REMOTE SENSING FOR GEOLOGY AND MINERAL RESOURCES, AN ASSESSMENT OF TOOLS FOR GEOSCIENTISTS IN THE FUTURE

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ABSTRACT:

The U. S. Landsat program received a major setback in 1993 with the launch failure of Landsat-6. Currently Landsat-5 continues to acquire data and the U. S. Government has made a commitment to fly an Enhanced Thematic Mapper-Plus on Landsat-7 in 1997. NASA is studying a Landsat-7 follow-on Millennium Mission which could fly a solid-state imager, atmospheric correction bands and a hyperspectral imaging spectrometer. The French SPOT program continues to post successes with the successful launch of SPOT-3 and approval of funding for SPOT-4 and SPOT-5. The Japanese JERS-1 program has successfully acquired both optical and synthetic aperture radar of much of the Earth's land surface. Several commercial programs in the United States propose to acquire 1 meter to 3 meter spatial resolution data and 3 to 5 meter global multispectral stereoscopic data. NASA recently selected TRW to provide a hyperspectral sensor with 384 spectral bands at 30 meter spatial resolution. Hyperspectral imagers are being developed in the United States, Europe and Japan that show promise for improving mineral and petroleum exploration. One such sensor, the Hyperspectral Digital Imaging Collection Experiment (HYDICE) acquires 210 spectral bands in the visible and reflected infrared, with 3 meter spatial resolution over a 2 kilometer swath from aircraft flight heights of 3000 meters. Multiband thermal emission mappers have been developed for flight in aircraft which show great promise for geologic and mineral resources applications and Japan, with the assistance of NASA, plans to fly a multiband thermal mapper (ASTER) by the end of the decade. The Japanese JERS-1 program has acquired a world-wide data set of L-band synthetic aperture radar data. The United States and Germany successfully flew Space Radar Laboratory-1 on the Shuttle in 1994 and acquired three frequency/four polarization imaging radar data over 30 percent of the Earth's surface. The Canadian Radarsat program launched a C-band imager in 1995. Interferometric SAR is a revolutionary breakthrough for geoscientists. 36 new earth resources satellites are planned for launch in the next eight years. Computer technology has now rapidly evolved to place robust desktop workstations and laptop computers easily within the reach of individual consulting geoscientists working in remote areas of the world. Earth resources data are now being made available through the World Wide Web. Geoscientists should be able to purchase georeferenced satellite data by the pixel in standardized formats, by the pixel and on CD-ROM within the next decade. Airborne geophysical remote sensing (airborne magnetics, gravity and electromagnetics) are being successfully analyzed in conjunction with aerospace remote sensing data, and ground geoscience information, using geographic information systems technology for mineral exploration in poorly mapped, remote areas. Very low cost processing and analysis software is now available to geoscientists.

1.0 INTRODUCTION

The decade of the 1990's has been revolutionary in terms of the introduction of new technology and the acceptance of current technology for global geologic and mineral resources investigations. Today, Landsat and SPOT image data are routinely used by geoscientists as aerial photography was two decades ago. In many cases, SPOT and Landsat data provide the mapping base for field investigations and the Global Position System (GPS) is now routinely used to survey in field locations at 10 meter accuracy. In poorly mapped, remote areas, geographic information systems (GIS) and GPS are now used to co-register remote sensing and ground-based geoscience information. The next century will see the acquisition of global data sets, at high spatial and spectral resolutions, over much, if not all of the Earth's land surface area. Such data will be rapidly furnished to geoscientists in the stable and easy to use form of optical disks and through global data and information networks. Geoscientists will be able to analyze such data in the most remote areas of the world using low cost, high efficiency portable computer systems. This paper summarizes the state-of-the art of current aerospace remote sensing technology during the decade of the 1990's and it forecasts developments in remote sensing technology for geological and mineral resources in the next century. This paper summarizes the findings of Working Group VII/4 of Commission VII, ISPRS for the period 1992 to 1996. Working Group VII/4 members, who also contributed to this report, are listed in section 9.1.

2.0 CURRENT RESOURCE SATELLITES

2.1 Landsats -1 through -5.

Even today, Landsat Multispectral Scanner (MSS) data is still used by geoscientists because it is the only earth resources satellite data available. Geoscientists found that MSS data was found to be useful for mapping topographic patterns of large dimensions, linear alignments of drainage and landforms. MSS spectral data, while limited in comparison to Landsat Thematic Mapper data, can be processed to effectively display the abundance of iron oxide minerals often associated with mineralized areas. MSS data was successfully processed to display vegetation anomalies associated with nickel laterite deposits in Indonesia, (Taranik, et. al, 1978).

Landsat Thematic Data are now routinely used by explorationists in most of the remote, unexplored areas of the world. Thematic Mapper data are routinely processed to display clay, carbonate and iron oxide abundance, and vegetation anomalies associated with mineralization. Landsat TM data have been the data set of choice because nine SPOT scenes are required to cover the same area as one TM full scene (185km by 185km), Taranik, (1990).

2.2 SPOT

SPOT data is used for geologic and mineral resources applications in areas where there is no Landsat-TM coverage, or where the user wishes to sharpen Landsat-TM data by using SPOT panchromatic data. SPOT cross-track stereo data has seen limited use by explorationists because of the complexity of its analysis and the costs for multiple data set acquisitions. However, SPOT multispectral data has been found to be more useful for mapping iron oxide abundance than TM data because of the location of the SPOT bandpasses. SPOT-1 currently is parked in orbit and SPOT-2 is in standby mode. SPOT-3 is acquiring data and is planned to continue operation until 1997. SPOT satellites 1 through 3 have the same sensor configuration and the same data characteristics.

