C-band used in Radarsat do not penetrate the canopy cover, therefore, the return signal comes from vegetation. Therefore, variations in the vegetation cover, topography, or land use are used to define lithology. The longer wavelength radars such as L-band generally penetrate canopy cover and therefore there is a larger contribution from surface roughness to the return signal.

Radar image interpretation is a skill similar to air photo interpretation when applied to geologic investigation. The analyst relies on the same elements as those defined in Figure 1 for photo interpretation for defining surface morphology and extrapolating this to underlying geology. However, radar imaging is not photographic imaging and it is important that the analyst keeps in mind the radar system parameters of wavelength, polarity, and incidence angle when interpreting the data.

The explorationist can optimize the value of imaging radar for target definition by careful selection of available system parameters. Airborne radar surveys are obviously more versatile than satellite systems. The user can select the orientation of the survey, altitude (and hence ground spatial resolution), angle(s) of incidence, wavelength(s), and polarizations to suit the problem at hand. Satellite imaging, however, is less expensive and provides a better synoptic view because of altitude.

- **Look direction/Orientation of survey:** Probably the biggest disadvantage of using satellite imaging is the fixed look direction. The look is *side-looking* and perpendicular to the orbital path. Surface structures that are most optimally enhanced are those that are perpendicular to the look direction (parallel to the orbital path). The strength of the return signal is actually at a maximum approximately plus or minus 20° from normal but then decreases rapidly from there to a minimum at parallel to the look direction. Therefore structures that may be of interest for a particular region or target area will scarcely be visible if parallel to the radar look. This situation can be avoided in aircraft radar surveys by planning the flight paths parallel to structures of interest (i.e., perpendicular to the look direction).
- **Incidence angle:** Geometric distortion effects of shadow, foreshortening, and layover are functions of the angle of incidence the radar beam makes with the surface terrain. The shallower the incidence angle the greater the shadowing effect and consequently the more structure will be enhanced, although information is lost in the shadow zones. Still, in areas of low relief, a shallow incidence angle would be preferable for enhancing structure. To reduce the effects of shadowing and information loss a steeper incidence angle could be selected, however, foreshortening and layover effects would then prevail, particularly in extreme relief. One solution for reducing shadow, foreshortening and layover effects is to illuminate the area of interest with two opposite looks with shallow incidence angles. This, of course, would double the cost of data acquisition, but from this stereo imagery could be produced and, if desired, DTM's.
- **Wavelength:** Short wavelength radars such as C-band on board ERS-1, ERS-2, and Radarsat do not penetrate canopy cover. In a completely vegetated environment, any structural information assumes that vegetation mirrors the topography. Also, any surface roughness information is virtually lost so lithologic mapping is almost impossible unless lithology specific flora are present. Longer wavelength radars, such as L-band available on JERS-1, SEASAT, and SIR-A, -B, -C, do penetrate canopy cover and thus give a truer rendition of surface characteristics and topography.
- **Polarity:** Polarity, whether *like* or *cross*, will determine what information is received back from the surface terrain. Generally, structural information seems to be best defined by horizontal polarity.

SUMMARY

The preceding discussions illustrate the usefulness of both spectral and radar remote sensing techniques for mapping the earth's surface, particularly when used in an imaging capacity. Explorationists have been quick to identify the potential of electro-optical systems such as Landsat TM for lithologic mapping, and targeting areas of ferric oxide and hydrothermal alteration in arid and semi-arid environments which may be indicative of economic mineralization. Also, the broad synoptic view offered by satellite platforms allows for local, regional, and even continent-wide structural studies. Although the visible, NIR, and SWIR regions of the electromagnetic spectrum provide exciting information about iron, carbonate, phyllosilicate, and sulphate mineralogy they do not directly identify silicates. Fortunately, the mid-infrared region has proven to be extremely useful in this regard.