2.3 JERS-1 (FUYO-1) Payload.

JERS-1 was launched by Japan on February 11, 1992 into a 568.5 km orbit with a local equatorial crossing time of 10:34AM. The satellite carried an optical sensor (OPS) and an a synthetic aperture radar (SAR) sensor. Initially the SAR antenna panels failed to deploy and there is suspicion that when the panels did deploy they did not correctly orient themselves to the satellite flight path. Although the OPS experienced problems with the infrared focal plane early in the JERS-1 mission, some SWIR data were acquired. The SWIR bands (three in the 2.2 micrometer region of the spectrum) added a measurement capability not provided by the Thematic Mapper on Landsat or SPOT. The early SWIR data showed a detector overshoot problem which causes a streaking around the edges of bright objects. This streaking problem is most evident in bands 5 and 6, but band 7 appears to be very useful. The other bands, 1 through 4 appear to provide excellent data.

The JERS-1 SAR system has produced exceptionally good L-band imagery of most of the terrestrial land surface of the globe. However, there are some imaging artifacts, probably due to asymmetry in the alignment of the antenna pattern including: azimuth ambiguity ghosting and electronic interference.

2.4 Indian Government Resource Satellites

In March 1988 the Indian Government launched IRS-1A into orbit. The spacecraft carried two types of linear array sensors. The Linear Imaging Self-Scanning sensor (LISS-1) and LISS-IIA and LISS-IIB. The LISS-1 sensor has a ground instantaneous field of view of 73m and a swath of 148km and the LISS-II sensors provide a 37m GIFOV across a 145km swath. The spectral bands for the sensors are similar to the first four bands of Landsat-TM data.

The IRS-1B satellite was launched into orbit in the spring of 1995 and it carried three sensor systems. A panchromatic sensor, a LISS-III sensor and a wide-field sensor (WiFS). The panchromatic sensor will provide 10 meter spatial resolution over a 70km swath. The LISS-III sensor will provide 20 meter spatial resolution in three VIS/NIR multispectral bands over a swath of 142km and 70 meter spatial resolution in one SWIR band over a swath of 148km. The WIFS will provide synoptic coverage over a 774 swath in two VIS/NIR multispectral bands for vegetation indices. EOSAT is making IRAS satellite data available to the public.

2.5 ERS-1 and ERS-2 Synthetic Aperture Radar System

In 1991 the European Space Agency launched the first in its series of synthetic aperture radar (SAR) imaging satellites, ERS-1. This satellite provides imaging SAR data at C-Band wavelengths (5.7cm) from a vertically polarized antenna at 28 meter spatial resolution. The swath width is 100km and the incidence angle on horizontal surfaces is 23 degrees. ERS-2 was launched in 1995 and has the same imaging characteristics. The orbit of ERS-2 is being adjusted in 1996 to closely follow ERS-1 thus facilitating the acquisition of global SAR interferometric data.

2.6 Canadian Radarsat.

In 1995 the Canadian Government launched Radarsat its first commercial venture into space satellites. Radarsat International, the commercial operator under the program is selling radar data to the public. The satellite was launched into a near polar orbit at an altitude of 798 km in November 1995. The satellite carries a Synthetic Aperture Radar (SAR) that operates at C-band frequencies (5.3 GHz or 5.6 cm wavelength). The SAR utilizes electronic beam steering to image areas on the ground at 20 to 49 degree incidence. The SAR can image areas at variable spatial resolution with the highest resolution at 10 meters over 45 km areas with 37 to 48 degrees of incidence. This mode will be particularly useful for geologists, because the geometry of imaging is almost ideal for mapping of topographically related features on the earth's surface. However, in the synoptic SCANSAR mode with 50 meter spatial resolution over a 300 Km swath will be valuable for mapping structural features of large dimensions, particularly in areas having cloud cover at high latitudes. The standard resolution of the system is approximately 25 meters over a 100 Km wide swath with 4 looks.

3.0 CURRENT AIRCRAFT SAR SYSTEMS

3.1 Goodyear Aerospace X-Band Synthetic Aperture Radar

Large areas of South America, notably Columbia, Venezuela and Brazil and in the Asian Pacific region were flown in the 1970's and 1980's by Goodyear Aerospace/Litton Aeroservice using a Caravelle Jet platform and a version of a military reconnaissance radar. This radar was an X-band (3cm wavelength system) which provided about 10 meter spatial resolution over approximately a 10km swath. Normally, swaths of coverage were mosaiced together to provide quadrangle coverage. Litton Aeroservice no longer provides this service because of the proliferation of spaceborne radar systems.

3.2 Motorola-MARS X-Band Real Aperture System

During the 1980's Motorola-MARS provided X-band radar data from an AN/APQ-94 reconnaissance radar system mounted in a Mohawk aircraft. This system has acquired data in Africa and in Indonesia however no new data are currently being acquired.

3.3 Intera SAR System (STAR-1)

Intera currently operates the only airborne SAR system available for commercial surveys worldwide. Its STAR-1 system consists of an X-band (3cm wavelength) synthetic aperature radar which operates in two modes: 6 meter GIFOV with 23 km swath and 12 meter GIFOV with 46 km swath. Intera has acquired over 50 million square kilometers of data worldwide, a significant part of which is for geological mapping and mineral exploration.

3.4 ERIM Multiband SAR System

Currently, the Environmental Research Institute of Michigan is flying a multiband SAR System which also has the capability of acquiring interferometric SAR data. The system simultaneously acquires X, C and L-band data at 10 meter spatial resolution using a Convair 550 platform.

4.0 ADVANCED IMAGING SYSTEMS

4.1 Jet Propulsion Laboratory AIS and AVIRIS

Beginning in the early 1980's NASA and the Jet Propulsion Laboratory began to develop the first hyperspectral imagers. In 1982, Dr. A. F. H. Goetz, using Director's development funds at the Jet Propulsion Laboratory, developed the first Airborne Imaging Spectrometer (AIS). That instrument was first flown over the Cuprite area near Goldfield, Nevada, and analysis of its data clearly demonstrated not only could mineral species be discriminated by remote sensing techniques, they could be uniquely identified. The AIS was followed by an Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) which moved hyperspectral imaging from the breadboard stage to an operational stage. AVIRIS has 220 bands with 9.6nm bandwidths covering the spectral interval from 410nm to 2450nm. AVIRIS was flown at an altitutde of 20km in a U-2 aircraft and from that height it produced 20 meter pixels over an 11km by 11km area. In 1994 and 1995 AVIRIS data over Cuprite were analyzed by the U. S. Geological Survey and they found that different temperatures of alunite formation could be discriminated. NASA is considering mounting AVIRIS in a C-130 aircraft to provide 5 to 10 meter spatial resolution. In 1995 the signal to noise in the instrument was significantly improved to over 300 to 1.

4.2 NASA TIMS

NASA Developed a Thermal Infrared Multispectral Scanner (TIMS) in the early 1980's. The instrument was developed by the Jet Propulsion Laboratory and has been flown on Lear Jet and C-130 platforms by NASA Stennis Space Center and NASA Ames Research Center. TIMS uses six spectral bands in the 8000 to 12000nm portion of the long-wave thermal infrared spectrum. The bandpasses range from 400nm to 1000nm and the Noise Equivalent Temperature Difference (NEDT) ranges from 0.01 degree Kelvin to 0.3 degree Kelvin at the longer wavelengths. TIMS overflights are supported by ground-based thermal emission spectrometers developed by NASA and Geophysical Environmental Research.

4.3 Geophysical Environmental Research Imaging Spectrometer (GERIS)

In 1986, Geophysical Environmental Research (GER) began flying a 63-band hyperspectral imager called GERIS. The system utilized an optical-mechanical scanning approach and three spectrometers to cover the solar spectrum from 430 to 2500 nanometers. The first 25 bands had bandwidths of 25 nanometers, the second 7 bands had bandwidths of 120 nanometers and the last 31 bands had bandwidths of 16 nanometers. At a flight height above terrain of 4000 meters it had an 8000 meter swath and collected data from 16 meter ground instantaneous field of view (GIFOV). Because of its high signal-to-noise it became the commercial hyperspectral remote sensing instrument of choice by most of the mineral exploration companies in the western United States.

4.4 GER Environmental Probe Sensor Series

Geophysical Environmental Research has developed a number of advanced imaging systems as environmental probes. The EPS A Series are a 32 channel systems with 28 channels in the VIS/NIR and 2 channels in the SWIR (1.6 and 2.2um) and 2 channels in the thermal infrared (3-5un and 8-14um). The GER-DAIS 3715 is different than the EPS-A in that it has 37 channels with 32 in the VIS and 3 in the SWIR.

4.5 GER DAIS 7915

The Geophysical Environmental Research GER DAIS 7915 has 79 possible spectral band combinations. The VIS/NIR spectral bands range from 498nm to 1010nm with 16nm bandwidths (32 spectral bands). The SWIR-1 has 8 bands with 100nm bandwidths over a spectral interval of 1000nm to 1800nm. The SWIR-2 has 31 bands with 15nm bandwidths over a spectral interval of 1970nm to 2450nm. There is one band in the 3um to 5um region with a 2000nm bandpass and six bands in the 8um to 12.3um region with 600nm bandpasses. The swath is 5km at 3000 meter AGL and the spatial resolution is 10 meters at the same altitude.

4.6 GER DAIS-2815

Geophysical Environmental Research built an ASTER Simulator for Japan Geophysical Institute in 1992. That instrument has three spectrometers: 700 - 1000 nanometers with a 300 nanometer bandwidth, 3000- 5000 nanometers with three, 600 nanometer bandpasses and 8000 to 12000 nanometers with 20, 200 nanometer bandpasses. The instrument has a variable IFOV ranging from 1.0, 2.5 and 5 milliradian.

4.7 GEOSCAN

In 1984, an Australian company, GEOSCAN PTY. LTD, began development of a prototype MKI airborne multispectral scanner with 24 spectral bands. Currently, GEOSCAN has developed an advanced hyperspectral imager with up to 48 spectral bands. The instrument uses three spectrometers: 500 - 850 nanometers with 20-71 nanometer bandpasses (32 channels), 2050 - 2500 nanometers with 60 nanometer bandpasses (8 channels) and 8000 to 12000 nanometers with (6 channels). The GEOSCAN MK II can make hyperspectral measurements from 10-meter GIFOV's over a 10,000 meter swath. The GEOSCAN instruments have been extensively used by industry for mineral exploration in the western United States, South America and Australia.

4.8 CASI.

In 1988, the Canada Center for Remote Sensing undertook development of the Compact Airborne Spectrographic Imager (CASI). CASI can acquire 15 bands in imaging mode or 288 spectral bands in radiometer mode. Its spectral range is from 430 nanometers to 870 nanometers and it has 3 nanometer bandpasses. CASI has 578 pixels/line and can achieve 5 meter spatial resolution depending on the flight height above terrain.