The major encumbrance in using satellite systems for geologic studies has been the coarse spectral resolution of the sensors. At best, only families of minerals, rather than mineral species, can be identified. Hyperspectral sensors in aircraft, however, have shown spectacular results in actual mineral mapping.

Active radars, specifically those with wavelengths greater than about 3 cm can penetrate cloud cover and rain, therefore an image of the earth is always attainable. Because active radars provide their own illumination of the earth, they can acquire data day or night. This obviously can be advantageous in polar regions that may be dark for several months. Imaging radars are very sensitive to variations in topographic relief and are therefore excellent at defining structure, although differences in transmitted wavelength, such as C-band versus L-band, will determine what is actually being sensed as topography. Conversion of return signal radar data to a two-dimensional image will produce geometric distortion artifacts of shadow, foreshortening, and layover. This can lead to difficult image interpretation, particularly if these effects are severe. Mapping lithologic units using imaging radars, although possible in arid or semi-arid environments, becomes extremely difficult in tropical environments, especially if imagery created from short wavelengths (that do not penetrate forest canopy) are used. For vegetated terrains the analyst relies on image tone, texture, pattern, shape, size, and association for defining surface morphology and ultimately geology.

The invention of SAR made radar imaging from a spacecraft possible. However, because of the fixed look direction of satellite radars structures of interest that are close to parallel to the look direction will not be sensed. Airborne radar surveys by contrast can be custom designed to maximize structural information.

The true worth of the information acquired by remote sensing systems is best expressed through the power of digital image processing and analysis using image analysis software. Within this environment image statistics can be evaluated, algorithms useful for spectral and spatial analysis and interpretation can be developed, and data integration with other information can occur.

Data integration is essential for accurate interpretation, and interpretation is the key to success. The greater the number of different data sets available for a particular region the greater the likelihood of success, assuming the input data is accurate. Spectral and radar remote sensing are simply two more layers of information routinely used for mineral exploration. Their value increases when integrated with geology, geophysics, geochemistry, and with each other. The data layers can be interrogated in various combinations within a geographic information system (GIS) environment or as standard band combinations, arithmetic combinations, and statistical transform combinations (such as principal components) using RGB color composites. This would include RGB color radar images whereby differences in temporal, polarity, or wavelength data is used as input. Also, colour space transformations such as intensity-hue-saturation (IHS) are extremely useful for integrating and displaying data, for example, combining radar information with spectral information. Because radars *see* different things than spectral systems they are excellent compliments of one another particularly in arid and semi-arid environments. Radars measure geometric and dielectric properties of the surface and spectral sensors measure electronic charge transfers and transitions and bending-stretching vibrations at the molecular level. IHS is also routinely used for integrating geological, geophysical, geochemical, and radiometric data.

Stereo imagery can be acquired from optical, electro-optical, and radar systems. From this DTMs can be created and hence a three dimensional spatial data set. Integration of terrain elevations with spectral or radar data enhances structural information and provides a more intuitive look to the data. Extremely accurate elevation data, usually within a few centimeters, is also possible from aircraft mounted SAR interferometry. Existing satellite radars are also capable of this using GPS location information, but with slightly less accuracy.

Spectral and radar remote sensing has evolved rapidly, particularly in the last 15 years, from something that was not much more than *pretty pictures from space* to quantitative information quite capable of aiding in the discovery of an economic mineral deposit.