4.9 CCRS SWIR Full Spectrum Imager (SFSI)

The Canada Center for Remote Sensing (CCRS) has developed a hyperspectral imager called the SWIR Full Spectrum Imager (SFSI) which detects solar reflectance from 1220 to 2420nm in 22 to 115 bands. The system can simultaneously acquire the full spectrum at 10.4nm bandpass spectral resolution. Ground instantaneous fields of view can range from 50 cm to 4 meters over a swath of up to 2km. In June 1995 the SFSI acquired extensive data over mineral deposits in Nevada.

4.10 Daedalus Airborne Thematic Mapper (AADS)

The Daedalus Airborne Thematic Mapper is an 11 channel scanner that acquires seven Thematic Mapper bands to simulate TM data. There are 5 bands in the visible, 3 bands in the near-infrared, two bands in the short-wave infrared and one band in the thermal infrared. This sensor has been used by several exploration firms to acquire higher spatial resolution data than Landsat.

4.11 DAEDALUS MIVIS

In 1993 Daedalus Enterprises of Ann Arbor Michigan developed the Multispectral Infrared and Visible Imaging Spectrometer (MIVIS). That instrument was developed from the mineral exploration and environmental assessment communities. It has four spectrometers: 430 - 830 nanometers (20 channels with 20 nanometer bandwidths), 1150 - 1550 nanometers (8 channels with 50 nanometer bandwidths), 2000 - 2500 nanometers (64 channels with 8 nanometer bandwidths) and 8200 - 12700 nanometers (10 channels with 500 nanometer bandwidths).

4.12 HUGHES Wedge Imaging Spectrometer (WIS)

The Santa Barbara Research Center (SBRC) of Hughes Aircraft Corporation developed a Wedge Imaging Spectrometer (WIS). The WIS can collect 126 spectral bands of data with bandpasses of 6 nanometers to 20 nanometers. The entire instrument can easily fit in a container 6 inches by 10 inches in size.

4.13 HUGHES HYDICE Hyperspectral Imager

In 1993 the Hughes Danbury Optical Systems began development of the Hyperspectral Digital Imaging Collection Experimental Sensor (HYDICE). This sensor is collecting 210 spectral bands with bandpasses ranging from 2nm to 14nm over a spectral range of 385nm to 2500nm. The system provides 1meter to 3 meter spatial resolution over a 500m to 2km swath. The radiometric resolution is 12 bits.

4.14 NASA ASAS

Beginning in 1987, NASA Goddard Space Flight Center began developing an Advanced Solid-State Array Spectrometer (ASAS). This instrument is unique in that it can acquire data on the ground at seven different viewing angles. ASAS has 62 bands in the 400-1060nm region of the spectrum and with 11.5 nm bandwidth.

4.15 French ISM

The ISM was built by the Observatorie Paris-Mendon, the Institut d'Astrophysique Spatiale and the Department d'Etude Spatiale. It has 64 bands in the 800-1700nm region with 12.5nm bandwidth and 64 bands in the 1500-3000nm spectral region with 25.5 bandwidth.

4.16 German ROSIS

ROSIS is the Reflective Optics System Imaging Spectrometer developed by MBB, DLR and GKSS. It has 128 spectral bands from 450-850nm and bandwidths of 5nm.

4.17 China MAIS

The Shanghai Institute of Technical Physics has been developing the Modular Airborne Imaging Spectrometer (MAIS). It uses three individual spectrometers: Spectrometer I is a Silicon linear array and covers the 440-1008nm region with a 20 nm bandpass for 32 bands. Spectrometer II is a PbS linear array and covers the 1500-2500nm region with 30nm bandpasses for 32 bands. Spectrometer III is a HgCdTe linear array and covers the 7800-11800nm spectral region with a spectral resolution varying from 400 to 800nm in 7 bands. The MAIS is flown on a Cessna Citation aircraft at an altitude of 3000 meters and has a ground resolution of 12 meters at nadir. The swath width is 512 to 1024 pixels using a selectable mirror.

4.18 Dutch CEASAR and MARCS

The Dutch International Institute for Aerospace Survey and Earth Sciences (ITC) has been involved in the development of the CCD Airborne Experimental Scanner for Applications in Remote Sensing (CEASAR). This instrument covers the 400 to 1100nm spectral region with 3 bands, 3-50nm bandwidth, between 535-895nm in the "land observation mode" and 9 bands of 20-60nm bandwidth in the 400-1100 region in the "sea observation mode." MARCS is the Multispectral Airborne Reference-aided Calibrated Scanner covering the 310 to 1300nm spectral region with 8 bands in the 310-1100nm region, 2 bands in the 1600-1780nm region, 2 bands in the 2100-2380nm region, 2 bands in the 3400-5300nm region and 2 bands in the 9000-13000nm region. The scanner bandpasses range from 50nm to 150nm in the VNIR/SWIR region and 700nm to 5000nm in the TIR region. The ground instantaneous field of view is 4.2 meters at a flying altitutde of 500 meters.

4.19 Summary

Within the next decade a new generation of instruments will be developed that will have great application to mineral resources and geologic applications. These instruments should enable geoscientists to not only discriminate important mineral species, but to identify the minerals themselves. By being able to characterize mineral assemblages in this manner, geoscientists should be able to better describe mineral resource potential and develop critical information for engineering and environmental geology.

5.0 ADVANCED RADAR SYSTEMS

5.1 SIR-C/X-SAR

In April and October 1994 NASA flew the Space Radar Laboratory on the Shuttle Endeavor in a 215 kilometer orbit with 57 degree inclination. This $366 million radar system was the most sophisticated system ever flown in space. The synthetic aperture radar imaging system had three different frequencies (L-band, C-band and X-band) and four different polarizations which transmitted and received data vertically or horizontally (HH, VV, HV or VH). The system provides data in standard products at approximately 25 meter spatial resolution, in scenes that cover approximately 20 by 60 kilometers. The system is a calibrated system which maintains calibration below 5dB. During the two missions a total of 50 hours of data, corresponding to roughly 50 million square kilometers of ground coverage was covered on each mission. The ground swath varied between 15 to 90 kilometers depending on the incidence angle.

The SIR-C instrument was built by the Jet Propulsion Laboratory of the California Institute of Technology and consisted of the L-band and C-band antennas. The L and C bands use distributed phased-array antennas with electronic beam steering. The X-SAR was built by Dornier and Alenia Spazio companies and is a single-frequency radar which uses a passive slotted waveguide and a tilt mechanism to point the antenna.

The data products consist of survey strips of data in hard copy film form, or in CD-ROM form. Approximately 50 CD-ROM's were produced for the survey data for each mission. These products are four-look data for SIR-C and eight-look data for X-SAR with 50 meter pixel spacing and 100 meter resolution. The precision product is a frame image of a subset of the data. The precision products have 12.5 meter pixel spacing and approximately 25 meter resolution. The precision products are provided on 9-track, 6250 bpi tapes or on Exabyte tapes.

Preliminary analysis of SIR-C/X-SAR data has shown that it is an exceptional data set which covers parts of most of the continental areas of the world. After the Principal Investigators complete their initial investigations of the data, the data set will be transferred to the EROS Data Center in Sioux Falls, South Dakota and that government facility will make the data available to the general public.

While SIR-C/X-SAR was an experimental system and two experimental flights were planned in the original mission, the Jet Propulsion Laboratory is seeking to fly the system again, in the winter months and/or perhaps have the Shuttle payload flown as a free-flyer for two to three years. This system would provide near-global coverage within a few months of launch. The data produced would be outstanding for explorationists and would compliment the commercial monospectral radars.

5.2 Interferometric Synthetic Aperture Radar (IFSAR)

An interferometric SAR uses two different antennas, separated by 1 to 30 meters in space while looking at the same terrain on the ground. The antennas may be mounted on the same imaging platform or on two platforms that have the same imaging characteristics at the time of imaging. The amount of separation is limited by the wavelengths utilized by the SAR. The displacement of terrain in the images is small, but because the SAR illumination is coherent, the phase difference in each pixel can be measured to meter or better accuracy, (Mussio and Light, 1995). In one year of mission operations an interferometric SAR might be able to provide a digital global map of terrain at 5 meter heighting accuracy in 30 ground instantaneous fields of view. Experiments with ERS-1, JERS-1 and SIR-C/X-SAR have demonstrated applications ranging from analysis of earthquake displacements to pre-eruptive deformation of volcanoes. Currently, the Jet Propulsion Laboratory is seeking to develop this capability for the United States and Japanese MITI and NASDA are in the pre-development phases for a satellite system.

5.3 Japanese VSAR

The Japanese plan to fly a second spaceborne L-band SAR which will have 20 to 50 degree incidence angle imaging, 10 meter spatial resolution over a 70km swath and dual polarization (HH or VV). In SCANSAR mode the system should be able to acquire 100 meter spatial resolution over a 250km swath (Osawa, et. al., 1995). This mission is planned to acquire a world-wide data set within one year of the planned launch in 1999. The Ministry of International Trade and Industry and Japanese earth resources industry is sponsoring the new mission.

6.0 PLANNED EARTH RESOURCES SATELLITES

Within the past several years several commercial ventures have been proposed in the United States. Lockheed has proposed the development of a commercial satellite system that will provide 1 meter spatial resolution data. CTA has proposed the initial flight of a 3 meter spatial resolution system and eventually a 1 meter spatial resolution system.

6.1 LANDSATS -6, -7 and -8.

Landsat-6 was launched on October 5, 1993 and although the Enhanced Thematic Mapper (ETM) operated to specifications, the spacecraft failed to achieve orbit when the orbit kick motor inadvertently drove the spacecraft bus back into the atmosphere and ultimately the Indian Ocean. For the first time in the history of the Landsat program no backup spacecraft was funded by the government and this shortsighted economy, plus a complex management scheme, has resulted in a serious setback for the U. S. Landsat program. The ETM on Landsat-6 was to provide the Landsat TM bands used on Landsats -4 and -5, and also a panchromatic sharpening band that would have provided 15 meter spatial resolution data.

The U. S. Government has made a committment to fly Landsat-7 in 1997 with an Enhanced Thematic Mapper-Plus (ETM+) sensor. This plan deletes the planned High Resolution Multispectral Stereo Imager (HRMSI) under development by Hughes Santa Barbara Research Center. That sensor would have provided along track synoptic multispectral stereoscopic imagery with 5 meter spatial resolution. The ETM+ will have the same bands as the Landsat-6 ETM, but will also have a thermal band with 60 meter spatial resolution.

There is no formal commitment to the Landsat program beyond Landsat-7, however the U. S. Government is supporting studies of government requirements for land satellite data beyond Landsat-7, Landsat-7 follow on must provide continuity with Landsat TM data, but will demonstrate new technology. NASA currently plans to drop the thermal band beginning with the Landsat-7 follow-on experiment. Landsat-7 follow-on will be a NASA "New Millenium" mission that will be a proof of concept for new solid state imaging technologies. Currently NASA is considering providing Landsat ETM-Plus bands, some atmospheric correction bands and a wedge imaging spectrometer for flight in 1999.
Landsat-8 would fly in 2004, on EOS-AM2 in this scenario.