THE FUTURE

The remote sensing industry currently sits at the threshold of an *explosion* in spectral data as previously classified *spy* satellite systems and new high spatial and spectral systems become available. Today French, Russian, and U.S. governments are slowly relaxing policy to allow the satellite remote sensing industry to expand commercially. Unfortunately, the bulk of the electro-optical satellites scheduled for launch in the near-term have limited geological applications other than providing synoptic views of a region, structural information, stereo viewing and the ability to create DTMs. Probably the most remarkable of these satellites, at least in terms of spatial resolution, are expected from private industry in 1997-98. EarthWatch Inc. will be launching the *EarlyBird* satellite in mid-1997 which will have 3 metre resolution panchromatic and 15 metre resolution multispectral (3 band: visible, NIR) capabilities. This will be followed by the launch of *QuickBird* satellite in late 1997 which will have a 1 metre resolution panchromatic band and 4 metre resolution multispectral (4 band: visible, NIR) sensor. Space Imaging Corp. will be launching a satellite, also in late 1997, which will also have a 1 metre resolution panchromatic band and 4 metre resolution multispectral (4 band: visible, NIR) capabilities. ORBIMAGE, a subsidiary of Orbital Sciences Corp., will be launching the *OrbView-1* satellite in early 1998 which will have a 1 and 2 metre resolution panchromatic band and a 8 metre resolution multispectral (4 band: visible, NIR) sensor.

These are several satellite sensors planned for the next decade that will have important geologic capabilities. NASA in conjunction with TRW will be launching the *LEWIS* satellite by mid-1997. LEWIS is a 384 channel hyperspectral scanner covering the 400 nm to 2500 nm range of the electromagnetic spectrum and therefore should be capable of mapping mineral species. Its ground spatial resolution will be 30 metres. The satellite will be operated as a research instrument for at least a year before possible commercialization.

An Australian government–private industry consortium plans to launch a commercial satellite known as *ARIES-1* by 1999. ARIES-1 will have a ground spatial resolution of 30 metres and a hyperspectral sensor covering the wavelength region of 500 nm to 2500 nm. Mineral mapping capabilities will be possible from this system.

A joint venture between Japan (through MITI) and the U.S. (through NASA) will launch the *ASTER* satellite by early 1999. ASTER will provide 6 channels in the SWIR region from 1600 nm to 2430 nm with a ground spatial resolution of 30 metres. Although not capable of mineral identification it should be able to differentiate hydroxyl and sulphate minerals from carbonate. ASTER will also have 5 channels in the mid-IR from 8.1 microns to 11.6 microns with a ground spatial resolution of 90 metres. This should allow for some discrimination of silicate-group minerals.

NASA will launch Landsat 7 TM in early 1999. It will be identical to its predecessors Landsat 4 and 5 TM except that the mid-IR channel will have a ground spatial resolution of 60 metres, rather than 120 metres, and there will also be a panchromatic channel.

The Earth Observation System (EOS) AM2 *LATI* (Option II) sensor, to be operated by NASA, is scheduled for launch in 2004. LATI will have 50 channels covering the 400 nm to 900 nm region and 24 channels covering the 1200 to 2400 region of the spectrum, all with a ground spatial resolution of 20 metres.

Airborne hyperspectral sensors continue to be built both by private industry and government supported research groups. Detector/sensor improvements are being made to improve signal to noise ratios. Although higher spatial resolution is available with aircraft mounted systems versus satellite systems so too comes orders of magnitude more data. Considering that most hyperspectral sensors have hundreds of channels, data correction, processing, analysis, and interpretation will be the real challenge in handling the voluminous amounts of information from these systems.

Satellite radar systems will become more versatile. Russia plans on launching a series of three radar satellites commencing in mid-1998 with *ALMAZ-1B*, and followed by *ALMAZ-1C*, and *ALMAZ 2*. They will have variable transmission incidence angles, both like and cross polarization, and 3 transmission wavelengths: X-band, S-band, and LP-band.

The European Space Agency (ESA) will be launching a C-band SAR satellite, known as *POEM* in 1998.

Japan will launch the *ALOS* satellite in 2002 which will carry on board the *VSAR* radar. This radar will transmit a L-band wavelength with both HH and VV transmission/reception parameters and have variable incidence angle capabilities. Four additional satellite SAR missions from Japan are planned in that decade.

Our ability to accurately map the surface of the planet using spectral and microwave remote sensing techniques has improved exponentially over the last few decades. This trend shows no signs of abating for the foreseeable future.

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