6.2 SPOT-4, 5 and 6.

SPOT-4 will be launched in 1997 and it will have improved data storage capabilities and a 1.6 micrometer band. SPOT-5 is planned for a launch at the turn of the century and it will have a panchromatic sensor with fore and aft stereoscopic viewing and 5 meter spatial resolution. The multispectral focal plane on SPOT-5 will provide 10 meter spatial resolution data. A mid-infrared focal plane may also be included on SPOT-5 and it may collect thermal data in the 10.2 to 12.5 micrometer band. SPOT-6 could be launched in the 2003 to 2010 time frame. These plans are testimony to the commitment the French Government has placed on the SPOT program.

6.3 Japan Advanced Land Observing Satellites

ASTER. The next Japanese earth observations mission will occur on EOS-1 platform in 1998. NASA will provide launch and on orbit services for the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a three sensor instrument that will provide synoptic stereoscopic data at 15 meter spatial resolution in 3 bands, 30 meter shortwave infrared data in six spectral bands and multiband thermal data in five spectral bands with 90 meter spatial resolution

AVNIR-2. The Japanese are developing an Advanced Visible and Near Infrared Radiometer-2 for launch after 2000. This instrument will have 10 meter spatial resolution, across a 70km swath, in four multispectral bands similar to those on the Thematic Mapper. The multispectral sensor will be pointable across track. It will also have a panchromatic sensor which will provide 2.5m spatial resolution in across a 35km swath and will provide a base to height ratio of 1.

6.4 Lewis and Clark Satellites

Clark. Recently NASA selected CTA of McLean, Va to build a low-cost satellite ($49 million) to be launched later in 1996 and would provide the user community with high-spatial resolution data. Known as Clark (after the explorers Lewis and Clark), it will carry a 3-meter resolution sensor operating in panchromatic mode with a 6 km swath width and a 15 meter spatial resolution sensor operating in the VNIR with a 30 km swath width. A second satellite of This type is planned for launch later in the decade, with a 1 meter spatial resolution panchromatic sensor.

Lewis. Under the same program, NASA also selected TRW to build and launch the first spaceborne hyperspectral imaging sensor. The spacecraft is known as Lewis and its sensor is the Hyperspectral Imager (HSI). The HSI will acquire contiguous spectral data from 400nm to 2500nm in 384 spectral bands, which will be resampled to 175 spectral bands to improve the signal-to-noise ratio. The sensor will have an innovative design, weighing only 21 kg. Spatial resolution for this sensor will be 30 meters and it will be sharpened by a 5 meter panchromatic sensor. The swath width would be less than 15 km.

6.5 EarlyBird and QuickBird

EarthWatch (formed by the merging of Worldview Corp and Ball Aerospace in 1995) is building two small lightweight satellites. The first is called EarlyBird and will be launched in 1996 with two sensors: one operating in panchromatic mode (450nm to 800nm) with 3 meter spatial resolution and the other in multispectral mode (3 bands in the 500-590nm, 610 to 680nm and 790 to 890nm ranges) with 15 meter spatial resolution. Data from both sensors will be conbined into a single dataset with improved spatial and spectral resolution. The satellite will orbit at 470km, will have 30-degree fore-and-aft and side-to-side pointing capability for stereoscopy. Swath width will be 6 km in panchromatic mode and 30 km in multispectral mode.

The second satellite is called QuickBird and is planned for launch in 1998, with improved spatial and spectral resolution. The panchromatic sensor will cover a spectral range of 450nm to 800nm with 1 meter spatial resolution and the multispectral sensor will have 4 meter spatial resolution and four spectral bands in the 450 to 520nm, 530 to 590nm, 630 to 690nm and 770 to 900nm ranges. Orbit parameters and stereoscopic capabilities will be similar to EarlyBird.

6.6 Space Imaging

Space Imaging Inc, is a partnership with Lockheed-Martin Co., E-Systems/Raytheon, Mitsubishi Corp. and Eastman Kodak Co. They plan to launch a satellite in 1997 that will be similar to EarthWatch's systems in that it will carry both panchromatic and multispectral sensors. The panchromatic sensor will operate over a spectral range of 500 to 900 nanometers with 1 meter spatial resolution. The multispectral sensor will have 5 bands in spectral ranges of 450 to 520nm, 520 to 600nm, 630 to 690nm, 760 to 900nm and 1550 to 1750nm with 4 meter spatial resolution. The planned orbit will be at 680 km and the sensor will cover a swath width of 60 km. The sensor will have fore-and-aft and side-to-side pointing capability for stereoscopy.

6.7 Eyeglass

Orbital Sciences Corporation, in partnership with Itek and GDE is building the Eyeglass satellite to be launched in 1997. The satellite will carry a panchromatic sensor operating in the 500 to 900nm spectral range with 1 meter spatial resolution. The orbit will be at 700 km, with a swath width of 15 km and it will have along track stereo capability.

6.8 Resource21

Boeing and Pioneer Hi-Bred International are developing a multisatellite system with 10 meter spatial resolution to provide weekly information to farmers.

6.9 Multispectral Thermal Imager (MTI)

The U. S. Department of Energy, Sandia Laboratories is developing a 15 band instrument with 10 bands in the VNIR/SWIR and 5 bands in the TIR. Nine of the reflectance bands have 5 meter spatial resolution and 5 bands in the TIR and 1 band in the SWIR have 40 meter resolution over a 12km swath. The preliminary design phase for the instrument has been completed and launch is expected in 1998.

6.10 Sacagawea

The Jet Propulsion Laboratory is developing a light satellite that will provide spatial resolution of 15m to 30m in 5 - 10 spectral bands in the 3 to 5um and 8 to 14um portions of the spectrum, (Kahle et. al., 1995).

6.11 China-Brazil Resources Satellite (CBERS)

A cooperative ongoing program between China and Brazil is to launch a natural resources satellite in 1997. The satellite will carry 3 sensors: a CCD camera, an Infrared Multispectral Scanner and a Wide Field Imager. The CCD camera will have 1 panchromatic band (510 to 730nm) and 4 spectral bands (450 to 520nm, 520 to 590nm, 630 to 690nm and 770 to 890nm). The CCD camera will have 20 meter spatial resolution and a 120 km swath. Off nadir viewing will provide a revisit time of 3 days, while nadir viewing will revisit every 26 days. The IR-MSS will have 1 panchromatic band (500 to 1100nm) with 80 meter spatial resolution and 3 multispectral bands with 160 meter spatial resolution (1550 to 1750nm, 2080 to 2350nm and 10400 to 12500nm bandpasses), and a 120 km swath width. The Wide Field Sensor (WFI) will have two bands (630 to 690nm and 760 to 900nm), spatial resolution of 260 meters and a ground swath of 900km. It will provide cloud-free coverage every 3 to 5 days.

6.12 Importance of High-Spatial Resolution/Stereoscopic Systems for Geologic and Mineral Resources Applications

Satellite systems which provide 5 meter or less spatial resolution over swaths of more than 30 kilometers will allow geoscientists to construct digital topographic maps at 1:25,000 scale with 10 meter contour accuracy. Furthermore those systems which also collect multispectral data at 5 meter to 15 meter spatial resolution will allow thematic maps of general surface cover types to be constructed at 1:25,000 scale. These data types, coupled with Global Positioning System data, will revolutionize geologic investigations in relatively poorly mapped areas.

6.13 Government Sponsored Versus Commercial Market-driven Satellite Technologies.

In 1996, 36 new satellite systems were planned for launch within the next eight years. About one third of the 36 new satellite systems are entirely new commercial satellite systems. These commercial ventures range in initial capital expenditures from $70 million to over $300 million and the return on the corporate investments is to be generated through the commercial sale of imagery. Over the next decade a market-driven image data economy will emerge and this new marketplace will change the paradigms of image data availability and the costs for earth resources data.

7.0 RECENT ADVANCES IN DATA PROCESSING AND INTEGRATION

The above advances in sensor technology, combined with the prospects of improved spatial resolution becoming available in the near future, and being paralleled by the development of new and innovative approaches for data processing and integration. Much of this effort is likely to bring considerable benefits to geological and mineral resources applications of remotely sensed data. Furthermore, the rapidly increasing processing power of affordable desktop computers, combined with the advent of graphical user interface driven software, is progressively putting data processing within the reach of even small mineral resource companies and geoscientists.

One experimental area which is rapidly developing is that of detailed mineral identification and mapping, and their applications to exploration, mapping and environment. A number of techniques have been developed to take full advantage of hyperspectral data, such as spectral angle mapping (Kruze, et. al., 1993), convex geometry analysis (Boardman and Kruse, 1994), constrained energy minimization (Ferrand and Harsanyi, 1994) Tricorder (Clark et al. 1994; Crosta et al., 1996) and automated neural network analysis (Merenyi et. al., 1996). Lee and Landgrebe have developed techniques for extending minimum distance classification to higher spectral dimensions and Jia and Richards have developed a two-bit binary encoding technique for rapid spectral matching and hyperspectral image classification.

The need to integrate diversified and complex datasets in order to locate new mineral deposits is a consequence of exploration frontiers being moved to new and unknown environment. First realized by the petroleum industry, data integration is now becoming a daily routine for geologists working with remote sensing, geophysics, geochemistry and field data. Again, computer and software developments are facilitating this integration of multi-source data resulting in new discoveries (Dick, et al., 1993, Sabine, 1996).

8.0 GEOGRAPHIC INFORMATION SYSTEMS AND GPS

Geographical information systems represent a further step in data integration. They not only allow geoscientist to combine multi-source data sets for better and optimized use, but also they provide much more powerful analysis capabilities for extracting useful information from different data types. The combination of technologies such as remote sensing, geophysics, geochemistry, database management, GPS and GIS can provide geoscientist with resources exploration tools that were not even dreamed of one generation ago. These tools have started to be used in even the most remote areas of the world. In conjunction with telecommunication links, they are allowing geoscientists to take full advantage of all these technologies in the field, through the use of portable telephones, GPS and portable computers.

9.0 WORKING GROUP VII/4, ISPRS

Working group VII/4 deals with geological and mineral resources, including remote sensing applications in geology, geomorphology and engineering. Working Group activities are the following:

1. To identify and solicit distinguished scientists to serve as members of the Working Group and who will enable the Working Group to summarize the state-of-the-technology and science in the applications of remote sensing in geology, geomorphology and engineering.

2. Solicit papers for the Commission Symposium that demonstrate the state-of-the-art in the applications of remote sensing.

3. Submit a summary report of Working Group activities for the Commission Symposium and present the report.

4. If desired, hold a Working Group Workshop one year prior to the International Society Congress. The purpose of this workshop is to present papers which will demonstrate the state-of-the-science and -technology. These papers will serve as the basis for the Working Group's report to the Congress.

5. Solicit papers for the International Congress in Vienna that will be representative of the Working Group's findings and activities.

The focus of Working Group VII/4's interests are in the following areas:

1. Hyperspectral Remote Sensing in the visible, near-infrared and shortwave infrared.

2. Multispectral Remote Sensing in the thermal infrared.

3. Multispectral/Multipolarization radar.

4. High-spatial resolution stereometry and SAR interferometry.

5. Application of image processing and analysis technique to mineral and petroleum exploration and to engineering geology.

6. Application of geographic information system techniques to mineral and petroleum exploration and to engineering geology.

9.1 Current Membership in Working Group VII/4

James V. Taranik, Desert Research Institute, Chairman
Alvaro P. Crosta, University of Campinas, Co-Chairman
Michael Abrams, Jet Propulsion Laboratory
Robert Agar, GEOSCAN
Carmen Anton-Pacheco, Inst. Tech. GeoMinero, Spain
Robert Crippen, Jet Propulsion Laboratory
Chris Elvidge, Desert Research Institute
Jeff R. Harris, Geological Survey of Canada
Scott Hills, Chevron Petroleum Technology Company
I. Ioffe, Geological Institute, RAS, Russia
Anne B. Kahle, Jet Propulsion Laboratory
Fred Kruse, University of Colorado
Guillermo Re Kuhl, FMC Gold, Reno
Thomas McCord, University of Hawaii
Fernando P. Miranda, Petrobras, Brazil
Jose S. Moretsohn, TVX Gold, Chile
Sandra Perry, Denver, Colorado
David Mouat, Desert Research Institute
Larry Rowan, U. S. Geological Survey
Chuck Sabine, Desert Research Institute
Verne Singhroy, CCRS
David Spatz, BHP Minerals
Adelir S. Strieder, Univ. Rio Grande do Sul, Brazil
Dan Taranik, RTZ, Spain
Freek Van der Meer, ITC, Netherlands

The Working Group has held two workshop/meetings in conjunction with major international meetings. It met during the ASPRS/ACSM Annual Meeting in April 1994 in Reno, Nevada and during the 11th Thematic Conference on Geologic Remote Sensing in Las Vegas. Most of the activities of the Working Group are conducted through E-mail and conventional mail.

10.0 POST ECO RIO' 94 WORKING GROUP REPORT

At ECO Rio' 94 Working Group VII/4 presented 19 papers and published 19 papers in the proceedings. The papers that were presented and/or published were the following:

Recent Developments in Aerospace Remote Sensing for Geology and Mineral Resources (Taranik and Crosta)

Litho-Structural Mapping of the Area Containing the Riacho dos Machados Gold Deposit Using Landsat/TM imagery (Hernandes and Crosta)

Image Processing Applied to Detecting Hydrothermal Alteration Minerals in the Riacho dos Machados Gold Deposit Using Landat/TM (Hernandes and Crosta)

Exploration for Copper-Molybdenum-Gold Porphyry Deposits Using Multispectral and Hyperspectral Aerospace Remote Sensing Techniques (Spatz and Taranik)

Spectral Behaviour Analysis of Au and Cu-Pb-Zn Orebodies using Convolutional Correlation of TM-Landsat Data (Araujo and Carvalho)

Comparison of JERS-1, with SPOT and Landsat Image Data for Detection and Mapping of Hydrothermal Alteration at Goldfield-Cuprite, Nevada, U.S.A. (Taranik, et. al.)

Some South American Case Studies in Geobotany (Dyer)

Estimating the Degree of Serpentization of Ultramafic Rocks from GER 63-Channel Imaging Spectrometer Data (van der Meer)

Discrimination of Ignimbritic Rocks in Southern Argentina Using Landsat Thematic Mapper Imagery (Mehl and Reimer)

SAREX Imagery for Lineament Study in the Salobo Area, Carajas Mineral Province, Brazil (Liu, et. al)

Geology of the Southeastern Sirte Basin, Lybia, Based on Photointerpretation of Landsat TM images (Braun, et. al.)

Use of IHS Transformation in Integration of CSMAT, Geochemical and TM-Landsat Data (Carvalho, et. al.)

The GIS and Image Processing State of the Art in Petrobras/CENPES (Bentz, et. al.)

Joint Remote Sensing Study in Northeastern Brazil using GIS Techniques for Oil Exploration (Yamakawa, et. al.)

Xiangshan Uranium Exploration Spatial Data Base Creation and Preliminary Data Integration on GIS (Xu, et. al.)

Development of a GIS-Based Program for Environmental Management and Resettlement Purposes (Woolpert)

Image Processing and Data Integration for Gold Exploration: An Example of the Methodology Used in the Monthezuma Area, Northern Minas Geris State, Brazil (Franca, et. al.)

Identification of Tectonic Structures Through TM-Landsat Imagery: Natividade da Serra and Caraguatatuba Sheets, SP, Brazil (Okida, et. al.)

The paper presented by Dr. David Spatz of BHP Minerals in Tucson, Arizona was selected as the best of session for publication in the SELPER Special Review of the ECO RIO' 94 Symposium. Working Group VII/4's ECO RIO was also published in the December 1994, Volume of SELPER.

The Working Group met on February 28, 1996 in Las Vegas at the ERIM Thematic Conference on Exploration Geology. At that meeting the organization of the ISPRS Congress Meeting was discussed and the content of this final report. The Working Group has had 12 oral papers and 13 papers accepted for the ISPRS Congress in Vienna.

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